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MARINE SNOW

R. S. Lampitt, University of Southampton
Southampton, UK

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Introduction

Marine snow is loosely defined as inanimate particles with a diameter greater than 0.5 mm. These particles sink at high rates and are thought to be the principal vehicles by which material sinks in the oceans. In addition to this high sinking rate they have characteristic properties in terms of the microenvironments within them, their chemical composition, the rates of bacterial activity and the fauna associated with them. These properties make such particles important elements in influencing the structure of marine food webs and biogeochemical cycles throughout the world's oceans.

Such an apparently simple definition, however, belies the varied and complex processes which exist in order to produce and destroy these particles (**Figure 1**). Similarly it gives no clue as to the wide variety of particulate material which, when aggregated together, falls into this category and to the significance of the material in the biogeochemistry of the oceans.

Marine snow particles are found throughout the world's oceans from the surface to the great depths although with a wide range in concentration reaching the highest levels in the sunlit euphotic zone where production is fastest. The principal features which render this particular class of material so important are:

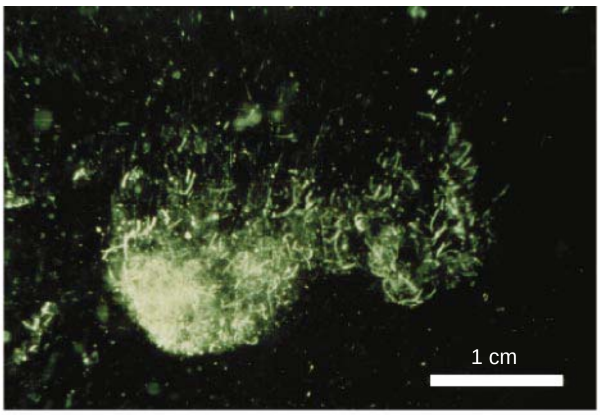
1. high sinking rates such that they are probably the principal vehicles by which material is transported to depth;
2. a microenvironment which differs markedly from the surrounding water such that they provide a specialized niche for a wide variety of faunal groups and a chemical environment which is different from the surrounding water;
3. Elevated biogeochemical rates within the particles over that in the surrounding water;
4. Provision of a food source for organisms swimming freely outside the snow particles.

Historical Developments

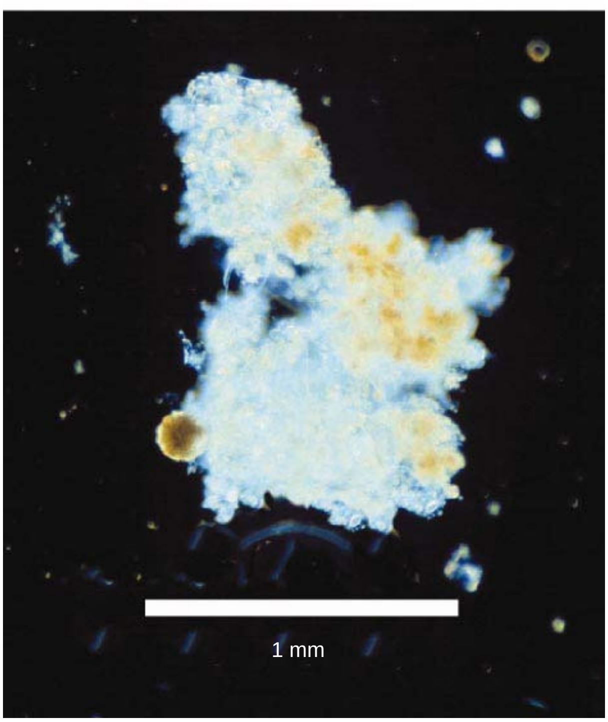
The debate about how material is transported to the deep seafloor has been going on for over a century but at the beginning of the last century some surprisingly modern calculations by Hans Lohmann came to the conclusion that large particles must be capable of transporting material from the sunlit surface zone to the abyssal depths. This was based on his observations that near bottom water above the abyssal seabed sometimes contained a surprising range of thin-shelled phytoplankton species, some still in chains and with their fine spines well preserved. He thought that the fecal pellets from some larger members of the plankton (doliolids, salps, and pteropods) were the likely vehicles and in many cases he was entirely correct. The process of aggregation is now thought to involve a variety of different mechanisms of which fecal production is only one (*see* **Particle Aggregation Dynamics**).

In 1951 Rachael Carson described the sediments of the oceans as the material from the most stupendous snowfall on earth and this prompted a group of Japanese oceanographers to describe as 'marine snow' the large particles they could see from the submersible observation chamber *Kuroshio* (**Figure 2**). This submersible was a cumbersome device and did n ot permit anything but the simplest of observations to be made. The scientists did, however, manage to collect some of the material and reported that its main components were the remains of diatoms, although with terrestrial material appearing to provide nuclei for formation.

In spite of these observations and the outstanding questions surrounding material cycles in the oceans, it was, until the late 1970s, a widely held belief that the deep-sea environment received material as a fine 'rain' of small particles. These, it was assumed, would take many months or even years to reach their ultimate destination on the seafloor. The separation of a few kilometers between the top and bottom of the ocean was thought sufficient to decouple the two ecosystems in a substantial way such that any seasonal variation in particle production at the surface would be lost by the time the settling particles reached the seabed. This now seems to have been a fundamental misconception. Part of the reason for this has been lack of understanding of the role of marine snow aggregates.



(A)

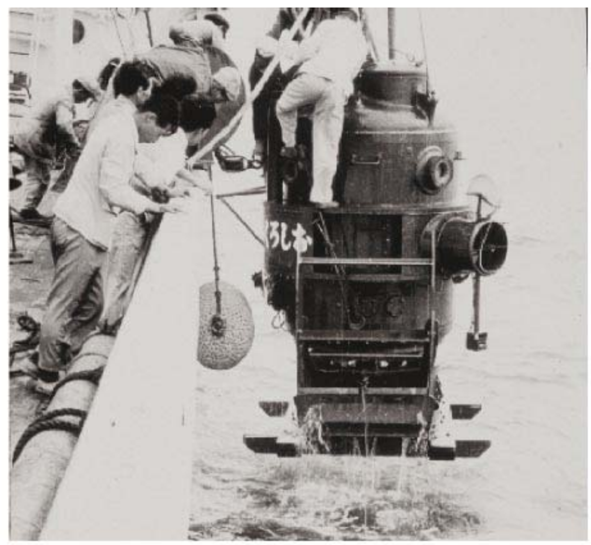


(B)

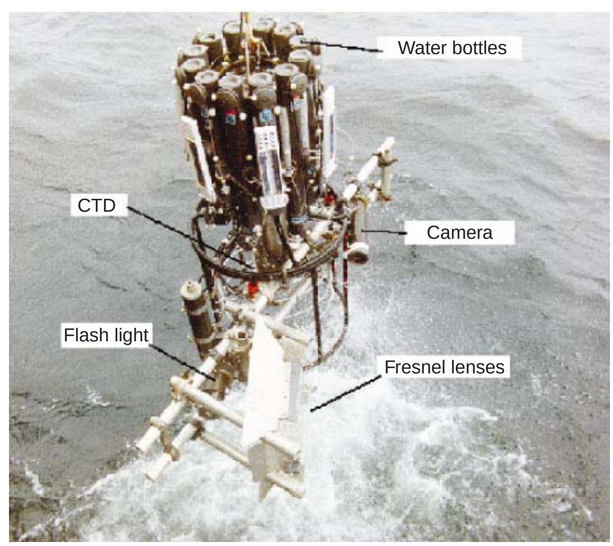
Figure 1 Examples of marine snow particles. (A) Aggregate comprising living chain-forming diatoms. Scale bar = 1 cm. (B) Aggregate containing a variety of types of material including phytoplankton cells rich in plant pigment (brown colored).

Methods of Examination

As stated above, the first use of the term was from submersible observations and *in situ* visual observa-



(A)



(B)

Figure 2 Devices for observing snow particles. (A) The submersible *Kuroshio* as used in the 1950s. (B) A photographic system incorporating a variety of other sensors and water bottles.

tion still serves a valuable role (**Figure 2**). This may be from manned submersibles or the rapidly evolving class of remotely operated vehicles (*see* **Remotely Operated Vehicles (ROVs)**) or by subaqua divers. Photographic techniques have developed fast over the past decade and the standard photography systems which provided much of the currently available data on distribution are being replaced by high definition video systems linked to fast computers which can categorize particles in near real time. Holographic techniques are also being developed for *in situ* use and these provide very high resolution images along with the three-dimension coordinates of the particles and organisms surrounding them.

An important goal in any of these studies is to be able to obtain undamaged samples of marine snow particles so that they can be examined under the microscope, chemically analysed, and used for experimentation. Some types of marine snow are, however, very fragile and the devices which are used to collect water often destroy their structure unless special precautions are taken in the design such that the water intake is very large and turbulence around it is reduced (**Figure 3A**). *In situ* pumping systems (**Figure 3B**) have been used for several years to collect material but in this case separation of the large marine snow particles which have distinctive characteristics of sinking rate, chemistry and biology from the far more abundant smaller particles is very difficult and may lead to erroneous conclusions as a result of this forced aggregation of different types of particle.

Sediment traps are the principal means by which direct measurement can be made of the downward flux of material in the oceans (*see* **Trapped Particulate Flux; Temporal Variability of Particle Flux**) and it may, therefore, be supposed that this provides a means to collect undisturbed marine snow particles (**Figure 3C**). Although the material collected in sediment traps may be considered as that which is sinking fast and is certainly the material which mediates downward flux, the characteristics of individual marine snow particles or even particles with features in common can not be determined as the boundaries between particles are not retained in the sediment trap sample jars. Furthermore the preservatives and poisons which are usually employed in such devices (formaldehyde, mercuric chloride, etc.) prevent experimentation on the recovered material and some types of chemical analysis.

Laboratory production of marine snow particles was first achieved in the 1970s (**Figure 4**) enabling researchers to produce a plentiful supply of material under controlled and hence repeatable laboratory conditions. This is done by enclosing water samples which have high concentrations of phytoplankton in rotating water bottles for upwards of several hours. After a while the sheer forces encourage aggregation of the solid material. Much progress has been made with these particles and insights have been gained into the ways in which they are formed and the factors which cause their destruction.

We should now ask the most basic of questions about this important class of material: what is marine snow? how is it distributed in time and space? and why is it of such significance?

Characteristics of Marine Snow

Microscopic Composition

The microscopic composition of marine snow particles reflects to a major degree the processes responsible for their creation, and at any one location, the composition varies rather little; in some places it is dominated by diatoms or dinoflagelates and in other places by the mucus webs from larvaceans. Various staining techniques have been used to reveal the presence of transparent exopolymer particles in snow particles dominated by some groups of phytoplankton and these are thought to be crucial components for the creation of some snow particles. Bacteria are invariably present in large numbers in snow particles.

Sinking Rate, Density and Porosity

As illustrated in **Figure 5**, sinking rates increase with particle size and this extends throughout the range of particle sizes considered to be marine snow. The rates measured are consistent with other observations on the time delay between phytoplankton blooms at the surface of the ocean and the arrival of fresh material on the abyssal seafloor (*see* **Floc Layers**). Although the dry weight of individual particles increases with increasing size, the density decreases and porosity increases (**Figure 5**). The relationships between size and these physical characteristics is invariably a poor one with much scatter in the data points, a factor which introduces considerable uncertainty in trying to deduce important rates such as downward particulate flux from the size distribution of particles. This variability is due in large part to the variety of sources of material which comprise the final aggregated snow particle, but also to the different processes which contribute to the aggregation mechanism. The processes occurring within the snow particles, such as microbial degradation and photosynthesis, will also have an effect on the physical properties.

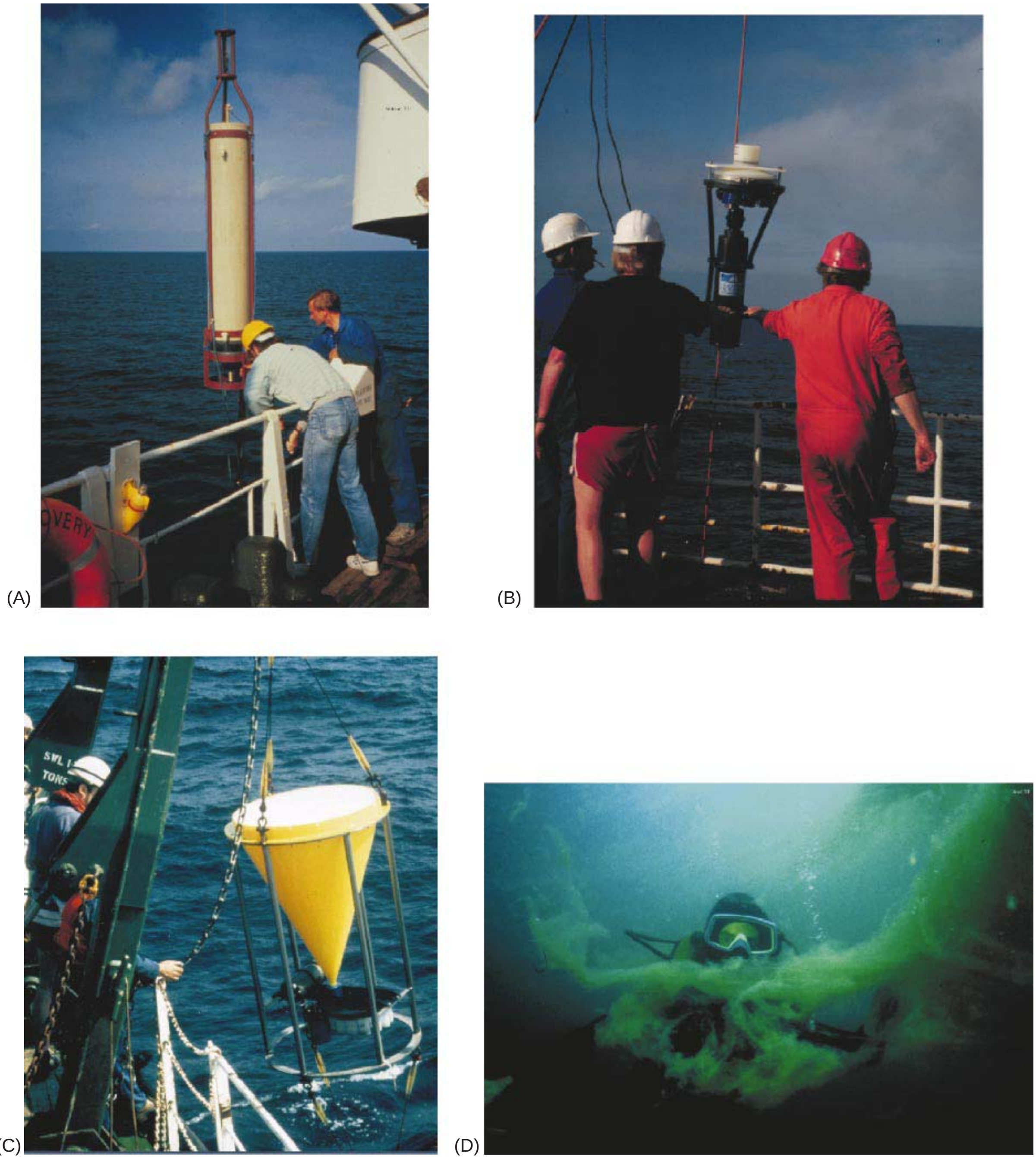


Figure 3 Methods of collecting marine snow particles. (A) A 100 l water bottle 'The Snatcher'; (B) a large volume filtration system; (C) a sediment trap; (D) a subaqua diver.

Chemical Composition

From the perspective of the biogeochemical processes occurring in the ocean, a knowledge of the chemical composition of snow particles and its variation with region, depth, and time are essential. The basic elemental composition in terms of carbon and nitrogen shows an increase, as expected, with particle size, but the proportion of the dry weight which is carbon or nitrogen tends to show a slight decrease reflecting the incorporation of lithogenic material with time as the aggregate becomes larger (**Figure 5**). In general, the composition of snow particles is not very different from that of the smaller particles found in the same body of water and from which the snow particles have been formed and to which they contribute when they are fragmented. This reflects the frequent and rapid

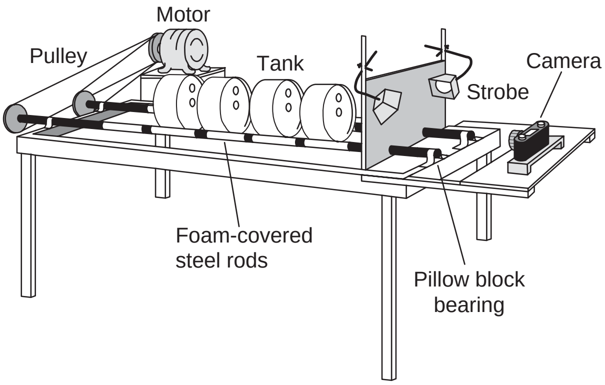


Figure 4 Device for producing marine snow particles in the laboratory.

transformations between the different size classes in the sea.

Biological Processes Within the Marine Snow Particles

Biological processes all occur at higher rates within marine snow particles than in comparable volumes of water outwith the snow. Furthermore, in the case of microbial activity, the rates of growth are often substantially higher than for comparable weights of smaller particles. Flagellate and ciliate populations also tend to be enhanced, presumably taking advantage of the elevated levels of bacterial activity. The effect of this is for snow particles to be sites where nutrient regeneration is enhanced. This does not, however, imply that formation of marine snow encourages nutrient regeneration at shallower depths. However, the high sinking rates of the marine snow particles tend to increase the depth of remineralization and the balance between these two processes can not be described with confidence at the present time.

Microenvironments

Diffusion of solutes within any particulate entity will depend on the physical composition of the particle to a large extent and the effect of such diffusion will depend on the distances involved. With increasing size of particle, the chances of generating distinctive microenvironments within the particle increase. There are several examples in the literature where anoxic conditions have been found within snow particles as a result of enhanced oxygen consumption within the body of the particle and diffusion rates being insufficiently high to restore the concentrations outside the particle. These experiments have been done using laboratory-made snow particles or naturally collected specimens, but in both cases exclusion of metazoans which may fragment snow particles introduces some doubts about the frequency of anoxia in the natural environment. If proved to be common in 'the wild', the effect is to create microenvironments within the particle which will have a profound effect on the chemical and biological processes which take place within it.

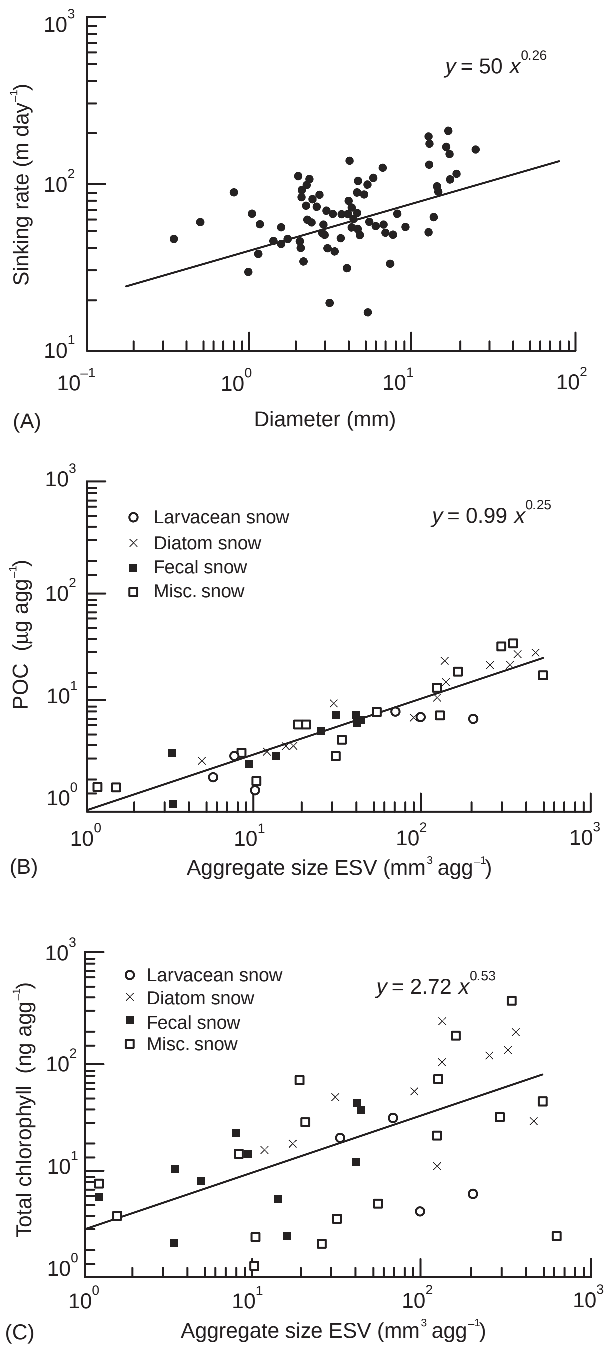


Figure 5 Relationships between marine snow particle size and (A) sinking rate, (B) organic carbon content and (C) chlorophyll content.

Adsorption and Scavenging

During descent through the water column, sinking particles accumulate smaller particles in their path and this scavenging is probably an important means by which small particles with very low sinking rates are transported to depth. Layers of fine particles commonly referred to as nepheloid layers (*see* **Nepheloid Layers**) may be reduced in intensity by the descent through them of sticky marine snow particles. Similarly, as with any solid surface, dissolved chemicals may be adsorbed onto marine snow particles and hence be drawn down in the water column at a much faster rate than would be possible by diffusion or downwelling.

Food Source for Grazers, Enrichment Factors

Not only do marine snow particles provide an attractive habitat in which smaller fauna and flora can live, but they are also a food source for a variety of planktonic organisms and fish. The species most commonly found associated with snow particles tend to be copepods, particularly cyclopoids, but there are also examples of heterotrophic dinoflagellates, polychaete larvae, euphausiids, and amphipods. In the case of the last of these groups one species, *Themisto compressa*, which was previously thought to be an obligate carnivore, was found to feed voraciously on marine snow particles. Recent experimental work has demonstrated the tracking behavior of zooplankton whereby they follow the odor trail left in the water by a sinking snow particle. Such sophisticated behavior suggests that snow particles are important food sources for some species of zooplankton. Enhancement of the concentration of bacteria or zooplankton associated with snow particles can be expressed as an 'enrichment factor' and, as shown in **Figure 6**, this factor appears to decrease with increasing size but at a different rate for the different faunal groups. The effect of this is that with increasing size, the metazoan zooplankton appear to become more important.

Distribution in Time and Space

Marine snow particles are found throughout the world's oceans in all parts of the water column. They are not uniformly distributed either in space or time but are usually found in higher concentrations in the upper water column and in the more productive regions of the oceans. Although it had been suspected since the early observations that their concentration decreases with increasing depth, this has been confirmed only recently. The profiles now becoming available do not however suggest a simple

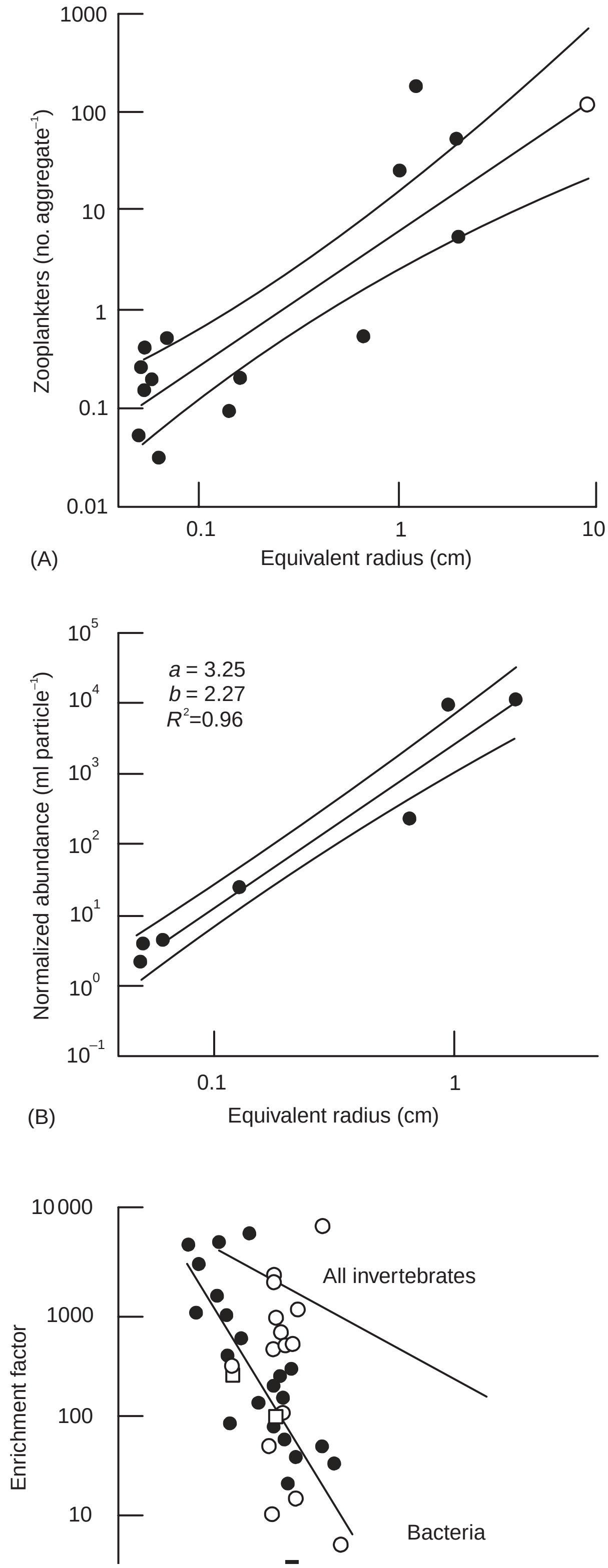


Figure 6 (A) Abundance of zooplankters associated with marine snow particles. (B) Abundance of all invertebrates after normalization to the size of the individual particles. (C) Enrichment factors for bacteria (●), ciliates (○), heterotrophic flagellates (□), and all invertebrates.

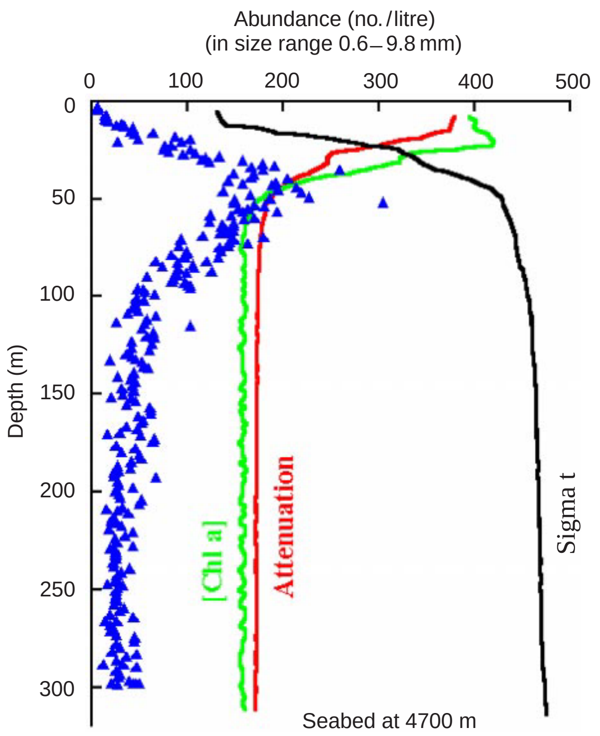


Figure 7 Vertical profile of marine snow concentrations (▲) in the north-east Atlantic (48°N 17°W).

decrease. There is considerable structure, undoubtedly related to the processes of production, destruction, and sinking, which are related to the physics, biology, and chemistry of the water column and of the particles themselves. **Figure** 7 shows an example of a profile from the north-east Atlantic. Bearing in mind the strong seasonal variation which can occur even well below the upper mixed layer and the different techniques employed by different researchers to obtain profiles, a common story seems to be emerging. Apart from profiles near to the continental slope where snow concentrations tend to increase near the seabed due to resuspension, there is generally a rapid fall in concentration over the top 100 m. Peak concentrations are not, however, found throughout the upper mixed layer but are located at its base, a feature which is directly related to the rates of production and loss of the marine snow particles in this highly dynamic part of the water column. Sinking rates may well decrease significantly in this part of the water column as the particles sink into water of higher density.

As might be expected for material which is so intimately related to the biological cycles of the oceans, a strong seasonal cycle in marine snow concentration is usually found even at depths below the euphotic zone. **Figure** 8 shows the concentration of marine snow at 270 m depth in the open ocean of the north-east Atlantic. It can be seen that the period of highest biological productivity in the spring elicits strong peaks in the marine snow

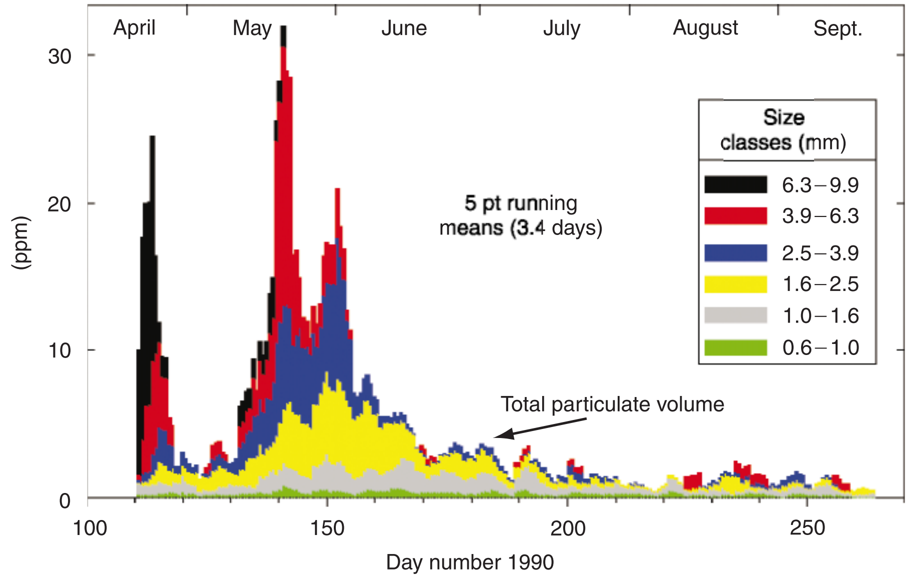


Figure 8 Seasonal change in the concentration of marine snow particles at 270 m depth in the north-east Atlantic (48°N 20°W). This is expressed as a volume concentration to emphasize the importance of the largest size category which are rare but contribute significantly.

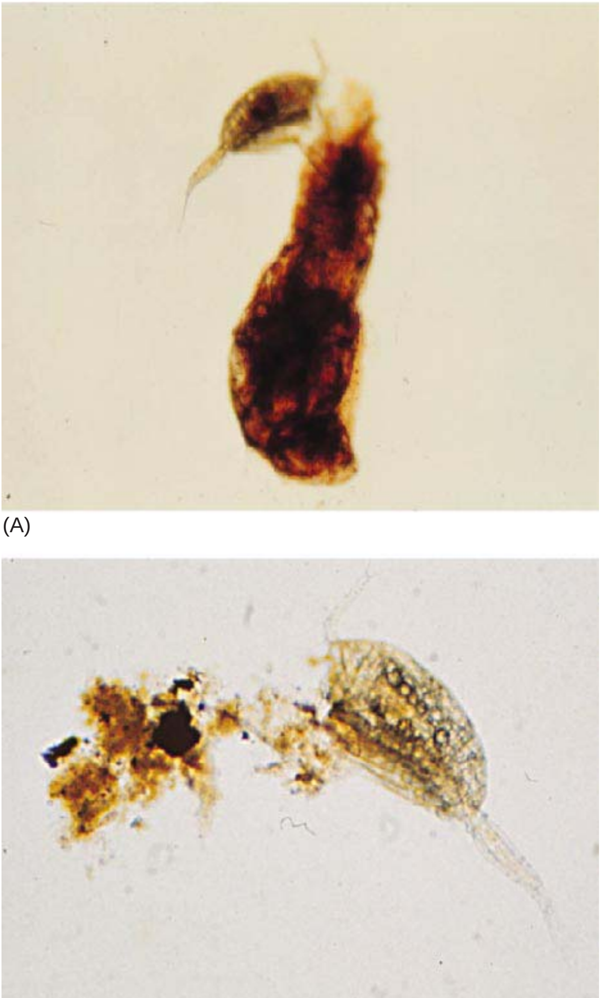
concentration particularly in the largest size categories. There are several examples of diel changes in marine snow concentration within the upper few hundred meters and this is probably related to the activity of the zooplankton.

Production and Destruction

Production of marine snow particles is, almost by definition, by a process of aggregation (*see* **Particle Aggregation Dynamics**). It can be divided into processes related to the sticking together of smaller biogenic particles such as individual phytoplankton cells, the discharge of mucous feeding webs from organisms such as larvaceans and pteropods or the ejection of fecal material from any organisms containing a gut. Although marine snow particles, whether they are amorphous aggregates or fecal pellets, retain their physical identity for many days or weeks if stored at ambient temperature, when in their natural environment, it is likely that their residence time is only a matter of hours or a few days. With apparent sinking rates of tens to hundreds of meters per day, it is in fact essential from the perspective of the economy of the upper ocean that the sinking rate of this material is retarded. The reason for this rapid destruction is likely to be that the zooplankton which swim between one snow particle and the next are able to fragment them and ingest some parts of them in the process (**Figure 9**). Even fecal pellets which one might think of as being an unattractive food resource, are readily broken up (**Figure 9**). Fragmentation by wave action seemed at one stage to be another likely mechanism but even for the more fragile particles, this now seems to be of minor importance as the sheer rates are not usually adequate to break a significant number of particles.

Conclusion

Marine snow particles play a crucial role in regulating the supply of material to the deep sea due to their high sinking rates. They provide a microenvironment in which most rates of biogeochemical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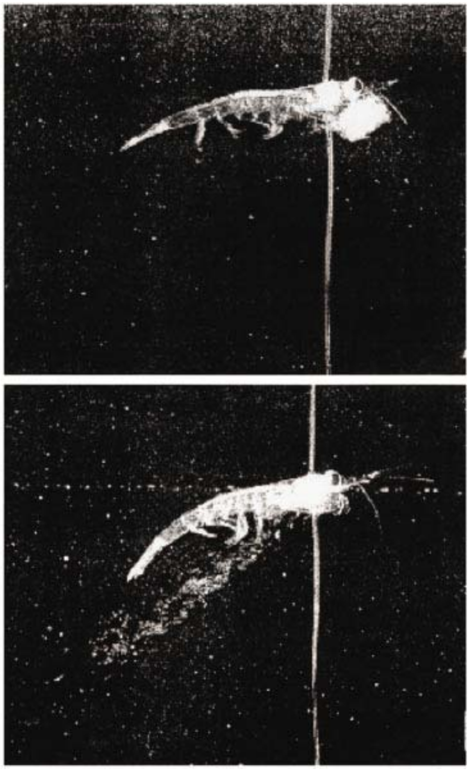
(C)

Figure 9 Zooplankton interactions with large particles: (A) feeding on a fecal pellet; (B) feeding on marine snow particle; (C) fragmenting marine snow particle.

processes are enhanced and in which many heterotrophic organisms obtain a living. They are a food source for a variety of free-living organisms some of which have already been shown to adopt complex behaviour in order to locate them.

See also

Floc Layers. Nepheloid Layers. Particle Aggregation Dynamics. Remotely Operated Vehicles (ROVs). Trapped Particulate Flux. Temporal Variability of Particle Flux.

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MARITIME ARCHAEOLOGY

R. D. Ballard, Institute for Exploration, Mystic, CT, USA

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Introduction

For thousands of years, ancient mariners have traversed the waters of our planet. During this long period of time, many of their ships have been lost along the way, carrying their precious cargo and the history it represents to the bottom of the sea. Although it is difficult to know with any degree of precision, some estimate that there are hundreds of thousands of undiscovered sunken ships littering the floor of the world's oceans.

For hundreds of years, attempts have been made to recover their contents. In *Architettura Militare* by Francesco de Marchi (1490–1574), for example, a device best described as a diving bell was used in a series of attempts to raise a fleet of 'pleasure galleys' from the floor of Lake Nemi, Italy in 1531. In *Treatise on Artillery* by Diego Ufano in the mid-1600s, a diver wearing a crude hood and air-hose of cowhide was shown lifting a cannon from the ocean floor. Clearly, these early attempts at recovering lost cargo were done for economic, not archaeological, reasons and were very crude and destructive.

The field of maritime archaeology, on the other hand, is a relatively young discipline, emerging as a recognizable study in the later 1800s. Not to be confused with nautical archaeology which deals solely with the study of maritime technology, maritime archaeology is much broader in scope, concerning itself with all aspects of marine-related culture including social, religious, political, and economic elements of ancient societies.

Early History

Sunken ships offer an excellent opportunity to learn about those ancient civilizations. Archaeological sites on land can commonly span hundreds to even