0.45% MgO (average = 0.67%), 0.02–0.05% MnO (average = 0.034%), 0.27–0.80% CaO (average = 0.50%), 5–20 ppm Cu of the uranium content. Leachable uranium content is 58.04–87.93%.

The source of uranium in Gondwana sediments appears to be uraniferous crystalline rocks of Surguja comprising quartzo-feldspathic cataclasite, biotite schist, sheared granite–gneiss and pink granite, in which established deposits of uranium, viz. Jajawal and Dumhath are already known in nearby areas. Uranium was most likely remobilized from Surguja crystalline into the sediments and then precipitated in feldspathic sandstone of the Talchir Formation in reducing environment caused due to hematitization of pyrites. Post-Gondwana fractures and faults have facilitated remobilization of uranium from the basement rocks. Uranium mineralization in this area may not occur in isolation and is expected to be widespread in Talchir sandstone. Thus, this discovery has opened a new target area for future exploration for uranium mineralization within the Lower Gondwana sedimentary rocks.

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Tiniest primary producers in the marine environment: an appraisal from the context of waters around India

Phytoplankton (0.2 µm–2 mm) are the major primary producers in the marine environment, thereby forming a basic link in the marine food web. They are categorized into different groups depending on their size range. Cells in the size range of 0.2–2 µm are known as picophytoplankton, which are the smallest known components of the phytoplankton community. Since its discovery in 1988 (ref. 1), vast amount of information has been collected on picophytoplankton in the world oceans[2,3], which shows that these organisms most often dominate the photosynthetic biomass. The picophytoplankton comprises of two cyanobacteria, *Prochlorococcus* and *Synechococcus*, and a range of picoeukaryotes. *Prochlorococcus* is the smallest known photosynthetic organism (0.6–0.8 µm) and the most abundant genus of phytoplankton in open oceans. It contains divinyl derivatives of chlorophylls *a* and *b*. *Synechococcus* (0.8–1.5 µm), which is characterized by an orange fluorescing pigment, phycoerythrin, is found in high abundance in coastal areas, but in low abundance in oligotrophic waters. Picoeukaryotes (1–2 µm), whose major pigment is chlorophyll *a*, include a variety of algal classes such as Prasinophyceae, Pelagophyceae and Bolidophyceae.

Despite the intense interest in the role of picophytoplankton in oceanic planktonic processes, the Northern Indian Ocean (Arabian Sea and Bay of Bengal) is least explored in terms of picophytoplankton distribution. Although there are reports of picophytoplankton from the western Arabian Sea[3,4], there is no detailed information available on the distribution of different picophytoplankton groups from the eastern Arabian Sea. Previous research in these regions was mostly limited to the larger phytoplankton community[5,6] through light microscopy, as a result of which the picophytoplankton went unnoticed due to their small size. With the advent of flow cytometry in biological oceanography, picophytoplankton studies have been made much easier even when compared with epifluorescence microscopy. In view of this, observations on picophytoplankton groups and their abundance are underway in the eastern Arabian Sea and Bay of Bengal (under the Indian Expendable Bathythermographic (XBT) programme) using flow cytometry (BD FACSAria™ II flow cytometer equipped with a blue and red laser emitting at 488 and 633 nm respectively). Some highlights of these observations are presented from the eastern Arabian Sea (coastal: Dona Paula Bay, Goa, 15°27.5′N, 73°48′E; offshore: off Lakshadweep, 10°00′N, 74°30′E; on-board *Sagar Sukti*) and Bay of Bengal (coastal: 21°00′N, 88°11′E; offshore: 16°00′N, 89°00′E). Samples were collected in duplicate at each station, preserved in paraformaldehyde (final concentration 0.2%) and stored in liquid nitrogen until analysis.

Flow cytometry is a technique that allows identification and quantification

Table 1. Cytometric parameters (arbitrary units) of the picoplankton groups observed in the Arabian Sea and Bay of Bengal

Picoplankton group	Forward light scatter (proxy for cell size)	Chlorophyll fluorescence	Phycocyanin fluorescence	Phycoerythrin fluorescence
Prochlorococcus	Smallest group of picophytoplankton	0.065–0.45		
Synechococcus PC	Smaller than picoeukaryotes and larger than *Prochlorococcus*	0.5–0.8	26–77	
Synechococcus PE	Smaller than picoeukaryotes and *Synechococcus* PC			
Synechococcus PE-I	Largest *Synechococcus* PE sub-group	0.16–0.46		0.068–0.13
Synechococcus PE-II	Smaller than *Synechococcus* PE-I	0.08–0.22		0.004–0.05
Synechococcus PE-III	Smaller than *Synechococcus* PE-II	0.011–0.15		0.004–0.006
Synechococcus PE-IV	Smaller than *Synechococcus* PE-III	0.096– 0.01		0.0028–0.003
Picoeukaryotes	Largest group of picoplankton			
Picoeukaryotes-I	Largest picoeukaryote subgroup	1–4.9		
Picoeukaryotes-II	Smaller than picoeukaryotes-I	6–20		
Picoeukaryotes-III	Smaller than picoeukaryotes-II	20–46		

These cytometric parameters were normalized to 2.0 μm diameter beads used as an internal reference.

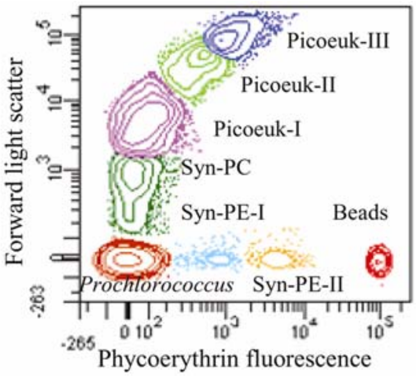

Figure 1. Examples of flow cytometry cytograms. Data of samples taken from the surface waters of Dona Paula Bay on 22 January 2008. Phycoerythrin fluorescence (phycobiliprotein-derived) versus forward light scatter (proxy for cell size).

of groups of cyanobacteria and picoeukaryotes on the basis of forward light scatter (FLS; proxy for cell size) and the cellular fluorescence from pigments such as chlorophyll *a*, phycoerythrin and phycocyanin. The group of cells fluorescing red with the largest FLS are the picoeukaryotes. The group with orange fluorescence represents the *Synechococcus* cells rich in phycoerythrin pigment (Syn-PE), and those with red fluorescence and lacking orange fluorescence are the *Synechococcus* cells rich in phycocyanin pigment (Syn-PC). The group of cells fluorescing red and with FLS smaller than *Synechococcus* and picoeukaryotes are the *Prochlorococcus*. Sub-groups observed in the Syn-PE and picoeukaryote groups were differentiated depending on the intensities of the orange and red fluorescence respectively (Table 1 and Figure 1).

The picophytoplankton groups observed in the Arabian Sea and Bay of Bengal are given in Table 1 and Figure 1. In the coastal region of the Arabian Sea, during the monsoon (June 2008) and post-monsoon periods (January 2009), Syn-PC and Syn-PE were the dominant picophytoplankton respectively. During the post-monsoon season, abundance of both the *Synechococcus* groups was much lower than that recorded during the monsoon season. Although the total abundance was low compared to that in the monsoon period, the picophytoplankton community was much diverse during the post-monsoon season. In the offshore region of the Arabian Sea, picophytoplankton abundance was 2–3 orders of magnitude lower than that recorded in the coastal region. *Prochlorococcus* was found to be the dominant group, both in the surface (November 2008) as well as the deeper waters (100 m; December 2008) followed by Syn-PE and picoeukaryotes. A similar order of dominance was reported from the western Arabian Sea[4]. In the coastal region of the Bay of Bengal, Syn-PE was the dominant group during the southwest (SW; August 2008) and northeast (NE; January 2009) monsoons. The picophytoplankton community was diverse as well as more abundant during the NE monsoon compared to that in the SW monsoon. In the offshore region of the Bay of Bengal (July 2009), surface waters were dominated by Syn-PE whereas bottom waters (120 m) by *Prochlorococcus*, whose abundance was higher than that in the surface waters of the coastal regions of the Bay of Bengal (Figure 2).

From the above observations, it is evident that in the coastal regions the highest abundance of picophytoplankton is found in the Arabian Sea during the SW monsoon followed by the coastal region of the Bay of Bengal during the NE monsoon. In the offshore region, higher abundance of picophytoplankton was found in the Bay of Bengal and the lowest abundance in the Arabian Sea. Overall, the coastal regions harboured higher picophytoplankton abundance than the offshore regions.

In the coastal Arabian Sea, during monsoon, due to precipitation, water temperature and salinity were lower compared to the post-monsoon season. Nutrient input and freshwater inflow from the land were also high during this period. All these factors could have led to the increased abundance of picophytoplankton during this season. The coastal Syn-PC group, which in the present study was found only in Dona Paula Bay, is known to exhibit higher growth rates on exposure to variable environments such as nutrient input and freshwater inflow from the land. The increased abundance of Syn-PC during this period compared to that in the post-monsoon shows that monsoon and riverine influx can bring about a change in the species composition and dominance. In the coastal region of the Bay of Bengal, although Syn-PC was not present, diverse sub-groups of Syn-PE were observed. However, here the total picophytoplankton abundance was one order of magnitude lower than that in the coastal Arabian Sea.

Prochlorococcus is known to dominate only in the oligotrophic oceanic regions. However there are a few reports that show the presence of this organism in coastal waters of the Mediterranean Sea, Japan and China[2,7,8]. In the present study, this group was observed at all the sampling stations, their percentage con-

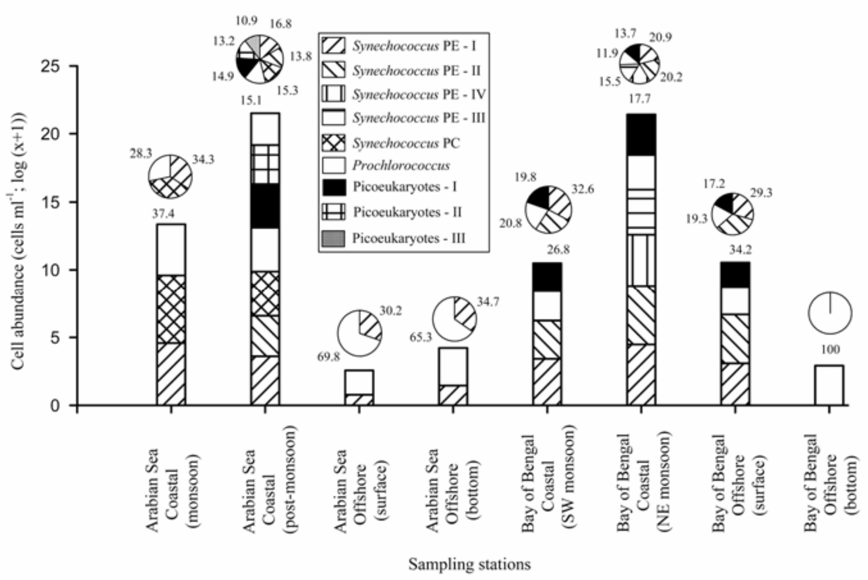

Figure 2. Cell abundance (cells ml^{-1}; bars) of picophytoplankton groups and percentage contribution (circles) of each group to total picophytoplankton abundance in the Arabian Sea and Bay of Bengal.

tribution being highest in the offshore regions compared to that in the coastal regions. The reason for their presence in the inshore waters is still speculative: whether it is due to advection from the offshore waters or due to their *in situ* growth capabilities.

This study on the picophytoplankton abundance in Indian waters shows that these organisms, which were neglected all these years while giving importance only to the larger organisms, are abundant in the Arabian Sea and Bay of Bengal, which is considered to be comparatively less productive. Although similar groups have been found in other world oceans, it is important to know how different or similar these groups are in terms of species/strains in comparison to the already existing database and also their contribution to the total photosynthetic biomass. Such detailed studies will reveal their contribution and role in biogeochemistry of these regions. Earlier studies have shown that in the eastern Arabian Sea, the contribution of picophytoplankton to the total phytoplankton biomass is 32.7% (ref. 9), whereas in the Bay of Bengal it is 70–80% (R. Naik, pers. commun.). The lower contribution by picophytoplankton in the Arabian Sea in spite of its higher abundance in comparison to the Bay of Bengal is because of the dominance of the phytoplankton community by nano and microphytoplankton, which is not the case in the Bay of Bengal.

Recently, it has been shown that like diatoms, picophytoplankton can also be an important source of new organic carbon for large zooplankton and detritus production, although to a lesser extent and can contribute significantly to carbon export from the surface layer of the ocean, in spite of their small size[10]. Also, with the increase in global warming and stratification, it is envisaged that the phytoplankton dominance will tilt towards the smaller species[11], which will have a cascading negative effect on the productivity and size structure of the pelagic and benthic food web and reduce the amount of carbon export to the deep[12]. Such shifts in the dominant species or overall abundance may bring about spatial variation in fishery yields[13]. In view of these observations, inclusion of picophytoplankton in the ecological models will provide insights into the ecosystem functioning of coastal, estuarine and oceanic regions and food-web dynamics, a major portion of which is shouldered by these tiny organisms. And since some of the *Synechococcus* strains have been reported to be nitrogen-fixers, it would be interesting to know their contribution to the total nitrogen budget in the marine ecosystem. From the context of the marine ecosystems around India, work in this direction is of utmost importance so as to improve our understanding of the food web and biogeochemical processes in these regions.

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