PATCHINESS IN THE DISTRIBUTION OF PLANKTONIC FORAMINIFERA IN OCEANIC WATERS AND ITS PROBABLE CAUSE

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ABSTRACT

The distribution of planktonic foraminifera in present day oceanic waters have been found to be highly irregular in terms of their abundance, thereby leading to their localized patchiness. The term "patchiness" of any marine micro-organism is defined to indicate the phenomenon leading to their localized aggregation in oceanic waters both horizontally and vertically and the area of aggregation is the patch or concentrate. This phenomenon is found to be the result of complex interactions of various physical, chemical and biological factors of the oceanic waters, of which, temperature, salinity, nutrients and illumination are more important. The interactions of all these factors are found to have multiple direct and inverse correlations, which induce chains of reactions within them.

The utility of mapping a patch in present day oceans for fishing industry, control of pollution and disposal of radioactive wastes is briefly discussed. The importance of such studies in micropalaeontological research is also stressed.

INTRODUCTION

Planktonic foraminifera, typical marine protozoans, are widely distributed in present day oceanic waters throughout the world, however, their distribution have been found to be highly irregular and erratic in terms of their abundance. HAECKEL (1890) was first to observe this phenomenon and it was later recorded by almost all the workers in this field. HARDY (1936) first introduced the term 'patchiness' describing the uneven distribution of planktons. Despite of being observed in present day oceans by various workers, actual cause of the patchiness is not well understood. On the other hand, this limitation in the knowledge results in serious drawback in the understanding of the general laws of plankton distribution and environmental interpretations. In recent years, the value of planktonic foraminifera as environmental indicators for a marine basin has increased many fold. It is, therefore, increasingly important that the cause for such patchiness may be studied in greater detail.

This phenomenon has also come to the notice of number of micropalaeontologists while studying the fossil planktons in a geological formation and tracing their lateral continuity and variations. While in many areas, no appreciable change in lithofacies and qualitative biofacies are noticed, localized abundance of certain types to almost negligible or total absence in surrounding areas are apparent. This feature has usually been ascribed to certain ecological factors which are not fully understood. The author, while working on the marine Cretaceous-Pliocene sequence of south Indian sedimentary basin, has recorded this phenomenon to be very common, which could not always be explained in terms of palaeobathymetry of the depositional basin or by certain other known simple

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ecological parameters. The author has also noticed the strange phenomenon of patchiness in planktonic foraminifera in central and northern Pacific and in northern Atlantic Oceans. The emphasis is laid in this paper to review the occurrence and cause of such phenomenon in present day waters and to suggest modified methods of their mapping in open sea.

This paper is based of the study carried out at the Atlantic Oceanographic Laboratory, Dartmouth, Canada, on the planktonic foraminiferal samples collected from central and northern Pacific between the latitudes 10°S to 55°N (Tahiti to Vancouver, see Text-fig. 1, arrow indicates the limit of the area).

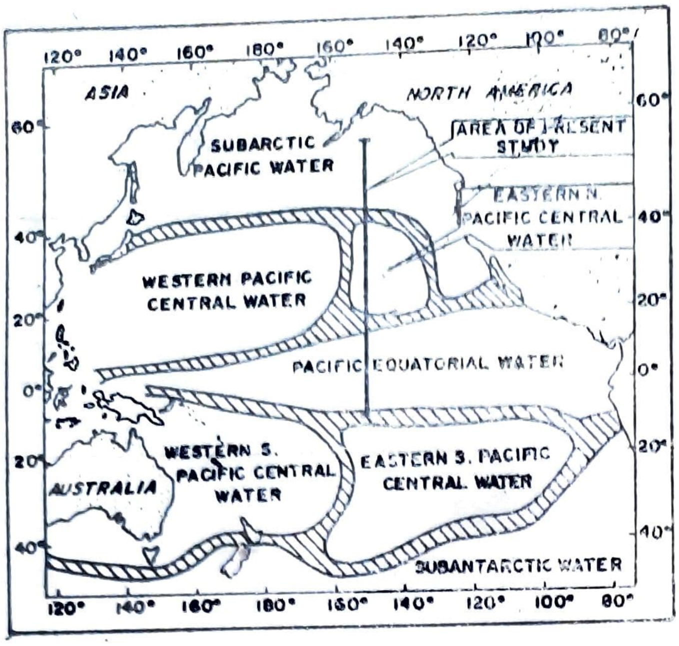
The Term Patchiness and its Usage

The phenomenon of patchiness has been observed in various marine organisms ranging from minute phytoplanktons to large whales. While planktonic foraminifera are largely used in biostratigraphic, ecologic and palaeoclimatic interpretations, little emphasis towards the applied aspects of this phenomenon has been given by various workers. The term 'patchiness' has been varyingly used by large number of workers while discussing the distribution of living planktonic foraminifera like those of Banerji *et al.* (1971), Bé (1959), Bé *et al.* (1967). (1967), Boltovskoy (1964), Boltovskoy *et al.* (1970), Bradshaw (1959), Cifelli (1962), Phleger (1960), Smith (1963) etc. As the usage of this term was restricted to different materials and persued different objectives, equal attention for its understanding was not given. Most of the workers do not give the actual count of the specimens, or their samples are collected too far apart, with the result biassed observational factors are introduced. Phleger (1960) was first to illustrate the uneven quantitative distribution of living planktonic foraminifera within a short distance. The number of foraminiferal specimens varied from 2 to 73 per cubic metres of filtered water at a distance of 25 nautical miles. Boltovskoy (1964) encountered from 0 to 1830 specimens at two stations 35 miles apart, however, the observation was not made out of quantitatively measured water samples. In Antarctic waters, Boltovskoy *et al.* (1970) observed the number of specimens varying from 0 to 165 in 12 cubic metres of water within 10 nautical miles. Banerji *et al.* (1971) recorded the variations from 1727 to 8205 in 1000 cubic metres of surface water in central Pacific between Lat. 10° S to 10° N. (Table 1; Text-fig. 1).

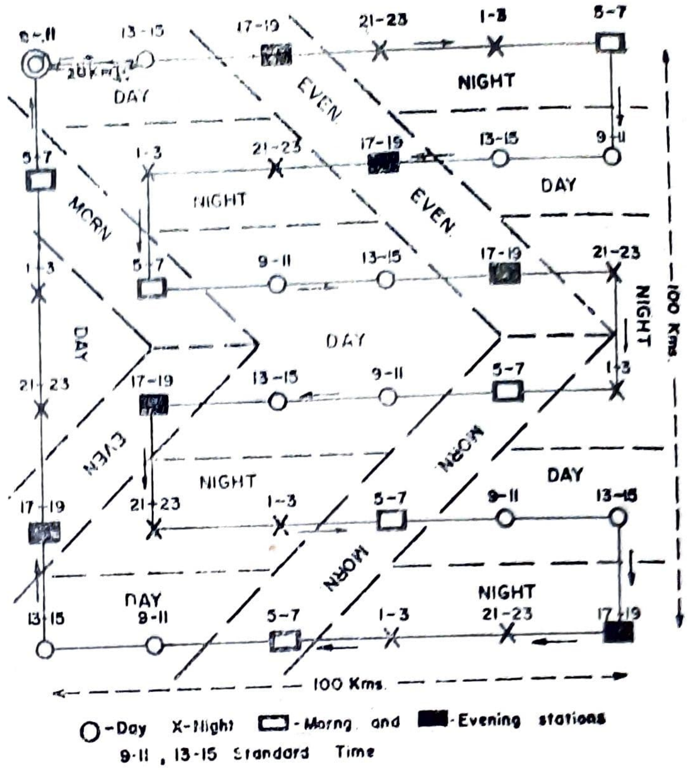
Table 1—Sampling depths and general faunal details in Pacific Ocean (During May-June, 1970, after Banerji *et al.* 1971).

Water Mass	Location (Lat. N-S)	Depth of Tows (in metres)	Volume of water (M3)	Absolute Abundance (in 1000 M3)	Species Diversity	Specimen to species Ratio
		0—190	194.20	8.205	50.00	547.00
	10° S ..	190—460	67.50	0623	30.00	69.22
		460—760	295.60	0231	30. 0	25.66
		0—200	261.80	7975	53.33	498.44
	05° S ..	200—435	878.30	0030	23.33	05.14
		765— 00	730.50	0057	20.00	09.50

	0°	..	0—800	2483.10	5847	46.66	417.64
	05° N	..	0—800	1638.50	3187	66.66	159.35
Southern Waters							
			0—190	409.60	1727	53.33	107.94
	10° N	..	190—460	595.40	1547	52.33	96.81
			460—750	532.00	0599	46.66	42.78
			0—170	565.80	2010	63.33	105.79
	15° N	..	170—450	426.50	0156	43.33	012.00
			450—780	553.20	0481	40.00	40.08
			0—180	384.20	2319	63.33	122.05
	22° N	..	180—440	426.50	0343	40.00	28.58
			440—1050	447.60	0060	26.66	07.50
			0—160	506.70	0273	36.66	24.81
	29° N	..	160—475	563.20	0263	40.00	21.91
			475—1030	532.10	0067	36.66	06.91
	36° N		0—320	777.00	0112	40.00	093.3
			3—900	1554.00	0244	30.00	01.39
Central Waters							
			0—185	443.40	1342	30.00	149.11
	43° N	..	185—850	2010.10	0746	36.66	67.81
			185—00	304.00	0810	30.00	90.00
	49° N	..	0—1050	3606.40	1538	20.00	256.33
			0—190	629.20	0906	20.00	151.00
Northern Waters	55° N	..	100—700	2326.80	0241	26.66	030.13
			100—00	312.50	1438	20.00	239.83



Text-fig. 1—Water masses of the Pacific Ocean and the area of present study.



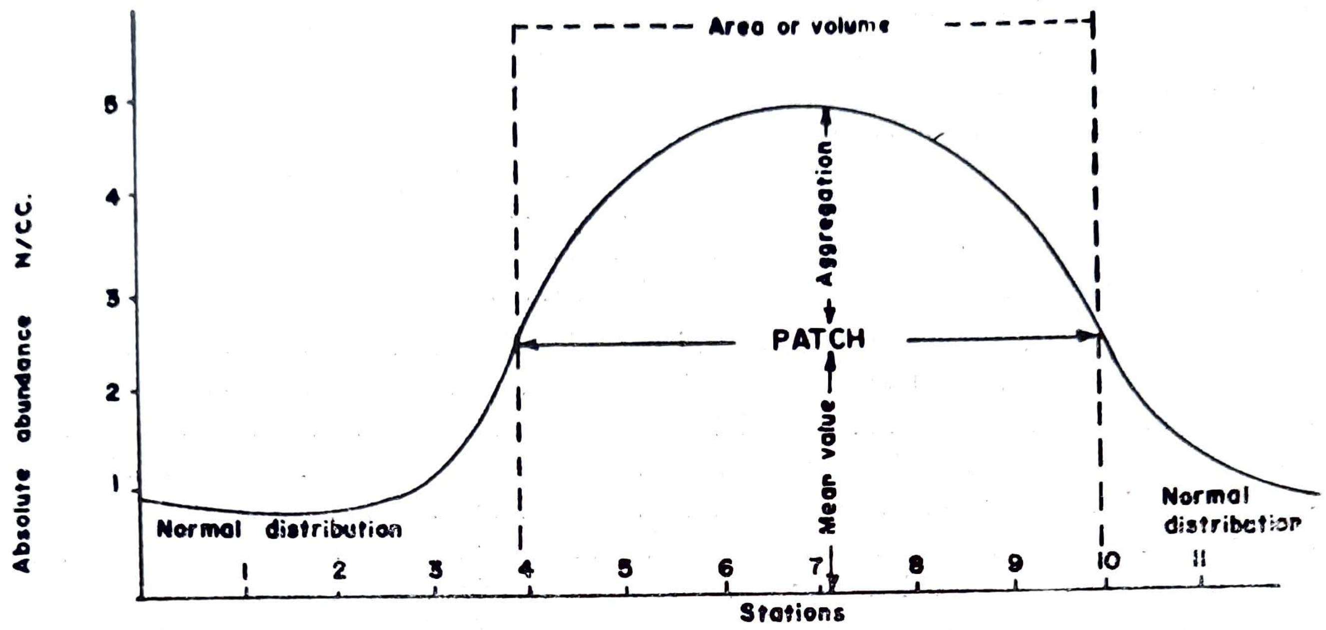
Text-fig. 3—Operation plan for sample collections in open sea.

Definition of the term 'Patchiness'

The term 'patchiness" of micro-organisms is defined to indicate the phenomenon leading to their localized aggregation in oceanic waters, both horizontally and vertically, and the area of aggregation is the 'patch' or 'concentrate' of those micro-organisms. The term patchiness has strict quantitative aspect and must be measured in terms of aggregation and total area of localization. Aggregation is described by the number of organisms per cubic metres of water and area by square kilometres if measured horizontally at a particular depth of water or by volume in cubic kilometres if measured in three dimensions. The patch is a mappable faunal or floral distribution unit in a water body, as defined by volume, area and time. As the patch may disappear and reappear later, the fourth dimensional factor-time, is very important. The mapping of a patch is useful in correlating various hydrological, biological and chemical factors of the oceanic waters; these may be superimposed directly upon the map. Such type of combination maps or charts may play useful role in certain fishing industry and in control of pollution of the oceans. The agglomeration of various types of micro-organisms in the geological past may give rise to excellent source for the generation of petroleum.

Determination of Patchiness

The quantitative estimation of patchiness in present day oceanic waters may be made by counting the number of specimens of micro-organisms in a given body of water and comparing it with adjacent water masses. The plotting of equipoints in the number of specimens in a surface or vertical profile will map the patch. The map must indicate the binomial name of the organism, specific period of mapping (in date, month and year), time of observation, *i.e.*, day or night and whether under bright light or cloudy conditions. The total number of specimens per cubic metre of water is genearlly described as absolute abundance which in case of planktonic foraminifera have been found to vary from less than one specimen up to 10^5 specimens. The patchiness can be recognised graphically by plotting the absolute abundance of the micro-organism in a sampling profile (Text-fig. 2).



Text-fig. 2—Linear plotting of a patch (hypothetical).

MATERIALS AND METHODS

During the course of the survey for patchiness, sampling methods and laboratory analysis and specimen counting procedures employed can also influence the range of fluctuations. Certain unavoidable factors may be introduced during sampling for example, the clogging of the sample net restricts the rate of filtration thus causing two counter affecting errors by lowering the estimate of the absolute abundance and by decreasing the effective mesh size thus resulting in the total catch of the specimens. The distributional patterns of the organisms obtained from such samples are usually very complicated and not readily amenable to interpretation and greatly modify the profile of the patch (BANERJI *et al.*, 1971). We shall now discuss the essential requirements of sampling and other analytical techniques to avoid such complications.

1. SAMPLING TECHNIQUES—One of the foremost requirements for such studies would be the adoptation of uniform sampling method. The sample station should be located as close as possible. The stations may be allocated in a chess board pattern and care should be taken that the sampling from all these stations must be completed within a short period, preferably within one season, whereby no appreciable differences in climatic factors could account for variations in faunal distribution. For obtaining such results, more than one ship may be put into operations and simultaneous sampling may be done in case where the expected patch is very large and the climatic fluctuations are frequent. However, it is extremely difficult for even best equipped institutions to get such advantage. It is, therefore, suggested that the entire area may be subdivided into smaller rectangular areas. In a 15 days operation, it is possible to map in a regional way two large rectangular to square areas of nearly 10,000 square kilometres each and the stations are placed at a distance of 20 kilometres (Text-fig. 3). The plan for sampling is given below.

Sampling Plan

Total area for mapping	.. ..	$100 \times 100 = 10{,}000$ sq. kms.
Total number of stations	.. ..	36
Average speed of the ship	.. ..	10 kms/hr.
Period of sampling and data collection at each station	.. .. ..	2 hrs. (average)
Total distance covered	.. ..	720 kms.
Total period of sampling and movement of the ship	.. .. ..	$(36 \times 2) \times (720/10) = 144$ hrs. *i.e.* Six days.
Delay due to unforeseen reasons	..	One day.
Total sampling period	.. ..	Seven days.

This generalised sampling plan for a week will give a fairly accurate idea of the patchiness for an area of 10,000 sq. kms. The ship may track the stations as per its own available navigation system and path. Most of the planktonic patches are fairly smaller than this area. This plan (Text-fig. 3) also takes into account the diurnal variations in distribution and four sub-areas viz. morning and evening, day and night collections are distinguished. Frequent alternations of cloudy and bright periods should be avoided. Sampling must be suspended during heavy showers, hurricanes and tsunamis.

2. Sampling Gear—The filtration of water through the plankton net should be quantitatively measured using pre-tested flow meters attached both outside and inside the opening frame. The net must be thoroughly cleaned immediately after each use so as to avoid contamination and clogging due to fine particles and sea-weeds. It is advisable to use a mesh of 63 micron size opening which is equally good for zoo- and phyto-planktons. In case the mapping is done for the surface layers, the sampling upto 200 metres of water depth is recommended. While vertical mapping, three successive hauls at depths ranging from 0—200 mts., 200—500 mts. and 500—1000 mts. may be made. In such cases, it is better to have simultaneous sampling to avoid the disturbances in the eco-system of the water mass due to repeated mechanical interference by the sampling gear. For this purpose, the modified multiple plankton sampler designed by Banerji *et al.* (1971) has been found extremely useful.

3. Laboratory Procedures—In the laboratory, it is advisable to avoid the splitting of the samples for the reduction in total amount of the biomass, as this process in itself introduces some biass due to personal handling. However, depending upon the collections, the splitting may be necessary up to a number of fractions. Following procedure for splitting is recommended. Three general cases are discussed.

I. Sample size small—No splitting is necessary. Such samples yield foraminifera to cover a layer on the examination tray to facilitate quick counting.

II. Sample medium sized—Three splitting may be necessary. Fractions marked with parentheses are to be studied.

SPLIT-I $\qquad$ *SPLIT II* $\qquad$ *SPLIT-III*

$$N \rightarrow \left[\frac{N}{2}\right] + \frac{N}{2} \qquad \frac{N}{2} \rightarrow \left(\frac{N}{4}\right) + \frac{N}{4} \qquad \frac{N}{4} \rightarrow \left(\frac{N}{8}\right) + \left(\frac{N}{8}\right)$$

The half of the first split $\left[\frac{N}{2}\right]$ may be stored for future reference use.

III. Sample exceptionally large—Splitting up to 7, 9, or 11 times may be necessary.

In IInd case, simple arithmetic mean of three values $\left(\frac{N}{4}, \frac{N}{8}, \frac{N}{8}\right)$ and in case of IIIrd, the median value is calculated.

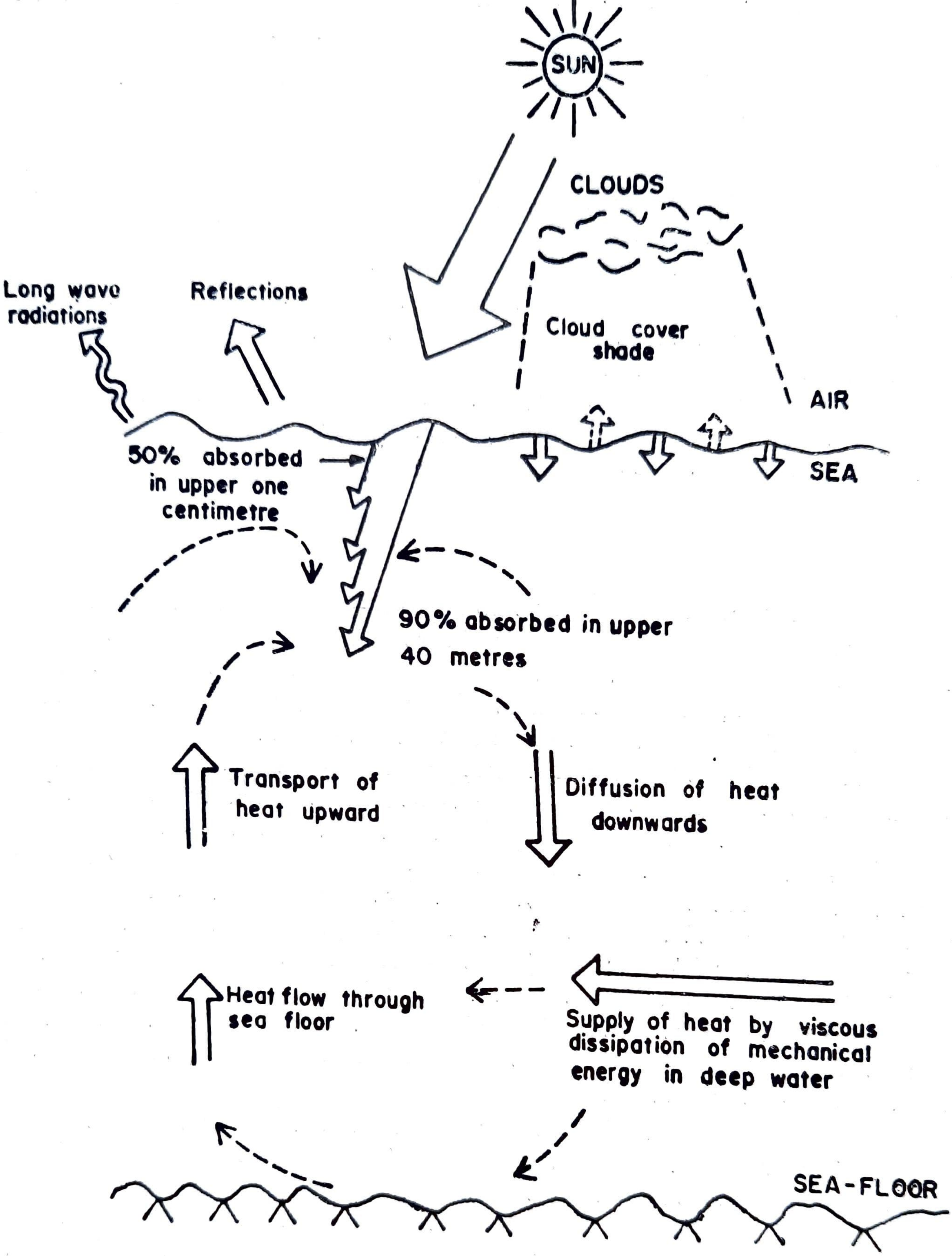
The split samples are then ignited in low temperature and low pressure asher to remove their organic constituents (BANERJI *et al.*, 1971; VILKS, 1970). The ignited samples after washing are examined under binocular microscope for counting the calcareous foraminifera according to their various taxonomic entity.

4. *Counting of living/dead specimens*—In such studies, the ratio of living and dead specimens is not a very significant factor, as it has been found that the percentage of dead specimens in material collected in uppermost layer is always very low, ranging from 0.1 to 3.8% (BOLTOVSKOY, 1969). It is suggested that 1% of the total abundance for every 100 metres water depth may be computed as dead specimens and the amount will be deducted from the absolute abundance.

CAUSES OF PATCHINESS

1. PHYTOPLANKTONS AND THEIR RELATED FACTORS—It is known that the distribution of micro-organisms is the result of complex interactions of various physical, chemical and biological factors of the oceanic waters of which temperature, salinity and nutrients are the most important. Phytoplanktons are the possible source of food for planktonic foraminifera, therefore the concentration of foraminifera depends upon the concentration of phytoplanktons. The latter in turn depends up on two main factors—illumination or solar radiations and nutrient salts like phosphates and nitrates and also dissolved oxygen. The intensity of light depends primarily upon latitude, season and cloud cover. Its penetration in sea water is also dependent upon certain other factors such as scattering by suspended particles and absorption by dissolved organic compounds and phytoplankton pigments. 50% of the radiation is absorbed in upper centimetre layer and 90% within first 40 metres of water (Text-fig. 4). This raises the temperatures of the upper layer of water. The limit of photosynthesis has been determined to be 120 metres in clear tropical waters, 40 metres in shelf waters and 15 metres in turbid waters of temperate latitudes and these incidently are also the limits of the development of patchiness of planktonic foraminifera under various water conditions.

The relationship between phosphate concentration and phytoplankton distribution is obscure. These are found to correlate inversely. This may be due to the fact that rich phytoplanktons have already consumed most of the phosphates, but for their further growth, continuous supply of phosphates would be required, failing which may result either their extinction or collective migration to new source of phosphates. This kind of accumulation gives rise to patchiness, however, depending upon other favourable factors as mentioned above. Similarly a negative correlation between phytoplanktons and zooplanktons can also exist. This is a grazing factor of the zoo-planktons. On the other hand, a positive correlation of abundance of phosphates with a rich planktonic fauna is well established in almost all the oceans. The concentration of phosphates and nitrates in sea water are taken as an index of productivity potential. This factor is greatly modified by the surface water circulation and by upwelling of water (as discussed later) and have a direct correlation with depth of water and inverse correlation with temperature and



Text-fig. 4—Solar and thermal radiations in oceans.

oxygen contents of the sea water (BANERJI *et al.*, 1971). The relationships may be enumerated to as follows:

Nutrients	$\propto$ depth . latitude
Depth of water	$\propto$ illumination^{-1} . temperature^{-1} . oxygen^{-1}
Phytoplankton production	$\propto$ nutrients . illumination . oxygen . depth^{-1}
Zoo-plankton distribution	$\propto$ nutrients . phytoplanktons . phytoplanktons^{-1}

Production of Zoo-plankton $\propto$ (nutrients.depth.latitude.illumination^{-1} . temperature^{-1} . oxygen^{-1}) $\times$ (nutrients.illumination.oxygen.depth^{-1})$^{-1}$

These complex inter-relationships like multiples of direct and inverse correlations between these few determinable factors induce chain of interactions within them. A critical phase of these interactions will determine either the complete elimination or concentration of zoo-planktons within a specified area. The variations in temperature, salinity and phosphate concentration values with respect to depth of water in central and northern Pacific are plotted along with the relationships of foraminiferal distribution with latitude in Text-fig. 5.

2. TRACE ELEMENTS—Almost all the naturally occurring elements and few man made ones are present in sea water, however, majority of them in minute quantities. These elements are found to be biologically or geochemically significant as they may have catalytic or destructive properties. Several processes can change the concentration of these elements either by precipitation, complex chemical reaction or by biological uptake. Many marine organisms can concentrate trace elements in their bodies or in their specific organs This uptake may be expressed as a concentration factor (BRAHTZ, 1971).

$$\text{C.F.} = \frac{\text{Concentration of trace elements in organisms}}{\text{Concentration of trace elements in sea water}}$$

For trace elements, concentration factor (C. F.) may be very large, conversely C. F. for major constituents to be very small. The higher C. F. demands for continuous supply of trace elements either by new introduction to the sea or by currents and upwelling of water. Minute variations-in concentration of these elements in sea water will be exhibited multifold by the organic activity leading to patchiness.

There is a dangerous aspect of this ability of the organisms to concentrate the trace elements having affected with radioactive radiations. This ability is more pronounced in case of planktonic micro-zoo-organisms. Nuclear explosion and deposition of radioactive nuclides will result in much larger concentration of radiations in bodies of these organisms and thereby may give rise to a highly radioactive patch which may ultimately destroy the normal ecosystem. Delineation of nuclear pollution is one of the most important aspects of the study of patchiness during the present nuclear age.

3. EFFECTS OF DENSITY STRATIFICATION:—The seasonal variations in warming and cooling the surface layers of water result in a density stratification. This presents an impediment to vertical mixing and later stratification of salinity, pH. and nutrients. In many parts of the world oceans like Sargasso Sea in Central Atlantic and other central oceanic gyres are permanently stratified and renewal of upper layers by deep mixing can not take place. Such conditions favour the development of horizontal patchiness. In regions of upwelling generally along the west coasts of the continents the winds remove surface waters, usually to the west, which are replaced by somewhat deeper nutrient rich waters very close to the western margin of the continents. The zone of upwelling may restrict rich growth of planktons and consequently to a linear patchiness. The density stratification further restricts them to lateral extensions rather than to vertical expansion. This is very well exemplified from the observations made in northern Pacific waters.

4. MIXING OF DIFFERENT OCEANIC WATERS—The ocean is driven by both thermal and mechanical energy fluxes. The earth's rotation has another additional factor control-

ling oceanic flows. Apart from these, the sea waves and currents drive their kinetic energy mostly from the winds of the atmosphere. The appreciable parts of the tidal energy resulting from the rotational energy of earth-moon-sun system are diverted into internal wave motions in the deep sea. The resultant of these complex energy systems is converted into vastly irregular water circulations over wide areas and also result in close regimes of water bodies having distinct physico-chemical characters. These are called oceanic water masses (Text-fig. 1). These individual water mass may lead to the development of patchiness in micro-organic distribution. The mixing of more than one type of water mass at their junctions result in change of the ecosystem in two ways, either by increasing or decreasing the favourable conditions of microfaunal development. For example, a cold water mass having high nutrient value mixing with another warm water having high oxygen content shall restrict the growth of the organisms at the fringes of the two water masses where the resulting conditions are optimum and highly favourable for fast growth. The salinity of oceanic water varies from 33 to 38 %. may give rise to variations in density, refractive index, pH., osmotic pressure, viscosity of water during the mixing of water masses having varying salinity. All these factors ultimately control the faunal distribution and agglomeration.

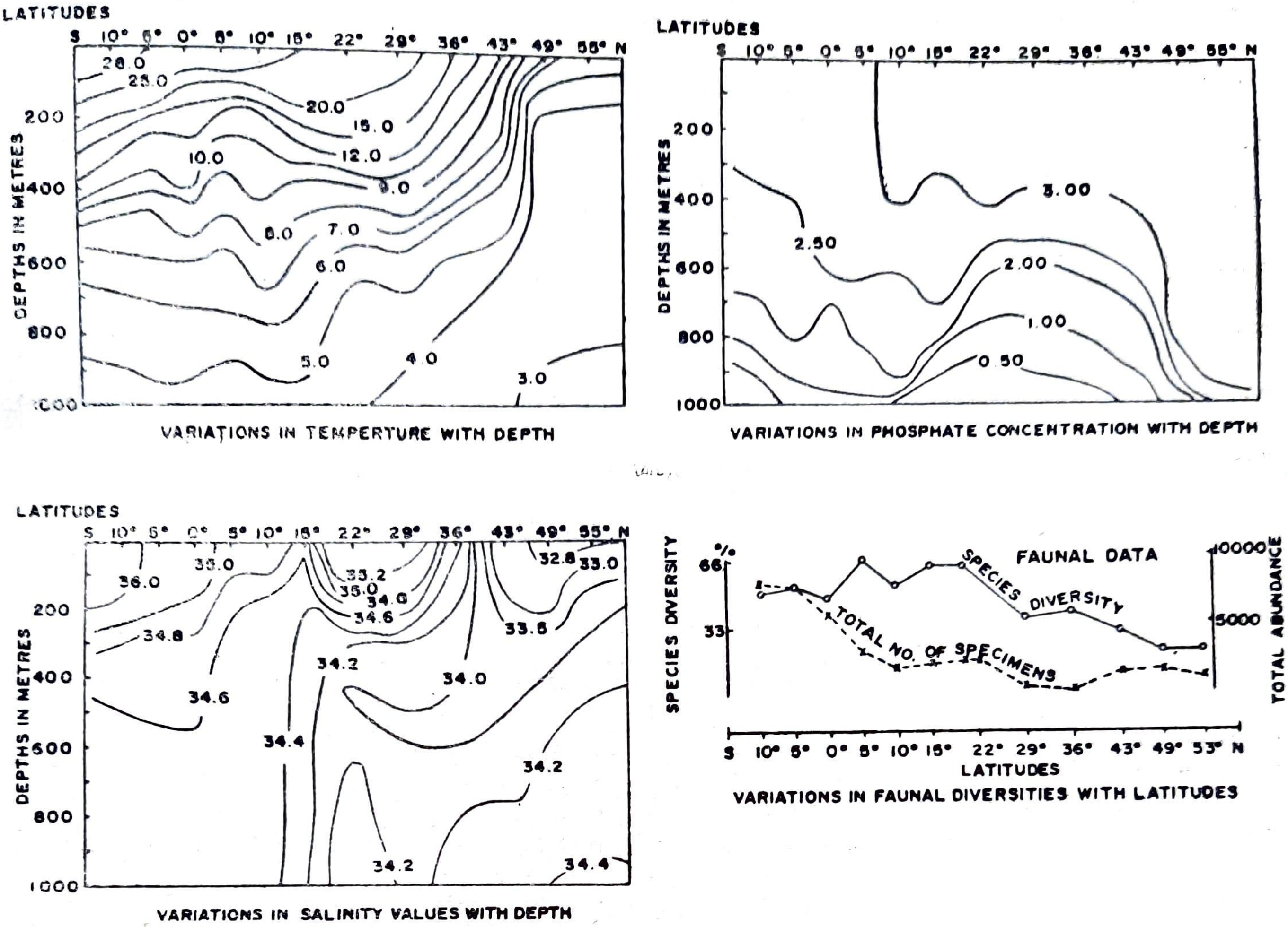
5. LATITUDINAL VARIATIONS—The latitudinal variations in composition of planktonic foraminifera may also result in patchiness. It has been observed that species diversity decreases towards higher latitudes (Text-fig. 5), therefore, higher concentration of variety of forms are expected near the equator. Two kinds of patches have generally been observed, one having large number of variety of forms and another comprising homogeneous taxonomic unit. The occurrence of these two types of patches are perhaps resultant of linear diversity values with respect to latitudinal variations. It is on the other hand well known that the role played by the latitude is itself resultant of variations due to solar radiations and temperature.

6. EFFECTS OF INDUSTRIAL POLLUTION—With the increase in industrialisation and urbanisation of coastal areas around the world, the danger of sea being polluted by industrial wastes is being greatly felt. The constant introduction of these wastes brings catastrophic change in the ecosystem and the resultant may be the complete elimination of certain marine organisms or their further agglomeration in specific areas to form patches, depending upon whether the pollutants are harmful or act as an extra food source. The details on various aspects of pollution are discussed elsewhere (BANERJI, 1973).

CONCLUSION

The patchiness of the planktonic organisms have been observed in all the major oceanic waters and is mainly due to the complex interactions of a number of physical, chemical and biological factors and also due to large number of poorly understood and hithertoo unknown factors. The more significant factors appear to be oceanic currents, temperature, salinity, illumination, nutrient supply and introduction of industrial wastes into the marine ecosystem. It is difficult to assess their individual or overall mechanism of influence. The resultant picture is very complicated in different areas and situations and the predominating factors also differ widely. A slight variation in any of the factors enumerated may bring the patchiness without resulting appreciable change in the total environmental regime.

The laws of patchiness of micro-organisms govern the distribution system of such organisms under wide physico-chemical conditions. These rules may be suitably applied.



Text-fig. 5—Variations in temperature, salinity and phosphate concentrations with depth of water and the variation in faunal diversities with latitudes.

not only in deciphering the environment of the water mass but also in better understanding of the general laws of marine sciences and fisheries and may be utilised for the control of pollution of sea water and for the disposal of radioactive wastes.

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