CONTROLS OF PHOSPHORITE FORMATION SUPERIMPOSED ON BIOLOGICAL ACTIVITY IN THE LESSER HIMALAYA, INDIA

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ABSTRACT

There are two essential controls on phosphogenic systems namely (i) up-welling and (ii) microbial activity. Upwelling is the principal mechanism which regularly exploits the phosphorus from the deeper ocean reservoir. Phytoplankton which grow profusely in the zone of upwelling are considered as primary consumers of phosphorus. The microbial communities (Cyanobacteria etc.) play a crucial role in phosphorite formation. Bacteria usually thrive on organic matter and aid in the release of its phosphorus content to the ambient water. Modern research has shown that chemolithotropic bacteria are found in phosphatic nodules. These bacteria accumulate nucleic acids, phospholipids and polyphosphate during their growth. The phosphorus is transformed into bacterial cellular structure completely composed of apatite after the death of the organisms. Deoxyribo nucleic acid (DNA) and Ribonucleic acid (RNA) and phospholipids play important roles in genetics and energy transfer reactions in all plant and animals. The primitive plants-*phytoplanktons* play a significant role in the extraction of phosphorus from the oceans. The stromatolitic (fossil *microbialite*) phosphorite deposits especially of Proterozoic-Cambrian age signify important global events in relation to the role of microbiology in phosphogenesis. The present study of Mesoproterozoic (Deoban-Gangolihat) and terminal Proterozoic-Lower Cambrian (Krol-Tal) phosphorite deposits of the Lesser Himalaya, India suggests that perhaps upwelling and microbial productivity have superimposed on each other for the formation of phosphorite.

INTRODUCTION

The spatial and temporal distribution of phosphorites, indicates that it first appears sporadically in the early Proterozoic. However, it attains significant abundance during the Late Precambrian-early Cambrian (Tommotian) (Tewari, 1991 b, Krazewski *et al.,* 1994). During the subsequent span of Phanerozoic time it becomes notably concentrated in the Ordovician, Permian, Jurassic, Upper Cretaceous-Eocene and Miocene-Pliocene Periods (see Table-1; Sheldon, 1964, 1980; Cook and McElhinny,1979; Chauhan, 1979; Cook 1982; Cook and Shergold, 1984; Banerjee

et al., 1986; and Dahanayake and Krumbein, 1985 and Brasier, 1992).

Several hypotheses have been proposed to explain the formation and distribution of phosphorite during the aforesaid specified periods, spanning nearly 2.2 billion years of the earth's history. The basic premise of these hypotheses is to consider the oceans of the geological ages as giant mixing pots in which the various chemical ingredients contributed by weathering, erosion and volcanicity were concentrated (Chauhan, 1989). Because of the specific

Table-1

PHOSPHOGENIC EVENTS	AGE (Million years)	COUNTRIES
MIOCENE-PLIOCENE	10-25	CONTINENTAL MARGINS : FLORIDA, NORTH CARO LINA, BAJA CALIFORNIA (U. S. A.): SECHURA, VENEZUELA, PHILIP PINES.
UPPER CRETACEOUS-EOCENE	60-100	SYRIA, JORDAN, ISRAEL, EGYPT, IRAQ, ALGERIA, TUNISIA, MOROCCO, SENEGAL, TOGO.
JURASSIC	149	RUSSIA, MEXICO, N., SOUTH AMERICA, W. EUROPE, W. AUSTRALIA, PAKISTAN, W. CANADA.
PERMIAN	250	W. U.S.A., URALS, SZECHWAN, INDO-CHINA, N. INDIA, TENNESSEE, CENTRAL AND SE. AUSTRALIA, BALTIC AREA, IOWA, E. CANADA, BOLIVLA, BAIKAL.
ORDOVICIAN CAMBRIAN	464	TENNESSEE, CENTRAL AND SE AUSTRALIA, BALTIC AREA, IOWA, E. CANADA, BOLIVLA, BAIKAL.
	542	KARTAU, RUSSIA, GEORGINA BASIN, CENTRAL AND SE. CHINA, VIETNAM, S. AUSTRALIA, KHUBSUGUL, TIEN SHAN.
TOMMOTIAN PRE-CAMBRIAN/CAMBRIAN BOUNDARY	570	SAYAN, CENTRAL KAZAKHSTAN, TENNESSEE, E. CANADA, MAURITANIA, MUSSOORIE, BIRMANIA, (INDIA), HAZIRA, (PAKISTAN).
NEOPROTEROZOIC	620	VOLTA AREA, MAURITANIA, CHINA,
	700-800	CENTRAL SIBERIA, BRAZIL ? CENTRAL AUSTRALIA.
MESOPROTEROZOIC	950±50	GANGOLTHAT, DEOBAN (INDIA), NEPAL, LESSER HIMALAYA.
PALAEOPROTEROZOIC	1,200-1,600	UDAIPUR, JHABUA CUDDAPAH (INDIA), RUM JUNGLE,
	1, 300-2,200	BROKEN HILL, MICHIGAN, FINLAND.

Modified from Cook and McElhinny, 1979 and Cook, 1982.

chemical attributes of phosphorus its reserves were built in the deeper cold reaches of the oceans. Phosphorite formation took place as a result of precipitation of apatite in shallow water environments, due to supply of phosphorus reserves of the deeper oceans there. This was facilitated by the development of an elevator-like system of upwelling currents of oceanic circulation.

Kazakov (1937) was first to propound the theory of upwelling current, according to which phosphorite formed as a result of upwelling of deep cold phosphate-rich oceanic waters on to the shallow shelf regions, where phosphorite precipitated essentially inorganically.

On the basis of an analysis of young phosphorites (late Tertiary to Recent), Sheldon (1964) pro-

vided a plausible explanation for the spatial distribution of phosphorite of the Phanerozoic eon. He suggested that most of the ancient phosphorite must have formed within 40^0 palaeolatitude. Obviously, phosphorite precipitation was confined to the warm climates. This was affirmed by Cook and McElhinny (1979) who added new dimension to this aspect of study of phosphorite. They invoked plate tectonics to explain that the lithospheric plates were pushed and pulled apart and drifted within and around the equatorial circle. As a consequence, new systems of upwelling currents were generated mainly in the newly formed oceans, and phosphorite formed in shallow water regions bordering the new land masses. Further, they were of the view that phosphorite in the Cambrian and late Cretaceous-Eocene, could form in abundance due to development of shallow low latitudinal east-west seaways. In contrast, the lack of phosphorite from the Silurian to Carboniferous periods and in the Triasssic was attributed to the paucity of coastal areas at low latitudes.

Sheldon (1980) further refined the upwelling model and suggested that the formation of phosphorite throughout the geological ages is related to the episodicity of phosphorite deposition, caused by variations in the oceanic circulation. Accordingly, the major episodes of the Cretaceous to early tertiary were due to phosphorus withdrawal from the deep ocean phosphorus sink, primarily by equatorial upwelling, at the time of high level warm seas; whereas those of the Cambrian, Ordovician, Permian and Miocene periods were due to trade wind belt upwelling at the time of transition (related to glacial episodes) from high level warm oceans to low level cold oceans.

From the foregoing discussin, it can be interpreted that phosphorite was formed through space and time due to the periodic exploitation of the deep ocean phosphorus reservoir. This was facilitated by the development of a powerful system of upwelling currents, as a consequence of the changing configuration of land and sea, caused by plate tectonics. However, the model discussed above does not provide a valid explanation for the lack of phosphorite in the early Precambrian. It appears that the situations were altogether different in Proterozoic times. Cook and McElhinny (1979) pointed out that due to lack of

shallow seas, association with iron and comparatively little biomass, phosphorite could not form earlier than 2200 million years. Similarly, Sheldon (1980) expressed the view that the earliest phosphorite of the Precambrian owe its formation to the changing chemistry of the oceanic water. These chemical changes resulted from the change of the lifeless acidic ocean and oxygen free atmosphere to a biologically induced environment of alkaline ocean and oxygen rich atmosphere. Recently, Schidlowski (1988) has found a 3,800 million year isotopic record of life from carbon in sedimentary rocks.

The atmospheric, oceanographic and climatic changes which led to the formation of phosphorite and phosphatic stromatolite seem to have worked together more purposefully for the evolution of life on the surface of the earth, for example :

i) An increased ratio of ^{12}C to ^{13}C an indicator of the principal carbon-fixing reaction of photosynthesis is found in sedimentary organic matter dating back to almost four thousand million years ago, a sign of prolific microbial life not long after the earth's formation. Partial biological control of the terrestrial carbon cycle must have been established very early and was in full operation when the oldest sediments were formed (Schidlowski, 1988).

ii) Microbial structures attributable from the mat building activities of prokaryotic microbenthos (stromatolites) have been traced back to 3.5 b.y. but the biogenicity of the presumably oldest cellular microfossils is still disputed.

iii) The change from anoxic to oxic atmosphere served as a basic element for the evolving life to survive and change from primitive prokaryotic to advanced eukaryotic forms (Schopf, 1978).

iv) The warm climate helped in the proliferation of life, whereas transitions from warm to cold climates created ecological pressure to cause extinction and emergence of new species (Valentine, 1973; Valentine and Moore, 1974).

Thus, there appears to be close connection between the events of phosphorite formation, and evolution of atmosphere, hydrosphere and biosphere. This aspect is meticulously discussed by Cook and
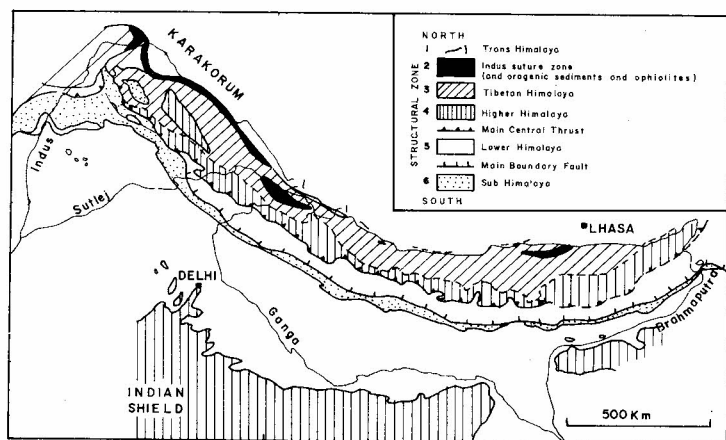
Fig. 1a Structural zones of the Himalaya, India (after Gansser, 1974) showing Precambrian-Cambrian sedimentary belt of lower or Lesser Himalaya (5).
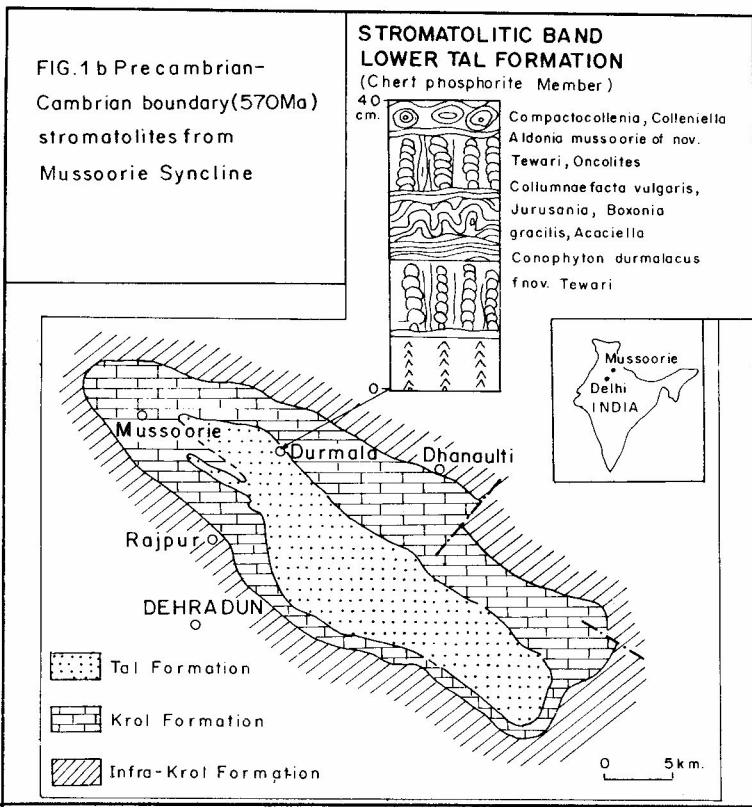

Fig.1b Precambrian-Cambrian boundary stromatolites from the Mussoorie syncline, Lesser Himalaya, India along which isotopic excursions were obtained.

Shergold (1984) in an analysis of the global phosphogenic events around the Precambrian-Cambrian boundary. The late Precambrian/early Cambrian was a time of oceanic chemical events. An exteme rise in the sulphur-isotope (δ^{34} S) curve has been termed the *'Yudomski Event'* and attributed to the catastrophic mixing of brine in local basins with the surface ocean water. A phosphogenic event has been postulated for this time. In this contest, it is to be emphasized that the appearance of a biological system on the scene of phosphogenic system can not be without purpose. It seems to have served as one of the basic elements of the phosphogenic system.

Carbon isotope excursions in Precambrian/Cambrian boundary beds (carbonates and phosphorites) have been obtained from Morocco, Siberian platform, and Lesser Himalaya, India (Fig. 1,a, b, Fig.2) (Tucker, 1986; Aharon *et al.,* 1987; Tewari, 1989, 1991 a, b, 1993 a,b, Brasier, 1992). A positive δ^{13}C excursion at the end of Precambrian and a negative δ^{13}C excursion in phosphorite (Lower Cambrian) has been obtained (Fig 3).

CONTROLS OF PHOSPHORITE FORMATION

There seems to be two essential controls of phosphogenic system, namely, (i) upwelling, and (ii) organic activity.

The concentration of phosphorus in the oceanic water is not uniform. For example, in the surface layer of water in the open southeast Atlantic Ocean it ranges from 0 to 0.15 ug/1, whereas in deeper colder reaches it rises to 90 ug/1 (Baturin, 1982). Apart from the microbiological factors, these variations in the concentration of phosphorus are considered due to variation in pH conditions of the surface warm and deeper cold oceanic waters caused by variation in the partial pressure of CO_2 (Gulbrandsen and Roberson, 1973; Sheldon, 1980).

Upwelling is the principal mechanism which constantly exploits the deeper ocean phosphorus reservoir. According to the estimates of Baturin (1982), upwelling supplies nearly 10 million tons of dissolved phosphorus to the zone of modern phosphorite formation each year, which is more by an order of magnitude, than all rivers on the land bring to world oceans, (Baturin *et al.*, 1995) and is one of the most essential elements of the

Fig. 2 — Biota and phosphatic cycles in the Neoproterozoic-Cambrian sequence table:

Formation / Member	LITHO-COLUMN	MAX. THICKNESS (mtrs)	Algae, Cyanobacteria	Acritarchs	Stromatolites	Oncolites, Catagraphs	Ediacaran fossils (Metaphyte & metazoa)	Pre-Ediacaran	Brachiopods	Trilobites	Small shelly fossils	Trace-fossils	AGE
SUBATHU FORMATION													Eocene
SHELL LIMESTONE FORMATION													Cretaceous
TAL FORMATION — QUARTZITE MEMBER E		180											Botomian Stage
QUARTZITE MEMBER D		300			I I				T				
QUARTZITE MEMBER C		50											(=Tsanglangpuian Stage)
QUARTZITE MEMBER B		100							I	I		T	
QUARTZITE MEMBER A													
CALCAREOUS MEMBER		50							I	I			Aldabanian Stage? (Qiongzhusion Stage)
ARENACEOUS MEMBER		550											(Meishucunion Zone III)
ARGILLACEOUS MEMBER		450											
CHERT - MEMBER		150		I	I								(Meishucunion Zone I)
UPPER KROL E			I			I				T		I	
UPPER KROL D				I	I	I						I	Ediacaran
UPPER KROL C												I	
MIDDLE KROL B													
LOWER KROL A			I			I							
INFRA KROL FORMATION		400	I	I									Vendian
BLAINI FORMATION		500	I	I	I								
JAUNSAR - SIMLA GROUP		+500		I	I								Upper Riphean
DEOBAN GROUP		+500	I		I	I							Lower to Middle Riphean

Right margin ages: Lower Cambrian; ?–? ; Terminal Proterozoic

LEGEND

- ▦ Limestone
- ▨ Dolomite
- ▦ Shale/Slate
- ▦ St
- ▤ Purple & greenish shale
- ▨ Siltstone / Calc. siltstone
- ▦ Quartz-arenite
- ▦ Felspathic arenite
- ▧ Chert - phosphorite
- ▦ Diamictite

Not to Scale

Fig. 2   Biota and phosphatic cycles in theNeoproterozoic-Cambrian sequence of theLesser Himalaya, India (modified after Ravi Shankar and Mathur,

phosphogenic system throughout geologic time.

Organisms are the principal consumers of phosphorus. Upwelling works as a main agency of supply of phosphorus to marine life in the photic zone. It is important to note that areas of upwelling constitute less than 1 percent of the present day oceans, yet they supply 50 percent of the total marine biomass (Cook and McElhinny, 1979).

Phytoplankton which grow profusely in the zone of upwelling are considered as primary consumers of phosphorus. Secondary consumers are zooplankton, benthos, fish, sea birds and mammals. It is important to note that primitive plants-phytoplankton-

also play a significant role in the extraction of phosphorus from the oceans. It is estimated that phytoplankton as a whole, in the zones of upwelling, extract nearly 100 million tons of dissolved inorganic phosphorus per year and produce up to 4 million tons of organic carbon (Baturin, 1982).

The pressing demand of the organic world for phosphorus is due to the fact that it enters into the constitution of its every living cell as a vital component. It constitutes structural elements of enzymes, adenosine triphosphate. RNA, DNA, nucleic acid and phospholipids, which play important role in genetics and energy transfer reactions in all plants and animals. However, a detailed C,O,S,N, Sr isotopic studies and microbial geochemistry (GC-MS study) have to be done to establish this relationship on a global scale.

The various microbial communities mentioned above work in two ways in the phosphogenic system. Firstly, the significant proportion of phosphorus tied up in phytoplankton is considered to be the most mobile. It is added to the deeper oxygen minimum layer of shallow oceanic water and/or to the interstitial water of bottom sediments, in which they collect on their death, by bacterial decomposition. The phosphorus content of soft parts of higher organisms is also similarly added to the interstitial water of bottom sediments in which they are buried. Secondly, vertebrates and some invertebrates directly contribute to phosphorite formation because their hard parts are formed of hydroxyl-apatite. However, very small quantities of phosphorite have formed in this manner (Riggs, 1979; Sheldon, 1981).

Thus, it is clear from the above discussion that upwelling and high organic productivity have some sort of cause-effect relations, superimposed on each other and they work together in enhancing the concentration of phosphorus necessary for the formation of phosphorite.
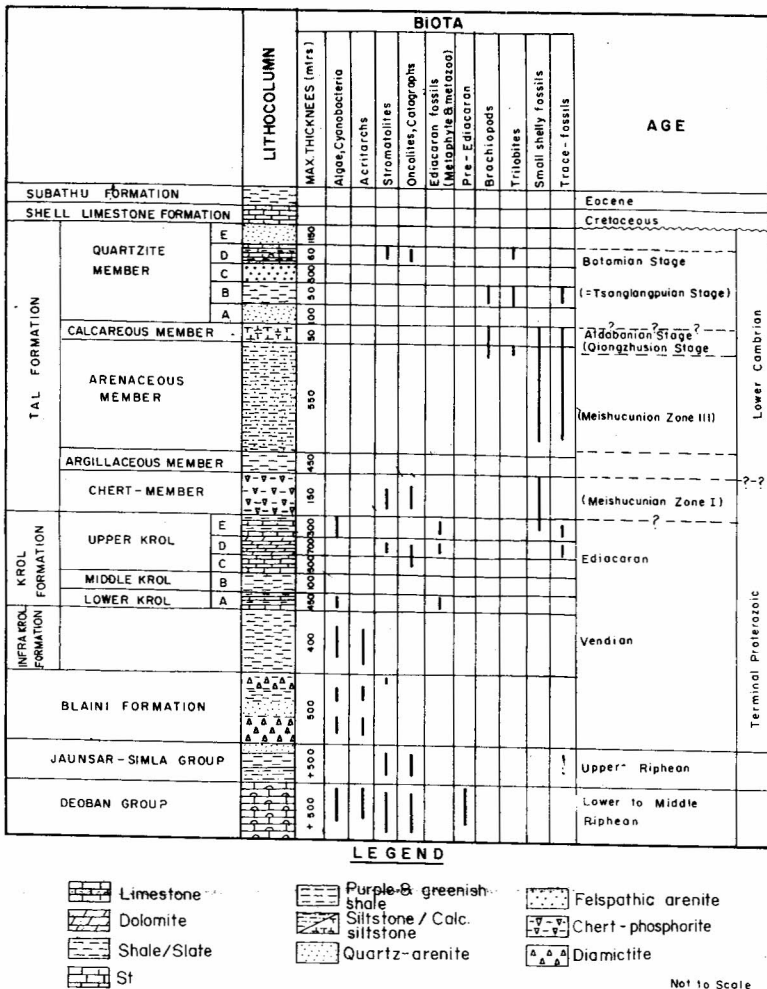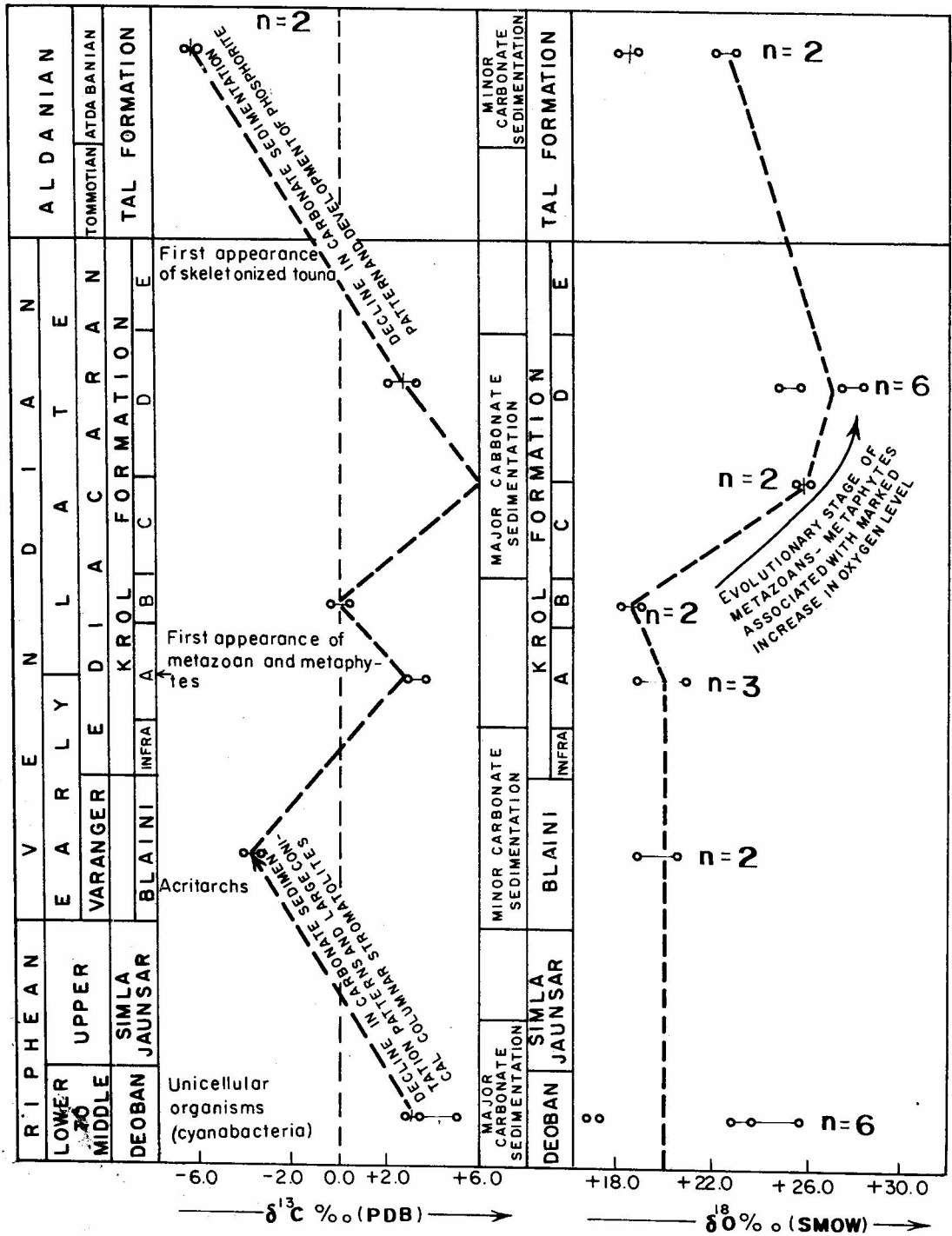
Fig. 3 Carbon and oxygen isotopic changes and biotic events in the carbonate phosphorite sequence of the Lesser Himalaya.

MICROBIAL ACTIVITIES ACROSS GEOLOGICAL HISTORY

The microbial communities play a crucial role in phosphorite formation. Bacteria usually thrive on organic matter and aid in the release of its phosphorus content to the ambient water (Chauhan, 1989; Krajewski et al., 1994). In addition, there are some

marine bacteria which have a remarkable capacity to assimilate dissolved inorganic phosphorus to the extent of 30 mg p/1 day and fix it firmly. This assimilated phosphorus may enter into phosphorite formation (cf. O' Brien *et al.,* 1981).

Cayeux (1936, in Riggs, 1979) observed bacteria in a number of Precambrian and Tertiary phosphorite deposits and concluded that they were present in phosphorite of all the geological ages. Riggs (1979) pointed out that the association of bacteria with phosphorite is universal and as such the two may be genetically related. Krajewski *et al.* (1994) have further supported this idea.

Recent finding of 'O' Brien *et al.* (1981) and Riggs (1982) proved further revealing. O' Brien *et al.*(1981) discovered certain types of facultative chemolithotrophic bacteria from the late Pleistocene to Holocene phosphate nodules of the East Australian continental margin. According to them, these bacteria, accumulate normal to even elevated concentration of nucleic acids, phospholipids and polyphosphate during their growth. This assimilated phosphorus is transformed into bacterial cellular structure fully composed of apatite after the death of the organisms. The apatite so formed, appears to have given rise to the nodular phosphate. Riggs (1982) reported similar bacterial structures also composed of apatite from the Neogene phosphorite of the Atlantic Coastal Plains and arrived at similar conclusions. The presence of bacterial structures in the phosphatic nodules of the Mussoorie phosphorite can also be explained by a similar process.

Other microbial life also operates in similar ways in the phosphogenic system is not known. However, certain form of green algae have been reported to accumulate as much as 20 percent PO_4 of their dry weight under exceptional conditions (Asad and Brochardt, 1970, in Riggs, 1979). In a recent study of Djebel-Onk phosphorite of Algeria-Tunisia (Upper Cretaceous to Eocene) Dahanayake and Krumbein (1985) have nicely elucidated the role of fungal mats in the formation of phosphate bearing ooidal and oncoidal structures.

The above studies suggests that some form of life or the other is involved in the formation of phosphorite throughout the geological ages, including the Holocene. However, the lack of appreciation of the role of biological processes in phosphorite formation is due to the fact that most of the biogenic signatures are obscure and often erased in the course of reworking and/or deformation cycles, through which most of the phosphorite deposits of the World have undergone (Bushinski, 1969; Cook, 1982; Cook and McElhinny, 1979; Riggs, 1979; Chauhan, 1979, 1989; Chauhan and Sisodia, 1981; Baturin, 1982 and Krajewski *et al.,* 1994).

ROLE OF STROMATOLITES IN PHOSPHO GENESIS

Phosphate bearing stromatolites ranging in age from early Proterozoic to Eocene, have been reported from different parts of the World. They have accumulated varying amounts of phosphorus throughout these ages. It appears that they were the sole repository of phosphorite in early Proterozoic time. However, they also constitute a significant proportion of some important Phanerozoic phosphorite deposits (Monty, 1973).

The common compositional attributes of these stromatolites are :

(a) Phosphate occurs within the body of the stromatolites.

(b) Phosphate and carbonate in varying proportion constitute the body of the stromatolites.

(c) Stromatolites occur enclosed within predominantly carbonate matrix.

The above features have been variously interpreted by a number of workers (Chauhan, 1979, 1989; Chauhan and Sisodia, 1981; Banerjee, 1971, Banerjee *et al.,*1980, Banerjee *et al.,* 1986; Valdiya, 1972; Southgate, 1980; Krajewski, 1981; Krajewski *et al.,* 1994; Krasilnikova and Paul, 1983; Tewari, 1984 c,d, 1989, 1991b, 1993b, 1994; Eganov, 1988; Kumar and Muller, 1988) to formulate the process of formation of stromatolitic phosphorite. Two views emerged from these studies:

i) Phosphate formed due to replacement of carbonate stromatolites.

ii) Phosphate formed due to direct precipitation of phosphate within the body of stromatolites.

In view of the above considerations, the following process of formation of stromatolitic phosphorite

can be envisaged. Certain cyanobacterial communities probably coccoid, in association with some bacteria flurishing in phosphate-rich intertidal to subtidal water were on the one hand accreting carbonate structures principally by *in situ* precipitation of calcium carbonate, on the other hand their other cyanobacterial partners (perhaps filamentous) changed the chemical environment of the ambient water and initiated apatite formation by more or less simultaneous replacement of the developing carbonate structures.

PALAEOMICROBIOLOGY AND PHOSPHO-GENESIS

The stromatolitic (fossil microbialitic) phosphorite deposits signify important global events in relation to the role of microbiology in the phosphogenic system.

The Palaeo to Neo proterozoic stromatolitic phosphorite deposits of the Russian platform, Peninsular and Himalayan regions of India and China further suggest that prokaryotic biota, including vase shaped microfossils, worked at a number of places as an esssential component of the early phosphogenic system (Tewari, 1991b). The evolution of cyanobacteria suggests that certain members of their palaeomicrobial communities must have continued to work unaided as one of the essential components of the global phosphogenic system until their competitors, like Ediacaran metazoans and eukaryotic algae appeared on the scene, in the terminal Proterozoic (cf. Garrett, 1970; Monty, 1973; Schopf, 1978; Schopf and Walter, 1982; Tewari, 1984 c,d, 1989, 1991 a,b, 1993 a,b, Fig 2). The richest and largest phosphorite deposits of the World are found near the Precambrian-Cambrian boundary, where major changes in Earth's atmosphere, biosphere and explosive radiation of life took place (Brasier, 1992; Fig. 2). Major changes in isotopic signatures have also been recorded (Tucker, 1986; Aharon et al., 1987; Tewari, 1991 a,b, Fig. 3). The sporadic occurrence of low grade stromatolitic phosphorite deposits in the Phanerozoic suggests that the cyanobacterial communities could not excercise their full influence in the younger phosphogenic system due to the appearance of higher life (cf. Walter and Heys, 1985)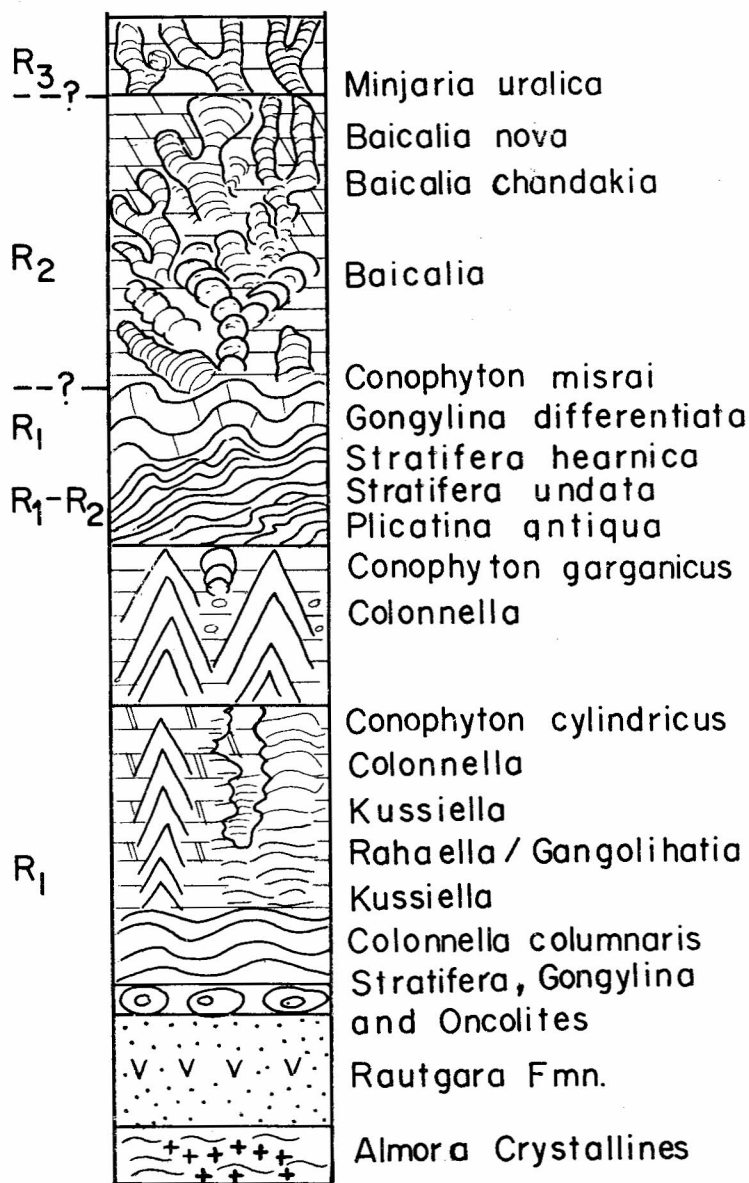. However, it is to be noted that their contemporary prokaryotic bacteria continue to play a crucial role even in the Holocene phosphogenic system (Riggs, 1979, 1982; O' Brien et al., 1981.).

PROTEROZOIC-LOWER CAMBRIAN MICROBIAL PHOSPHORITES: EXAMPLES FROM THE LESSER HIMALAYA AND THE INDIAN SHIELD

PROTEROZOIC PHOSPHORITES

The origin of the Proterozoic and Lower Cambrian phosphorite deposits of India including those associated with stromatolites has been studied by Chauhan (1979, 1989), Banerjee (1971), Banerjee et al. (1980), Banerjee, et al. (1986), Kumar and Muller (1988),Tewari (1984 c,d, 1991b, 1993b, 1994). Banerjee (1971) and Banerjee et al. (1980) proposed a genetic connection of phosphorites with stromatolites, however, they could not define the role of stromatolites in the precipitation phosphorous in Aravallian phosphorite. Neither could the direct role of bacteria/algae in precipitated of phosphorite nor the palaeoenvironmental conditions (e.g. reduction of phosphate by bacteria under reducing conditions) be established. The main assemblage of Palaeoproterozoic stromatolite found associated with Aravallian phosphorite are identified as *Kanpuria* sp., *Minicolumella* sp.,*M. burmanae*, *M. chauhanae*, *Butinella* sp., *Sundosia* sp. *Butinella* and *Sundosia* are also found in the Lower Proterozoic rocks of Karelia (Makarikhin, personal discussion).

Valdiya (1972) and Tewari (1981, 1991b) also tried to establish the origin of Mesoproterozoic phosphatic stromatolites of the Gangolihat Dolomite of Kumaun Lesser Himalaya (Fig. 4). Valdiya (1972) explained that algae were instrumental in the localization of collophane and contended that collophane was emplaced subsequent to the deposition of the constituent carbonate of the stromatolites. The decay of algae in the restricted basin released phosphorus which caused the contemporaneous diagenetic transformation of the marginal part of the stromatolites. However, he could not explain the mechanism by which replacement of carbonate by phosphate took place. Chauhan (1979) and Chauhan and Sisodia (1984) have also envisaged a replacement theory for the genesis of Arvallian phosphatic stromatolites. Other workers have also supported phosphatization

R₃? Minjaria uralica
Baicalia nova
Baicalia chandakia

R₂ Baicalia

--? Conophyton misrai
R₁ Gongylina differentiata
Stratifera hearnica
R₁-R₂ Stratifera undata
Plicatina antiqua
Conophyton garganicus
Colonnella

Conophyton cylindricus
Colonnella
Kussiella
Rahaella / Gangolihatia
Kussiella
R₁ Colonnella columnaris
Stratifera, Gongylina
and Oncolites
Rautgara Fmn.

Almora Crystallines

(Modified after Tewari, 1981)

Fig. 4 Distribution of the stromatolites in the Mesoproterozoic (Riphean) Gangolihat Dolomite, Lesser Himalaya, India. The *Baicalia* sp. and *Minjaria* sp. stromatolites (R2 biostrome in upper part) is highly phos-

lish such a hypothesis.

Banerjee *et al.* (1986) have done the carbon and oxygen isotope analysis of a few representative samples of Indian Upper Proterozoic and Lower Cambrian phosphorite. The inferences drawn from the francolite, carbonate and organic carbon from four different phosphorite provinces of India suggest that each of these provinces represents a clearly defined and isotopically distinctive sedimentary facies. The isotopic signatures of the structurally bound CO_3 in carbonate fluorapatite and its comparison with that of the host carbonate allow a discrimination of authigenic versus diagenetic origin of the phosphorite province. In the case of the phosphatic stromatolites of Aravalli, the isotopic evidence suggests a diagenetic nature but the geological and petrographic evidence, and microstructures of the stromatolites strongly support a microbial origin for the phosphate (Tewari, fig. 16 in Krajewski *et al.*, 1994). Similarly, the phosphorite deposits of the Gangolihat Dolomite (Plate 1 Figs. a,b,c,d,e) and the Mussoorie Syncline (Plate 2, Figs.,a,b,c,d,e,f) have been interpreted as of diagenetic origin (formed by phosphatization of a carbonate precursor). Therefore, the controversy about the origin of phosphatic stromatolites, whether they are exclusively diagenetic or microbial, is still unexplained and the detailed study of the stable isotopes and microbial geochemistry will certainly help to understand this specific problem of some of the oldest phosphorites of the world located in the Asian Continent.

Kumar and Muller (1988) have proposed following two microenvironments responsible for two different types of palaeomicrobial communities for the genesis of the Mesoproterozoic Gangolihat stromatolitic phosphorites.

1. The microenvironment above the sediment/ water interface.

2. The microenvironment below the sediment/

of the stromatolitic structures due to selective response of the microbial assemblage by way of fixing phosphate from the sea water under a certain exclusive geochemical environment. However, the detailed geochemical/microbial geochemical or isotopic studies have not been done by earlier workers to estab-

water interface.

The palaeomicroenvironment above the sediment/water interface was well oxygenated and suited for the growth of organic life resulting in the development of stromatolites in which a particular community (aerobic forms) of microorganisms flourished. The first community of microbiota was held responsible for the development of non-phosphatic columnar stromatolites (Tewari, 1981, 1984c, 1989, 1991b, 1993b, 1994; Shukla, et al., 1986). The second community which flourished below the sediment/water interface constituted a distinct microenvironment characterised by an anaerobic (reducing) environment. In this oxygen free reducing environment the microorganisms received their energy for the metabolic activity by breaking the organic matter and in this process released phosphorous.

Tewari (1981, 1984C, 1989, 1991b, 1993b, 1994, 19950, Shukla et al. (1986), have recorded a very rich assemblage of phosphatic stromatolites (Plate 1, Figs. a & e) and microbiota (cyanobacteria, eubacteria, vase shaped microfossil, acritarchs, phytoplankton Chuaria circularis etc.) from the Deoban (type area) and the Gangolihat black cherts, oolites and oncolites and stromatolitic phosphorite horizons (Fig. 2 and 4). The Mesoproterozoic Gangolihat-Deoban Dolomite is a product of carbonate tidal flat (Kumar and Tewari, 1986; Tewari, 1984a, 1991b, 1994) and the luxuriant growth of fossil microbialite indicates that the palaeomicroecosystem was highly oxygenated and well suited to support the microbial activity (first community). Recently, some biomarkers (amino and fatty acids and hydrocarbons) have been recorded from the Deoban stromatolites (Tewari, 1995). The deposition of phosphate can occur in an environment rich in such organic matter which is in a stage of active decomposition under the influence of microorganisms. However, the second microbial community which must have played the main role in formation of stromatolitic phosphorite is still not known. Microbial community of the second microenvironment has to be identified and their biogenicity and palaeomicrobiolgy has to be established.

PRECAMBRIAN/CAMBRIAN BOUNDARY (KROL-TAL) STROMATOLITIC PHOSPHORITE ASSOCIATION, LESSER HIMALAYA

The Neoproterozoic-Lower Cambrian shelf of shallow marine carbonate-phosphorite-siliciclastic sequence of Krol belt is well developed in Mussoorie Syncline of the Lesser Himalaya (Fig. 1b). Recently, this sequence has been established as a succession of Precambrian/Cambrian boundary (Table 2 and Fig. 2) in contrast to the century old traditional idea of Late Palaeozoic-Mesozoic age for phosphorites. (Tewari, 1984 a, b, 1985c, 1987, 1988, 1989, 1991a,b, 1993 a,b, and the references therein). The record of phosphatic stromatolites, oncolites and microstromatolites (Plate 2, Figs. a,d, & e), Ediacaran metaphytes and metazoans, Lower Cambrian shelly fauna, trilobites and brachiopods (Fig. 2) are well documented from Mussoorie as well as adjoining Korgai, Nigalidhar, Garhwal and Nainital synclines (see Tewari, 1989, 1991a,b, 1993 a,b,), and Tewari & Joshi, 1993)

Aharon et al. (1987) and Tewari (1989, 1991a,b) documented a significant isotope variation in Krol-Tal marine sediments of the Lesser Himalaya (Fig. 3). The Upper Krol organic poor carbonates (Corg= 0.02 to 0.03%) yield $\delta^{13}C$ values that are compatible with a marine carbon source (-1.3 to 4.9%). By contrast, the organic rich (C org=0.4 to 2.2%) apatite bound carbonate and the calcites from the Tal Chert Phosphorite Member display negative $\delta^{13}C$ depletions bearing the mark of pore waters whose carbon chemistry was greatly modified by bacterial processes operating in oxygen-deficient sediments (Aharon et al., 1987). A world-wide phase of phosphogenesis at or near, the PC/C boundary supports the inference of biological controls driven by ocean fertility changes acting on the marine carbon reservoir. Similar data has also been generated from the other crucial Precambrian/Cambrian boundary sections of Asia (Iran, China etc.) and elsewhere (cf. Brasier, 1992). A correlation of Precambrian-Cambrian sediments of South Asian region is shown in Table 3. A major unconformity between the Tal Quartzite (Lowet Cambrian) and the Shell Limestone (Cretaceous) was established on the basis of glauconite (Srivastava & Tewari, 1986)

Microbial microstructures and microfacies of the Deoban, Upper Krol carbonates and Lower Tal chert phosphorites were studied by Tewari (1993b, 1994), Tewari and Qureshy (1985) and Tewari and Joshi

Table-2 Terminal Proterozoic and Lower Cambrian Stratigraphy of Lesser Himalaya of India (Tewari, 1995)

			INDIA
		Upper	Quartzite Member (Phulchatti Member)
Lower Cambrian	Tal Group	Middle	Calcareous Member Arenaceous Member
(Tommotian to Toyonian)		Lower	Argillaceous Member Chert - Phosphate Member
	—Diastem		—
Neoproterozoic III/Terminal Proterozoic	Krol Group		Upper (Krol C, D, E) Middle (Krol B)
(Vendian = Ediacaran)			Lower (Krol A) Infra Krol Formation Blaini Formation
	— Unconformity—		
Neoproterozoic II	Jaunsar/Simla Group		Nagthat Chandpur Mandhali
	— Unconformity ?		—
Mesoproterozoic (Lower to Middle Riphean)			Deoban/Garhwal Group Damta Group

(1993). The microbial mat facies are characterised by the profuse development of bird's eye structure, irregular fenestral fabric in bird's eye dolomite (Plate 2, Fig. c), fossil microbialites, smooth and crenulated biolaminites, calcareous algae, microstromatoli tes, oncolites and oolites (Plate 2, Figs. a, b, c, d, e).

Tewari (1994) and Tewari and Qureshy (1985) have interpreted that the microfacies of the Deoban-Gangolihat Group and the Upper Krol Formation in Mussoorie and Garhwal syncline is essentially microbially deposited by precipitation and entrapment of carbonate particles by cyanobacteria in tidal flat environment. The microbial mat of intertidal flats is dominated by crenulated biolaminites and stromatolites. The bird's eye fenestral fabric is prominent in the supratidal zone which results from desiccation where carbonate sediments are subaerially exposed.

(Plate 2, Fig. c)

The columnar stromatolitic (Plate 2, Figs.a,d) and oncoidal (Plate 2, Figs.d,e) microbialite microfacies of the Lower Tal Chert, Phosphorite Member represent a facies change from intertidal-supratidal to protected tidal flat or shallow lagoon with restricted circulation. The outstanding features of this microfacies are the development of columnar, columnar layered, stratified, passively branching, domal, laterally linked, stromatolites (Plate 2, Fig a) and microbial oncoids with phosphorite (Plate 2, Figs. d & e). The Lower Cambrian (Tommotian) stromatolite *Collumnaefacta vulgaris* was discovered in this facies (Tewari, 1984 c,d). Subsequently, Tewari (1987, 1988, 1989, 1993 a,b) recorded the Precambrian/Cambrian boundary stromatolites *Aldania (Jurusania) mussoorica, Compactocollenia, Conophyton* msp, *Conophyton durmalacus, Boxonia gracilis, Colleniella* from the

Table-3 Regional correlation of the Precambrian and Lower Cambrian Sedimentary sequence of the Lesser Himalaya in South Asia (India, Pakistan, Nepal and Bhutan)

Age/Stage Period/Group	Western Lesser Himalaya India Formation	Pakistan Formation	Nepal Group/Formation	Eastern Lesser Himalaya Bhutan (including Sikkim and Arunachal)
Lower Cambrian (Aldanian/*Talian*) Tal Group 570 (624± 10 Ma)	Lower Tal Formation (with shelly microfossils and stromatolites of Tommotian/ Meischucunian age/*Talian*)	Hazira Formation (with shelly microfossils of Tommotian age)	Upper Nawakot Group/ Upper Kali Gandaki Group/Upper Midland Metasediments	Miri Group (with Lower Cambrian Ichnofossils)
Krol Group (650-570 Ma)	Krol Formation (with Vendian stromatolites, algae, metaphytes, metazoans) (Ediacaran/*Krolian*)	Abbottabad Formation (stromatolites in Sirban limestone)	Kerabari Formation (stromatolites) Riri Member	Buxa Group (Carbonates with stromatolites of Kudashian-Vendian affinity) Tatapani Formation
	Blaini Formation (Varangar/*Blainian*)	Tannakki Formation (Conglomrate)	Ramdignat Formation	
	——— Unconformity ———	——— Unconformity ———	——— Unconformity ———	——— Unconformity ———
Neoproterozoic Jaunsar/ Simla Group (950-650 Ma)	Nagthat Formation Chandpur Formation Mandhali Formation/ Simla Formation (Upper Riphean/*Jaunsarian*)	Tanawal (Tanol) Formation Hazara Formation	Saidikhola Beds	Phuntsholing Group
Deoban Group (1300-950 Ma)	Jammu (Great) Limestone Dharamkot/Larji/Shali/ Deoban/Gangolihat/Tejam Dolomite (with abundant Riphean stromatolites, microbiota, *Chuarias*/ (Lower to Middle Riphean/*Deobanian*)	Salkhala Formation Stromatolitic carbonates equivalent to Jammu/ Great Limestone ?	Middle Kali Gandaki Group/Baitadi and Darchula Groups (Darsing Dolomite) (Khoraidi Dolomite) Dhading Dolomite) (with abundant Riphean stromatolites)	
Damta Group (1600-1300 Ma)	Rautgara Formation Chakrata Formation (Lower Riphean)		Lower Kali Gandaki Group Lower Nawakot Group Lower Midland Metasediments	Jainti Formation Sinchula Formation
	——— Tectonic/Thrust ? Contact ———			
Almora Jutogh Group	Crystallines	Basement Crystallines	Kathmandu Complex Dadeldhura Group Crystallines	Daling Formation

(Vertical column labels: KALI GANDAKI SUPERGROUP)

Left margin vertical age labels: PROTEROZOIC / TERMINAL / NEOPROTEROZOIC / PROTEROZOIC MESO / MESOPROTEROZOIC

same phosphorite facies (Fig. 1b).

The laminae of stromatolites are made up of phosphatic (black) and carbonate (light laminae (Plate 2 Fig. b). The intercolumnar space is occupied by phosphate grains, oncoids, pyrite grains and chert (Plate 2, Figs. a,d). The laminae are phosphatic as well as pyritic. Petrographic studies show euchedral crystals of pyrite associated with phosphatic stromatolites. This microfacies represents a reducing environment which stopped further growth of microbialites. The carbonaceous shales associated with chert and phosphorite also confirm the existence of anaerobic conditions (Plate 2, Fig. f). Oncoids of 0.5 to 2 cm in diameter are also found in association with smaller columnar phosphatic stromatolites (Plate 2, Figs a, b). The concentric laminae of oncoid are phosphatic stromatolites. The concentric laminae of the oncoids are phosphatic and pyritic and the core is filled with chert (Plate 2, Fig. e). Scattered grains of collophane are found in the matrix as well as in the microbial laminites (Plate 2, Fig. d). This microfacies represents moderate (restricted) circulation on sheltered tidal flat. The SEM study has shown peculiar cellular chain structures preserved in the phosphorites as if a macromolecule (DNA) is broken into the smaller molecules (proteins) a common phenomenon recorded in the modern examples known as 'Organochemotrophic decomposition of cells.'

Lucas and Prévót (1981b) have synthesised apatite experimentally under bacterial action using Ribonuclic acid (RNA).

CONCLUSION

Microorganisms must have contributed towards the growth of stromatolites, oncolites and phosphorite formation. The association of profusely developed stromatolites with phosphorites is a unique feature to Neoproterozoic-early Cambrian Lesser Himalayan sequence of India and other Asian sections but the role of these structures in the deposition of phosphorite is not properly understood.

The actual role of organisms involved in phosphorite deposition, the biochemical environment that determines whether phosphorus is fixed in sediment or released from it in anaerobic/reducing or negative Eh conditions remains to be solved.

According to Krumbein and Garrels (1952) the pH-Eh perameters control the precipitation of phosphorite, pyrite, silica, organic matter and uranium, the main constituents of the black shale, limestone-phosphorite association (similar to Mussoorie phosphorite), generally referred to as the phosphorite suite of rocks. Apart from these models, a few other workers have also tried to explain the origin of phosphorites associated with stromatolites by the upwelling hypothesis (Patwardhan, 1980; Patwardhan and Ahluwalia, 1973). Detailed palaeogeographical reconstructions during Proterozoic-Cambrian times on the Indian subcontinent will shed more light on the phosphogenesis.

ACKNOWLEDGEMENTS

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EXPLANATION OF PLATE 1

Fig. a : *Baicalia* (branching) stromatolite showing the concentration of phosphorite in outer margins as well as in the stromatolitic laminae. Gangolihat Dolomite, Pithoragarh area.

Fig. b Oolitic structures in Gangolihat Dolomite showing phosphate (dark) and carbonate (light) concentric laminae.

Fig. c Microstructure of the phosphatic *Baicalia* stromatolite (Fig. a). Phosphate is concentrated in the outer margins.

Fig. d Oolitic structures in the Gangolihat Dolomite showing concentration of phosphorite in the concentric laminae.

Fig. e *Minjaria uralica* stromatolite in the Gangolihat Dolomite showing concentration of phosphorite mostly along the outer margins of the stromatolite and scattered grains are also found within the stromatolitic structure. Vase shaped microfossils (VSM's) and spheroidal microbiota *Huronispora* sp. are found in this phosphatic stromatolite.

PLATE 1   TEWARI 151
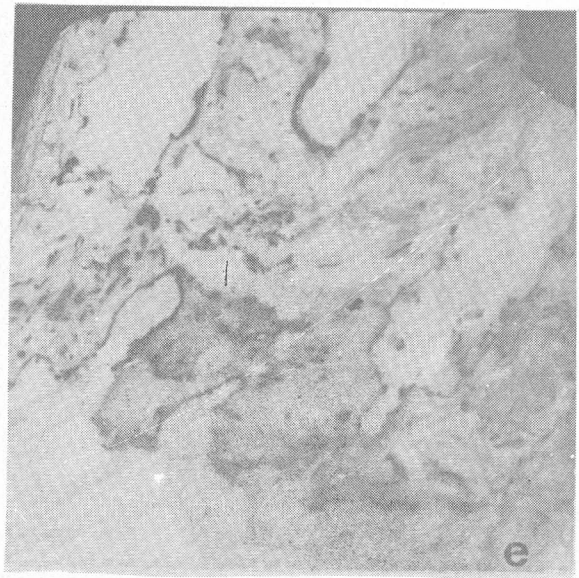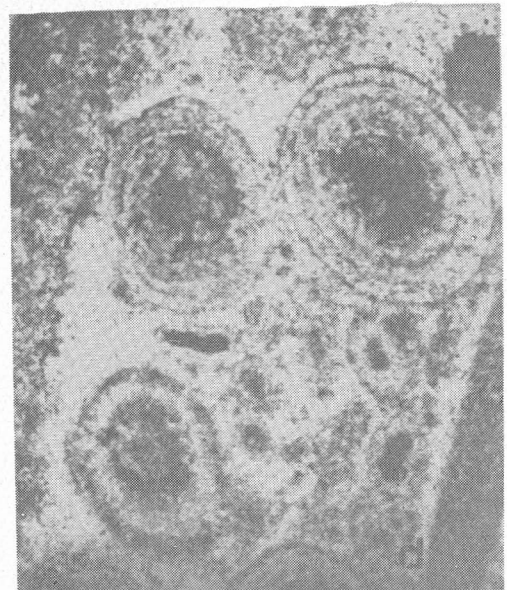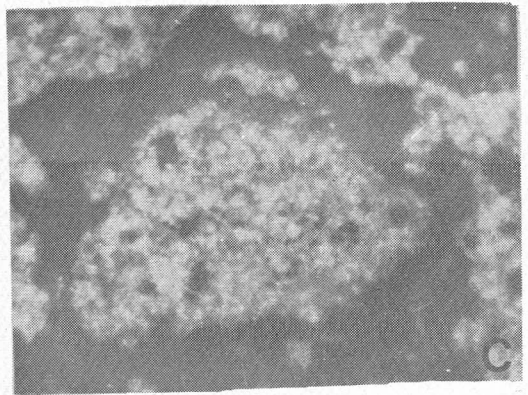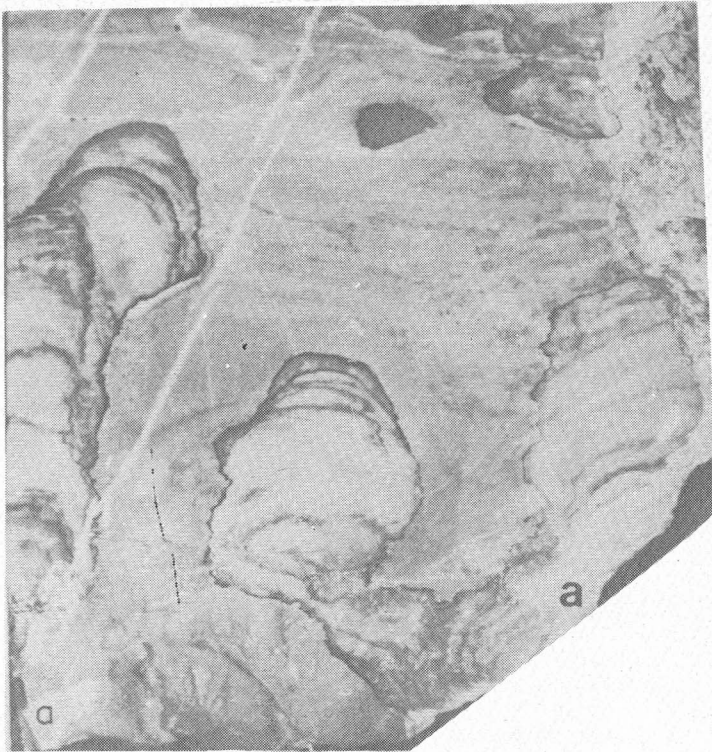
EXPLANATION OF PLATE 2

Fig. a   The columnar stromatolitic and oncoidal structures in the Lower Tal phosphorite (Durmala mine, Mussoorie Syncline) showing columnar layered, stratified, domal, laterally linked, phosphatic cherty and pyritic laminae.

Fig. b   The alternate laminae of stromatolitic microstructure showing phosphatic (black) and cherty (light) mosaic in the Lower Tal phosphorite, Mussoorie Syncline.

Fig. c   The microbial mat facies of the Upper Krol Formation, Garhwal Syncline showing irregular fenestral fabric. The radial fibrous fabric showing original growth pattern of algae.

Fig. d   Oncoidal microbialite microfacies of the Lower Tal Formation showing concentration of collophane in the stromatolitic laminae, between the inter columnar space and oncolitic concentric laminae. Durmala mine, Mussoorie Syncline.

Fig. e   Microstructure of a large oncolite showing phosphatic black and cherty (white) laminae, Lower Tal Formation, Mussoorie Syncline, the core is filled with chert.

Fig. f   Field photograph showing the alternate bands of shales, cherts and phosphorite in the Lower Ta' Formation, at Masrana, Mussoorie Syncline.

PLATE 2   TEWARI 153