The earliest biosphere - Past of the terrestrial flora*

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नासदासीन्नो सदासीत्तदानीं नासीद्रजो नो व्योमा परो यत् ।
किमावरीवः कुह कस्य शर्मन्नम्भः किमासीद्गहनं गभीरम् ।।१।।

न मृत्युरासीदमृतं न तर्हि न रात्र्या अह्न आसीत्प्रकेतः।
आनीदवातं स्वधया तदेकं तस्माद्धान्यन्न परः किं चनास ।।२।।

तम आसीत्तमसा गूह्ळमग्रेऽप्रकेतं सलिल सर्वमा इदम् ।
तुच्छयेनाभ्वपिहितं यदासीत्तपसस्तन्महिनाजायतैकम् ।।३।।

कामस्तदग्रे समवर्तताधि मनसो रेतः प्रथमं यदासीत् ।
सतो बन्धुमसति निरविन्दन्हृदि प्रतीष्या कवयो मनीषा ।।४।।

तिरश्वीनो विततो रश्मिरेषामधः स्विदासी३दुपरि स्विदासी३त् ।
रेतोधा आसन्महिमान आसन्त्स्वधा अवस्तात्प्रयतिः परस्तात ।।५।।

को अद्धा वेद क इह प्र वोचत्कुत आजाता कुत इयं विसृष्टिः ।
अर्वाग्देवा अस्य विसर्जनेनाथा को वेद यत आबभूव ।।६।।

इये विसृष्टिर्यत आबभूव यदि वा दधे यदि वा न ।
यो अस्याध्यक्षः परमे व्योमन्तसो अङ्ग वेद यदि वा न वेद ।।७।।

NASDĪYA SUKTA ṚG VEDA X 129

THE Nasadiya Sukta talks of a state before the existence of matter and energy.

1. The first hymn speaks of "*Sat*" meaning "existence" — the primordial matter which is transformable into energy. In the beginning there existed "Asat" the unseen and unperceptable energy which desired to transform into "*Sat*", the energy that can be perceived. The latent energy manifested. This cosmic consciousness, indeed, brought in the transformation or manifestation. There did not exist the elements. There was neither land nor sea. When there was no place to exist how can life exist? It was much later that water came into being which triggered the birth of life and started the great cycle of evolution.
2. There was neither death nor immortality. There was neither day nor night. Matter transformed into energy. This transformation or the "desire to manifest" is life. This is called "*Chaitanya*".
3. There was darkness. Everything was latent, that is unmanifest.
4. There arose desire, the desire to manifest. The nonexistent became existent. The manifestation of consciousness in matter is indeed the transformation of non-living to living, born out of the desire to manifest.
5. The manifestation spread across, the light rays extending across darkness, the creative force and the fertile power expressing its energies all over.
6. Wondering as to who knows how it was manifested? Words beyond description!
7. There is no beginning and no end. How the universe arose and how it developed the entire living and the nonliving world, is not known and who knows it. "He" even may not know!

The origin and age of our planet, the Earth, have been a topic of speculation and debate since times immemorial, as has been the case for the Universe too.

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Venkatachala *et al.* (1988) summarised the important philosophical and scientific observations and hypotheses on origins and beginnings of the universe. As discussed by them, the vast universe was once condensed into an ultra-dense, ultra-small primeval unit. This primordial unit exploded about 15 billion years (Ga) ago (referred to as the Big Bang), started expanding and gave rise to the universe. Energy, matter, space, and time were simultaneously created. Consequent with a sharp fall in the temperature of the universe, matter became gravitationally more important than the radiant energy. Radiation separated from matter and light could travel through space. The matter which was uniformly spread accumulated into giant gaseous clouds — the protogalaxies. This gas soon condensed into stars and formed quasors and galaxies (Nicholson, 1979). Our galaxy *Akashganga* or the Milky Way was formed around 10 Ga ago. A cloud made of dust and gases (Hydrogen and Helium, the most ancient elements in the Universe) whirled through the empty space about 6 Ga years ago.

The interstellar matter present in this massive solar nebula condensed and gave rise to several rotating oblate accretion discs. They were denser at the centre and became progressively more rarified towards the periphery. The temperature was also highest at the centre and lowest at the periphery. Thus about 4.6 Ga ago, the solar system was born and also our planet--the Earth. The formation of solar system and its unique character lie in the high degree of order, the preferred sense of rotation, the coplanarity, circularity and regular spacing of planetary orbits and the grouping of planets into compositional classes in accordance with their distance from the Sun (Stevenson, 1983). Though development of solar system and the transformation of several discs into protoplanets is a different aspect altogether and its discussion here would be out of context, it is relevant to mention that models or transformation of these clouds of dust and gases into protoplanets and ultimately to planets have been discussed by Cameron (1978), Goldreich and Ward(1973), Dermott (1978), Ringwood (1979) and Lee *et al.* (1977).

The earth which was formed about 4.6 Ga ago is known as the Hadean Earth. Our understanding of the Hadean Earth (i.e. of the period before the deposition of the first terrestrial sedimentary rock at ~3.8 Ga) holds clue for the development of early atmosphere, lithosphere as also for the origin of the first biological entity and ultimately the early biosphere. The interaction initiated among lithosphere, atmosphere and biosphere (LAB) during this period decided the eventual course of events during the subsequent Phanerozoic Era. These and certain other related events leading up to the Precambrian-Cambrian boundary (at ~545-570 Ma) (Pl. 1) are discussed.

THE HADEAN EARTH (4.6-3.8 Ga)

Plate 1

It is believed that the Earth accreted prior to 4.6 Ga. The accretion segregated the three layers of earth-core, mantle and crust. The vigorous subsolidus convection and melting of free iron due to high temperature resulted in radiation of silicates. The crystallization of the uppermost part of the mantle formed a thin lithospheric basement, and thus a protocrust, probably covering the entire globe, was formed. The palaeoatmosphere-hydrosphere systems formed by outgassing followed this major geochemical differentiation.

The primordial atmosphere on the prebiotic earth constituted by interstellar gaseous matter was gradually lost due to lower atomic weight. Intensive volcanism and consequent release of gases from the secondary atmosphere cooled the earth. The atmosphere was further altered by interaction with organisms. This explains the absence of any trace of primary atmosphere inherited from the Solar nebula (Walker, 1977; Pollack & Yung, 1980; Brown, 1949; Suess, 1949; Suess & Urey, 1956; Rasool, 1972; Cameron, 1980). Continued outgassing of the mantle gradually released several reducing and more stable gaseous components, e.g., water vapour, carbon mono - and di-oxides, methane, hydrogen sulphide, ammonia, nitrogen dioxide, and some trace elements, such as helium and neon (Towe, 1983; Walker, 1983).

Oparin (1938) and Urey (1952) on one hand, and Rubey (1955) on the other, expressed strongly divergent views on the composition of early atmosphere. Urey's view was later revised by Miller and Urey (1959) and Horowitz and Miller (1962). These views remained unchallenged until Holland (1962) put forward his model of evolution of Earth's early atmosphere, based on mantle degassing. A significant contribution to the secondary environment was made by chondritic material (Anders & Owen, 1977; Chang, 1979; Lazcano-Aranjo & Oro, 1981) and related volatile-rich interplanetary material (Weatherill, 1980).

The level of carbon dioxide in the prebiotic atmosphere was three times more than the level of carbon dioxide in the present atmosphere (Owen *et al.*, 1979) This higher level of carbon dioxide had a major impact and contributed to large scale development of limestone formations of the early Archaean Era. The carbon of carbon monoxide and carbon dioxide played a major role in the prebiotic synthesis which ultimately paved way for appearance of the first unit of life.

Recent developments in the field of astronomy and atmospheric reaction have opened a fresh dimension about the presence of oxygen, one of the most debated issues, in the early atmosphere (Canuto *et al.*, 1983). It

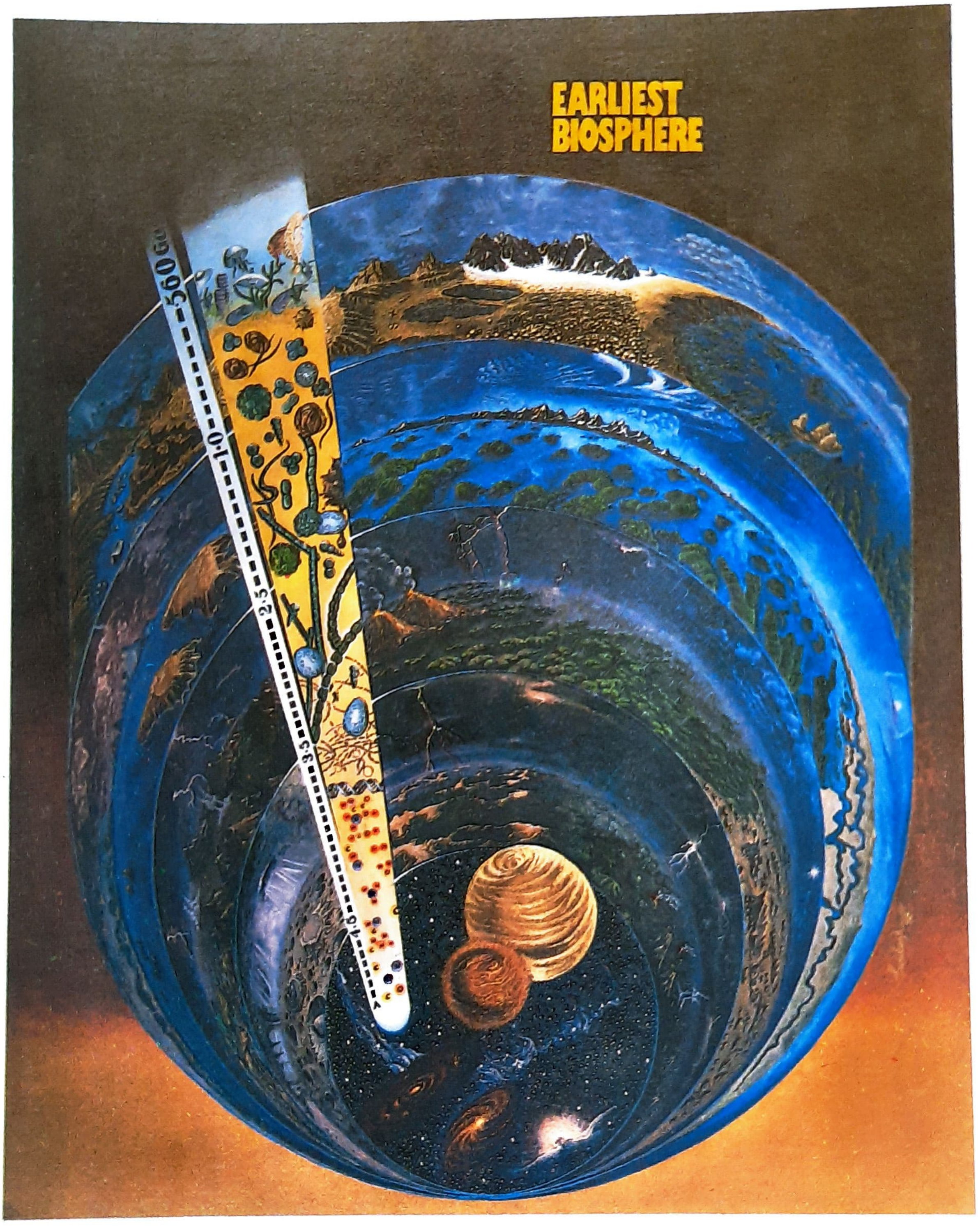

Plate 1

Earliest Biosphere—The Precambrian Eon encompasses several major steps in the evolution of life. In this scenario the sphere at the base corresponds to the origin of earth. The four semispheres above correspond to the advent of life, role of oxygen, appearance of eukaryotes and ultimately the appearance of plant and animal life, respectively. (Reconstruction by B.S. Venkatachala, Manoj Shukla and Mukund Sharma; art work – Pradeep Mohan) is presumed that absence of the ozone layer in the atmosphere and consequent influx of ultraviolet radiations resulted in the photolysis of water vapour and carbon dioxide, and ultimaely in the exospheric escape of atomic hydrogen and beginning of reactions involving the hydroxyl radical thus producing the initial levels of oxygen. Early organisms, specially the oxygen-producing ones, later played a significant role in increasing the level of oxygen in the atmosphere.

Thus, increase in the carbon dioxide level by volcanic emanation also enhanced the production of oxgen to several (six orders of magnitude) folds in association of ultraviolet flux. Oxygen increase by a factor of 10^6 was achieved without actually restoring to the photosynthetic process. The co-existence of oxidised iron and reduced uranium in the oldest rocks is the best possible evidence of the presence of higher amount of oxgen in the early atmosphere (Klein & Bricker, 1977; Towe, 1978; Grandstaff, 1980).

As a result of intense devolatilisation of the mantle, enormous quantities of water vapour accumulated in the palaeoatmosphere. These volatiles condensed into hot rains which accumulated and formed early seas. They formed the veneer of protocrust material. The earth also evidenced large scale meteoritic and cometary bombardment from outer space. The impact of meteorites and comets induced large crators on the surface of earth (Goodwin, 1976; Lazcano-Aranjo & Oro, 1981).

Prebiotic Synthesis

Scientists of seventeenth and eighteenth centuries supported the hypothesis of spontaneous generation of life. New dimensions were added by Oparin (1924). Haldane (1929) and Miller (1953) who propounded the chemical evolution hypothesis and provided experimental support for it. It has been suggested that chemical reactions in the palaeoatmosphere, at some unknown moment, accidentally completed the first step in the origin of life — the transition from inorganic to organic — from chemical to biological. Thus, the first biotic entity arose naturally through a complex process of chemical evolution of abiotic material, which was initiated in the atmosphere and culminated in the sea. Fox and Dose (1977) consider that chemical evolution of organic compounds ultimately led to biological evolution in primitive sea. The products of early abiogenic synthesis such as amino acids, nucleic acids, bases, sugars and fatty acids gathered in these seas. It is referred to as the prebiotic soup, a dilute broth that spawned life. The synthesis of prebiotic soup on the earth was advocated presuming several sets of conditions from highly reducing (H_2, NH_3, CH_4, H_2O) to mildly reducing (CH_4, H_2, N_2, CO, CO_2) to non-reducing (H_2O, N_2, CO_2) (Miller, 1953; Oparin, 1938; Rubey, 1955; Holland, 1962).

There are several models postulating the origins of life. Origins of life near hydrothermal vents have been advocated by Baross and Hofmann (1985) and Corliss *et al.*, (1981). Crick and Orgel (1973) postulated life's origin elsewhere in the universe and seeded on the earth. It is commonly known as "Directed Panspermia Theory". The evaporation pond model proposed recently envisages cyclic changes in humidity and temperature yielding significant amounts of oligopeptides (Hawker & Oro, 1981), oligonucleotides (Odum *et al.*, 1982) and phospholipids (Rao *et al.*, 1982). Eichberg *et al.* (1977) accomplished synthesis of glycerols in the laboratory and indicated the possibility of comparable reactions on early earth for the formation of complex heterogeneous mixture of monomeric and polymeric organic compounds (Oro *et al.*, 1980; Lazcano-Aranjo & Oro, 1981; Miller, 1953). The shock waves, lightening, ultraviolet radiation and solar radiation provided energy to these reactions on the primordial earth, converting simple molecules to complex organic chains which could replicate themselves, thus causing the advent of life. It has been suggested that reaction among simple molecules brought to earth by interstellar dust, comets and meteorites as well as substances formed by electric discharge, ultraviolet light and other energy sources acting on earth's primitive atmosphere, led to the origin of life (Ferris *et al.*, 1987).

The presence of complex organic molecules, including those containing phosphorous has been detected in the interstellar molecular inventory. These building blocks for biological molecules, viz., molecular hydrogen, carbon monoxide, ammonia, water and hydrogen sulphide are also present in the interstellar material (Irvine, 1987). They must have acted as raw materials for the formation of hydrogen cyanide and acetaldehyde which are precursors to amino acids — the building blocks of proteins. The other constituents necessary for life include cyanoacetylene, phosphorous nitride and water which formed nucleic acids, the carriers of genetic information. Formaldehyde, formic acid and cyanamide synthesised sugars and lipids which formed the membranes essential to life.

The study of the organic constituents of carbonaceous chondrites/meteorites (Hayes, 1976; Nagy, 1975), extra-terrestrial dextro-rotatory and laevo-rotatory amino acids (Kvenvolden *et al.*, 1970, 1971; Oro *et al.*, 1971), nucleic acid bases (Stokes & Schwartz, 1981) and amino acids (Cronin *et al.*, 1980, 1981; Cronin, 1982), indicates that organic compounds were a part of the material from which the proto-planets were formed. If the necessary ingredients of life were actually present in the interstellar space then it is possible that the source of prebiotic constituents was transferred from these to earth, possibly on meteorites and comets (Blake & Carver, 1977; Towe, 1981; Ferris *et al.*, 1978).

Arrehenius (1903) has hypothesised that seeds of life perhaps came from interstellar space (Panspermia Theory), but there are conflicting opinions and claims with regard to this possibility.

In the presence of all necessary components for the emergence of life on the primitive earth, a proper catalyst then triggered the first biological polymer RNA/DNA into existence. RNA, which has catalytic properties of protein, can also perform function of DNA and store the genetic information. Its structure is similar to that of protein and it is constituted of similar compounds as DNA. Thus, it is quite probable that RNA was the first biopolymer which later gave rise to DNA and other proteins. The synthesis and evolution of organic matter on the primitive earth, before the emergence of life, took place in three major steps (Oro *et al.*, 1978). Different types of energy reacted with the "HAL" (Hydrosphere, Atmosphere and Lithosphere) to form biochemical compounds, viz., amino acids, purines, pyrimidines, sugar and fatty acids which dissolved themselves in bodies of water. The condensation and polymerisation of these monomers in the early seas formed oligopeptides, oligonucleotides and lipids. The first living system must have formed by the selective interaction and association of these oligomers leading to the emergence of replication, formation of liposome and the cooperative association process (Oro, 1980; Lazcano-Aranzo, 1981).

Chemical evolution preceded biological evolution and has continued along with it. But it is still not clear how the self replicating systems evolved from the chemical aggregate in the ancient "sea".

The biosynthesised organic compounds which are part of the carbon cycle in the earliest seas have been found preserved in sediments. These are known as chemical fossils. The organic compounds or isotopic fractionation effects derived from the organisms or molecular remnants of the organisms can be understood from the study of chemical fossils (Schopf, 1970). Chemicals belonging to four major categories, viz., n- alkanes, isoprenoids, porphyrins and C^{13}:C^{12} values provide valuable data to understand the organic evolution in earliest rock records where there are neither body fossils nor trace fossils. However, these isotopic geochemical signatures of early life have so far failed to distinguish between kerogenous remnants of aerobes and anaerobes, oxygen producing and oxygen photosynthesisers.

THE ARCHAEAN EARTH AND EARLY LIFE (3.8-2.5 Ga)

During the early Archaean Eon (3.8-2.5 Ga), the differentiation of mantle and formation of crust took place in association with the plate tectonic movements which formed the shallow seas, lakes, intra-cratonic basins, shelf zones and lastly the deep oceans. The supracrustal rocks of Isua in Greenland which are composed of amphibolite, ultramafic sediments, metacarbonates and metaconglomerates containing volcanic clasts are the oldest known rocks on the earth's surface (Allart, 1976; Moorbath *et al.*, 1973). The sedimentary and detrital nature of these rocks helps to infer prior existence of anorthositic and fine-grained cover of sedimentary rocks. The earliest record of rocks is engulfed by tonalitic and granodioritic gneisses emplaced about 3.6 Ga ago (Moorbath, 1975; Moorbath *et al.*, 1973).

The Archaean rocks are broadly divisible into two groups, viz., granulites which are high grade metamorphic rocks, and greenstone belts which are cyclic development of low grade metamorphic volcano-sedimentary sequence. The Greenstone belts have green colour imparted by chlorite. These are characterised by the dominance of volcanic and sedimentary rocks; the latter derived primarily from volcanics. The greenstone belts have provided more reliable evidences of the Archaean environment than the granulite terrains.

The Canadian shield including Superior, Slave and Wyoming Provinces; Pilbara and Yilgirn blocks of Australia; Dharwar, Singhbhum and Jeypore-Bastar nuclei of India; the erstwhile Rhodesian and eastern Kapwaal Craton and Barberton mountainland of South Africa; the cratons of Greenland, and Kangerdlugssuag Fjord, east Greenland represent the possible sites for the study of gradual development of Archaean lithosphere.

Most of the Archaean sediments are deep water deposits. Limited examples of shallow marine shelf deposits including carbonates are known from the Pongola Basin in South Africa (Beukes & Lowe, 1989) and Dharwar Craton in India (Srinivasan & Srinivas, 1968, 1972; Srinivasan & Ojakangas, 1986). The near absence of shallow marine sediments, terrestrial and fresh water deposits of Archaean age indicates that either the shallow marine, terrestrial and fresh water deposits were not laid down at all or were later destroyed by recycling.

The first organisms must have floated in the early seas in areas covered by the cratonic shields. In the absence of the ozone layer, the organisms had to live below the water column to avoid ultraviolet radiation. They were also vulnerable to oxygen. Oxygen toxicity was met with such strategies as metabolic adaptations. Chemoluminesence is apparently one such strategy which is found even today in certain forms. It is possible that a mutant photosynthetic sulphur bacteria acquired reaction energising electrons by splitting water molecules instead of hydrogen sulphide and thus produced free oxygen. These organisms were able to use both water as well as hydrogen sulphide as energy sources. After further mutation they developed enzymatic protection against higher oxygen concentration. Such mutants with the ability to tolerate oxygen were better adapted in comparison to their competitors and thus more successful.

Hence, the first organisms to develop on early earth were anaerobic chemoautotrophs. The methanogenic bacteria were probably the first to flourish on the earth (Woese & Fox, 1977; Fox *et al.*, 1980). They have been responsible for the fractionation of carbon and deposition of graphites and mineral deposits in the Early Archaean sediments. With time the anaerobic chemoautotrophs learnt the use of organic substances as electron source in light-induced reduction of CO_2. These organisms could produce organic compounds and release chemical energy which could be used by the organisms themselves.

Extant photosynthetic bacteria are known at the interphase of the oxidising and reducing environment where continuous break down of organic matter is taking place, in a near-shore aqueous environment (Pfenning, 1978). Structural fossil records of such bacteria are yet not known. The aerobically photoautotrophic forms — the cyanobacteria and prochlorophytes must have formed the next step in the evolution of Archaean life. These forms with cholorphyll-A could utilise energy of light and carbon dioxide along with water as the source of electron, necessary for the reduction of CO_2, to form food required by the organism. Unequivocal evidence of the presence of aerobic photoautotrophs — the organisms which had shed their inhibition for oxygen, is available in the stromatolites after 2.8 Ga (Schopf *et al.*, 1983). These organo-sedimentary structures are formed by binding and trapping activity of cyanobacteria. With the advent of aerobic photoautotrophs, the process of underwater greening commenced. The capacity to withstand the oxygenic environment was a major step in the organic evolution.

The appearance of oxygen in the atmosphere was important for biological synthesis. Free oxygen in the atmosphere oxidised the carbon and hydrogen compounds into carbon dioxide and water and also led to the formation of the ozone layer. This layer reduced the percentage of harmful ultraviolet radiation reaching the surface of the earth.

Definite records of aerobic photoautotrophs are not found earlier than 2.9 Ga; there, however, is sufficient evidence to infer that they may have lived as early as 3.5 Ga. By analogy with several recent stromatolites, it is inferred that these structures in the upper layer were formed by blue-green algae and the lower layers contributed by reducing bacteria.

The oldest known stromatolites are from Towers Formation of Warrawoona Group, Australia (Lowe, 1980; Walter *et al.*, 1980; Hickman, 1980). These bulbous and nodular stromatolites developed in shallow hypersaline peritidal environment (Dunlop & Buick, 1980) and were later reworked in turbulant waters (Dunlop, 1978; Barley *et al.*, 1979; Walter *et al.*, 1980). Lowe (1980) described tabular biostromes of 60 cm thickness composed of pseudocolumnar erect parallel unbranched columnar units of 2-6 cm units. Walter *et al.* (1980) described partially linked, spaced nodular and stratiform varieties, and inferred their development in shallow marine shelf. They also show influence of evaporite facies.

Stromatolites are also known from Kromberg Formation of Onverwacht Group (Lowe & Knauth, 1977) and Fig Tree Group of Swaziland Supergroup (Byerly *et al.*, 1986), Insuzi Group, South Africa (Mason & Von Brunn, 1977; Von Brunn & Mason, 1977), and Ngesi Group, Belingwe Greenstone belt, Zimbabwe (Abell *et al.*, 1985a,b). In India, the oldest known stromatolites are from the red chert belt of Iron Ore Group in the Banaspani area (Bonai-Keonjhar districts) of Jeypore-Bastar Craton, eastern India (Avasthy, 1977, 1980). Microbial stromatolites have been recorded from the Archaean sequences of Sandur, Chitradurga and Shimoga schist belts (Murthy & Reddy, 1984; Baral, 1986; Mallikarjuna *et al.*, 1987; Srinivasan *et al.*, 1989; Mukhopadhyay & Ghosh 1983; Vasudev *et al.*, 1989) of the Archaean Dharwar Craton (> 2600 Ma). They occur in carbonate (limestones and dolomites) members of an orthoquartzite-carbonate shelf type association of sediments (see Venkatachala *et al.*, 1989) (Pl. 2, figs 1-5).

The morphological diversity of various forms of stromatolites in the Archaean Dharwar Craton appears to be significant being extremely rare in the pre-Riphean sequences. Morphologically diverse forms are known from the 2.3 Ga old Aphebian sequence of Canada (Hofmann, 1977, 1978), and the Malamani Formation of Zimbabwe (Orpen & Wilson, 1981; Beukes & Lowe, 1989). The pre-Riphean records from India, Canada and Zimbabwe suggest that the stromatolite morphologies considered characteristic of Riphean manifested as early as the Archaean and seem to have stabilised only during the Riphean. The physiological evolution of microoganisms which contributed to the formation of these stromatolites

Plate 2 →

1, 2, 3. Naked wall stromatolites from Bhimasamudra locality, Chitradurga Schist Belt.

4 & 5. Stratified stromatolites from Kumsi area, Shimoga Schist Belt.

6. *Phormidella sandurense* Venkatachala *et al.*, microfossils from black bedded cherts of Sandur Schist Belt. Scale 50 µm.

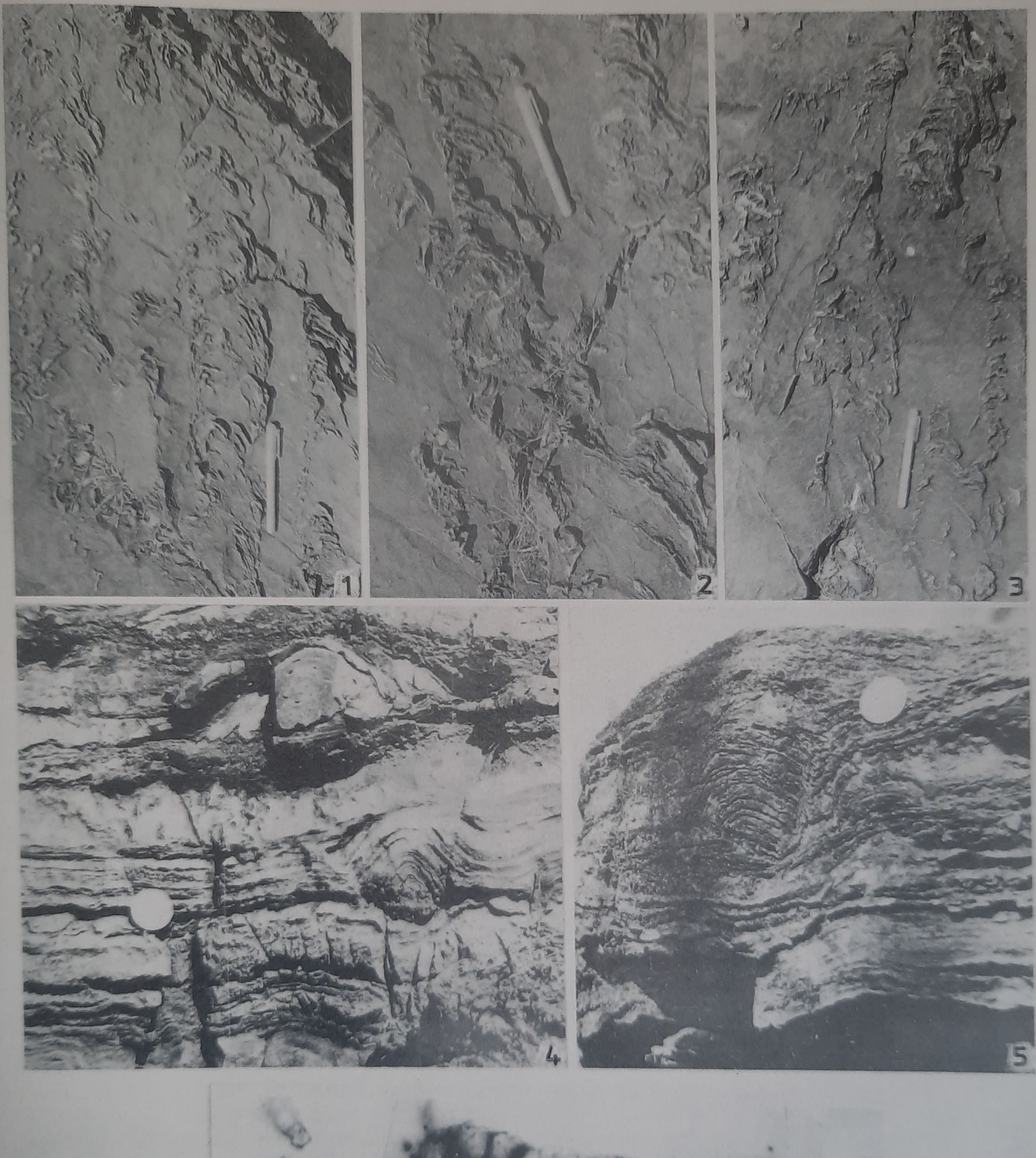

Plate 2

is evident from sedimentological and isotopic evidences. The microbes that formed the stromatolites were not necessarily oxygenic. The latter are facultative photosynthesisers that can use H_2S rather than H_2O as an electron donor (Garlick *et al.*, 1977), and can support the formation of benthic mat (Krumbien & Cohen, 1977; Hirsch, 1978).

The search for the evidences of life in the Early Archaean commenced with Isua supracrustal, the first terrestrial rock. Yeast-like microfossils, known as *Ramsaysphaera* and *Isuasphaera* have been recorded from Swartikoppie chert of Swaziland, and Isua Series of Greenland respectively (Pflug, 1978 a-c; Pflug & Jaeschke-Boyer, 1979; Pflug *et al.*, 1979). According to Pflug *et al.* (1979), their evolutionary level was far below the yeast of today. Palaeobiologists now regard these structures as inorganic and of non-biogenic origin (Bridgewater *et al.*, 1981; Schopf & Walter, 1983; Venkatachala, 1986).

The oldest chemical signatures have also been reported from these areas. They are apparently syngenetic with the deposition (Walters *et al.*, 1979). Later workers do not attest the above finding (Walters *et al.*, 1981; Nagy *et al.*, 1981; Walters & Ponnamperuma in Schopf *et al.*, 1983). High degree of metamorphism has inhibited evaluation of isotopic values of kerogen. Schopf and Walter (1983) consider the Isua kerogen to be chiefly inorganic and partly organic. However, it is quite difficult, if not impossible, to discern the syngenetic nature of such kerogen of organic, non-metamorphic origin.

Anaerobic chemoheterotrophs, the fermenting organisms draw their cellular carbon, energy and reducing power from the catabolism and assimilation of exogenous organic compounds. In Early Archaean their presence is suggested by S^{34} values which support the presence of sulphate reducers in the Aldan shield, Siberia (3 Ga) and in the 2.75 Ga years old Michipicoten and Woman River Banded Iron Formation of Canada (Schidlowski, 1979). Venkatachala *et al.* (1987) reported sulphur bacteria embedded in syngenetic pyrite grains from the Kudremukh Iron Formation (>2.6 Ga) of India. Earlier Klemm (1979) had reported bacteria from the Banded Iron Formation of Transwaal Group in South Africa. These presumptive evidences attest and substantiate the appearance of sulphate reducers in the interval between 2.6 and 3.0 Ga. It is suggested that the sulphate utilised by the first sulphate reducers was derived probably from oxidation of reduced sulphur compounds by photosynthetic sulphur bacteria (Muir & Grant, 1976; Junge *et al.*, 1975). According to Schidlowski (1979) photosynthetic sulphur was greatly abundant during the Archaean because of the probable abundance of hydrogen sulphide due to excessive surface and submarine volcanism.

Methanogenic bacteria which were chemical autotrophs, used CO_2 as their immediate source of carbon by a metabolic process which was independent of light (Woese & Fox, 1977; Fox *et al.*, 1980; Woese, 1977). The analysis of graphite samples for distinctive kerogen formed by these organisms indicates their presence ~2.8 Ga ago. The palaeobiological data support the appearance of anaerobic chemoautotrophs in Late Archaean. Neobiological considerations suggest their earlier origin (Schopf *et al.*, 1983).

In India, Scanning Electron Microscope studies of graphite samples from Ganacharpur and Nagavand have revealed the presence of probable bacteria. Isotopic evidences from these graphites indicate the presence of biogenic carbon and probable activity of methanogenic and methanotrophic bacteria during the Archaean (see Venkatachala *et al.*, 1989).

A group of anaerobic photoautotrophs capable of anoxygenic photosythesis are the photosynthetic bacteria. They are widespread at the surface in modern aqueous environment (Pfenning, 1978). This group probably was the precursor of the later oxygenic photosynthesisers. However, the fabric of Archaean stromatolites indicates a photosynthetic bacterial origin. The data suggest that either photosynthetic bacteria or anaerobic photosynthetic bacteria, or both, were extant at least as early as ~3.5 Ga ago. The fossil records of these bacteria constitute presumptive evidence of presence of anaerobic photoautotrophy as early as 3.5 Ga. In India, diverse types of microfossils were reported from Chitradurga Schist Belt, e.g., algal filaments and syngenetic microfossils from Dodguni cherts (Pichamuthu, 1945; Suresh, 1982; Suresh & Raju, 1983). Syngenetic filamentous microfossils recorded in the black cherts interlayered with the BIF of the Donimalai Formation, Chitradurga Group in Dharwar Craton (Naqvi *et al.*, 1987; Venkatachala *et al.*, 1990) are significant. The two identifiable forms are more akin in character and morphology to the living *Phormidium*. The uniseriate, unbranched flexuous trichomes with constricted septa and rounded apices are named *Phormidella sandurense.* The other form *Phormidella tenui* is broadly similar to *P. sandurense.* (P1. 2, fig. 6) except for its long and cylindrical cells (Venkatachala *et al.*, 1990).

The next step in the physiological evolution were the aerobic photoautotrophs. These organisms produced oxygen as a by-product of photosynthesis. The direct evidences from fossil record date back the oxygenic photosynthesis to 1.0 Ga, whereas the oldest known eukaryote puts this date at 1.4 Ga. Since oxygen fluxes were required for the deposition of Iron Formation, it is presumed that these organisms flourished as early as ~2.8 Ga, i.e., when major iron formations of the world were deposited. Other evidences suggest their presumptive occurrence even at 3.5 Ga (Schopf *et al.*, 1983).

Gradually an intermediate group of organisms — the amphianaerobes, evolved. They had the ability to change from anaerobic photoautotrophy to aerobic photoautotrophy according to need and they evolved prior to aerobic photoautotrophs. Since the presumptive evidences for aerobic phototrophs extends to ~2.0 Ga, the amphianaerobes were probably extant by Late Archaean. Along with the amphianaerobes, the obligate aerobes evolved parallelly and dispersed throughout the globe between 1.7 and 1.5 Ga ago.

From the microfossil assemblages, it is established that these organisms were present when the rocks were deposited, and if the preserved fossils are representative of the population that actually inhabited the early Archaean Earth, it is further inferred that early microorganisms were morphologically simple and prokaryotic in cellular organisation. The presence of stromatolites in the same sequence suggests that at least some early microorganisms were phototactic (Walter, 1983). The carbon isotope analysis permits the inference that photoautotrophs were important constituents of early carbon cycles. Finally the geochemistry of the sediments (which contain these microfossil evidences) reveals that the Early Archaean microorganisms were anaerobic (see Holland, 1984).

The Late Archaean geological record, as evident from the foregoing discussions, contains evidences which could be interpreted as an indication of continued morphological, physiological and behavioural diversification of microorganisms (Schopf *et al.*, 1983). By the Late Archaean, several physiologically advanced organisms had invaded all suitable niches available on the earth. What is potentially important about this distribution is the sudden decline in the occurrence of Banded Iron Formations (BIFs) and subsequent increase in oxygen level about 1.7 Ga ago. According to Cloud (1972, 1973), this increase in oxygen concentration in the palaeoatmosphere was because the source of photosynthetic oxygen finally exceeded the amounts required for oxidation of available free mineral matter, gases, etc. in the atmosphere and oceans. Thus the oceans were swept free of reduced compounds and a stable aerobic environment became established. This is indicated by the presence of red beds which are detrital sedimentary rocks with pigments of reddish-brown ferric oxide coating the mineral grains, filling pores, or dispersed in a clay matrix (Van Houten, 1973). In the Late Archaean, they generally formed in fluvial or alluvial environment on land. The production of ferric oxides resulted from subaerial oxidation. Thus their presence has been interpreted as indicative of free oxygen in the atmosphere. The geologic record of red beds suggests that oxidising atmospheres arose infrequently during the Archaean, but became increasingly common in the middle to latter part of the Early Proterozoic, i.e. between 2.0 and 1.8 Ga ago.

PROTEROZOIC AND DIVERSIFICATION OF LIFE FORMS (2.5----0.57-0.54 Ga)

Plate 1

The second stress phase, which included plate tectonic events, was initiated at the beginning of the Middle Proterozoic. These events resulted in the opening of rift systems. This was the onset of the Hudsonian Orogeny (2.0 to ~1.2 Ga ago). In the Hudson tectonic regime (1.9-1.7 Ga), the tectonic events within intra-sialic mobile belts reached their peak. The geomorphic effect of this orogeny was the formation of rift grabens and valleys which gave rise to lacustrine and fluvial systems of the early earth. These rifts sometimes became deeper and wider and eventually formed oceanic basins between 1.0 and 0.6 Ga ago. Firm evidences indicate development of stromatolites in these basins owing to precipitation of calcium carbonate, and other sediments brought by rivers. Occurring at the time of the peak of thermal events 1.7 Ga ago, these stromatolitic mats contain diverse assemblages of organic microfossils with a dominance of coccoid and filamentous blue-green algae.

Late Proterozoic microfossils recorded from over 150 localities indicate considerable biological diversity and ecological variability. Fossiliferous Proterozoic formations are known from Africa, Australia, Canada, China, Greenland, India, Russia and USA. In India, authentic biota occurs, both as carbonised remains in shales and permineralised remains in cherts from Precambrian sequences of peninsular India as well as the Himalayan regions. They show low to medium grade of metamorphism. Records of life in the form of stromatolites and organically preserved microbiota are many (see Acharyya *et al.*, 1989; Venkatachala *et al.*, 1990; Kumar & Singh, 1979; Kumar, 1978; Maithy *et al.*, 1983; Maithy & Shukla, 1977, 1984; McMenamin *et al.*, 1983; Raha, 1980; Shukla *et al.*, 1986; Salujha *et al.*, 1971a, b, 1972; Salujha & Rehman, 1971; Venkatachala *et al.*, 1990; Schopf & Prasad, 1978; Sastry *et al.*, 1972) The various forms which have been described are : *Oscillatoriopsis, Cyanonema, Eomycetopsis, Siphonophycus, Gunflintia, Tetraphycus, Eoentophysalis, Melasmetosphaera, Kheinjuasphaera, Glenobotrydion, Myxococcoides, Globophycus, Nannococcus, Huroniospora, Biocatenoides, Sphaerophycus, Archaeotrichion, Animiekia, Eosynechococcus, Cephalophytarion, Corymbococcus, Eoastrion, Archaeorestis, Palaeoscytonema, Palaeolyngbya, Kildinosphaeridium, Leiosphaeridium, Lophosphaeridium, Syplaso sphaeridium, Palaeohystrichosphaeridium, Stictosphaeridium*, etc (see Pl. 3 for some of the forms).

Eoentophysalis sp., one of the dominant coccoidal forms also reported from Belcher Islands, Hudson Bay, Canada, (Hofmann, 1976) suggests eukaryotic organisation, an important step in evolution. The Late Precambrian oceans were relatively narrow and served as suitable niches for further evolution of eukaryotes and emergence of marine multicellular life.

The evidences of eukaryotes in Precambrian rocks have been discussed eversince the major breakthrough in the Precambrian palaeobiology by Barghoorn and Tyler (1965). The origin of eukaryotes is uncertain and opinions differ on the possible timing and nature of eukaryotic evolution. Margulis (1970) suggested that eukaryotes arose from symbiotic association between formerly free-living prokaryotes, each kind giving rise to mitochondria, to chromoplasts, or to parts of the flagella. The criteria of recognition of eukaryotes in Precambrian have been discussed in detail (Awramik *et al.*, 1972; Schopf, 1968; Knoll & Barghoorn, 1975; Schopf & Oehler, 1976; Cloud, 1976; Oehler, 1977; Knoll *et al.*, 1978; Peat *et al.*, 1978; Schopf, 1978; Knoll, 1983). The main criteria for their recognition includes "Spot cells" spheroidal unicells with intracellular organic matter, tetrahedral tertrads, filamentous microfossils, large spheroidal microfossils, acritarchs and macroscopic carbonaceous ribbon-shaped remains.

Eosphaera from the Gunflint cherts of Canada possibly represents a *Volvox*-like planktonic green algal colony, which after about 1,500 Ma became widespread in stromatolitic cherts and shales (LaBerge, 1986). There is some evidence to suggest that vegetative and sexual reproduction evolved during the Late Precambrian. The sexual eukaryotic organisation has substantial selective advantages over the asexual prokaryotic way of life, particularly with regard to the exchange of genes and other forms of genetic recombination. The evolution of eukaryotic sexuality must have resulted in a prodigiously increased genetic variety of organisms as is expressed by an increased rate of evolution in the fossil record. The presence of eukaryotes with prominent nucleus in Precambrian rocks is thus a matter of debate. Also the post-mortem degradation, followed by diagenesis, alters the structures of the organisms giving rise to forms resembling eukaryotes.

Shukla *et al.* (1986) described coccoid microfossils containing amber to black-coloured, eccentrically placed pyrenoid-like bodies from the Deoban Formation. These microfossils are represented by *Glenobotrydion aenigmatis, G. majorinum, Glenodiopsis* and *Globophycus*. The authors concluded that these taxa apparently represent eukaryotic green algae. Schopf (1968) suggested that the consistency in size, shape and distribution among the members of each species establishes that they are either fossilised nuclei or pyrenoid or possible cell organelles found in eukaryotic algae. His views were supported by TEM studies demonstrating the differentially high electron density of these bodies in comparison to other cytoplasmic remains (Oehler, D.Z., 1977). In contrast of this view, field and experimental studies of degradation suggest that they probably represent degradational artifacts and are possibly due to shrinking and collapsing of prokaryotic cytoplasm (Awramik *et al.*, 1972; Knoll & Barghoorn, 1975; Knoll & Golubic, 1979). However, the eukaryotic cytoplasmic degradation may also produce similar intracellular structures. At present there are no unequivocal means of determining the actual affinities of such intracellular dark organic bodies.

Acritarchs are considered as eukaryotes. They represent resting stage or reproductive cyst-forming stage of planktonic photosynthetic unicellular, probably eukaryotic algae (Vidal, 1984; Vidal & Knoll, 1983). Their large size (more than 20 µm), robust walls, complex wall structure and morphology distinguish them from prokaryotic organisation. *Kildinella, Trachysphaeridium, Leiosphaeridium, Stictosphaeridium, Eomychrystridium* and some simple sphaeromorphs are common acritarchs. However, while discussing the biologic affinities of *Kildinella*, Horodyski (1980) suggested that they may be (i) sheath of a cyanobacterial unicell, (ii) outer common sheath of a colonial cyanobacterium, (iii) outer wall of a cyanobacterial spore or sporangium, (iv) vegeta-

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Plate 3

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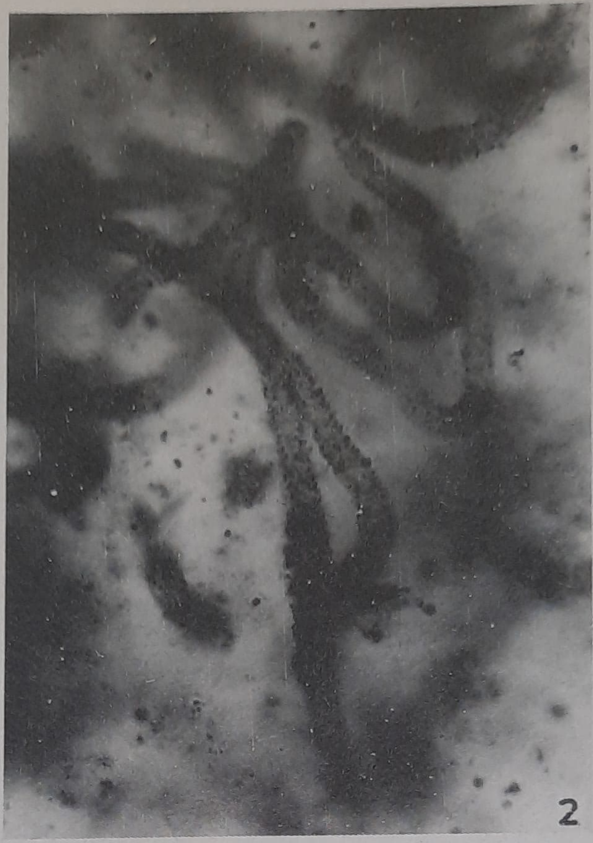
(Scale in Fig. 1 is same for all the specimens except for Fig. 5)

1. *Siphonophycus kestron* Schopf, from Jaradag Fawn Limestone Formation.
2. *Eomycetopsis robusta* Schopf, from Deoban Limestone Formation.
3. *Gunflintia minuta* Barghoorn, from Deoban Limestone Formation.
4. *Sphaerophycus parvum* Schopf, from Deoban Limestone Formation.
5. *Tyrastotaenia* Gnilovaskaya, from Suket Shales, Semri Group.
6. *Leiosphaeridia* (Eisenack) Downie & Sarjeant, from Suket Shales.
7. *Myxococcoides* Schopf, from Deoban Limestone Formation.
8. *Glenobotrydion aenigmatis* Schopf, note the eccentrically placed black pyrenoid-like intracellular bodies from Deoban Limestone Formation.
9. *Nucellosphaeridium* Timofeev, from Suket Shales, Semri Group.
10. *Glenobotrydion majorinum* Schopf & Blacic, from Deoban Limestone Formation.

1



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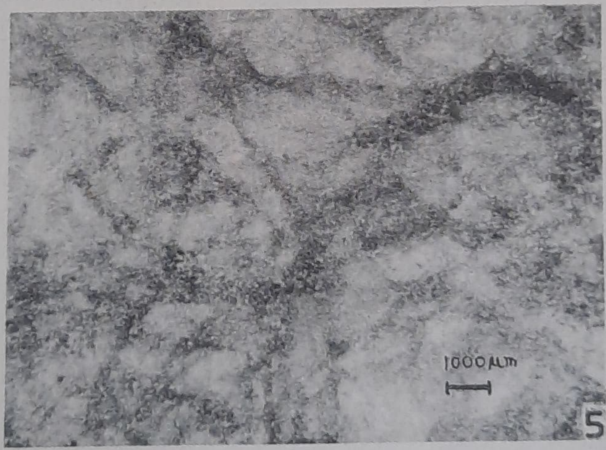

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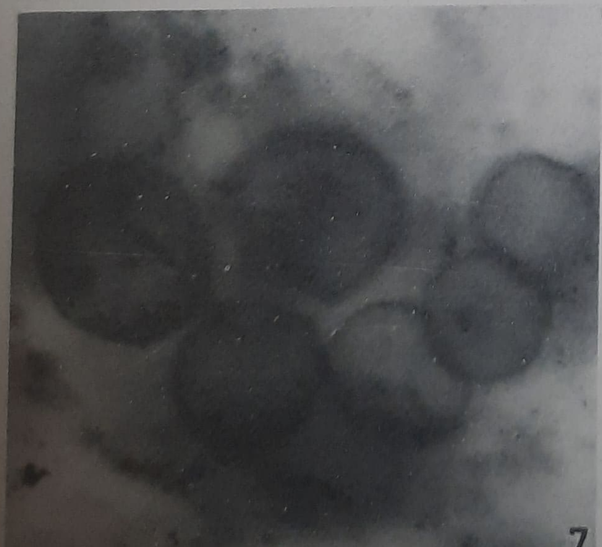

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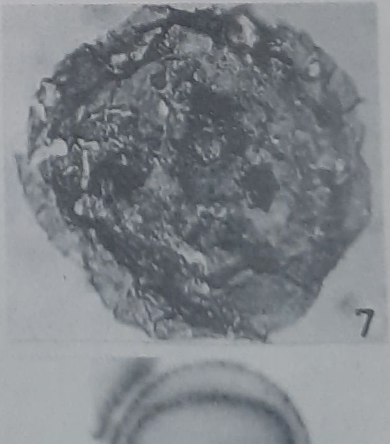

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Plate 3

tive eukaryotic alga, or (v) cyst of a eukaryotic alga.

The presence of spheroidal unicells containing intracellular dark bodies and acritarchs gives an excellent picture of eukaryote evolution. "Spot cells" probably indicate the initial stages of development of eukaryotic organisation while the acritarchs represent an advanced stage of eukaryotic organisation.

Some acritarchs resemble the existing colonies of spherical cyanobacteria called Chroococcales (Vidal, 1984). These forms are typically found in large numbers in marine sediments laid down under glacial conditions during the Varangerian Ice Age (about 650 Ma ago). The Varangerian tillite deposits found in Greenland and Norway (Vidal, 1981) represent more or less a continuous stratigraphic record of the Late Proterozoic Era and Early Cambrian period. They contain fossil remains of both benthic and planktic life forms. A major decline in planktic diversity, however, is noticed during the Late Proterozoic Varangerian episode. This earlier hypothesis of an end-Proterozoic extinction, which is poorly constrained in time but probably coeval with Varangerian glaciation is now being replaced by one of a major turnover just before the Ediacaran radiation. At the end of the Varangerian ice age, as a result of glaciation, abundant water soluble inorganic and organic nutrients, e.g., Nitrogen and Phosphorus were restrored which resulted in the second major radiation of new acritarchous microfossils in the latest Proterozoic. These constitute the pre-Ediacaran biota. One such assemblage of pre-Ediacaran biota has been reported from China. According to Yin (1987), large and complex microfossils occur in formations immediately beneath the strata bearing the Ediacaran metazoans. The fossil assemblage described by Yin (1987) will perhaps replace the orthodox depiction of Precambrian life which does not visualise a biotic diversity during this period. Occurrence of very small forms, morphologically comparable to jelly fish cf. *Cyclomedusa* Sprigg, megascopic sheet algae comparable to *Tyrasotaenia* (Pl. 3, fig. 5) and pelmatazoan holdfast-like structures in Suket shales (Shukla & Sharma, 1990) and *Katani singhii* Tandon & Kumar (1977) comparable to *Grypania*- like red algae are also important in understanding the antiquity of eukaryotic multicellular forms. The stabilisation of crust and formation of shallow marine shelf and platform in India (see Shukla *et al.,* 1989) could have facilitated the development of metaphytes and metazoa as early as 950 Ma. According to them stabilisation of crust was a prior requirement to biological evolution and these two events are not coeval and could have occurred earlier in India. These findings of pre-Ediacaran large acritarchs and other diverse biotas at this period of time in India and other places in the world along with evidences of an early stabilisation of crust as discussed by Srinivasan and Ojakangas (1986) emphasize on the ecological complexities and structured modification of lithosphere which contributed to the evolutionary dynamics of the pre-Ediacaran biotas.

Pre-Ediacaran period was an active evolutionary period; apparently transitional between the primitive unicellular eukaryotes and the emergence of multicellular life–metaphytes and metazoans.

Ediacaran Biota

The Ediacaran fauna, best known from the Ediacara Hill in Southern Australia, comprises authentic oldest multicellular animals. This fauna has been found in many parts of the world, including the Kubis Quartzite of the Nama System in south-west Africa, in the Maphewell Series in Leicestershire, England, in the Vendian Series from the Kola Peninsula and from Northern Siberia. All these deposits appear to be of the same age. Tillites were apparently quite abundant in these sediments. Even though the exact age of these fossils has not been radiometrically determined, it is clear that they are from the very top part of the Precambrian (formerly called the Upper Proterozoic, Eocambrian or Infracambrian). Most representatives of the Ediacaran fauna comprising about 124 species occur only in relief, and this has been partly the reason for the difficulties in assigning systematic positions. Most species are comparable to medusan coelenterates. However, those few which are preserved physically are so divergent from the Cambrian fauna that they must be considered as distinct species.

Most of the more than two dozen Ediacaran species are comparable to medusan coelenterates. Other, bisymmetrical, fossils like *Dickinsonia* and *Spriggina* have been classified as annelids; but this assignment has been disputed. Another bisymmetrical fossil *Pennatularia,* which was described by Gürich (1930) as *Rangea* has been investigated by Pflug (1973) from the Nama System; he concluded that they were echinoderms (Echinodermata).

Though highly developed life forms existed by the Late Precambrian, and were widely distributed by this time, multicellular organisms with hard internal or external skeletons had not yet evolved. Possibly the seas at the time did not have enough calcium in solution or, there was an excess of CO_2 (which increases calcium solubility) which prevented extraction of calcium from the water. Evidence for this is the fact that in brachiopods, the shells contained increasing amounts of calcium carbonate during the Cambrian and the percentage of such brachiopods with calcium carbonate shell also increased.

Widespread accumulation of carbonate deposits in the form of stromatolites and archaeocyathid limestone in the Terminal Precambrian and Lower and Middle

Cambrian resulted from the metabolic activity of living organisms. The necessary elements to serve as protecting cover of the animals and plants in the form of carbonates, phosphates and iron were already present in solution. The necessity was only felt by these organisms where there was stiff competition for survival to safeguard themselves from predators.

Gradually protective elements in the organisms became more powerful to cope with active predators. Of course, the need for hard body parts was increased with evolution. Later in evolution, strength in such body parts was increased by incorporating mineral deposits in them, replacing the purely organic substances used for protective and supporting functions. Inorganic minerals were superior for this purpose and so the process of natural selection caused this kind of adaptations to develop. All the important invertebrate animal groups were already present in the Cambrian. It can be thus surmised that highly organised animals were in existence in the Late Precambrian.

The few finds that we have from this distant era are not a reflection of scarcity of speices but a result of the fact that the organisms present at this time lacked the kinds of the body parts that fossilise readily. Fossilisable internal and external skeletons were not yet selected in evolution. This does not exclude the possibility that the basic body plans of various invertebrate groups developed during the Precambrian Era.

ECOLOGICAL CONSEQUENCES OF EUKARYOTE/METAZOAN EVOLUTION

The early eukaryote evolution in the Proterozoic ecosystem had profound ecological consequences. The diversification of unicellular eukaryotes added new dimensions to the complex microbial system. These protists were capable of phagocytosis, i.e., they acted as micropredators. As they evolved and specialised, they made more intricate food webs. Further eukaryotic algae contained various pigments which utilised the variable photic energy at different depth and thereby increased primary productivity via photosynthesis using H_2O as the electron donor. Thus, their evolution increased global rates of both primary productivity and respiration. Further, they altered the geography of ecosystems by greatly increasing the biomass. The oldest eukaryotic fossils are the presumable cysts of planktonic algae. This eukaryotic algae rose to ecological dominance in the Late Precambrian planktonic realm (Vidal & Knoll, 1983).

Open marine coastal planktic biotas were taxonomically more abundant and diverse than those in the restricted lagoons and other inshore environments. While the eukaryotes occupied the Late Precambrian planktonic realm, the prokaryotes occupied the benthonic realm where benthic microbial mat communities were dominant (Knoll, 1982). These microbial mats upon diagenesis gave rise to abundant stromatolites in the upper Proterozoic Era. Shallow subtidal embayments support only a limited variety of eukaryotic benthos. Presence of such benthic microbes in few open shelf subtidal stromatolites suggests that though the prokaryotes maintained their importance over wide stretches of the shallow sea floor, the eukaryotes, however, few in number, competed with them in space, grazing and burrowing. As a result, the prokaryotic activity diminished to a great extent whereby the stromatolitic diversity also reduced considerably.

Neoproterozoic carbonaceous megascopic ribbon-shaped fossils preserved in detrital rocks are generally regarded as algal ramains and range in age from Early to Late Proterozoic (Hofmann, 1985). Salient examples are *Vendotaenia* Gnilovskaya, a phaeophyte (Brown algae) or a rhodophyte (red algae, see Gnilovskaya, 1971); *Longfengshania* Du — a benthic sessile alga (Du & Tian, 1985); *Enteromorphytes* Zhu & Chen — a twig-like megascopic fossil, interpreted to be a chlorophyte or green alga (Zhu & Chen, 1984); and a millimetric size body fossil with a central cavity and protuberances in the outer membrane from Late Proterozoic Hedmark Group in Southern Norway, comparable to dasycladacean algae (Chlorophyta, see Spjeldanes, 1963). Similar carbonaceous megascopic films have also been reported from Southeast and North China (Zhang, 1989; Duan, 1982; Du & Tian, 1985; Chen & Zhang, 1986). *Chuaria* Walcott and *Tawuia* Hofmann have also been regarded as metaphytes by some palaeobiologists (Zheng, 1980; Duan, 1982). However, most of these megafossils lack well-preserved microstructures; their multicellular organisational level and systematic position are also quite uncertain.

These metaphytes and metazoans of Late Precambrian continued to thrive in the marine realm. One of the most interesting and intriguing topics is the origin of the terrestial flora. The green algae (Chlorophyta), commonly abundant in the Late Proterozoic ecosystems, have been suspected as the most likely progenitors of land plants. The geologic history of green algae is quite extensive and there are numerous reports of fossil green algae, some dating well back into the Precambrian (see Schopf & Blacic, 1971). The cell biologists and phycologists have unravelled several features in living algae that phytogenetically unite them with land plants.

The *Thallophyca* sp. and *Wengania* sp. the two multicellular megascopic thallophytes reported by Zhang (1989) from ~680 Ma old Late Proterozoic phosphate rocks of Duoshantuo Formation, South China are important from the point of view of transition from marine to terrestrial realm because they show conclusive evidence of differentiation of tissue. The morphological attributes of the thalli suggest that these Late Proterozoic thallophytes had a sessile habit, and lived in shallow water of intertidal to subtidal environments. Attainment of thallophytic morphology was the first significant step in the preparatory phase of transition from sea to land. These earliest multicellular algal sheets gradually developed features like branching. They were still inhabiting the aquatic media where the nutrients were in plenty and easily available to all parts of the organism. Perhaps due to depleting nutritional resources of the early sea, the living system felt the need to move and occupy land. The appearance of the land flora, probably was a result of the pace of biotic differentiation (i.e., following the appearance of metaphyte and metazoans) or may be, it was conditioned by external environmental factors such as decrease in sea level. These factors may have stressed near shore communities leading to the evolution of stress tolerant intertidal and subtidal algae such as *Thallophyca* and *Wengania*. These algae perhaps adapted to a degree of desiccation, gained potential to explore terrestrial environments. An initial exploration of the land environment presumably by a green algal lineage was conditioned by a number of vegetative adaptations, such as deposition of water impermeable substance such as a cuticle to protect against desiccation. The time of transition from brackish to freshwater to terrestrial habitat has been suggested to be during 80 million year interval from the Ordovician to the end of Devonian, occurrence of *Cooksonia* at Silurian-Devonian boundary provides a datum line for tracing the structural and morphological adaptation in early land plants. But vascular plants have even been suggested as occurring as early as the Precambrian based on the presence of aromatic free radicals recovered from the Gunflint Chert. Further, discoveries of palaeosols and burrows in rocks of Ordovician age (Retallack, 1985) and the discovery of various fungal remains from Early Palaeozoic have been used to underscore the diversity of organisms already established in terrestrial ecosystems at an early point in geologic time. During this time, there was an elaboration and differentiation of trophic structure, increase in productivity and shifts in dominant ecological strategies from resource acquisition and mortality replacement to resource conservation and competition.

EPILOGUE

The game of organic evolution which started with the first primitive cell passed through phases of crisis and after each crisis adapted itself with addition of new morphological and structural changes and thus prepared itself to conquer the land. Today these plants grow in every ecological niché and many major steps of morphological/structural modification also took place since they first conquered the land. But the major steps in physiological adaptation and most of biopolymers had already appeared by close of the Precambrian era. Therefore continued study of Precambrian biotas is important to understand the total evolutionary game to unravel the early evolutionary history of plants.

To conclude I quote from the Taittiriya Upanisad II-1-1.

> तस्माद्वा एतस्मादात्मन आकाशः संभूतः । आकाशा-
> द्वायुः। वायोरग्निः । अग्नेरापः । अद्भ्यः पृथिवी ।
> पृथिव्या ओपधयः । ओषधीभ्योऽन्नम् । अन्नात्पुरुपः ।
> स वा एप पुरुषोऽरसमयः। तस्येदमेव शिरः। अयं दक्षिणः
> पक्षः। अयमुत्तरः पक्षः । अयमात्मा । इदं पुच्छं प्रतिष्ठा ।
> तदप्येप श्लोको भवति ।।१।। इति प्रथमोऽनुवाकः ।।

"From the great desire of the universal consciousness to manifest arose space, from space air, from air fire, and from fire water, from water the earth, from the earth the vegetation, from vegetation food, from food the entire creation, Man is a product of all this seen and unseen, perceived and unperceived transformation". Thus from "Asat" the unseen and unperceptible energy arose everything that is now the atmosphere, lithosphere, hydrosphere and biosphere.

ACKNOWLEDGEMENTS

I am extremely thankful to The Palaeobotanical Society for awarding me this prestegious International Award. Material for this lecture has been drawn from several published and unpublished sources as well as discussions with several of my collaborators. I have been greatly stimulated by the apparent and hidden meanings of the message that we get in understanding the manifestation and evolution of life during its beginnings. The translation of Vedic script is not literal, I have tried to convey the essense of this great knowledge. I am only sharing this experience with you. I am extremely thankful to my colleagues Dr. Manoj Shukla and Mr. Mukund Sharma for their constant help in preparing this lecture.

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