gests that microbial life, if any, will not be distributed ubiquitously in harsh environments. In addition, it raises new questions regarding the vulnerability of Mars to contamination by terrestrial microorganisms (*15*).

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References and Notes

1. G. A. Llano, in *Antarctica*, T. Hatherton, Ed. (Methuen, London, 1965), p. 331; W. L. Boyd, J. T. Staley, J. W. Boyd, in *Antarctic Soils and Soil Forming Processes, Antarctic Research Series*, J. C. F. Tedrow, Ed. (American Geophysical Union, Washington, D.C., 1966), vol. 8, p. 125; R. E. Cameron, *Jet Propulsion Laboratory Space Programs Summary No. 37–44* (California Institute of Technology, Pasadena, 1967), vol. 4, p. 224; R. E. Benoit and R. E. Cameron, *Bacteriol. Proc.* **1967**, 3 (1967).
2. L. E. Allison, *Soil Sci. Soc. Amer. Proc.* **24**, 36 (1960).
3. R. E. Cameron, G. B. Blank, D. R. Gensel, *Jet Propulsion Lab. Tech. Rep. No. 32–908* (1966).
4. P. G. Simmonds, G. P. Shulman, C. H. Stembridge, *J. Chromatogr. Sci.* **7**, 36 (1969).
5. Soil No. 542, stored in standard bags, was used for some of the other experiments described here for which interference was below detectable levels.
6. R. E. Cameron, C. N. David, J. King, *Antarctic J. U.S.* **3**, 164 (1968).
7. O. N. Allen, *Experiments in Soil Bacteriology*, (Burgess, Minneapolis, ed. 3, 1957).
8. M. E. di Menna, *Antonie van Leeuwenhoek J. Microbiol. Serol.* **32**, 29 (1966).
9. G. G. C. Claridge and I. B. Campbell, *Nature* **217**, 428 (1968).
10. R. E. Cameron, in *Arid Lands in Perspective*, W. G. McGinnies, B. J. Goldman, P. Paylore, Eds. (Univ. of Arizona Press, Tucson, in press).
11. J. Kosaka, C. Honda, A. Iseki, *Soil Plant Food Tokyo* **5**, 77 (1959).
12. P. J. Geiger and J. P. Hardy, in preparation.
13. T. C. Hoering, in *Researches in Geochemistry*, P. H. Abelson, Ed. (Wiley, New York, 1967), vol. 2, p. 87.
14. A. D. Allen, *N.Z. J. Geol. Geophys.* **5**, 278 (1962).
15. N. H. Horowitz, R. P. Sharp, R. W. Davies, *Science* **155**, 1501 (1967).
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Precambrian Columnar Stromatolites in Australia: Morphological and Stratigraphic Analysis

Abstract. *The stratigraphic distribution in Australian Precambrian rocks of columnar stromatolites, organosedimentary structures formed by blue-green algae, has been investigated. Their morphology is being studied according to methods developed in Russia. The discovery of successive different assemblages supports not only regional but also intercontinental stratigraphic correlations which are in agreement with available isotopic datings.*

"Stromatolites stand in roughly the same relation to blue-green algae as coral reefs to corals" (*1*). They are sedimentary structures produced by life processes of Cyanophyta in various associations of species and genera, possibly also with other algae and bacteria. From these undisputed facts the conclusion was drawn (*2*) that the variable gross form of these structures was due to variations in environmental factors, although the microstructure rarely if ever shows identifiable remains of algal cells. Hence any evolutionary change which could be morphologically ascertained and lead to stratigraphic correlations based on stromatolite occurrences was considered unlikely. Correlations by means of these fossils, at ranges in time and space greater than those of specific local environments, were discouraged.

Undeterred by these views, a group of Russian workers (*3, 4*) carried out systematic studies of the morphology and stratigraphic distribution of stromatolites from many regions of the U.S.S.R. From the results of their work we concluded that although the gross forms and structures of most stromatolites may be too simple to allow recognition of diagnostic characters and some variations are due to environmental factors, nevertheless, columnar forms do exhibit sufficiently clear diagnostic characters (Figs. 1 and 2). Their distribution in four successive assemblages of form genera has been convincingly described from many sequences of Precambrian rocks in the U.S.S.R. A division into five assemblages has recently been suggested (*4*).

We collected or obtained material from all major areas of essentially unmetamorphosed Precambrian sediments in Australia, and studied selected specimens according to Krylov's method of "graphic reconstruction" from serial sections of columns. Illustrations of examples of form taxa and a brief discussion of most of the characters used in their distinction are given by Raaben (*4*). Although accepting most of these taxa, we concur with some other Russian workers in attributing more significance to gross features and less to microscopic structures which are commonly affected by diagenesis. Figure 1 illustrates terms to be used in diagnoses. Character combinations rather than single features distinguish form genera and species. Some characters vary considerably within single species, but dominance of a modal form makes it possible to recognize distinctive characters.

The results of work on two areas which is nearing completion are here reported (Fig. 3). The Skillogalee Dolomite, occurring low in the Burra Group ("Torrensian"), in the Adelaide Geosyncline, South Australia, contains a uniform assemblage of *Baicalia* spp. over a distance of 450 km. The formation typically comprises pale-colored, relatively pure dolomite and minor clastics in its lower part, and dark gray, either massive or thinly bedded argillaceous dolomites, together with sedimentary magnesite conglomerates, secondary black chert, and minor clastics in its upper part. In different localities, *Baicalia* spp. occur in each of these rock types except the clastics. Many Russian form species of *Baicalia* have been distinguished by textural features of the lamination which are at least in part diagenetic. This makes identification with previously described form species uncertain.

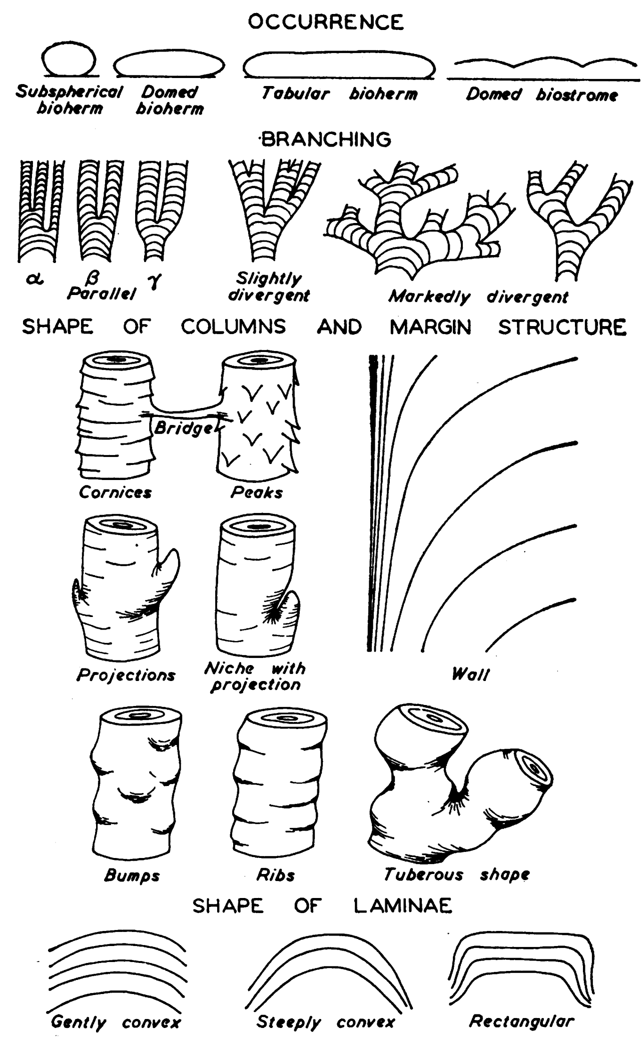
Conophyton cf. *garganicus* was found in a large dolomite raft in a diapir. The age of the dolomite is uncertain but it must be older than the upper part of the Burra Group, which the diapir intrudes; it probably came from the lower Burra Group or the underlying Callanna Beds. Although textures of stromatolites must be interpreted cautiously, structures (shape and thickness variations of laminae) of conophytons are distinctive and significant for the subdivision of the form genus into form species. *Conophyton* cf. *garganicus* is identified by its even dark and light laminae, the dark laminae being uniformly lenticular. *Conophyton* cf. *garganicus* occurs *in situ* in the Irregully Formation of the Bangemall Group, in the Capricorn Ranges of the North West Division, Western Australia.

The Burra Group is everywhere overlain, often with demonstrable unconformity, by the Umberatana Group, which has a tillite ("Sturtian") at its base. The stromatolite assemblage of the Umberatana Group is radically different from that of the Burra Group. In the Southern Flinders Ranges, the Brighton Limestone contains *Katavia* sp. nov. and *Inzeria* sp. nov. II, while farther south, a higher unit contains *Patomia* sp. nov. *Gymnosolen* sp. has so far been found only in limestone blocks in a sedimentary breccia on the flanks of a small diapir. Its exact age is unknown, but it cannot be younger than the Tapley Hill Formation in which the breccia is intercalated.

The upper member of the Bitter Springs Formation in the Amadeus Basin, Central Australia, contains a rich and varied assemblage of stromatolites, including at least five columnar types. The most common and widespread form was described by Howchin (*5*) as *Cryptozoon australicum* (and *C. tesselatum*, a synonym). Edgell (*6*) identified this form species from the Duck Creek Dolomite of Western Australia, discarding the generic name *"Cryptozoon"* in favor of *"Collenia."* Both these names are inappropriate. The specific identification of the Western Australian fossil is unacceptable (i) because it is based on one small, inadequate specimen, the gross features consequently being unknown, and (ii) because in this specimen the laminae are consistently more steeply domed than in *Cryptozoon australicum*. Edgell also suggested that several other described forms are synonymous with his *Collenia australasica* (sic), but his supporting data are insufficient. Howchin's species represents a new form genus.

Other stromatolites occurring in the upper member of the Bitter Springs Formation include *Boxonia* sp. nov., *Inzeria* sp. nov. I, *Linella avis* Krylov, and *Minjaria* sp. nov. *Inzeria* sp. nov. I closely resembles *Inzeria tjomusi* Krylov, from which it is distinguished by having proportionally smaller and frequently transversely elongated niches and niche projections, a more irregular shape, and a different mode of occurrence. *Tungussia* sp. nov. II occurs in the lower member of the Bitter Springs Formation.

The lower tillite (Areyonga Formation), lying disconformably above the



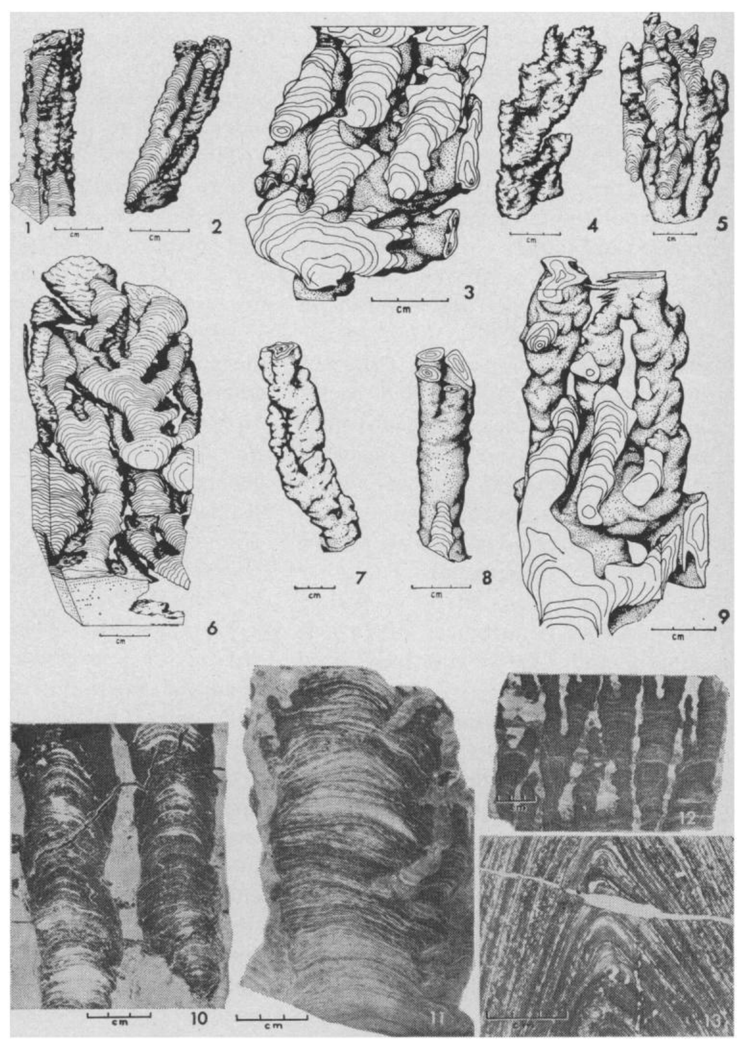


Fig. 1 (left). Diagnostic terminology. Fig. 2 (right). Australian Precambrian stromatolies. *1–9*: Reconstructed from longitudinal serial sections. Only selected laminae drawn on cut surfaces. *10–13*: Longitudinal sections. (The few illustrated specimens do not show the total range of variation.) *1, 2, 4,* and *5* are of the Umberatana Group. *1, Patomia* sp. nov.; *2, Katavia* sp. nov.; *4, Inzeria* sp. nov. II; *5, Gymnosolen* sp.; *3,* Ringwood Member, *Tungussia* sp. nov. I; *6,* Burra Group, *Baicalia* sp.; 7–12, Bitter Springs Formation; *7, Linella avis* Krylov; *8, Boxonia* sp. nov.; *9, Tungussia* sp. nov. II; *10, Minjaria* sp. nov.; *11, Inzeria* sp. nov. I; *12, "Cryptozoon" australicum* Howchin; *13,* Bangemall Group, *Conophyton* cf. *garganicus* Korolyuk—only half-width of column shown. (Specimens in the Department of Geology, University of Adelaide.)

ADELAIDE GEOSYNCLINE: ROCK UNITS	ADELAIDE GEOSYNCLINE: FOSSILS	AMADEUS BASIN: ROCK UNITS	AMADEUS BASIN: FOSSILS	CORRELATION
HAWKER GROUP: WILKAWILLINA LS. PARACHILNA FM.	STROMATOLITES, ARCHAEOCYATHA, BRACHIOPODS, ETC. WORM BURROWS	LOWER CAMBRIAN LS.	ARCHAEOCYATHA, BRACHIOPODS, ETC.	LOWER CAMBRIAN
WILPENA GROUP: POUND QUARTZITE (CLASTICS)	EDIACARA FAUNA TRACE FOSSILS	ARUMBERA FM. (CLASTICS)	WORM BURROWS, TRACE FOSSILS, MEDUSA, RANGEA CF. LONGA	VENDIAN 650–570 M.Y.
UMBERATANA GROUP: (UPPER TILLITE) (CLASTICS AND LS.) BRIGHTON LS. TAPLEY HILL FM. (LOWER TILLITE)	PATOMIA SP. KATAVIA SP., INZERIA SP. II GYMNOSOLEN SP.	PERTATATAKA FM. (DOLOMITES, CLASTICS) (UPPER TILLITE) (CLASTICS) RINGWOOD MEMBER; AREYONGA FM. (LOWER TILLITE, CLASTICS)	TUNGUSSIA SP. I	
—?—	?	BITTER SPRINGS FM. (UPPER MEMBER) (LOWER MEMBER)	"CRYPTOZOON" AUSTRALICUM LINELLA AVIS, BOXONIA SP. MINJARIA SP. INZERIA SP. I TUNGUSSIA SP. II	UPPER RIPHEAN 950–650 M.Y.
BURRA GROUP: (CLASTICS & DOLOMITE) SKILLOGALEE DOLOMITE (SANDSTONE & QUARTZITE)	BAICALIA SPP. CONOPHYTON CF. GARGANICUS	HEAVITREE QUARTZITE		MIDDLE RIPHEAN 1350–950 M.Y.
CALLANNA BEDS: (CLASTICS, DOLOMITE, VOLCANICS)		—?—		

Fig. 3. Stratigraphic distribution of some Australian Precambrian fossils (FM, formation; LS, limestone).

Bitter Springs Formation, is overlain by the Pertatataka Formation, which only rarely contains columnar stromatolites. One such fossil, *Tungussia* sp. nov. I, occurs in the Ringwood Member, not far above the lower tillite.

The stromatolites of the Bitter Springs Formation are mostly easily distinguishable in the field. No intermediate types are known, except possibly for *Linella avis* and *Minjaria* sp. nov., which occur together in one biostrome. Different stromatolites occur in identical rocks, within less than a meter of each other stratigraphically. *"Cryptozoon" australicum* occurs frequently and is widely distributed over distances of more than 300 km, and *Boxonia* sp. nov. is known from two areas 100 km apart. The other forms are not known to be so widely distributed, but occurrences of *Inzeria* sp. nov. I and *Linella avis* have been traced for up to 1 km.

The stromatolite assemblages of the upper member of the Bitter Springs Formation and the Skillogalee Dolomite of the Burra Group have no form genera in common. In the Skillogalee Dolomite, similar stromatolites occur in various rock types, while the Bitter Springs Formation contains a very varied assemblage in identical rocks. Concluding, therefore, that environmental variations within the carbonate facies do not explain satisfactorily the differences between the stromatolites of these two formations, we suggest that they are not of the same age. Correlation of what is now known as the Heavitree Quartzite and the Bitter Springs Formation with the "Torrensian" had been proposed by Mawson (*7*) and accepted by later authors, though some (*8*) considered the Bitter Springs Formation as older than the Burra Group.

Time ranges of the stromatolite form genera, as determined from many parts of the U.S.S.R. (*3, 4*), indicate that with the exception of *"Cryptozoon" australicum,* so far not reported by Russian investigators, and *Linella avis,* whose stratigraphic position is still doubtful, the Bitter Springs assemblage is characteristic of the Upper Riphean (950 ± 50 to 650 ± 50 million years), while *Baicalia,* found in the Burra Group, is generally restricted to the Middle Riphean (1350 ± 50 to 950 ± 50 million years), and also occurs in the lowermost part of the Upper Riphean in Central Siberia.

We stated that a specimen of *Conophyton* cf. *garganicus* comes either from the Burra Group or from older sediments (Callanna Beds). This form species is known only from Lower (1600 ± 50 to 1350 ± 50 million years) and Middle Riphean. As the Callanna Beds are unlikely to be older than 1350 to 1400 million years (*9*), a correlation either of the Callanna Beds or of both these rock units of the Adelaide System with the Middle Riphean receives paleontological support from this find. The occurrence of the same fossil in the Bangemall Group of Western Australia is in good agreement with a radiometric age determination of 1080 ± 80 million years of a shale several hundred meters above the Irregully Formation (*10*).

The stromatolites of the Umberatana Group assemblage are restricted to the Upper Riphean (*Inzeria, Katavia* and *Gymnosolen*) and possibly Vendian (*Patomia*), indicating a probable Upper Riphean to Vendian age, that is 950 ± 50 to 570 ± 15 million years. The occurrence in the Pertatataka Formation which includes shales dated at about 790 million years (*10*), of *Tungussia* (Middle Riphean to ?Vendian), does not conflict with its correlation with the Umberatana Group of the Adelaide Geosyncline where Upper Riphean to Vendian stromatolites occur.

The first results of the morphological and stratigraphic analysis of Australian stromatolites confirm their potential value for the discrimination and stratigraphic correlation of otherwise unfossiliferous Precambrian strata. This is an important addition to their recognized paleoecological significance as indicators of a lagoonal, littoral, or sublittoral environment (*2*).

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References and Notes

1. V. P. Maslov, *Trans. Geol. Inst. Akad. Nauk S.S.S.R. No. 41* (1960).
2. P. E. Cloud, Jr., *Amer. J. Sci.* **240**, 363 (1942); B. W. Logan, R. Rezak, R. N. Ginsburg, *J. Geol.* **72**, 68 (1964); R. Rezak, *U.S. Geol. Surv. Prof. Pap. No. 294 D* (1957), p. 127.
3. B. M. Keller, *Dokl. Earth Sci. Sect.* (English transl.) **171**, 132 (1967); B. M. Keller, G. A. Kazakov, I. N. Krylov, S. V. Nuzhnov, M. A. Semikhatov, *Izv. Acad. Sci. U.S.S.R. Geol. Ser. No. 12* (1960), p. 21 (translation, 1961); V. A. Komar, *Trans. Geol. Inst. Akad. Nauk S.S.S.R. No. 154* (1966); ———, M. E. Raaben, M. A. Semikhatov, *ibid. No. 131* (1965); I. K. Koroljuk, *Int. Geol. Congr. 21st Copenhagen Proc. Sect. 8* (1960), p. 113; I. N. Krylov, *Trans. Geol. Inst. Akad. Nauk S.S.S.R. No. 69* (1963); *ibid. No. 171* (1967); M. A. Semikhatov, *ibid. No. 68* (1962).
4. M. E. Raaben, *Amer. J. Sci.* **267**, 1 (1969). (This paper came to our notice after our report had been submitted to *Science*. We are not entirely in agreement with the proposed major classification and terminology but find our basic conclusions substantiated in this contribution.)
5. W. Howchin, *Trans. Roy. Soc. S. Aust.* **38**, 1 (1914).
6. H. S. Edgell, *J. Geol. Soc. Aust.* **11**, 235 (1964).
7. D. Mawson, *Aust. J. Sci.* **19**, 162 (1957).
8. P. R. Dunn, K. A. Plumb, H. G. Roberts, *J. Geol. Soc. Aust.* **13**, 593 (1966).
9. B. P. Thomson, *ibid.*, p. 203.
10. W. Compston and P. A. Arriens, *Can. J. Earth Sci.* **5**, 561 (1968).
11. We thank V. V. Menner, I. N. Krylov, and M. A. Semikhatov for discussions and information. Drs. B. W. Logan and R. G. Brown conducted two of us (M.R.W. and W.V.P.) about the stromatolite occurrence at Shark Bay. Specimens belonging to the Geological Survey of Western Australia were lent by J. H. Lord. Supported by a grant from the Petroleum Research Fund of the American Chemical Society (to M.F.G.), a Conzinc Riotinto of Australia Ltd. postgraduate research scholarship (to M.R.W.), and a Commonwealth postgraduate award (to W.V.P.).

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