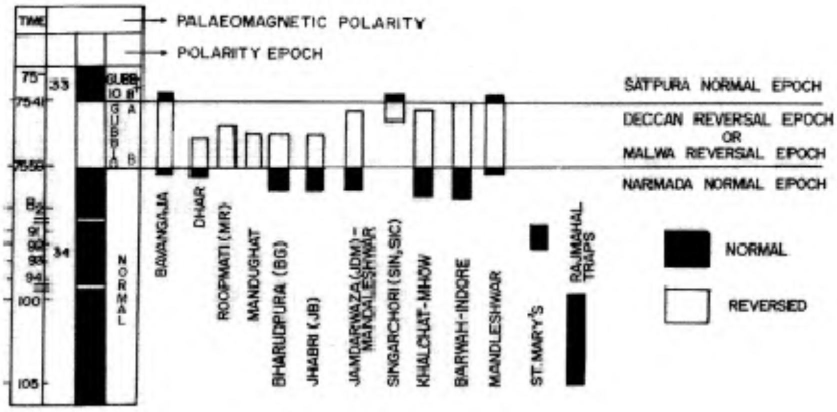

Figure 3. Correlations of geomagnetic polarity transitions of Singarchori sequence with other selected sequences from the Narmada region and Mesozoic volcanic traps with marine magnetic scale of La Brecque *et al.*[8] and polarity epochs of Harland *et al.*[9].

volcanics, India perhaps might have occupied the Southern latitude of 29° and drifted to 50° North to occupy the present position, which is more than 5000 km distance since the time of formation of these lavas.

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Role of micro-organisms in weathering of the Konkan–Goa laterite formations

Mineralogy, microbial ecology and weathering in the subsurface are an intimately linked biogeochemical system. It is established beyond doubt that the microorganisms play an important role as geologic agents. For example, it is known that since the early Precambrian, the microbes have played an active role in the evolution of the earth's surface including the uppermost lithosphere and the hydrosphere. All types of igneous, sedimentary and metamorphic rocks are susceptible to microbial weathering, including siliceous and calcareous rocks[1]. Bacterial communities dissolve the primary rock-forming minerals to obtain essential nutrients and also act as nucleation sites for the precipitation of secondary minerals. Generally, the biological weathering of silicates is driven by the nutrient requirements of the microbial communities. The progression of mineral weathering may also be influenced by a mineral's nutritional potential with the microorganisms destroying only the beneficial minerals.

Fungal activity is reported to release metallic and silicate ions from minerals and rocks[2]. Cyanobacteria are important actors in weathering of rock surfaces[3]. The activity of *Clostridium butyricum* results in reduction of pedogenic iron oxides[4]. Lichen activity in granites results in the formation of bioweathered granitic biotite[5]. Various kinds of bacteria, fungi, algae and protozoa serve as geochemical agents in the uppermost lithosphere, promoting rock weathering and mobilizing the mineral constituents[1]. Eubacteria

Table 1. Total organic carbon, organic matter, dehydrogenase activity (DHA) and total heterotrophic bacterial count and actinomycetes

Site	Zone	Lithology	% Carbon	% Organic matter	DHA (μg/g/24 h)	Count	
Panaji, Goa							
	P1	Partially altered quartz-chlorite-biotite schist	0	0	0		
	P1-2	Altered quartz chlorite biotite schist	0	0	0		
	P1-3	Lithomargic clay	0	0	0		
	P1-4	Fe-laterite	0.012	0.02064	0		
	P1-5	Lateritic soil	0.624	1.0732	1.46^{-03}	2×10^1	Actinomycetes
						10×10^1	Bacteria
Bogdha, Vasco							
	V1	Altered quartz chlorite schist	0	0	0		
	V1-2	Iron-bed	0	0	0		
	V1-3	Lithomargic clay	0	0	0		
	V1-4	Fe-laterite	0	0	0		
	V1-5	Duricrust	0	0	0		
	V1-6	Lateritic soil	0.48	0.8256	1.32^{-03}	3×10^1	Actinomycetes
						1×10^1	Bacteria
Zari, Goa							
	V2-1	Altered trap	0	0	0		
	V2-2	Lithomargic clay	0.012	0.02064	0		
	V2-3	Laterite	0.768	1.32	1.84^{-03}	7.8×10^2	Bacteria
						5×10^1	Actinomycetes
Ponda 1							
	K1	Altered quartz chlorite schist	0	0	0		
	K1-2	Lithomargic clay	0.306	0.526	1.02^{-03}	2×10^1	Actinomycetes
						4×10^1	Bacteria
	K1-3	Lateritic soil	1.35	2.322	5.8^{-03}	92×10^1	Bacteria
						2×10^1	Actinomycetes
Ponda 2							
	K2-1	Partially altered quartz chlorite schist	0	0	0		
	K2-2	Altered quartz chlorite schist	0	0	0		
	K2-3	Laterite	0	0	0		
	K2-4	Lateritic soil	1.506	2.59	2^{-03}	23×10^1	Bacteria
						1×10^1	Actinomycetes
Konkan 1							
	M1	Altered basalt	0	0	0		
	M2	Iron-bed	0	0	0		
	M3	Fe-laterite	0.012	0.02064	0		
	M4	Al-laterite	0.48	0.8256	1.32^{-03}	5×10^1	Bacteria
Konkan 2							
	M2-1	Altered basalt	0	0	0		
	M2-2	Lithomargic clay	0	0	0		
	M2-3	Lateritic	0	0	0		
	M2-4	Duricrust	0.192	0.33024	0		

and archaebacteria have shown the ability to bind metal ions at the cell surface or for various intracellular functions[6]. It is known that the three bacteria (*Pseudomonas chromaticans*, *P. chromatophila* and *Aeromonas dechromatica*) are able to reduce Cr(VI) to Cr(III) resulting in the precipitation of $Cr(OH)_3$ (ref. 7). Studies involving the reduction of iron by bacteria have been done in the Brazilian laterites[8]. Oxidation of Fe^{2+} with the participation of iron bacteria *Gallionella* during the transformation of goethite to hematite via ferrihydrite was reported from the weathering crust of Western Georgia[9]. Presence of iron-oxidizer *Gallionella* was cited from copper mines and of *Bacillus coagulans* from the waste dumps of bauxite mines in India[10]. *Gallionella* was also identified from the lateritic soils of south Kerala[11]. There are reports about the occurrence of widespread bacterial populations at glacier beds and their relation to rock weathering and carbon cycling[12].

In the present investigation, seven lateritic profiles from the Konkan–Goa coastal belts were sampled for understanding the hitherto underexplored biological weathering mechanisms under tropical climatic conditions. A typical laterite profile consists of a soil horizon, duricrust, bauxite zone, saprolite zone and parent rock. The parent rocks in the study area are basalt and metamorphics.

To study the geochemical behaviour, five profiles from Goa and two from the Konkan coast were sampled, labelled and brought to the laboratory for analysis (Figure 1). Each profile had various zones though all the zones were not found in all the profiles. They revealed distinct colour, textural and mineralogical variations with depth. The zones include (a) top layer of lateritic soil (b) intervening zones of bauxite, aluminous and ferruginous laterite (c) clay zone and (d) the zone of weathered and altered parent material.

Table 2. Microbial type culture collection – Bacterial identification report

Tests	Results			
	1	2	3	4
Morphological test				
Gram's reaction	+	+	+	+
Shape	Rod	Rod	Rod	Rod
Size	M	M	M	M
Spore Endospore	+	+	+	+
Position	ST	C	ST	ST
Shape	Oval	Oval	Oval	Oval
Sporangia bulging	+	+	+	+
Motility	+	+	+	+
Fluorescence (UV)	–	–	–	–
Pigments	W	W	W	W
Physiological test				
Growth at temperature	1	2	3	4
4°C	–	–	–	–
10°C	+	–	+	–
15°C	+	–	+	–
42°C	+	+	+	+
45°C	+	+	+	+
55°C	+	–	+	–
65°C	–	–	–	–
Growth at pH				
pH 5.0	+	+	+	+
pH 8.0	+	+	+	+
pH 9.0	+	+	+	+
pH 11.0	+	+	+	+
Growth on NaCl (%)				
2.5	+	+	+	+
5	+	+	+	+
7	+	+	+	+
9	–	–	–	–
10	–	–	–	–
Growth under anaerobic condition	+	–	+	+
Biochemical tests				
Growth on Macconkey agar	–	–	–	–
Indole test	–	–	–	–
Methyl red test	+	+	+	+
Voges Proskauer test	–	–	–	–
Citrate utilization	–	–	+	+
Casaein hydrolysis	+	+ (weak)	+	+
Starch hydrolysis	+	+	+	+
Urea hydrolysis	–	–	–	–
Nitrate reduction	–	–	–	–
Nitrite reduction	–	–	–	–
H_2S production				
Cytochrome oxidase test	+	+	+	+
Catalase test	+	+	+	+
Oxidation/fermentation (O/F)	–	–	–	–
Gelatin liquefaction	+	+	+	+
Arabinose	–	–	–	–
Dextrose	+	+	+	+
Fructose	+	–	+	+
Galactose	–	–	–	–
Inositol	+	–	+	–
Lactose	–	+	–	+
Maltose	+	–	+	–
Mannitol	–	–	–	–
Melibiose	–	–	–	+
Raffionose	–	–	+	–
Salicin	+	–	+	–
Sorbitol	–	–	–	+
Sucrose	+	±	+	–
Trehalose	+	–	+	+
Xylose	–	–	–	–
Adonitol	–	–	–	–
Cellobiose	+	+ (w)	+	–
Dulcitol	–	–	–	–
Inulin	–	–	–	–
Rhammnose	–	+	–	–

Identification is as follows: 1, *Bacillus megaterium*; 2, *B. coagulans*; 3, *B. coagulans*; 4, *B. coagulans*.

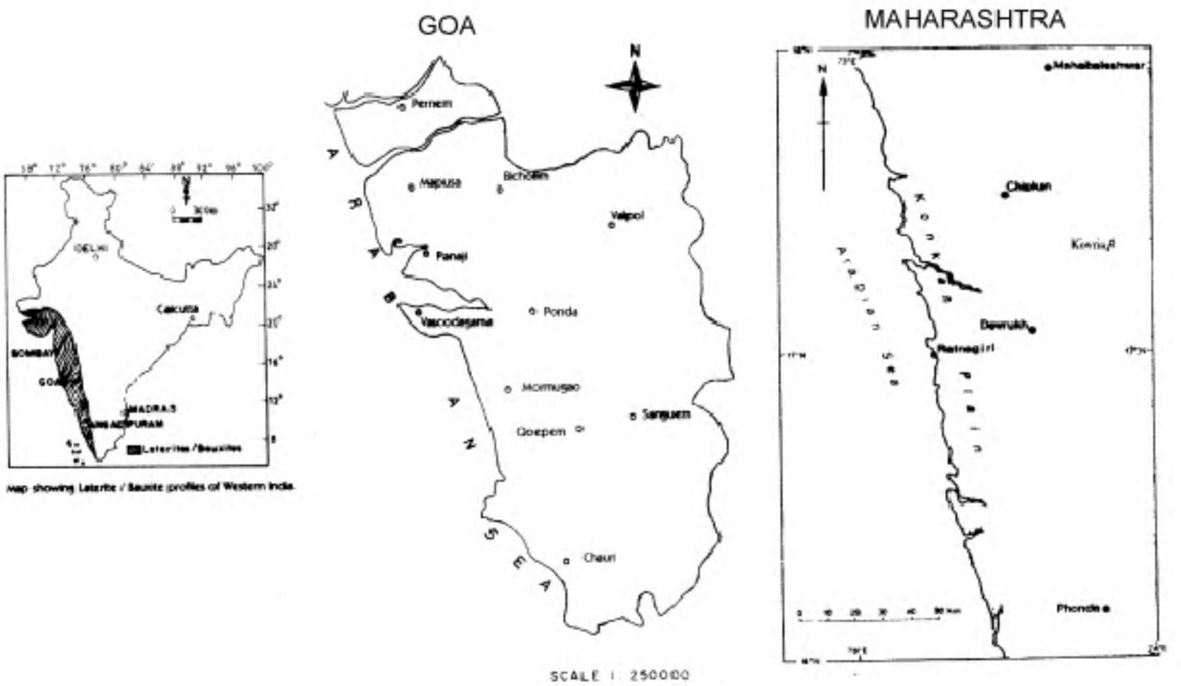

Figure 1. Location map.

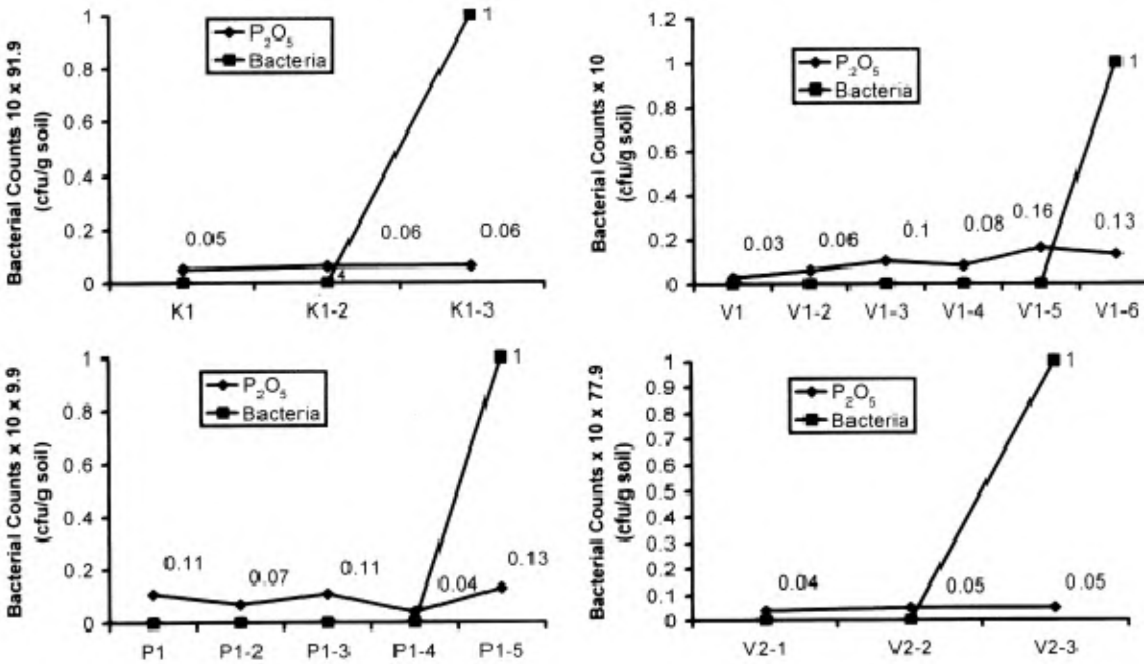

Figure 2. P_2O_5 concentration (wt%) and bacterial counts (cfu/g soil) in some representative profiles.

The five profiles chosen for the study from Goa are Khandepar bazar, Ponda (K1, K1-2, K1-3)-14 ft thick, 2 km South West of Khandepar bazar, Ponda (K2-1, K2-2, K2-3, K2-4)-10 ft thick, Panaji (P1, P1-2, P1-3, P1-4, P1-5)-12 ft thick, Bogdha–Tariwada (V1, V1-2, V1-3, V1-4, V1-5, V1-6), Vasco-da-gama-Mormugao-21 ft thick (V2-1, V2-2, V2-3)-Zari, Mormugao-12 ft. The two profiles from Konkan coast are Wilson Point 2 km from main Mahabaleshwar (M1, M2, M3, M4)-10 ft, 200 m away from Wilson Pt., Mahabaleshwar (M2-1, M2-2, M2-3, M2-4)-8 ft thick (Table 1).

Total organic carbon (TOC) in various zones of laterite profiles was determined using Walkley and Black's rapid dichromate titration method[13]. Soil dehydrogenase activity (DHA)[14] and the isolation and identification of total heterotrophic bacteria were performed using standard plating and streaking techniques[15] (Table 1). The cultures isolated in pure form were identified at IMTECH, Chandigarh by performing standard morphological, physiological and biochemical tests (Table 2).

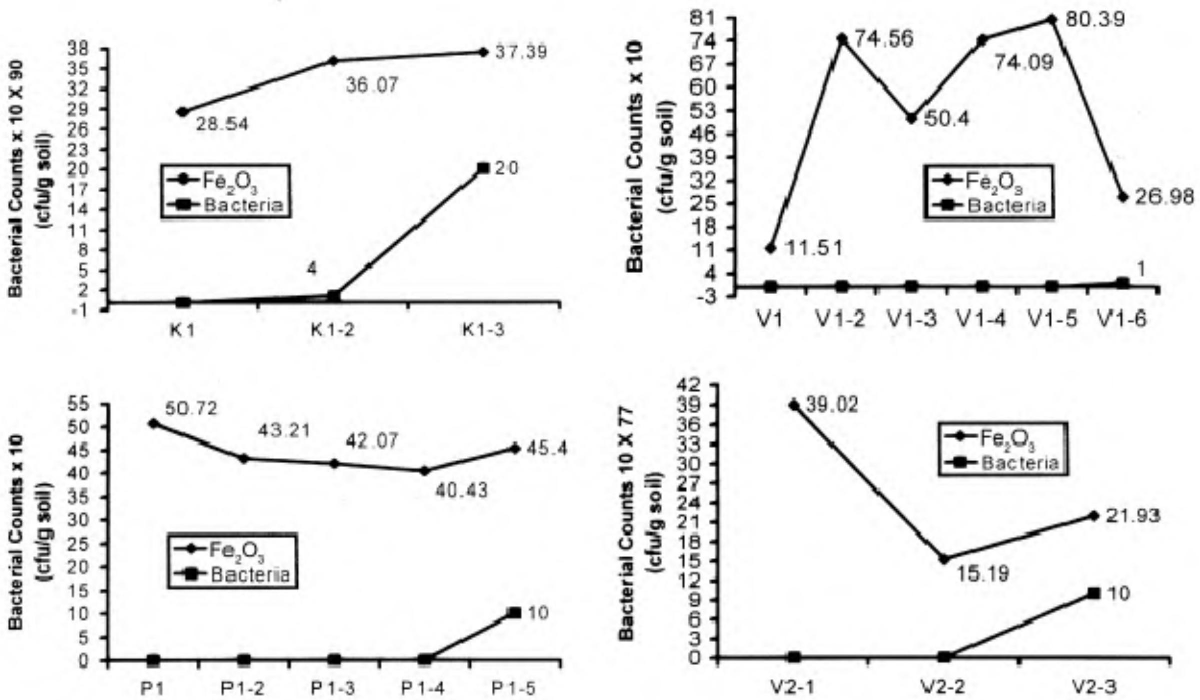

Figure 3. Fe_2O_3 concentration (wt%) and bacterial counts (cfu/g soil) in some representative profiles.

TOC and DHA contents were estimated as indices of the biological activity possibly involved in the weathering processes. The results indicate that the upper zones comprising the lateritic soil layer and sometimes even the lithomargic clay show the presence of organic carbon, the values being high in lateritic soil zones. K2-4 of Khandepar, Goa showed the highest concentration of 1.506% carbon.

Dehydrogenases are most common soil enzymes produced by microorganisms which mediate several oxidation–reduction reactions in the soil[16].

Presence of high TOC is a clear indication of good biological activity in the zone. The organic carbon incorporated into the soil has originated from the organic biomass present therein. Further evidence for the presence of microbial activity in these profiles is provided by our results on soil dehydrogenase activity (Table 1). Soil enzymes are understood to be of immense importance in mineralization process; and organic matter turnover and dehydrogenase activity, in particular, reflect the total range of oxidative activities of soil microflora.

The role of DHA is particularly important in the initial stages of oxidation of organic matter[17] and a strong correlation exists between DHA and TOC[18]. In our study also, the zones K1-3 and K2-4 which had higher TOC showed higher DHA values of 5.8^{-03} µg/g/24 h and 2^{-03} µg/g/24 h. However, as compared to DHA values of well-formed productive soils, the DHA in these soils was low, indicating initial stages of establishment of microbial populations in the upper zones of rock profiles.

The presence of microorganisms in the rock profiles was also revealed through direct plating technique. A good number of heterotrophic bacteria and actinomycetes was found to be present in the upper zones.

The total heterotrophic bacteria (Table 1) was maximum in the K1-3 zone with a count of 92×10^1 cfu/g soil and 2×10^1 cfu/g soil actinomycetes. The microorganisms that were identified were *Actinomycetes micrococci, Bacillus megaterium* and some strains of *Bacillus coagulans*. The three strains of *B. coagulans* were morphologically identical but exhibited several biochemical and physiological variations as revealed by the tests (Table 2). All the bacteria showed a wide range of temperature and pH tolerance, thus enabling them to thrive and establish under acidic pH and high temperature conditions. A substantially high bacterial and actinomycetal density in the zones showing higher values of DHA indicates a close relationship between the two.

In order to examine the possible interrelationship of the existing microbial populations with weathering process, the concentrations of Fe_2O_3 and P_2O_5 in different zones of the laterite profiles were determined using XRF (Table 3, Figures 2 and 3).

The major means of solubilization of phosphorus is known to be by microbially mediated acid productions. In our study *Bacillus megaterium*, commonly referred to as phosphobacteria, was identified and the substantial rise in phosphorus concentrations in the weathering profiles can be noticed (Table 3). *B. megaterium* colonies were predominantly found in the Konkan samples, thereby explaining the highest phosphorus concentration in these profiles. *Bacillus megaterium* is a Gram positive, rod-shaped spore-producing bacteria. It is a Eubacterium and is found in the soil. Colonies form in chains due to sticky polysaccharides on the cell wall. It is one of the largest Eubacteria with the length being 6 µm and width 2 µm. This can survive in temperatures 42°C to 55°C (Table 2). The poly-beta-hydroxybutyric acids of *Bacillus megaterium* help in the solubilization of the mineral apatite, $Ca_3(PO_4)_3$ (F, OH, Cl) and other phosphate-bearing minerals. *Bacillus megaterium* takes Fe(III+) as its electron acceptor (oxidant) and reduces the ferric

Table 3. P_2O_5 and Fe_2O_3 concentrations in various zones of laterite profiles

Sample	Depth	P_2O_5 (%)	Fe_2O_3 (%)
K1	0	0.05	28.54
K1-2	4	0.06	36.07
K1-3	8	0.06	37.39
K2-1	0	0.08	34.31
K2-2	3	0.1	53.86
K2-3	6	0.13	52.39
K2-4	8	0.1	26.13
M1	0	0.14	28.87
M2	3.5	1.1	78.12
M3	4	2.6	68.6
M4	6	0.23	14.01
M2-1	0	0.03	10.46
M2-2	1	0.41	42.28
M2-3	3	0.38	37.67
M2-4	6	0.44	42.41
P1	0	0.11	50.72
P1-2	2	0.07	43.21
P1-3	3	0.11	42.07
P1-4	6	0.04	40.43
P1-5	9	0.13	45.4
V1	0	0.03	11.51
V1-2	1	0.06	74.56
V1-3	9	0.1	50.4
V1-4	12	0.08	74.09
V1-5	14	0.16	80.39
V1-6	16	0.13	26.98
V2-1	0	0.04	39.02
V2-2	3	0.05	15.19
V2-3	6	0.05	21.93

0, indicates the level of parent rock.

iron to ferrous. It is an anaerobic, thermophilic and ferric iron-reducing bacterium. The increase in iron concentrations (Table 3) in the zones containing these bacteria may be partly attributed to their activity. Ferric iron is an electron acceptor for energy metabolism in a wide variety of bacteria. Haematite and goethite are some of the most common iron-bearing minerals encountered in top zones of the profiles as revealed by XRD studies. Bacterial Fe^{3+} reduction can lead to the solubilization of iron, which is an important geochemical process.

By XRD studies, phosphate-bearing minerals were identified. They include iron manganese aluminium phosphate hydroxide, hydrate-childrenite, iron phosphate hydrate-phosphosiderite, aluminium uranyl phosphate hydroxide hydrate-sabugalite and copper phosphate hydroxide-libethenite. *Bacillus megaterium* is able to solubilize phosphate from these minerals and as indicated in our studies there is increase in phosphate concentration in the uppermost zones.

Also, vast quantities of carbon dioxide are emitted by bacteria as part of their life processes and the resulting weak carbonic acids (pH 5–6) enhance the weathering processes. The liberation of hydrogen ions during bacterial oxidation reactions causes acidification and subsequent mineral dissolutions and the presence of dehydrogenase activity in the laterite zones provides evidence for the same. The mineral dissolution favours the bacteria's survival as a source of energy. Mineralization of soil organic matter by *Bacillus megaterium* and various strains of *Bacillus coagulans* produces organic acids. These acids speed up the weathering of minerals. Lichens and true mosses, believed to be pioneers in the succession processes, were also encountered on the rock surfaces which are known to produce weak acids and dissolve certain minerals in the rocks. Their presence provides ample evidence for progression of weathering process leading to the development of well-formed soil that would be so essential for ecological succession on the bare rocks. All of the above evidences prove the role of microorganisms and primitive plants in the weathering process. Further systematic research in geomicrobiology, involving interdisciplinary teams of both biologists and geologists, would help in understanding the hitherto less known but very important process of biological weathering in the region.

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