

ROLE OF PLANTS AND MICRO-ORGANISMS IN THE FORMATION OF ROCKS AND MINERAL DEPOSITS OF ECONOMIC IMPORTANCE*

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Of the various processes of formation of minerals and rocks in nature, the role played by plants and, of late, micro-organisms, has been very recently recognised. This recognition is based on the idea that micro-organisms are important in the cycles of the various elements in nature, like carbon, nitrogen, phosphorus and sulfur. Thus, V. I. VERMADSKIY, in the first quarter of this century, pioneered in propounding the concept concerning the participation of micro-organisms in the geological processes. According to him, the micro-organisms cause geochemical changes during a geological process, leading to the formation or breakdown of a particular mineral or rock. The presence of the element carbon, which forms the essence of all organisms, living or dead, is of utmost significance in bringing about, or in participating in various geochemical processes. It has been calculated that the total quantity of organic matter produced, each year on the earth, is about 50-100 billion tons. A more or less similar figure has also been arrived for the annual mineralisation of organic matter and its transformation into carbon dioxide. Thus, one can easily realise the role of micro-organisms in the transformation and destruction of organic material in nature in general, in geological processes, in particular.

Studies on isotopic fractionation, as well as on the fossils and living micro-organisms from geological deposits, have thrown light on extensive geomicrobial activity in Proterozoic, Palaeozoic and Mesozoic times (THODE, *et al.*, 1962). Thus, the applications and principles of Microbiology, which, includes the study of microbes and microbial activity, is gaining significance in explaining the formation of rocks and minerals. As a matter of fact, microbes include principally bacteria, actinomycetes, filamentous fungi, yeasts, and also algae and protozoa. All these are microbial inhabitants of sediments, soils and waters. It may be mentioned that the first four, i.e. bacteria, actinomycetes, filamentous fungi and yeasts, constitute the real mineralisers of organic matter in nature. Besides, micro-organisms also play important role in sedimentation, diagenesis as well as even metamorphism, in combination with other physico-chemical parameters. Thus, a comparatively new branch of science—geomicrobiology—which, as an experimental science, includes the study of microbial processes that take place in the sediments of various bodies of water, in ground waters circulating through sedimentary and igneous rocks, and in the weathered earth's crust. Besides, this science also encompasses the physiology of specific micro-organisms that take part in various geochemical processes.

MICRO-ORGANISMS AND GEOLOGICAL PROCESSES

We shall now discuss the geological environment of micro-organisms, as well as their role in various geological processes. Of the various factors that control the development

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of micro-organisms in nature, mention may be made of light, temperature, pressure, moisture, the presence of organic matter and biogenic elements, oxidation—reduction conditions and salinity. However, in the geological environments, in particular, the activity of micro-organisms differs widely in different lithologic, chemical and particle size compositions. Rocks once formed, are subjected to the dynamic movement of fluids within the earth's crust as well as the action of weathering at or near the surface. The process of weathering is an interplay of physical, chemical and biological processes.

Theoretically, all living cells cause small-scale transformations of trace elements necessary for enzyme activation and function (SILVERMAN & EHRLICH, 1964). It has been shown that large-scale microbial mineral transformations can be brought about by direct enzymic oxidations or reductions. The biochemical reactions in which micro-organisms take part, are of two major types: chemosynthetic and photosynthetic. As a result of chemosynthetic reactions, the minerals are, in a way, oxidized in order to obtain both the energy and reducing power, required for CO_2 assimilation. The photo-synthetic autotrophs, on the other hand, assimilate CO_2 with the aid of radiant energy of sunlight; the reducing power is being supplied by oxidation of minerals. Thus, large-scale mineral transformations are caused mainly due to the magnitude of requirements for energy and reducing or oxidizing power of the micro-organisms.

In the geological environment, the micro-organisms also play an important role in the formation or degradation of minerals, by the development of complexing agents or metal complexes. As a matter of fact, the naturally occurring complexing agents are of biological origin, having been formed by microbes. It has been shown (ALEXANDER, 1961; BAER, 1955) that some inorganic ions in aqueous solution, particularly Fe^{+2} , Cu^{+2} , Mn^{+2} , Zn^{+2} , Ca^{+2} and Mg^{+2} , form chelates or complexes with certain organic chemicals, such as amino acids, proteins, various organic acids and others. The complexes thus formed help in maintaining the inorganic ions in solution and also keeping them from being rapidly oxidized or reduced. Depending on the pH and Eh of the environment, the ions released precipitate as hydroxides, oxides, or salts (ALEXANDER, 1961; CLARK & RESNICKY, 1956).

The non-enzymic proteins, mainly due to the interaction with end products of metabolism, have also been shown to cause mineral transformations. The inorganic and organic acids may dissolve insoluble minerals, like limestone, gypsum, anhydrite, silicates, and others. WEBLEY, *et al.* (1963) have shown that certain bacteria, actinomycetes, and fungi associated with silicate rocks can dissolve synthetic Ca, Mg and Zn silicate and wollastonite (CaSiO_3). Ammonia and organic bases have also been shown to cause precipitation of heavy metal ions in the form of hydroxides by raising the pH of the environment.

Mineral transformations also take place due to the gaseous products of microbial metabolism, such as CO_2 , O_2 and H_2S . Under suitable conditions, CO_2 forms carbonic acid, which dissolves limestone and other carbonates in acid pH environment, and on the other hand precipitates carbonates in the alkaline pH environment. Liberation of O_2 due to photosynthesis, may cause autoxidation of ferrous and manganese ions. H_2S reacts (reduces) heavy metal ions like ferric iron, precipitating, thus, the sulfide salt.

The sheathed bacteria (chlamydo-bacteriales) and certain flagellates also cause mineral transformations due to the adsorption of mineral matter on the cell surface (SKERMAN, 1959). It has already been shown (ZAPPE, 1931) that the chemical composition of the cell surface of these bacteria, has affinity for iron and manganese ions; the latter become fixed at the surface of the cell as hydroxides or salts (ALEXANDER, 1961; THIMANN, 1955).

Iron oxide is a good adsorbent for anionic substances, while manganese oxide is good adsorbent for cationic substances. The end product of all these non-enzymic processes is the preferential accumulation of iron and manganese in the sheaths or stalks of some bacteria. The bacterium *Galionella* deserves special mention—in this milieu.

Microbial interactions with inorganic substances, which mainly involve oxidation or reduction of inorganic ions, also lead to the formation or breakdown of minerals. For example, sulfate is readily reduced to H₂S in the presence of *Desulfovibrio* spp. or *Clostridium nigrificans*, thus precipitating the heavy metals dissolved in the reaction mixture. Most of the syngenetic metal sulfides, as they occur in nature, are largely formed in this way. The formation of uranium oxide by the reduction of uranyl ion with biogenic H₂S, due to the action of sulfate-reducing bacteria, is an illustrative example of this process.

MICRO-ORGANISMS AND THE FORMATION OF ROCKS AND MINERALS

In the light of the above discussion, it may, therefore, be said that micro-organisms play an important role in the formation and degradation of minerals and rocks. We shall now discuss, individually, the formation of various types of rocks and minerals under the activity of micro-organisms. At the very outset, it may be mentioned that micro-organisms, together with other physico-chemical factors, play an important role, either directly or indirectly, in the formation of petroleum and natural gas, limestones, phosphorite, magnesite, coal, salt, bauxite, amber, metallic minerals like iron, copper, manganese, sulfur and sulfide, and uranium ores.

PETROLEUM

The manifestation of the role and activity of living organisms, including micro-organisms, is the formation and destruction of organic matter. It has been estimated that about one billion metric tons of organic compounds are oxidised to carbon dioxide and water on the earth annually (RABINOVICH, 1951). At this rapid rate of decomposition, and without the formation of new supplies, all the organic matter on this planet would be consumed in 10 to 20 years only (KUZNETSOV, *et al.* 1963, p. 71). But, in this process of oxidation, a major part of (chemical) energy present in the organic matter is consumed in the biosphere for supporting life, and an even greater part is lost as heat. As a result, only a small part of this energy is left unutilised and is preserved in the form of coal, peat, oil or natural gas for millions of years within the sedimentary piles of the lithosphere.

The ultimate crude petroleum resources of the world have been estimated at about 8×10^{11} barrels (approximately 30 cubic miles) (cf. DAVIS, 1967, p. 31). However, this is a very small figure when compared with the estimated 20 million cubic miles of the earth's total sedimentary rocks (KNEBEL, 1949).

The average organic matter content of the ancient sediments is about 1.5 per cent (TRASK & PATNODE, 1942). Thus, according to this figure, the sedimentary rocks may contain up to 3,00,000 cubic miles of organic matter, of which only 0.01 per cent. yields the estimated resources of petroleum of the world.

Oil is mostly believed to have an organic origin, though, on the other hand, an inorganic origin can also not be ruled out. Restriction of a great bulk of oil in sedimentary rocks, presence of various hydrocarbons, O₂, N₂, S and porphyrins, etc. strongly support the derivation of oil from organic matter. Plant material and micro-organisms play a vital role in the formation of oil. Bacterial activity is supposed to be one of the most important processes to give rise to oil. Kerogene is the chief source material for oil. In fact, kerogene, together with coal, constitute more than 90 per cent of the earth's entire supply

of organic matter (SADLER & TRUDINGER, 1967). Recently, kerogene has been found to be constituted predominantly of pollen, spores and algae. On the basis of carbon isotope studies (SILVERMAN, 1964), the lower plants and animals are believed to be the principal biological sources of petroleum.

Fundamentally, the formation of petroleum is due to the decomposition, polymerisation and disproportionation reactions of the source molecules (SADLER & TRUDINGER, 1967). During these processes, the source molecules, according to SILVERMAN (1964), form simple molecules relatively rich in hydrogen on one hand and more complex molecules containing less hydrogen on the other hand.

Conversion of organic matter into petroleum is also brought about by diagenesis of the sediments, though after a series of biochemical reactions. In the process, the organic material is changed to hydrocarbons by losing O_2 and N_2 . The dominant sources of energy for such transformations are heat, pressure, radioactivity and bacterial action.

Microbiological processes also accentuate the formation of petroleum by forming gases of biochemical origin and, possibly, they lead to the formation of bituminous substances and unsaturated naphenic hydrocarbons.

In brief, the ultimate formation of petroleum is due to the interaction of a number of chemical, biochemical, and microbiological processes operating upon the microorganisms and the lower plants.

COAL

Coal is fossilised plant matter, and is formed mainly due to the compaction or induration of various altered plant remains. Most of the coals were formed in widespread swamps similar to those found today, but the plants which gave rise to the coals were different from their modern counterparts. Those primitive plants mostly belong to the gymnosperms (Glossopterids), large ferns and lycopods that dominated the ancient swamp environments.

Coal is generally formed due to the interaction of various geochemical, biochemical and dynamochemical processes, known together as coalification. The microscopically identifiable components of coal are known as macerals, which are of three types: *vitrite*, *micrinite* and *exinite*. The major plant tissues that contribute to coal macerals are woody and cortical tissues on one hand and cork-like tissues from leaf cuticles and spore exines on the other. Woody tissues are mainly composed of cellulose and lignin (an aromatic substance (WEDEPOHL, 1970)). These woody tissues are converted into the vitrine macerals. The leaf cuticles, spores, waxes, resins are incorporated and converted into exinite macerals (VAN KREVELEN, 1963).

The first steps in the coalification process are the formation of peat and humic substances. This is known as the biochemical stage of coalification, because fungi and aerobic bacteria play an important role at this stage. After this stage of microbial decomposition is over, and after further subsidence, the increase in coalification entirely depends upon temperature. As the rank, i.e. the degree of metamorphism increases, there is a general decrease in oxygen and hydrogen which consequently results in a relative increase in carbon content (WEDEPOHL, 1970).

In India, most of the coal deposits are confined to the Lower Gondwana, which account for about 90 per cent of the total coal production. Of the major plant groups, gymnosperms and Cordaitales, (*Noeggerathiopsis*) play vital roles in the formation of most of the Indian coal deposits, However, Glossopteridae forms the main component of all the

Palaeozoic coals. Though, the genus *Gangamopteris* is less important in the formation of coals, it is an important index fossil of Lower Permian (SURANGE, 1966). Palynologically, the Lower Permian coals are characterised by radial monosaccate genera, while the Upper Permian coals are distinguished by disaccate genera (BHARADWAJ, 1972, 1974). It has now been recognised that the elements in the coal flora has a direct bearing on the composition and properties of coal (NAVALE, 1972, 1975).

In India, excellent work is being done on the various aspects of coal. Special mention may be made here of the work by Geological Survey of India, Coal India, Central Fuel Research Institute, Birbal Sahni Institute of Palaeobotany, and some universities.

LIMESTONES

The limestones, in general, are rocks of chemical origin, i.e. they are mostly the products of chemically active environments, which can be either organic or inorganic. Organic life, including micro-organisms play an active biochemical role in precipitating the limestone. In the relief of the sea bottom, where the depth of water is not more than 60-80 metres, so that light is able to penetrate, algae and bryozoa may develop and grow abundantly (KUZNETSOV, *et al.* 1962, p. 6). In sediments, the presence of organic life is clearly indicated by fossils of all ages right from the Precambrian. Recent studies have also shown the presence of fossil bacteria, even dating back to early Precambrian. The oldest definite occurrence of fossil bacteria has been reported from the 3.1 billion years old. Precambrian Fig Tree Series rocks of South Africa (BARGHOORN & SCHOPF, 1966). It is a well preserved rod-shaped coccoid bacteria, morphologically comparable with certain modern iron bacteria.

Fundamentally, the formation of limestone is mainly due to the precipitation of CaCO_3 . As such, its formation depends, besides other factors, on enzymic production of CO_2 and NH_3 from organic nitrogenous compounds, including urea, followed by subsequent precipitation of CaCO_3 at neutral or alkaline pH by non-enzymic processes. The formation of limestones also depends on the microbiological reduction of CaSO_4 with organic carbon to form H_2S and CaCO_3 or it may also depend on the photosynthetic consumption of bicarbonate from $\text{Ca}(\text{HCO}_3)_2$ in solution (ZOBELL, 1946; UMBREIT, 1964, p. 169).

Laboratory experiments by SAZONOVA (1961) have shown that the precipitation of secondary calcite in some of the petroliferous horizons, is caused by desulfurizing bacteria that form CaCO_3 , due to the reduction of SO_4 in CaSO_4 which is invariably present in the stratal waters of oil deposits. On the other hand, studies on the marine calcareous oozes have shown the presence of calcite crystals. It is held (KUZNETSOV, 1962, p. 113) that the calcite is precipitated due to the oxidation of calcium sulfide as well as due to the photosynthetic activity of the phytobenthos.

Algae, for example the blue-green, or the Cyanophyceae, Dasycladaceae or Rhodophyceae algae, also play an important role in biochemical precipitation of limestones, e.g. the precipitation of stromatolitic or algal limestones is, in fact, brought about by the metabolism of the algae which in turn controls the CO_2 , and pH and the other physico-chemical parameters of the environment. Formation of modern algal limestones can be seen in the Carribeans, Florida Bay, eastern coasts of Australia, etc., where the sea is extensively populated by various types of algae.

In India, a large number of Precambrian calcareous rock formations have been shown to have formed due to the action of algae. Recent work by myself and my students (MISRA

& VALDIYA, 1961; MISRA & KUMAR, 1968; MISRA & BANERJEE, 1968; MISRA & BHATTACHARYA, 1973; VALDIYA, 1969; BHATTACHARYA, 1976) on the widespread carbonate belt of the Kumaon Himalaya, have indicated definite presence of algae, emphasizing, thus, the role of algae in the formation of extensive limestone deposits. Similar occurrences of Precambrian algae have also been reported from the Vindhya (MISRA & AWASTHI, 1962; VALDIYA, 1969; MOHAN, 1968), the Bijawars (KRISHNA MURTY, 1972), Aravallis (BANERJEE, 1971), and the Cuddapahs (VISWANATHIAH & RAO, 1967).

MAGNESITE

Magnesite, i.e. $MgCO_3$, is supposed to have formed due to a few processes, either directly or due to interaction amongst some of these processes. Of these, the process of (primary) precipitation of $MgCO_3$ from the sea water, is an important process. In fact, the precipitation of $MgCO_3$ is aided by the algal activity; because the algae by way of their photosynthesis, control the various physico-chemical parameters of the environment, required for $MgCO_3$ precipitation. It is well known that the secretion of algae contains as much as 25% $MgCO_3$. Further, being holophytic, the algal bodies themselves contain Mg as an essential constituent of chlorophyll. The role of algae in precipitating $MgCO_3$ has been emphasised by various workers (cf. JOHNSON, 1942). In the Pithoragarh district, Kumaon Himalaya, the close association of magnesite with algal colonies of *Collenia* is well known (MISRA & VALDIYA, 1961).

Australian and Manchurian deposits of sedimentary magnesite deposits owe their origin to largely direct precipitation of magnesium carbonate brought about by the action of algae.

PHOSPHORITE

The term phosphorite is mainly used for marine phosphate-bearing rock and, as such, is mainly constituted of a number of phosphatic minerals, like fluor-apatite ($Ca_{10}(PO_4CO_3)_6$), dahllite ($3Ca(PO_4)_2 \cdot CaCO_3$), francolite ($Ca_3F_2(PO_4)_6(O, OH)_{24}(CaCl)_4$), wavellite ($Al_3(PO_4)_2(OH, F)_3 \cdot 5H_2O$) and agnelite ($Al_3(PO_4)(OH)_{12}$), etc. Primary precipitation of phosphorite is one of the important processes of its formation. The general sequence of deposition of most of the phosphorite deposits, comprises of calcareous sediments followed by a combined precipitation of calcium carbonate and calcium phosphate. The most important physico-chemical conditions for phosphorite deposition include: a high pH in the range of 7.7 to 8.1; reduced partial pressure of CO_2 , and a depth range of 50 to 200 metres. Role of biological activities in bringing about the suitable chemical parameters, is being emphasised over the years (McKELVEY, *et al.* 1953). Recently my former student BANERJEE (1971) working on the Precambrian phosphorites of Rajasthan, has suggested the role played by algal stromatolites in trapping and precipitating the dissolved inorganic phosphorous from sea water. The Mussoorie phosphorite is also believed to be of biochemical origin (PATWARDHAN & AHLUWALIA, 1975).

SALT

The micro-organisms also play, though indirectly, some important role in depositing as well as in controlling the composition of salt. The resistance of individual species of micro-organisms to the concentration and composition of salts in water depends largely on the conditions under which the given micro-organisms live in nature (KUZNETSOV, *et al.* 1962, p. 36). It has been found that salt-resistant species do not grow if the sodium chloride concentration in the nutrient medium is lower than 1.5 per cent (KUZNETSOV, *et al.*

1962, p. 36). It has been found that salt-resistant species do not grow if the sodium chloride concentration in the nutrient medium is lower than 1.5 percent (KUZNETSOV, *et al* 1962, p 37). On this basis, VAN DEKDEN (1904) established the existence of two species of sulfate-reducing bacteria; the saline *Vibria aestuarii* and the fresh-water *Vibrio desulfuricans*. Later, BAARS (1930) showed that one form could be changed into the other by gradually changing the salt concentration in the nutrient medium.

In some of the oil fields, salt is found in close association with oil and sulfur. On the basis of experimental studies, the salt, in such cases, may be ascribed to have been formed due to the various stages of biofractionation of sulfur isotopes by the bacteria *Desulfotribrio desulfuricans* (THODE, *et al.* 1951; DAVIS, 1967, p. 79).

ROLE OF DIATOMS

Very recently, diatoms have been found to play an important role in segregating silica. Thus, MILLIMAN AND BOYLE (1975) have found that about 25 per cent of the dissolved silica carried by the Amazon river is depleted through diatom production in the river estuary. Annual production of opaline frustules is estimated to be about 15 million tons. However, few diatoms accumulate in modern shelf sediments and chemical recycling has been shown to be very slight. MILLIMAN AND BOYLE (1975) have shown that many frustules are transported landward into the river system where they deposit in dunes and layers on and within the mud and sand bars.

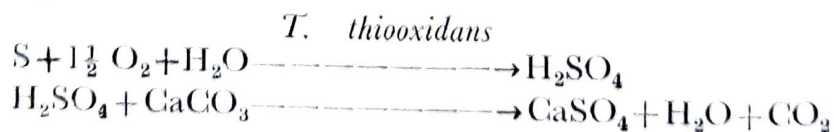
Diatomite which consists of microscopic siliceous tests of diatoms and rarely of other silica-secreting organisms, is used as a filler and filter, for heat and sound insulation, abrasives, in building materials, ceramics, and for chemical purposes. The largest deposits are in California belonging to Tertiary age. True diatomite has not been found in India, but recent muds in our coastal areas are rich in diatoms.

AMBER

Amber has been classified as a semi-precious stone. In fact it is a fossil resin derived from a particular variety of pine trees. It is mostly used for beads. Its chief source is Oligocene glauconitic sediments on the coasts of East Prussia (BATEMAN, 1962, p. 854). Eocene blue shales of Burma have been a source of gem amber for many centuries.

GYP SUM

Gypsum is a sulfate of calcium (CaSO_4) and is usually formed due to the evaporation of sea-water or also by inorganic processes in the calcium-rich solutions. However, microbial activities have also, of late, been given due significance in precipitating some sulfates like gypsum. Thus, under certain conditions, the secondary reaction of sulphuric acid with carbonate salts may give rise to sulfate salts. (UMBREIT, 1964, p. 186). On this basis, KARAVAİKO (1962) has shown that the oxidation of a limestone-bearing sulfur ore by the bacteria *Thiobacillus thiooxidans* may result in the formation of gypsum, according to the following reactions:



BAUXITE

Bauxite is chiefly a combination of aluminous minerals with Fe_2O_3 and some TiO_2 . It is one of the most important minerals formed due to the subaerial weathering of suitable rock types, and is, therefore, regarded as a residual mineral. However, very recently,

quite a different type of origin has been postulated by TAYLOR AND HUGHES (1975). According to them, bauxite can also be formed due to biogenic degradation of andesitic volcanic ash sediments in a shallow-water lagoon environment. They have studied the Rennel bauxite deposits of the British Soloman Islands. The bauxite deposits of all these areas are generally associated with nearby raised barrier—or fringing—reef limestones. Pliocene to Recent volcanism is widespread in the region. The adjacent lakes and lagoons are rich in anaerobic (reducing) bacteria *Clostridium nigrificans* and *Desulphovibrio* sp. On the basis of detailed studies, TAYLOR AND HUGHES (1975) have shown the bauxite deposits of these islands could have formed due to the bacterial degradation of andesitic volcanic ash sediments in the shallow-water lagoons of the area.

In the late forties, A. G. VOLOGDIN, while studying the Cambrian bauxites of Bukson in the Eastern Sayam Mountains of the U.S.S.R., has also reported the presence of some 40-50 per cent by volume, of nodular accumulations of filamentous bacteria. He described them as iron bacteria.

In the Uralian bauxites of Devonian age (cf. OPPENHEIMER, 1963) from the Krasnaya Shapochka of the U.S.S.R. the microscopic studies have revealed the presence of yellowish brown accumulations of fossilised iron bacteria cells in the layering of oolitic grains.

A number of Mesozoic bauxite deposits of the U.S.S.R., with pisolitic structures, have been found to contain colonies of iron bacteria (cf. OPPENHEIMER, 1963), which occur mainly as loosely formed concretions in the pisolitic grains.

The above studies clearly indicate the role played by iron bacteria in the process of bauxitisation, leading to the formation of bauxite.

IRON AND MANGANESE DEPOSITS

As a matter of fact, the geochemistry of iron and manganese is closely related. They not only show widespread and, in most of the cases, simultaneous occurrence, but also show complementary properties of most of their compounds. The (biogenic) formation of these two metals will, therefore, be discussed together here.

Role of bacteria in precipitating iron has long been recognised. HARDER (1919) distinguished three types of such bacteria, i.e. those precipitate (i) ferric hydroxide from ferrous bicarbonate solutions by absorbing carbon dioxide, (ii) ferric hydroxide without requiring ferrous carbonate, and (iii) ferric hydroxides or basic ferric salts from iron salts of organic acids. According to him, these are mostly the thread and soil bacteria, belonging to the form *Crenothrix*. Widespread deposits of iron ores have been caused by this bacteria.

ZAPFFE (1931), in a similar manner, also found that soil bacteria play vital role in precipitating manganese from the subsurface waters.

Detailed studies on this subject have clearly indicated the vital roles of micro-organisms in the formation of some common iron and manganese minerals, mostly their carbonates, oxides, sulfides, sulphates and silicates (UMBREIT, 1964), described below.

The biogenic ferro-manganese carbonate include rhodochrosite (MnCO_3) and siderite (FeCO_3), formed mainly due to the action of the bacteria *Leptothrix* and *Gallionella ferruginea*.

The biogenic ferro-manganese oxides include: pyrolusite ($\text{MnO}_2 \cdot \text{H}_2\text{O}$), manganite ($\text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O}$), hausmannite (Mn_3O_4), pyrochroite ($\text{Mn}(\text{OH})_2$), manganosite (MnO), goethite ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$), magnetite (Fe_3O_4) and limonite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$). The various bacteria involved in their formation are *Bacillus macerans-polymyxa*, *Thiobacillus thiooxidans*, *Bacillus circulans*, *B. megaterium* and *Aerobacter aerogenes*.

The sulfides include alabandite (MnS), troilite (FeS), hydrotroilite ($\text{FeS} \cdot n\text{H}_2\text{O}$), pyrite and marcasite (FeS_2) and pyrrohotite ($\text{Fe}_n \text{S}_{n+1}$). The various types of sulfate-reducing bacteria that help in the formation of these minerals include: *Thiobacillus*, *Sphaerotilus*, *Desulfovibrio*, *Clostridium*, *Chromatium*, etc.

The biogenic ferro-manganese sulfates include melanerite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) and coquimbite ($\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$). The accumulation of these minerals requires a very acid pH and a high concentration of sulfate, which are largely or wholly brought about by intense microbial activity on iron sulfides in the micro-environments (UMBREIT, 1964, p. 192). The bacteria involved in their formation include: *Thiobacillus thiooxidans*, *T. concretivorus*, *T. ferrooxidans*, *Ferrobacillus ferrooxidans*, and *F. sulfooxidans*.

The silicates of probable biogenic origin are: thuringite, chamosite, greenalite and glauconite. Their chemical compositions are very complex. The detailed biogeochemical actions are not fully known. However, adsorption by diatoms is believed to be a possible mechanism in precipitating ferro-manganese silicates (MOLISCH, 1910).

IRON PYRITES

The well known Amjhore pyrites deposits of Shahabad Dt. Bihar belonging to Vindhyan formation, which have been found suitable for the manufacture of sulphuric acid, owe their origin to bacterial activity (MUKTINATH, 1974).

SULFUR DEPOSITS

The sulfur deposits occur in nature either as elemental sulfur or as salts of sulfides and sulfates. The cycle of sulfur in nature is the result of the activities of plants, animals and micro-organisms as well as nonbiological processes (UMBREIT, 1964, p. 170). Both the chemosynthetic and photosynthetic bacteria play major roles in aerobically or anaerobically oxidising the hydrogen sulfide of biological, volcanic or hydrothermal origin, to the elemental sulfur. Of all the bacteria, *Thiobacillus* species cause most large-scale conversion of elemental sulfur to sulfates. The other important sulfate-reducing bacteria are *Desulfovibrio* spp. and *Clostridium nigrificans*.

The bacterial activity to form sulfur deposits, is not only confined to lakes and ponds, but also takes place in deep underground mineral waters to cause mineral transformations and degradations, though under anaerobic conditions. Thus, the sulfate minerals like gypsum and anhydrite are reduced to sulfur by the action of sulfate-reducing bacteria (KUZNETSOVA & PANTSKHAVA, 1962).

The major habitats of sulfate-reducing bacteria are surface muds of the littoral zones of oceans and inland bodies of water (ZOBELL, 1946). Present day deposition of biogenic iron sulfides can be seen in the dark coloured bottom deposits of the Black Sea (SOROKIN, 1962; ZOBELL, 1946), and in the black muds of tidal flats and littoral zones of oceans (UMBREIT, 1964, p. 175).

In India, the origin of syngenetic sulfur deposits has been studied by IYA AND SRENIVASAYA (1944). They investigated the sulfur deposits of the coastal areas of the Bay of Bengal, where sulfur occurs in the sandy and clayey littoral sediments, which were flooded with sea water during the Mussonian period. A layer of black hydrogen-sulfide clay underlies the sulfur-bearing sediments. The sulfur content is very high, i.e. up to 27-35 per cent. The black clay that underlies the sulfur-bearing sediments, has been found to contain active sulfate-reducing bacteria *Vibrio desulfuricans*. This clearly indicates the active role played by the sulfate-reducing bacteria in the formation of sulfur deposits.

GOPPER

Though widespread copper deposits of biogenic origin are not commonly found in nature, the inherent activity of bacteria to form copper minerals, is a more or less established fact. However, laboratory studies have proved and strengthened the validity of this fact. For example, BAAS BECKING AND MOORE (1961) prepared covellite (CuS) from chrysocolla ($\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$) or malachite ($\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$) as well as digenite (Cu_2S) from Cu_2O , by bacterial sulfate reduction in artificial sea water. During covellite formation from malachite, native copper was found to appear as an intermediate product.

URANIUM ORES

Fundamentally, the formation of biogenic uranium ore in nature is due to microbial interactions with inorganic compounds. This process also leads to mineral formation or breakdown. It has been found that sulfate is not readily reduced to H_2S in the absence of micro-organisms at ordinary temperatures, Eh and pH (JONES *et al.*, 1956). But in the presence of *Desulfovibrio* spp. or *Clostridium nigrificans*, sulfate is rapidly reduced to H_2S , which non-biologically precipitates the heavy metals dissolved in the reaction mixture (UMBREIT, 1964, p. 161). In accordance with this process, the sulfate-reducing bacteria have been found to cause precipitation of uranium oxide by reducing uranyl ion with biogenic H_2S (UMBREIT, 1964, p. 161). The uranyl ion may be of any origin-magmatic or hydrothermal, or may be derived by leaching of primary uranium deposits.

MICRO-ORGANISM AND HYDROLOGY

The number as well as the species composition of micro-organism in the internal waters and the rocks of the upper layers of the earth's crust have much to do to a hydrologist. It has been found that the presence of the various types of bacteria affects the composition of the ground water. This is more so in the waters of petroliferous regions. As early as 1926, BASTIN gave an account of sulfate-reducing bacteria in the stratal waters of U.S.A., Later, GINTZURG-KARAGICHEVA (1932) described sulfate-reducing, deitrifying, ammonifying and other bacteria from the stratal waters of Apsheron Peninsula, U.S.S.R. It has been shown (MEKMITIEYA & MALKOVA, 1958) that live active bacteria occur down to 800 metres, and their distribution is independent of the lithology, though, the grain size and mineral composition have been suggested (KUZNETSOV, *et al.*, 1962, p. 65) to be some effective and controlling parameters in this respect. Of the various bacteria, the thiobacteria, particularly *Thiobacillus thioparus*, has been found to cause much geochemical changes within the stratal waters.

BACTERIAL LEACHING

In recent years, the study of microbiology of the bacteria from different ores has opened some new vistas, especially in the field of economic geology and prospecting. It was found that the iron-oxidising thiobacilli play a vital role in oxidising metal sulfides and ferrous ions in sulfuric acid solutions. This, in a way, provided a means by which these bacteria could be utilised to regenerate the leach solutions. The process has, therefore, been utilised for leaching of low-grade ores as well as waste materials from the mines.

Theoretically, leaching is a redox reaction in which minerals are oxidised at the expense of some suitable ore solutions like ferric sulfate. Application of this process has been found to be of immense help, in many cases, for utilising or enrichment of low-grade ores or mine wastes. The operation is relatively simple. Huge heaps of low-grade ores are sprayed with a solution of certain nutrients in very dilute sulfuric acid. As this starter solution

percolates through the dump, *Thiobacillus* bacteria oxidise the nickel sulfides to sulfuric acid and release nickel, which is electrolytically separated, leaving sulfuric acid which is re-used.

The process of biological or bacterial leaching, as described above, is of immense help in the recovery of metals like copper, zinc, nickel, and uranium ores, which could otherwise not be recovered through the conventional methods of beneficiation. As a result of detailed researches on this subject, some *Thiobacillus* species have been discovered which can break down ore under alkaline conditions. Further, such bacteria which cause leaching of zinc silicates, have also been discovered recently.

Bacterial leaching is nowadays utilised in many countries for beneficiation and utilisation of low-grade ores and mine wastes. In our country also, such methods are being utilised, especially at the Metallurgical Research Institute, Jamshedpur. One great advantage of this process is that it does not cause atmosphere pollution. However the process is very slow.

MICRO-ORGANISM AND PROSPECTING FOR OIL

The micro-organisms are also nowadays utilised for prospecting of oil in conjunction with the conventional geological and geophysical methods. The microbes have helped in increasing the production of oil. As such, this practice, i.e. microbial prospecting, is being utilised in many petroliferous areas.

Studies on microbes in the oil strata have shown that sulfate-reducing bacteria are the most widespread group in oil stratal waters. Thus, the separation of oil from the reservoir rocks has become possible by the use of enrichment cultures of this very group of micro-organisms.

Detailed work by ZOBELL (1946, 1947) has shown that the secondary oil extraction through the action of microbes is quite possible. He suggested the following ways for increasing the oil production: (i) by the bacterial formation of acids, particularly carbonic acid, which facilitate the movement of oil by increasing the pore spaces in the limestone rocks, (ii) by the formation of gases which, being dissolved in the oil, increase its mobility, (iii) by the destruction of high-molecular hydrocarbons and the formation of the more mobile compounds with short carbon chains, and (iv) by the destruction of surface-active substances by bacteria. As a matter of fact, ZOBELL (1947) has shown in his laboratory experiments that these requirements are met by the sulfate-reducing bacteria, particularly *Desulfovibria hydrocarbonoclasticus* and *D. halohydrocarbonoclasticus*.

GEOBOTANICAL PROSPECTING

Plants have recently been proved to be an asset, especially in the prospecting of metals. The principle of using plants in the search of economic ore deposits is based on the ability of plants to absorb high concentrations of metals from the strata at considerable depths or from a mineralised halo around an ore deposit. Though, it is said that GEORGIUS AGRICOLA was the first to suggest this method as far back as the 17th century, it was the Russian geologist THALICH (1938) who put this method of metal prospecting on a sounder footing by advocating the use of indicator plants and plant ash analysis. This method has, of late, been proved to be of utmost value in metal prospecting. Thus, in Sweden, once the copper-moss *Merceya latifolia* was established as an indicator for copper, the various copper-ore deposits were located by merely noting the localities from which herbarium specimens of the plant were obtained in the various herbaria of the country. Nowadays,

a great number of such indicator plants, whose mere presence indicates the occurrence of a particular metal in the underlying strata, have been thoroughly established and are being utilised in the location of new ore deposits.

In India too, some work on these lines is being done by the Geological Survey of India. Recently TIAGI (1974) has undertaken a work on the geobotanical prospecting of the copper ore deposits of Madhya Pradesh, Rajasthan and Bihar. He has collected about 200 species of angiosperms, one species of Pteridophyta and a species of *Riccia*. As a result, certain species of the Grammineae, Cyperaceae, Portulacaceae and Labiatae have been found to be restricted only to the regions of the copper ore deposits. A species of the Scrophulariaceae, *Anticharis linearis*, has been found to be a wonderful accumulator of the metal copper accumulating up to 500 ppm of Cu, whereas in the other 10 species investigated so far, it ranges from 120 to 380 ppm.

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