Stromatolites: The living relics of Earth's Beginning

Nipa Sen
PG-II, Department of Applied Geology
Durgapur Government College
Durgapur-713214, West Bengal
Corresponding email: nipasen01@gmail.com

Abstract: Stromatolites are basically geological wonders. These are organo-sedimentary structures formed mainly in shallow marine conditions. Although the debate is still going on about the origin of stromatolites whether it is of biotic or abiotic origin, the biotic origin is widely accepted. Cyanobacteria forms microbial community which helps in trapping and binding the sediments together which become lithified to produce stromatolites. Also known as the earliest fossil form, stromatolites first appeared about 3.5 Ga ago and surprisingly still exist today, though rare. Because some morphological forms got extinct. When we see through geological time, we found during Archaean they are having a very low abundance, which rose to its peak during Early and Mid-Proterozoic and then again reduced during Late Proterozoic and Phanerozoic eon. Stromatolites are great paleoenvironmental and paleobiological indicators, and also have some astro biological significance.

Key Words: Biotic and abiotic origin, Cyanobacteria, Morphological forms, Abundance, Extinct, Paleobiology, Paleoenvironment.

Prologue

Stromatolites, a layered sedimentary structure creates a mystery on its own. The term was first used by E. Kalkowsky (1908). Here the Greek word "Stroma'' means "layer'' and "lithos'' means "rock''. There is not universally accepted definition as the origin of stromatolite is still debatable. A recent and widely accepted definition indicates that "Stromatolites are organo-sedimentary structures produced by sediment trapping, binding and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes" (Walter 1976). These are generally considered as lithified microbial mat formed by cyanobacteria almost 3.5 Ga ago. Being the oldest life form of Earth (found in both fossil and living forms surprisingly), it has witnessed the entire evolution of life on Earth; abundantly found during the Precambrian times and are also found today but rare.

Origin: The Ongoing Debate

Determining the origin of stromatolites is challenging, many researches are still working on this topic. There are two theories of origin mainly presented – Biotic (widely accepted) and Abiotic origin. Biotic origin suggests that the formation is totally by the activity of micro-organisms whereas abiotic one forms through entirely physical or chemical processes without interaction of living beings. Some studies suggest that biotic and abiotic processes act together in their formation. Stromatolites form through the trapping, binding, and cementation of sedimentary grains by biofilms of microorganisms. Mainly, the microorganisms are cyanobacteria (also known as blue-green algae), but sulphate-reducing bacteria and pseudomonadota (proteobacteria) also form stromatolites. The formation of stromatolite occurs in the following two steps:

1. Microbial Mat Formation: Stromatolites are generally formed in shallow water environments. Communities of microorganisms, mainly the cyanobacteria organize into layered "microbial mats''. By the process of photosynthesis, they produce adhesive compounds which help the microbial mats to trap and bind sediments (Fig. 1A), creating unique layered structures.

2. Accretion and Cementation: The trapped sediments accumulate over time as the microbial mats grow and these sediments are cemented together by the help of calcium carbonate precipitated from the water (Fig. 1B). As a result, layers of stromatolites build up gradually (as shown in Fig. 1C and Fig. 1D).

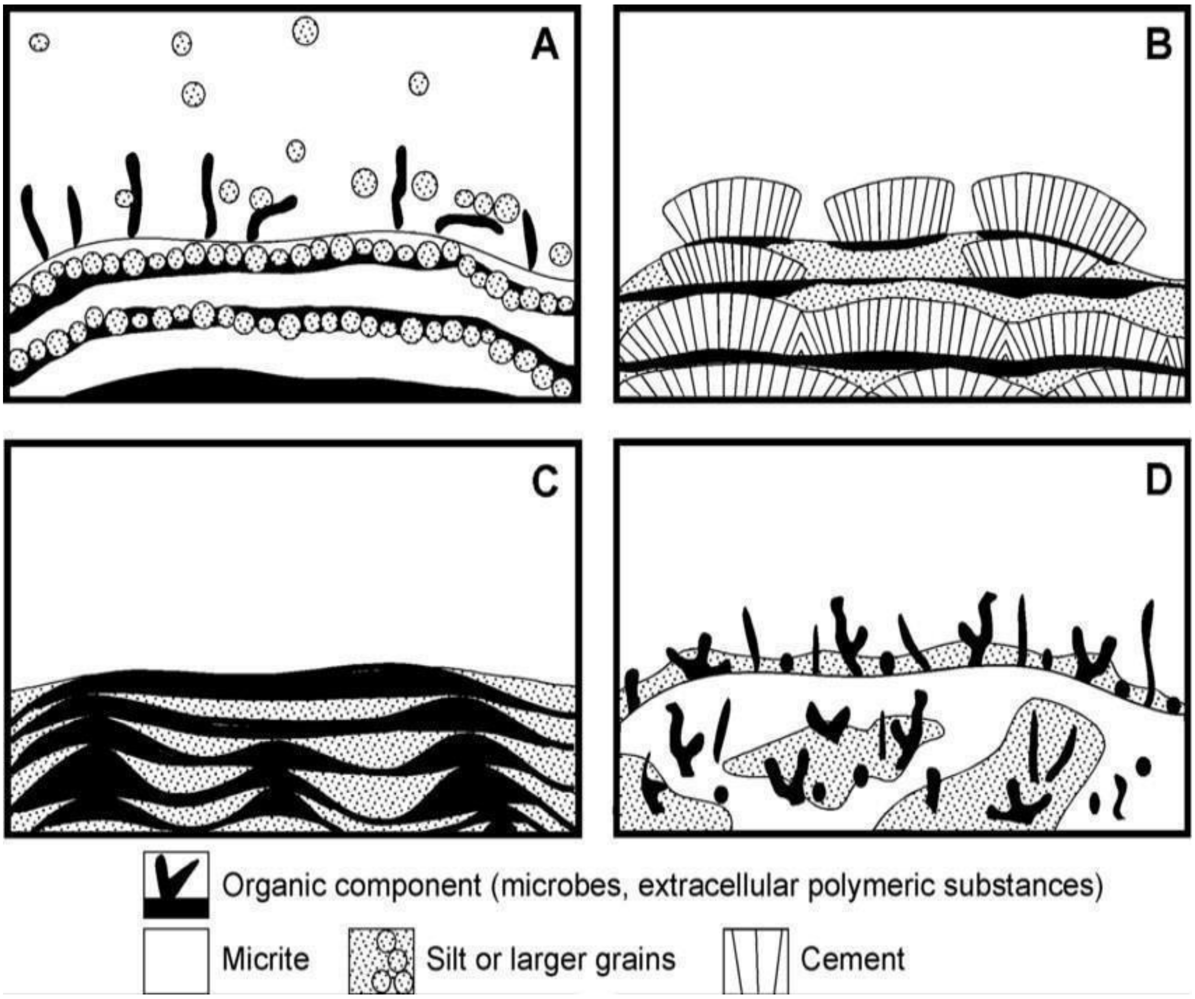

Fig.1. Diagrams of the four models of stromatolite accretion. (A) Trapping and Binding. Successive generations of microbial filaments trap grains or mud and bind the sediments via. precipitated cements. (B) Precipitation. Cements are nucleated either directly upon decaying organic compounds or adjacent to the organics with little or no clastic sedimentary component. (C) Sealing. Mechanical sediment accumulates in depressions and microbial communities spread over the sediments, sealing the deposit. (D) Skeletal. The microbialite is composed of microbial body fossils (external or internal molds, casts, permineralized sheaths) (Shapiro, 2007).

During the Precambrian eon, stromatolites were much more abundant than today, having a wide variety of sizes and morphologies, and built massive reefs of sediments whose organic and inorganic carbon isotopic signatures suggest large scale solar energy conversion with primary productivity comparable with that seen today in Coral reefs (Bosak et al.,2013). Oxygen producing cyanobacteria are generally considered to have appeared first during Early or Middle Archaean. So, what about the Archaean stromatolites if cyanobacteria was absence at that time? (John F. Allen, 2016). And there is also clear and multiple evidences that the Earth's oceans and atmosphere were anoxic for roughly half its history, until 2.4 billion years (Knoll et al., 2016). In South Africa and Western Australia, stromatolites dated a billion years before the start of the rise of oxygen concentration (Hofmann et al., 1999; Allwood et al., 2006; Nutman et al., 2016).

Abiotic stromatolites may form through fallout of suspended sediments (sediments settling out from the water column), downslope movement of sediment, surface normal precipitation and random effects such as various physical and chemical interactions.

The theory of biotic origin has been discussed in this article.

Morphology

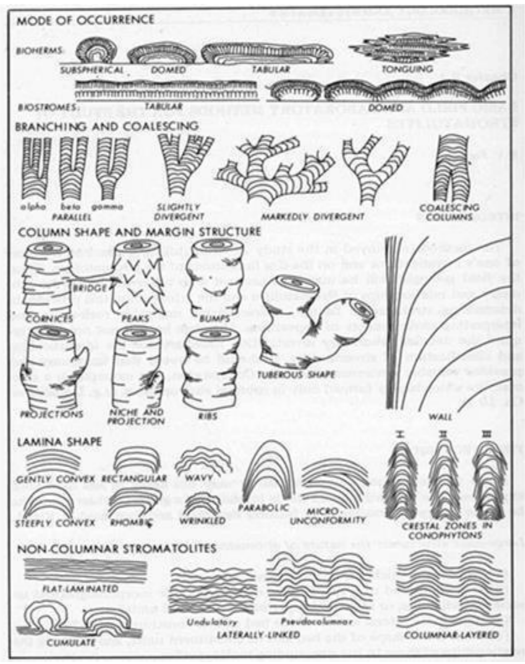

Fig.2. Morphology of Stromatolites (Stromatolites by M.R. Walter,1976)

Stromatolites show a wide range of morphology. They can grow in the form of single columns or domes, and they can range from low relief mounds, bulbous masses or long slender columns with branching extremities (some common morphological types have been shown in Fig.2) Major unique shapes include: cone-shaped structures (Komar et al.1965), laterally linked cones (Vlasov 1977), conical forms with branches (Shapovalova 1968), unbranched columns (Korolyuk 1960), branching columns (Krylov 1963), domes (Kennard1981), stratiform stromatolites or planar laminated stromatolites or "cryptalgalaminites";(Aitkin1967), round shaped thrombolites having no proper lamination have been found. These can occur in bioherms, biostromes, or they can also occur as isolated structures.

Fig.3. Lamination in Stromatolite

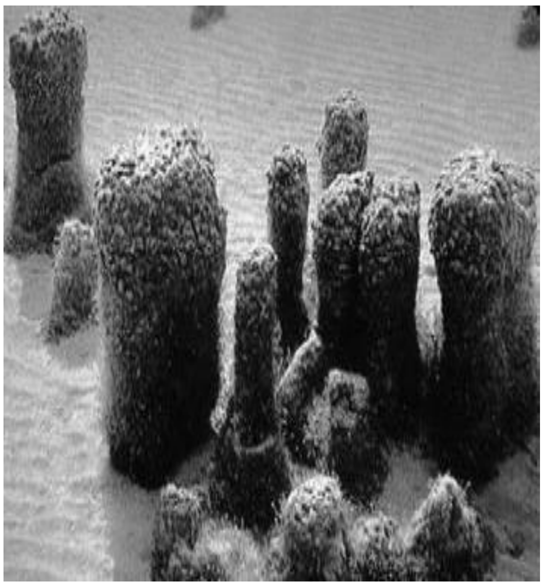

Fig.4. Column shaped Stromatolites

Fig.5. Dome shaped Stromatolites

Fig.6. Thrombolites

There are variability in the nature of the microstructure and laminae, on a mesoscopic to microscopic scale (Awramik,1992).

Size can vary from few milimeter to meter. As an example, conically shaped structures can vary in diameter from less than 1 cm for Recent forms in Yellowstone National Park (Walter et al. 1976) to 10 m in Middle Proterozoic of Canada (Donaldson 1976). Growth is mainly dependant on the quantity of sediment supply, availability of photic zone and amount of oxygen.

Though from the study it is found that in comparison to the Precambrian time, branching columnar stromatolites declined, conical stromatolites, *Conophyton* (57 forms had been described); got extinct (McNamara and Awramik,1992), the branching was bifurcating and less diverge, domical and non-branching stromatolite become common during Phanerozoic (Awramik,1992).

Stromatolite through the Eyes of Time

Archaean Stromatolites

The Archean stromatolites though not well understood; are found in thin localised sedimentary carbonate rocks mostly associated with volcanic sequences (Hofmann, 2000). The oldest known stromatolites dated back to 3500 Ma (Pidgeon 1978; Kroner and Todt 1988); are found in the Pilbara region of Western Australia (Lowe 1980b; Walter et al. 1980; Buick et al. 1981) and the Barberton Mountain Land of South Africa (Byerly et al. 1986). Stromatolites are rare during this eon, less than 20 occurences mainly from Late Archaean are known that includes some non-marine forms also (Fortescue stromatolites, Walter 1983; Ventersdorp stromatolites, Buck 1980).

Some varieties of stromatolites in Late Archaean time includes wavy laminated (stratiform), nodular, domical, pseudo-columnar, columnar, conical, and oncolitic types. Columnar and columnar-branching stromatolites were present (Cloud and Semikhatov 1969; Walter 1972b) but were not abundant until Early Proterozoic. There is a similarity of the macro and microstructure of these stromatolites to the younger ones, which sometimes suggest that cyanobacteria were involved to build them.

An Archaean stromatolite from the Chitradurga Group, Dharwar Craton, India was found and described by Sharma and Shukla (2004); which is more than 2.6 Ga in age. Here, stromatolites occur in the cherty dolomite member of the Vanivilas and Joldhal formations of the Chitradurga Group. The stromatolite morophotype is named as *Batiola Indica* (Fig.7); this name has been derived due to cup-shaped appearance of stromatolites.

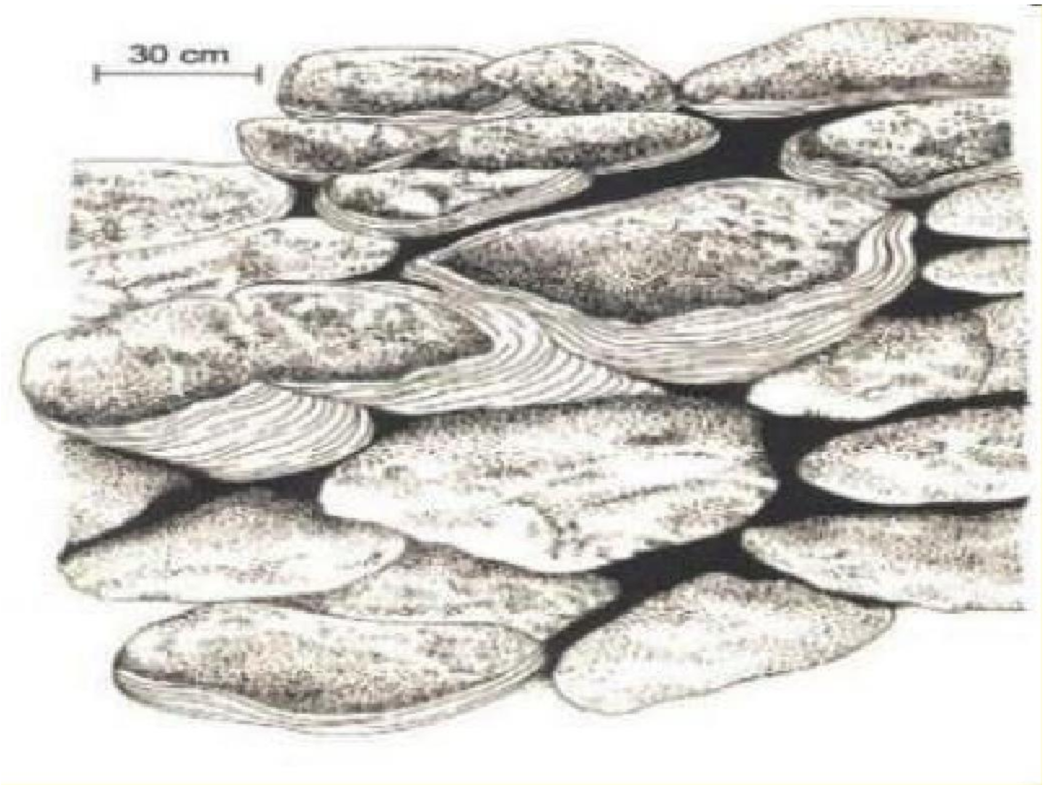

Fig. 7. Line sketch of *Batiola Indica* (after Sharma & Shukla, 2004)

Causes of Low Abundance during Archaean

Stromatolites already appeared earlier during this eon but major morphological varieties had evolved lately. So, the question arise why is it so? The answer could be mainly due to biological reasons, as in early Archaean times the basins are characterised by rapid deposition, formed in greenstone belts in subsiding basins or in unstable alluvial settings (Lowe 1980a). In this type of active setting, it is difficult for the phototrophic microbes to maintain themselves at or near the sediment-fluid interface, influence sedimentation, and produce stromatolites (Awramik, 1992). Whereas during Late Archean stable, shallow-water environment produced ideal conditions for microbial construction of stromatolites and their expansion due to development of continental shelves and platforms like feature (Cloud 1976) .

The Rise and Fall Of Stromatolites: Proterozoic Journey

Preoterozoic, the only time when stromatolites were in their peak of abundance and their morphology became very diverse. Few published data base and histogram from Awramik (1971), Walter and Heys (1985), again Awramik (1991) help to outline the pattern of stromatolite abundance. Though neither of these histograms are fixed new stromatolite taxa will continue to be added.

Here, in this frequency curve two diversifications occurred; one during the Early to Late Aphebian (2350 to 1925 Ma ago) and other during the Early to Middle Riphean (approximately 1500 to 1200 Ma ago). Then, again during Venedian (Late Proterozoic) and the Paleozoic (Phanerozoic) the abundance got decreased

Using the data of Walter and Heys (1985), Awramik published the following frequency curve:

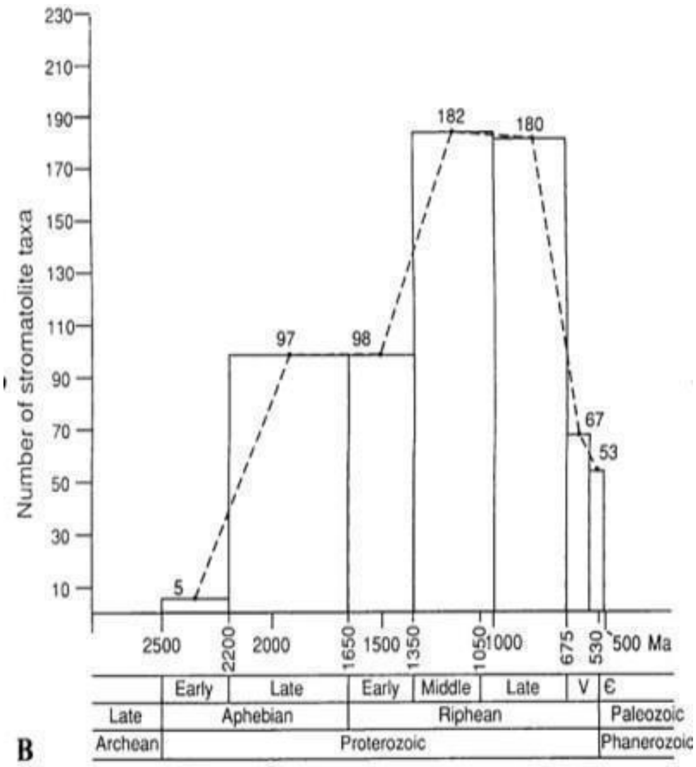

Fig.8. Frequency distribution of stromatolite taxa through time "evolving stromatolite histograms or diversity curves" (after Awramik,1992)

.

Causes of Diversification

According to Awramik (1991) around 2300 Ma (Paleoproterozoic), the environment started to become oxic (Cloud, 1976) and it caused rapid diversification of stromatolite building microbes. During that time, cratons were produced and intercratonic interactions created more basins. Hence, the shallow water environments favoured the growth of stromatolites. However, the second diversification was difficult to explain. A slight increase in cyanobacterial taxa is noticeable in the microbial fossil record (Schopf, 1977). Awramik (1991) explains that the appearance and diversification of eukaryotes played a significant role. During this time, benthic eukaryotic algae and cyanobacteria coexisted. The competition between benthic eukaryotic algae and cyanobacteria might have resulted in a further cyanobacterial diversification and so the number of stromatolite taxa also increased.

A Shift from Abundance to Decline

During Venedian (Late Proterozoic) and into the Paleozoic (Phanerozoic) these earliest life forms of Earth again reduced in number. Various reasons have been given in accordance to this. Awramik (1971) gave metazoans disturbance hypothesis, that the grazing animals feed on surface algal mats and the burrowing animals destroy sedimentary laminations. So, the abundance got decreased. This was later criticized by Monty (1973) as there were no direct evidence of bioturbated Venedian stromatolites. He proposed that this happens due to competitive exclusion of stromatolites by benthic algae (eukaryotes) and there is a role of changes in seawater chemistry. Later he suggested that it was due to glaciation.

Later, Walter and Heys (1985) agreed with Awramik. Meiofauna and zooplankton were mainly responsible for this decline, as these were common prior to 650 Ma. Due to biomineralization, in the latest Proterozoic, as the living organisms had produced minerals, the amount of coarse-grained sediments increased and it was hard to bind with this type of sediments. Other reason could be that stromatolites prefer to grow in low nutrient environment, and during that time new ocean basins were formed, so this new environment led the algae to compete against the cyanobacteria, causing the decline (McNamara and Awramik,1992).

Stromatolites Today

As discussed earlier, many stromatolite taxa declined; some morphological forms became rare, and some also became extinct during Phanerozoic. Though stromatolites are found today. During Paleozoic Thrombolites became common, thrombolytic stromatolite reefs were constructed during Cambrian to Ordovician, stratiform to dome-shaped stromatolite reefs were formed during the Late Devonian and Late Permian. Non-marine (lacustrine) stromatolites are abundant during Cenozoic. Lacustrine stromatolites are relatively smaller in size. Some examples of stromatolites, found today are shown in Fig.9 and10.

Fig.9. Stromatolites at Little Darby Island in – The Exumus

Fig.10. The Stromatolites of Hamelin Pool

In saline environments, these are found in Hamelin Pool, Shark Bay, Western Australia; Exuma Sound and Bahamas (a modern analog to ancient environments as these are the only example of modern stromatolites forming in open marine conditions). And in freshwater environments; Pavilion Lake, Canada; Cuatro Ciénegas Basin, Mexico.

Significance

- Paleoenvironmental Indicator: Study of stromatolites helps us to gain knowledge about the past environment such as oxygenic conditions, water chemistry, availability of nutrient, climate etc.

- Age Record: As stromatolites are the oldest known fossils, they hold the evidences of Earth's history through 3.5 Ga.

- Oxygen Production and Evolution of Life: These are great paleobiological indicators and the cyanobacteria producing stromatolites were the only source of oxygen during that time that helped the environment to become oxic and ultimately caused the Earth's atmosphere to increase its oxygen content from 1% to 21%, which allows plants, animals and humans to exist today.

- Uses in Astrobiology: Their simple biological requirements make them a good model to understand about the potential life on other planets like mars.

Epilogue

So, the stromatolites provide key insights into Earth's early life and environmental conditions. Their varied morphologies and ancient abundance illustrate the dynamic interplay between microorganisms and their habitats. Despite a decline in numbers due to changes in marine ecosystems, stromatolites persist in specialized environments, showcasing their resilience. Studying these ancient structures enhances our understanding of Earth's history and aids in the search for extraterrestrial life.

References

Aitkin JD (1967) Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta. J Sediment Petrol 37: 1163-1178.

Allen JF (2016) A Proposal for Formation of Archaean Stromatolites before the Advent of Oxygenic Photosynthesis.Front. Microbiol. 7:1784.

Allwood, A. C., Walter, M. R., Kamber, B. S., Marshall, C. P., and Burch, I. W. (2006). Stromatolite reef from the Early Archaean era of Australia. Nature 441,714–718.

Awramik SM (1971) Precambrian columnar stromatolite diversity: reflection of metazoan appearance. Science 174:825-827.

Awramik, S. M. (1992). The History and Significance of Stromatolites. Early Organic Evolution, 435–449.

Awramik, S. M., & Sprinkle, J. (1999). Proterozoic stromatolites Awramik SM (1991) Archean and Proterozoic stromatolites. In: Riding R (ed) Fossil algae and stromatolites. Springer. Berlin.: The first marine evolutionary biota. Historical Biology, 13(4), 241–253.

Bosak, T., Knoll, A. H., and Petroff, A. P. (2013). "The meaning of stromatolites,"in Annual Review of Earth and Planetary Sciences, Vol. 41, ed. R. Jeanloz (PaloAlto, CA: Annual Reviews), 21–44.

Buck SG (1980) Stromatolite and ooid deposits within the fluvial and lacustrine sediments of the Precambrian Ventersdorp Supergroup of South Africa. Precambrian Res 12:311-330

Buick R. Dunlop ISR. Groves DI (1981) Stromatolite recog nition in ancient rocks: an appraisal of irregularly lam inated structures in an Early Archaean chert-barite unit from North Pole. Western Australia. Alcheringa 5:161 181

Byerly GR, Lowe DR, Walsh MM (1986) Stromatolites from the 3.300-3.500-Myr Swaziland Supergroup,
Barberton Mountain Land. South Africa. Nature (London) 319:489-491.

Cloud P (1976) Major features of crustal evolution. Geol Soc S Afr Annexure 79:1-33.

Cloud PE Jr, Semikhatov MA (1969) Proterozoic stromatolite zonation. Am J Sci 267:1017-1061.

Donaldson JA (1976) Paleoecology of Conophyton and associated stromatolites in the Precambrian Dismal Lakes and Rae Groups, Canada. Developments in Sedimeentology, Volume 20, 523-534.

Grotzinger, J. P., & Rothman, D. H. (1996). An abiotic model for stromatolite morphogenesis. Nature, 383(6599), 423–425.

Hoffman P (1967) Algal stromatolites: use in stratigraphic correlation and paleocurrent determination. Science 157: 1043-1045.

Hoffman PF (1974) Shallow and deep-water stromatolites in Lower Proterozoic platform-to-basin facies change, Great Slave Lake, Canada. Am Assoc Petrol Geol Bul 58:856-867.

Hofman HI (1981) Precambrian fossils in Canada - the 1970's in retrospect. In: Campbell FHA (ed) Proterozoic basins in Canada. Geol Surv Can Pap 81-10:419-443.

Hofmann HI. Chen linbiao (1981) Carbonaceous megafossils from the Precambrian (1800 Ma) near lixian, northern China. Can 1 Earth Sci 18:443-447.

Hofmann, H. J., Grey, K., Hickman, A. H., and Thorpe, R. I. (1999). Origin of 3.45 Ga coniform stromatolites in Warrawoona Group,Western Australia. Geol. Soc. Am. Bull. 111, 1256–1262.

Hofmann HJ 2000. Archean stromatolites as microbial Archives. In: Riding RE & Awramik SM (Editors)—Microbial sediments.Springer-Verlag, Berlin, Heidelberg: 315-327.

Kalkowsky E (1908b) Oolith und Stromatolith im norddeutschen Buntsandstein.Zeitschrift der Deutschen geologischen Gesellschaft 60:68–125

Kennard J (1981) The Arrinthrunga Formation: Upper Cambrian epeiric carbonates in the Georgina Basin. central Australia. Bur Min Res Bull 211 :61 pp.

Knoll AH (1985) A paleobiological perspective on sabkhas. In: Friedman GM. Krumbcin WE (eds) Hypersaline ecosystems. Springer. Berlin. pp 407 -425.

Knoll AH. Bauld J (1989) The evolution and ecological tolerance in prokaryotes. Trans Soc Edinburgh Earth Sci 80:209-223.

Knoll AH. Golubic S (1979) Anatomy and taphonomy of a Precambrian algal stromatolite. Precambrian Res 10:115-151.

Knoll, A. H., Bergmann, K. D., and Strauss, J. V. (2016). Life: the first two billion years. Philos. Trans. R. Soc. B. Biol. Sci. 371.

Komar VIA. Raaben ME. Semikhatov MA (1965) Conophytons in the Riphean of the USSR and their stratigraphic significance. Tr Geol Ins!. Akad Nauk SSSR 131 :72pp (in Russian).

Korolyuk IK (1960) Stromatolites of the Lower Cambrian and Proterozoic of the Irkutsk Amphitheater. Tr Inst Geol Razrab Goryuch Iskop. Akad Nauk SSSR 1: 112161 (in Russian).

Kroner A . Todt W (1988) Single zircon dating constraining the maximum age of the Greenstone Belt. southern Africa. J Geophys Res 93: 15329-15337

Krylov IN (1963) Stolbchaty vetvyashchiesya stromatolity rifeiskikh otlozhenii yuzhnogo urala. Tr Geol Inst Akad Nauk SSSR 69:1-133.

Lowe DR (1980a) Archean sedimentation. Ann Rev Earth Planet Sci 8: 140-194.

Lowe DR (1980b) Stromatolites 3.400-Myr old from the Archean of Western Australia. Nature (London) 284:441-443.

Lowe DR (1983) Restricted shallow-water sedimentation of Early Archean stomatolitic and evaporitic strata of the Strelley Pool Chert. Pilbara Block. Western Australia. Precambrian Res 19: 239 – 283

Monty CL V (1973) Precambrian background and Phane rozoic history of stromatolite communities. An overview. Ann Soc Geol Belg 96: 585 624

McNamara K. J. and Awramik S.M. (1992) Stromatolites: a key to understanding the early evolution of life. Sci Progress Oxford 76, 345-364.

Nutman, A. P., Bennett, V. C., Friend, C. R. L., Van Kranendonk, M. J., and Chivas,A. R. (2016). Rapid emergence of life shown by discovery of 3,700-million-year-old microbial structures. Nature 537, 535– 538.

Pidgeon RT (1978) 3450 m.y. old volcanics in the Archaean layered greenstone succession of the Pilbara Block. Western Australia. Earth Planet Sci Lett 37 :421-428

Schopf JW (1977) Biostratigraphic usefulness of stromatoli tic Precambrian microbiotas. Precambrian Res 5:143 173.

Shapiro, Russell. (2007). Stromatolites: A 3.5-Billion-Year Ichnologic Record. Trace Fossils. 382-390. 10.1016/B978-044452949-7/50148-0.

Shapovalova IG (1968) 0 novoi gruppe stromatolitov lacutophyton iz verkhnego proterozoya vostochnogo sklona Aldanskoi anteklizy. In: Tektonika, Stratigrafiya, i Litologiya

Osadochnykh Formatsii, Yakutia. Dokl Nauk Sess Yakutsk Fil Sib Otd, Akad Nauk SSSR, 17:97- 103

Sharma M & Shukla M (2004) A new Archaean stromatolite from the Chitradurga Group, Dharwar Craton, India and its significance. Palaeobotanist 53(1-3) :5-16.

Walter MR (1972a) A hot spring analog for the depositional Vlasov FYa (1977) Dokembrickiikie stromatolity iz satkinskoisvity yuzhnogo urala. Akad Nauk SSSR, Ural Nauch Tsentr Materialy Paleontologii Srednego Paleozoya Urala Sibiri, pp 101-128.

Walter MR (1972 b) Stromatolites and the biostratigraphy of the Australian Precambrian and Cambrian. Spec Pap Palaeontology 11: 190 pp.

Walter MR (1983) Archean stromatolites: evidence of the Earth's earliest benthos. In: Schopf IW (ed) Earth's earliest biosphere: its origin and evolution. Princeton Univ press, Princeton. pp 187-213.

Walter MR, Heys GR (1985) Links between the rise of the Metazoa and the decline of stromatolites. Precambrian Res 29: 149-174.

Walter MR. Buick R, Dunlop ISR (1980) Walter MR. Bauld l, Brock TD (1976) Microbiology and morphogenesis of columnar stromatolites

(Conophyton, Vacerrilla) from hot springs in Yellowstone National Park. In: Walter MR (ed) Stromatolites. Elsevier, Amsterdam, pp 273-310.

Stromatolites 3.400-3,500 Myr old from the North Pole area, Western Australia. Nature (London) 284:443-445.