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Review paper

New scientific direction of the bacterial paleontology in Mongolia: an essence of investigation

Dorj Dorjnamjaa*, Gundsambuu Altanshagai, Batkhuyag Enkhbaatar

Department of Paleontology, Institute of Paleontology, Mongolian Academy of Sciences, Ulaanbaatar 15160, Mongolia

**Corresponding author. Email: ddorj2001@yahoo.com*

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ABSTRACT

We review the initial development of Bacterial Paleontology in Mongolia and present some electron microscopic images of fossil bacteria in different stages of preservation in sedimentary rocks. Indeed bacterial paleontology is one the youngest branches of paleontology. It has began in the end of 20th century and has developed rapidly in recent years. The main tasks of bacterial paleontology are detailed investigation of fossil microorganisms, in particular their morphology and sizes, conditions of burial and products of habitation that are reflected in lithological and geochemical features of rocks. Bacterial paleontology deals with fossil materials and is useful in analysis of the genesis of sedimentary rocks, and sedimentary mineral resources including oil and gas. The traditional paleontology is especially significant for evolution theory, biostratigraphy, biogeography and paleoecology; however bacterial paleontology is an essential first of all for sedimentology and for theories sedimentary ore genesis or biometallogeny

Keywords: microfossils, phosphorite, sedimentary rocks, lagerstatten, biometallogeny

INTRODUCTION

Bacteria or microbes preserved well as fossils in various rocks, especially in sedimentary rocks alike natural substances. Major types of sedimentary rocks form in the photic zone of epicontinental basins of the past, originated under influence of microorganisms. Photic zone, surface layer of the ocean receives sunlight. The uppermost 80 m or more of the ocean, which is sufficiently illuminated to permit photosynthesis by phytoplankton and plants, is called the euphotic zone? Within these oceanic expances, all the microorganisms had lived and propagated without breakdowns. Bacterial paleontological data accompanied by the data on the first origin of eukariotes, metazoan, etc. The essential role of bacteria and other microbes in the geological and biological processes was proposed long ago. Many specialists of the 19th century claimed that there is a tremendous role of bacteria in the formation of the sedimentary mineral resources, like phosphorite, bauxite, iron ores, oil, hydrocarbon, petroleum gas, gold, sulfide, sulfur and sulfate, etc. The most significant breakthrough was made after the introduction of electron microscopy to the study of microbial remains. Mongolian bacterial fossils from Precambrian and Cambrian sedimentary rocks and bedded phosphorite were examined using a Zeiss EVO50 SEM with an Oxford INCA microanalyzer (Energy 350) at the Paleontological Institute of the Russian Academy of Sciences were published repeatedly (Zhegallo et al., 2000). According to A.Yu.Rozanov a start of forming of the bacterial paleontology was kick-off research of the Mongolian phosphorite (Rozanov, 2016). New scientific technology revealed that almost all sedimentary rocks contain micro-scale bacteria. The main task for bacterial paleontology is to study the fossil microbes. The traditional paleontology deals with remains of ancient organisms. As known the main "users" of paleontology are the evolutionary theory, the history of organic world and the biostratigraphy. Bacterial paleontology or geomicrobiology is limited in its input data by the simplicity of the objects' morphology and specificity in systematization of the bacterial material. So, the bacterial paleontology is very important for sedimentology, and consequently for detailed study of the geneses of sedimentary mineral resources, including oil, gas, iron, phosphate, and gold. Geomicrobiology is a scientific field at the intersection of geology and microbiology (Dorjnamjaa et al., 2018, 2019). It concerns the effect of microbes on geological and geochemical processes and vice versa. Such interactions occur in the geosphere (rocks, minerals, soils, and sediments), the atmosphere and the hydrosphere. All kinds of microbes, including prokaryotes and eukaryotes and their symbiotic associations with each other and higher organisms, can contribute actively to geological phenomena, and central to many such geomicrobial processes are transformations of metals and minerals.

Indeed a diverse Proterozoic-Phanerozoic sedimentary stratigraphic rocks in Mongolia record and faunal, floral, and also bacterial localities (Mitrofanov et al., 1981; Dorjnamjaa and Bat-Ireedui, 1991, Bosak et al., 2011a, b; Barsbold and Byamba, 2012; Byamba, 2012; Dorjnamjaa, 2016; Dorjnamjaa et al., 2016; Dorjnamjaa, 2017; Anderson et al., 2017a, b, 2018). In Mongolia the oldest microorganisms from the Paleoproterozoic were found in the iron-bearing quartzite. In 1981, B.V.Timofeev (Russian palynologist of Leningrad Institute of the Precambrian geology and geochronology, RAS, who pioneered the study of Precambrian an Early Paleozoic acritarchs) described and published several new genera and species of acritarchs (Protosphaeridium sp., Gloeocapsomorpha priscata Tim., Trematosphaeridium sp., etc). These bacterial microfossils of the "bodaibin" type were extracted from Khangiltsig metacomplex (Khankhukhei block). Also T.N.German together with B.V.Timofeev have described number of bacterial fossils (Spheromorphides, Filamentous algae, etc.) from Meso-Neoproterozoic sedimentary and metaargillaceous rocks of the Tseel, Baidrag and Tarvagatai blocks (Mitrofanov et al., 1981). The presence of cyanobacteria in all mentioned rocks could be considered as a reliable fact. Also it has importance for paleogeography and paleoecology in the study of epicontinental basins as Khuvsgul and Zavkhan shallow basins in Mongolia (Ragozina et al., 2010; Serezhnikova et al., 2014). The Khuvsgul and Zavkhan basins host economic-grade phosphorite deposits (Ilyin, 1973; Dorjnamjaa and Soyolmaa, 2001). The high preservation potential of organic microfossils in phosphorites makes Mongolia an obvious target for new Lagerstatten, which might inform the debate about the phylogenetic affinities of these early organisms (Anderson et al., 2018). Just Anderson et al., (2018) have recently presented systematic palaeontology of the recently discovered Kheseen Lagerstatten, which includes Doushantuo-Pertatataka-type acanthomorphs and other microfossils, including animal embryo-like forms, and discussed its biostratigraphical and palaeobiological significance. A Lagerstatten (German:from storage, place) is a sedimentary deposit that exhibits extraordinarily preserved fossils with exceptional preservation, which sometimes include preserved soft tissues. These formations may have resulted from carcass like burial in an anoxic environment with minimal bacteria, thus delaying the decomposition of both gross and fine biological features until long after a durable impression was created in the surrounding matrix. Lagerstatten span geological time from the Neoproterozoic era to the present. Worldwide, some of the best examples of near-perfect fossilization and world's major Lagerstatten are the Precambrian Bitter Springs (1000-850 Ma, Southern Australia), Doushantuo Formation (600-555 Ma, China), Mistaken Point (565 Ma, Newfoundland, Canada), Ediacara Hills (550-545 Ma, Southern Australia), White Sea (550 Ma, Northwest Coast of Russia), the Cambrian Burgess Shale (505 Ma, British Columbia, Canada), Wheeler Shale (507 Ma, Western Utah,USA), Emu Bay Shale (525 Ma, Southern Australia), the Devonian Hunsrick Slates and Gogo Formation, the Carboniferous Mazon Creek, the Jurassic Solnhofen limestone, the Cretaceous Santana, Yixian and Tanis formations, the Eocene Green River Formation, and the Miocene Foulden Maar, so on.

We are fully conscious of the fact that microfossil assemblages of the acritarchs, known from Proterozoic-Lower Cambrian strata are commonly found in shale and chert, as well as carbonaceous lithologies that are sufficiently phosphatized (Zhegallo et al., 2000; Pruss et al., 2017; Anderson et al., 2018; Dorjnamjaa et al., 2018). Bacterial fossils from the Late Proterozoic of Mongolia are known. The Maikhan-Uul and Tsagaan-Olom formations in the Zavkhan phosphate basin and Arasan, also Kheseen Formation in Khuvsgul phosphate basin preserve diverse stromatolites, oncolites, sponge spicules, zooproblematica (Archaeooides sp.), bacterial fossils (Obruchevella sp., Siphonophycus sp., Tasmanites sp., Chuaria sp., Aspidella sp., Archaeooides sp., Acanthomorphs, Megasphaera, Archaeophycus, so on). The lower Cambrian Bayangol and Salaanygol formations within the Khasagt Khairkhan mountain and Zavkhan river area contain abundant trace fossils (Goldring et al., 1996), stromatolite (thrombolites), soft-bodied fossils (Spatangopsis mongolica, Paracharnia, Oldhamia radiata), medusoid (jellyfish) and small shelly fossils: protoconodonts, anabaritids, cap-shaped fossils, Salanacus, hyolithelminthes, coeloscleritophorans, tommotiids, orthothecimorphs, molluscs and calcareous brachiopods (Zhegallo et al., 2000; Dorjnamjaa et al., 2016; Anderson et al., 2018). Trilobites and Archaeochyathids are confined to the Salaanygol Formation in Zavkhan area, Salaanygol section and Erkhelnuur Formation (Kheseengol, Ongoliggol and Urandush sections) in western Coast of Khuvsgul Lake and Egiingol Formation (Myaras ovoo section, Blue Montain section, Chuulgant mountain section near the East Khargana river), Khoridulin, Jamatulingol and Ujiggol formations in western and southern Khuvsgul area (Dorjnamjaa et al., 1982).

RESULTS

The highest significance of bacterial paleontological data is obvious for study of biosphere evolution, especially in the Precambrian and the early Paleozoic. And finally, bacterial paleontology is one of the principle aspects for the astromaterials' study (Dorjnamjaa et al., 2012). The recent electron-microscopic studies of rocks varying both in chemical composition and age prove that fossilized microorganisms can be practically found in almost all sedimentary rock.

Bacterial fossils are the remains of animals or plants that are preserved in rocks, that bacteria

Fig. 1. Bodaibin type bacterial microfossils (Spheromorphides).Paleoproterozoic Khangiltsig metacomplex, Khankhukhei block in western Mongolia. Natural size of the microfossils is overstated 600 times (after Mitrofanov et al., 1981).

are neither plants nor animals. They belong to a group all by themselves. Bacteria, singular bacterium, any of a group of microscopic single-celled organisms that live in enormous numbers in almost every environment on Earth, from deep-sea vents to deep below Earth's surface to the digestive tracts of humans. Hence, bacteria are the beginning of life and found everywhere such as the air, water, top-soil, high-temperature springs, permafrost (frozen soils and rocks), different types of ice, and shifting sands of desert. Scientists have discovered bacteria growing in the hot springs of Yellowstone National Park, America, where the water reaches near boiling temperature. Bacteria have been found deep inside ice above Lake Vostok in the Antarctic. The Planet Earth is estimated to hold at least 5 nonillion (or $5x10^{30}$) bacteria. Much of the Earth's biomass is made up of bacteria. Modern bacteria's ancestors-single celled microorganisms-have appeared on the Earth about 4 billion years ago and were the very first form of life to exist on the Earth. For the following 3 billion years, all life forms on the Earth were microscopic in size, and included two dominant ones: 1. Bacteria, and 2. Archaea (classified as bacteria, but genetically and metabolically different from all other known bacteria). Bacteria come in three main shapes: 1. spherical or coccoid (like a ball), 2. rod shaped or vibrio, 3. spiral or spirochetes (Dorjnamjaa et al., 2018). Precisely these rocks contain fantastic preservation of diverse cyanobacteria and other microorganisms (Figs. 1-10).

On the whole, bacterium applies to an ordinary microscopic organism that consists of a single cell without noticeable nucleus, but possesses of colossal biochemical energy. Moreover, bacteria

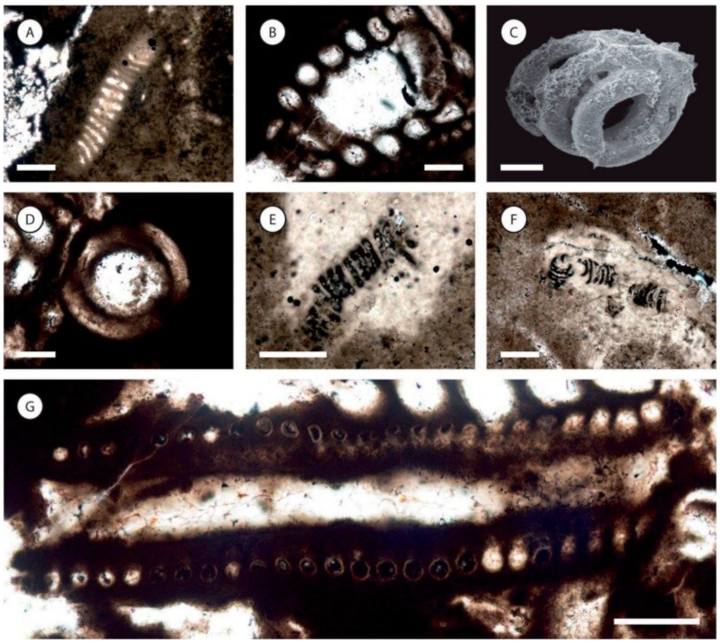

Fig. 2. Obruchevella, A, B and D–G are photomicrographs from thin-sections; C is a scanning electron micrograph of an acid-extracted specimen. In this and subsequent figure legends YPM numbers are given, in addition to rock sample/thin-section identifications and, where appropriate, England Finder coordinates for all illustrated sedimentary structures, microfossils and populations. A, O. delicata, YPM 536750, M602 176.0 B, E47/0; B, O. magna, YPM 536778, M618 33.0 A, F42/3; C, O. magna, YPM 538075, from YPM 536747, M618 320; D, O. magna in cross-section, YPM 536779, M618 33.0 A, F42/3; E, O. parvissima, YPM 536792, M618 33.0 C, S59/3; F, O. parvissima, YPM 536793, M618 33.0 C, M60/0; G, O. valdaica, YPM 536780, M618 33.0 A, F42/3. Scale bars D 50 mm (After Anderson et al., 2018). Khuvsgul phosphate basin, phosphate-bearing Kheseen Formation

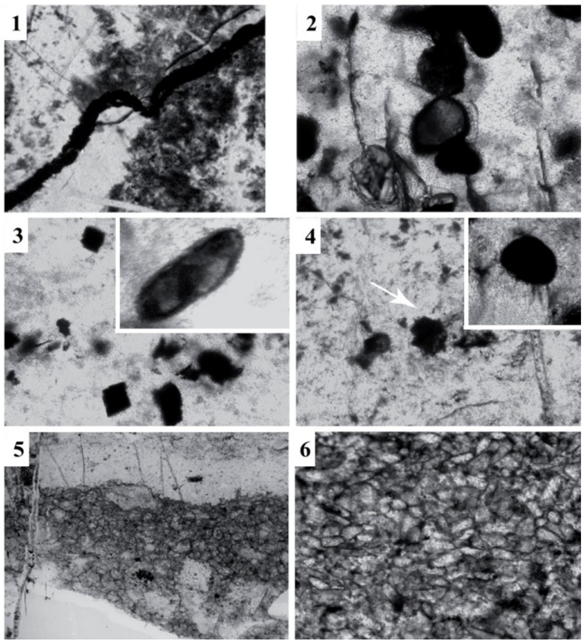

Fig. 3. 1-8. "Zavkhan biota" from the Ediacaran Tsagaan-Olom phosphate-bearing Formation of the Zavkhan basin, western Mongolia. 1-Tyraso-thaeniapodolica Gnilovskaya, 1991, specimen PIN no. 5492/7; 2-gr. forma Archaeooides sp. Tasmanites sp., specimen PIN 5492/8; 3-Octoedryxiumtruncatum Rud., 1989, specimen PIN 5492/3; 4-Problematicum Navifusa sp., specimen PIN 5492/9; 5-Tanarium sp., specimen PIN 5492/4; 6-Tanarium sp., specimen PIN 5492/10; 7-8-Tallophycoides sp., fragments of lamellae, specimen PIN 5492/11-12 (after Serezhnikova et al., 2014)

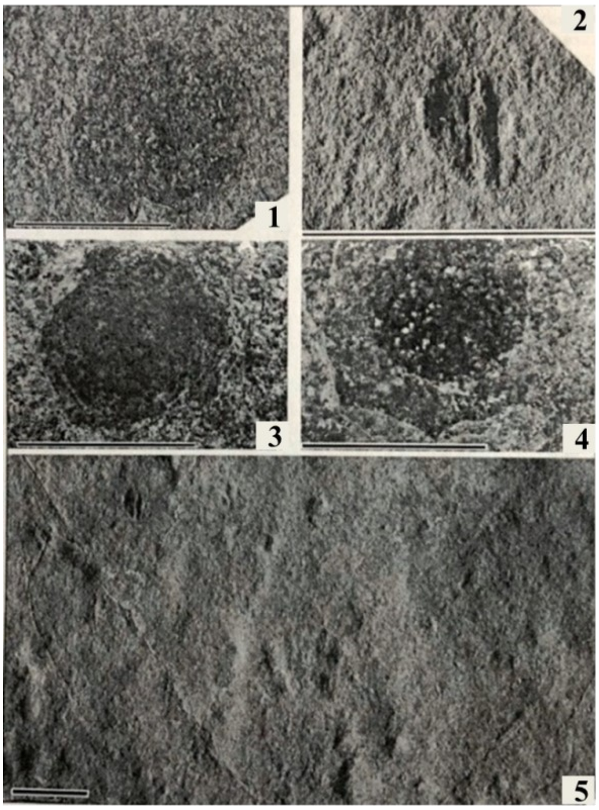

Fig. 4. 1-4- Problematical remains of Chuaria sp. and Aspidella-like imprint from the Tsagaan-Olom Formation of the Zavkhan phosphate basin, western Mongolia (modified after Ragozina et al., 2010). 5- Surface of fossiliferous layer, Tsagaan-Olom phosphate -bearing Formation (Dorjnamjaa et al., 2018).

Fig. 5. Mankhan-Uul phosphorite deposit, left-bank of the Egiingol river. Problematical discoidal and circular bacterial remains of Chuaria sp. and Aspidella-like imprint from the Kheseen Formation of the Khuvsgul phosphate basin. Photograph by D.Dorjnamjaa, 05.08.2019.

Fig. 6. New location of Spatangopsis mongolica Dorjnamjaa, phosphatic silty sandstone in the base of 18th bed of the Bayangol Formation indicative the limitotype boundary between Ediacaran and Lower Cambrian. Bayangol gorge. Photograph by D.Dorjnamjaa, 08.27.2017.

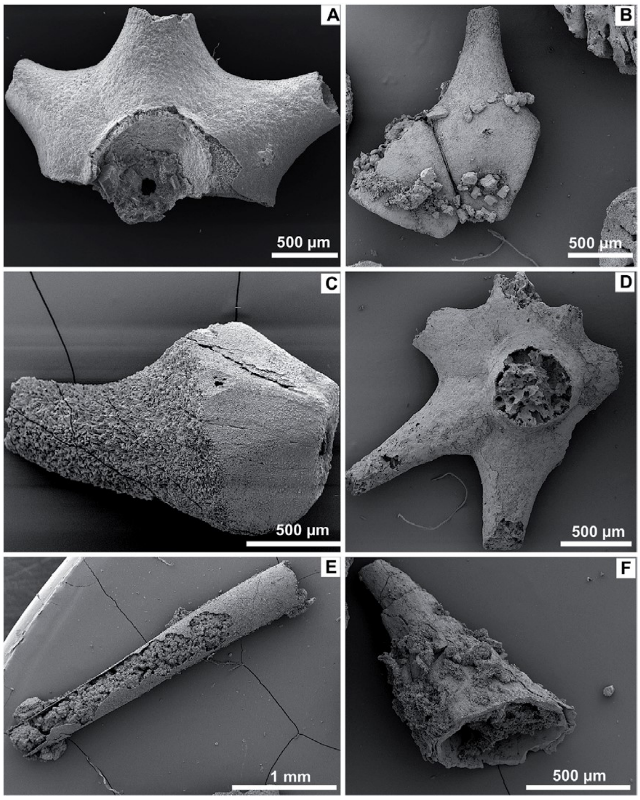

Fig. 7. SEM images of phosphatic small shelly fossils. A–D) Chancelloriid sclerites; E) hyoliths; F) Possible hyolith; identification uncertain (After Pruss et al., 2017). Lower Cambrian, Salaanygol Formation

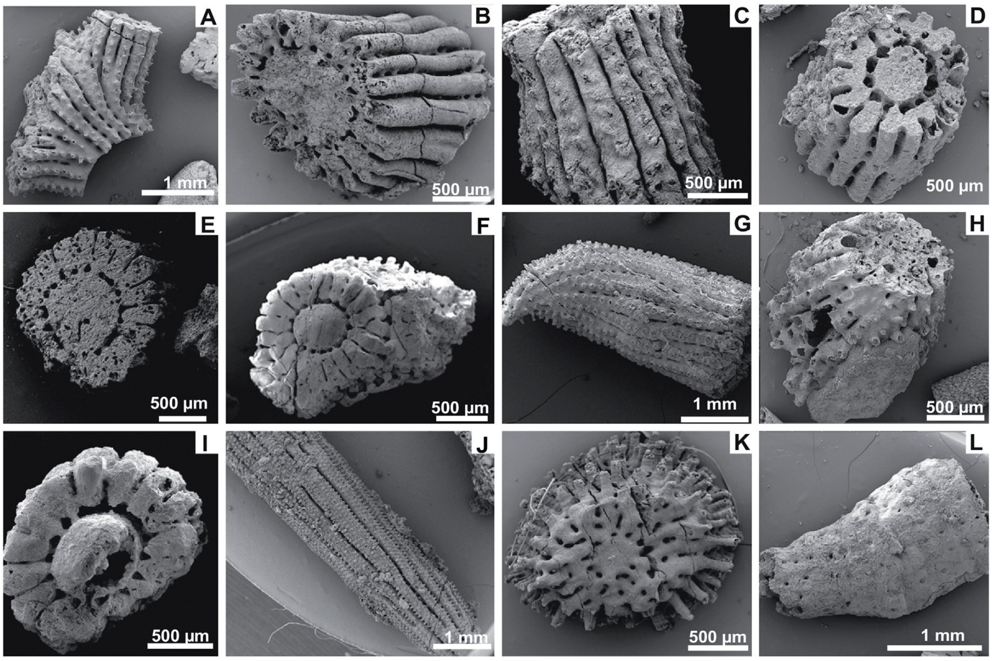

Fig. 8. SEM images of phosphatized archaeocyaths. A) Branching archaeocyath. B–J) Internal molds of archaeocyaths. K) Archaeocyathan pore system. L) Archaeocyath replaced by apatite (after S.B. Pruss et al., 2017). Lower Cambrian, Salaanygol Formation.

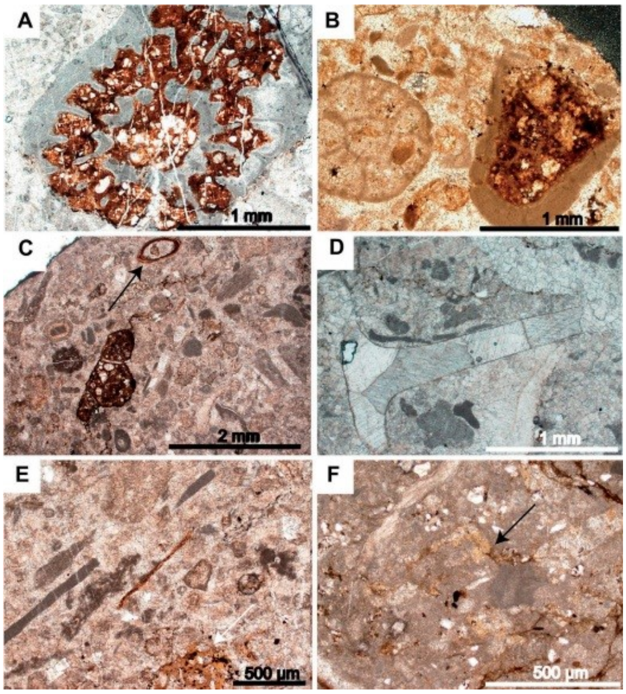

Fig. 9. Petrographic images of thin sections. All thinsections were made from the same hand samples as those used for dissolutions. A) Apatite filling a calcareous archaeocyath. B) Calcareous archaeocyath (left) and calcareous archaeocyath filled with apatite (right). C) Phosphatized hyolithid (black arrow). D) Calcareous small shelly fossil. E) Possible phosphatic brachiopod shell in the center of the picture, and phosphatic cement (white arrow). F) Glauconitic cement (black arrow). (after Pruss et al., 2017). Lower Cambrian, Salaanygol Formation.

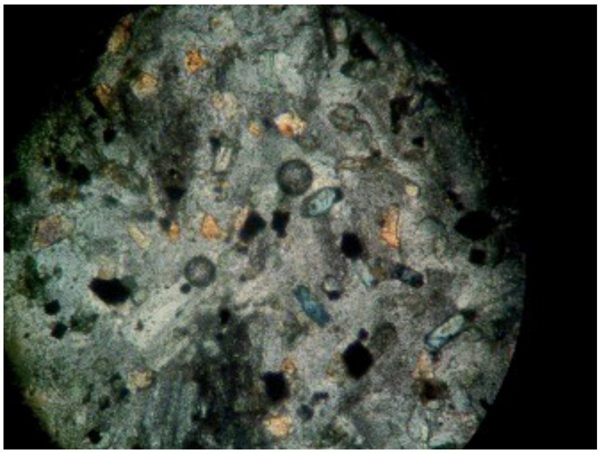

Fig. 10. Petrographic image of thin section. Possible ball-like biomicrobodies (?) in the meteor Pallasite from Tsenkher astropipe crater. Thin section 11/06. Japanese microscope Nikon ECLIPSE E400 POL (Dorjnamjaa et al., 2012).

were accepted an active participation in process of decomposition and oxidation of organic matter. Here it should be emphasized that by the process of mineralization primary matter of skeleton and cyanobacterial mats are substituted with other mineral matter or pseudomorphism. The most prevailing bacteriogenic mineral matters are calcium, mineral carbon, mineral oil, magnesium carbonate, phosphate, sulphide (pyrite), oxides and hydroxyls (silica in different

modification), and indigenous limonite.
So the ancient phosphorites have become the classic object for such studies (Dorjnamjaa, 2016).
All kinds of bacteria can be an active contribution to geological phenomena, and centre of many such geomicrobial and biometallogenical processes and transformation or bioremediation of metals and minerals. The deposits of sedimentary mineral resources give clearly show another perfect paradigm of the tremendous bacterial role in the ancient geological event. The ancient phosphorites have become the classic object for such studies. Thirty years ago, we were aware of twenty minerals that could originate with the microbial activity. In recent times, the number of such minerals grew significantly, and nowadays it is more than a hundred. Using new methodology and factual data we would like to introduce some sedimentary mineral resources (biogenic phosphorites, gold-forming black shale, uranium and oil-gas deposits) those could be formed with the significant assistance of bacterial microfossils. In addition to above mentioned phosphorites, iron ores, graphite, and rare metal ores, bauxites, sulfides, gold, etc. are noteworthy (Dorjnamjaa et al., 2018).

CONCLUSION

1. Summing up all that has been said, in conclusion of our paper using new methodology and factual information we would like to note that some sedimentary mineral resources (biogenic phosphorites, iron -bearing quartzites, gold-forming black shales, diaspore bauxite, supposed "coal-and-oil-gas- bearing Sabkha Formation"-salt domes) could be formed by significant assistance of bacterial microfossils (Dorjnamjaa et al., 2018, 2019). In general a major role for bacterial-paleontological investigation lies in consideration of problems of the Biosphere evolution, especially in the Precambrian and Early Paleozoic as well as in Astrobiology (Hoover et al., 1998, 2003a, b, 2004; Dorjnamjaa et al., 2012).
2. In fact biogenic phosphorites are concrete evidence and object for an academic research of bacterial paleontology. Bacteria were the beginning of an life. The "Khuvsgul" and "Zavkhan" biota were mostly cyanobacterial. The cyanobacterial mat community was preserved in phosphorites in the form of a stromatolite, microphytolite, blue-green algal remain, and micronodul side by side with trace and small shelly fossils (SSFs), also spiculate sponges. The micronodules are clearly predominant in our observations. The micronodule sizes usually vary from tens to several hundreds of microns (Archaeooides, Tasmanites, Obruchevella, Siphonophycus, Lagerstatten, so on). Soft-bodied animals resemble organisms such as coelenterates and annelids and may be early forms of these groups. In all probability, all the fossils are closely connected and intercommunicated by one's genesis and accumulation in the ancient phosphatic basins. This is a target for future investigation.

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REFERENCES

Anderson, R.P., Macdonald, F.A., Jones, D.S., McMahon, S., Briggs, D.E.G. 2017a. Doushantuo-type microfossils from latest Ediacaran phosphorites of northern Mongolia. Geology, 45(12), 1079-1082. https://doi.org/10.1130/G39576.1

Anderson, R.P., McMahon, S., Bold, U., Macdonald, F.A., Briggs, D.E.G. 2017b. Palaeobiology of the early Ediacaran Shuurgat

Formation, Zavkhan Terrane, south-western Mongolia. Journal of Systematic Paleontology, 11, 947-968. https://doi.org/10.1080/14772019.2016.1259272

Anderson, R.P., McMahon, S., Macdonald, F.A., Jones, D.S., Briggs, D.E.G. 2018. Palaeobiology of latest Ediacaran phosphorites from the upper Khesen Formation, Khuvsgul Group, northern Mongolia, Journal of Systematic Palaeontology,17(6), 501-532. https://doi.org/10.1080/14772019.2018.1443977

Barsbold, R., Byamba, J. (eds). 2012. Geology and Minerals Resources of Mongolia, Paleontology, vol. II. Ulaanbaatar, 529 p.

Bosak, T., Lahr, D., Macdonald, F.A, Matys, E.D. 2011. Putative Cryogenian ciliate from Mongolia, Geology, 39, 1123-1126. https://doi.org/10.1130/G32384.1

Bosak, T., Lahr, D., Pruss, S.B., Macdonald, F.A., Dalton, L., Matys, E. 2011. Agglutinated tests in post-Sturtian cap carbonates from Namibia and Mongolia, Earth and Planetary Science Letters, 308, 29-40. https://doi.org/10.1016/j.epsl.2011.05.030

Byamba, J. (ed) 2012. Geology and Minerals resources of Mongolia, Stratigraphy, vol. I. Ulaanbaatar, 562 p.

Dorjnamjaa, D. 2016. Neoproterozoic-Cambrian Biostratigraphy of the Ancient Phosphate Basins of Mongolia and the Influence of Bacterial Communities on Phosphorite Accumulation: A Review. International Journal of Agriculture Innovation and Research, 5(3), 372-384. ISSN (Online) 2319-14735.

Dorjnamjaa, D. 2017. An Outline and New Aspects of the Regional Stratigraphy of Mongolia. Open Journal of Geology, 7, 1579-1589. https://doi.org/10.4236/ojg.2017.711106

Dorjnamjaa, D., Amarsaikhan, Ts., Enkhbaatar, B., Altanshagai, G. 2012. On new find of the meteor Pallasite from Tsenkher astropipe geostructure (visiting meteor from Venus). Explorationist, 46, 70-77 (In Mongolian with English Abstract).

Dorjnamjaa, D., Bat-Ireedui, Ya. 1991. The Precambrian of Mongolia. Ulaanbaatar, 182 p. (In Mongolian with English Abstract).

Dorjnamjaa, D., Bat-Ireedui, Ya., Ragozina, A.L., Altanshagai. G. 2018. Voinkov, D.M (ed) Bacterial paleontology of Mongolia. Ulaanbaatar, 177 p.

Dorjnamjaa, D., Bat-Ireedui, Ya., Voinkov, D.M., Enkhbaatar, B., Altanshagai. G. 2019. Study of new direction of the Mongolian bacterial paleontology and beginning, perspective of the geomicrobiologic science. Explorationist, 60, 51-61.

Dorjnamjaa, D., Bat-Ireedui,Ya., Enkhbaatar, B., Altanshagai, G. 2016. Voinkov, D.M (ed). Precambrian geology and paleontology of Mongolia Ulaanbaatar, 183 p. (In Mongolian with English Abstract).

Dorjnamjaa, D., Korobov, M.N., Pokrovskaya, N.V. 1982. Latest Precambrian-Cambrian biostratigraphy of the north Mongolia. Geology of phosphorus deposits and problems on phosphorite formation. Novosibirsk, 90-99.

Dorjnamjaa, D., Soyolmaa, D. 2001. Zavkhan phosphate basin (phosphorus, gold, diamond) Ulaanbaatar, 166 p. (In Mongolian with English Abstract).

Goldring, R., Jensen, S. 1996. Trace fossils and biofabrics at the Precambrian-Cambrian boundary interval in western Mongolia. Geological Magazine, 133, 403-415. https://doi.org/10.1017/S0016756800007573

Hoover, R.B., Jerman, G., Rozanov, A.Yu., Davies, P.C.W. 2003b. Biomarkers and microfossils in the Murchison, Tagish Lake and Rainbow meteorites. Proceedings volume. SPIE 4859, 5-31. https://doi.org/10.1117/12.463321

Hoover, R.B., Jerman, G., Rozanov, A.Yu., Sipiera, P.P. 2004. Indigenous microfossils in carbonaceous meteorites. Proceedings volume SPIE 5555, 1-47. https://doi.org/10.1117/12.566491

Hoover, R.B., Rozanov, A.Yu. 2003a. Microfossils, biominerals and chemical biomarkers in meteorites. Proceedings volume SPIE 4939, 10-27. https://doi.org/10.1117/12.501868

Hoover, R.B., Rozanov, A.Yu., Zhmur, S.I., Gorlenko, V.M. 1998. Further evidence of microfossils in carbonaceous chondrites. Proceedings volume 3441, 203-216. https://doi.org/10.1117/12.319839

Ilyin, A.V.1973. Khubsugul phosphorite-bearing basin. Moscow, Russia, 167 p. (In Russian)

Mitrofanov, F.P., Kozakov, I.K., Palei, I.P. 1981. Precambrian of west Mongolia an south Touwa. The Joint Soviet-Mongolian scientific research geological expedition. Transactions, vol. 32, Leningrad, 156 p.

Pruss, S.B., Dwyer, C.H., Smith, E.F., Macdonald, F. A., Tosca, N.J. 2017. Phosphatized early Cambrian archaeocyaths and small shelly fossils (SSFs) of southwestern Mongolia. Paleogeography, Paleoclimatology, Paleoecology, 513, 166-177.https://doi.org/10.1016j.palaeo.2017.07.002

Ragozina, A.L., Dorjnamjaa, D., Krayushkin, A.V., Serezhnikova, E.A., Enkhbaatar, B. 2010. Vendian-Cambrian biota of the Western Mongolia. Proceedings of IV International Symposium on Evolution of Life, Ed. Podobina: TML-Press, 187-190.

Rozanov, A.Yu. 2016. Considerable investigations in Mongolia in addition to vertebrates. The International Symposium "The 70th anniversary of Mongolian Paleontological expedition of Academy of sciences, USSR". Abstract volume, Ulaanbaatar, 61-63 (in Russian).

Serezhnikova, E.A., Ragozina, A.L., Dorjnamjaa, D., Zaitseva, L.V. 2014. Fossil Microbial Communities in Neoproterozoic Interglacial Rocks, Maikhanuul Formation, Zavkhan Basin, Western Mongolia. Precambrian Research, 245, 66-79. https://doi.org/10.1016j.precamres.2014.01.005

Zhegallo, E.A., Rozanov, A.Yu., Ushatinskaya, G.T., Hoover, R.B., Gerasimenko, M., Ragozina, A.L. 2000. Atlas of microorganisms from ancient phosphorites of Khubsugul (Mongolia). Huntsville, Alabama, USA, 168 p.