Standing, left to right:
Henry Blackburn, Fauzi Mantoura, Doeke Eisma, Chris Martens, Tim Jickells, Daniel Vaulot, Andreas Moll
Seated, left to right:
Scott Fowler, Jack Blanton, Renate Scharek, Yoshimi Suzuki

Group Report: What Determines the Fate of Materials Within Ocean Margins?

T.D. Jickells, Rapporteur
T.H. Blackburn
J.O. Blanton
D. Eisma
S.W. Fowler
R.F.C. Mantoura
C.S. Martens
A. Moll
R. Scharek
Y. Suzuki
D. Vaulot

INTRODUCTION

When this diverse group of physicists, chemists, biologists, and geologists first met, a wide range of issues were prepared for discussion and these were subsequently crystallized to six questions that incorporated most of our concerns over what we felt to be important but poorly understood factors controlling the fate of materials in margins. These questions were discussed and are presented approximately in a flow pattern, from the physics of energy exchange through water column processes to the sediments.

From the outset of our deliberations, it was evident that physical forcing by rivers, the atmosphere, and the oceans is a major determinant of all processes on continental margins. Furthermore, the type of forcing varies greatly from place to place, depending on the balance of the forcing functions and the geomorphology of the shelf. The group therefore began by first considering the physical forcings and their interactions with geomorphology before moving on to discuss biogeochemical cycles on and around ocean margins within their physical and geomorphological context. A theme of our deliberation was often to find common factors in shelves in order to simplify these complex systems. There is a danger that such attempts at rationalization will oversimplify the system, but it is also evident that some sort of simplification is necessary in order to begin to comprehend these complex and diverse systems.

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In attempting such a classification, several problems become evident. First, time and space scales over which such classifications should be done are uncertain. An annual scale may be appropriate, but rare extreme events may have major effects on a margin and the effects may persist for long periods. If seasonal water column stratification occurs, a seasonal time scale may be more appropriate. In terms of spatial scales, it is also clear that river plumes will effect only certain areas of a shelf, so that the geographic shelf boundaries may not be the relevant one. The group therefore concluded that this classification is potentially useful but requires refinement, which was not possible during the meeting. The group also noted that a compilation of the shelf areas in terms of the physical forcing functions and geomorphological types was not available in the scientific literature, but that this could be produced and then used to test the applicability of the approach.

Stratification

The effect of the forcing functions on a shelf will depend in part on the water structure on the shelf.

Horizontal density gradients (Fig. 2a) suggest efficient vertical mixing from surface to bottom; horizontal exchange across isopycnals is inhibited to some extent. On the other extreme, vertical density gradients (Fig. 2b) support efficient horizontal transport, and vertical exchange across isopycnals is inhibited. This is a particularly important state of stratification because it may allow efficient cross-shelf exchange of material between inner margin sites with those on outer margins. Spatial gradients in vertical mixing and inputs of buoyancy plus the influence of eddies and advection (e.g., wind-generated upwelling or downwelling) may produce a combination of horizontal and vertical gradients in which a secondary circulation regime has potentially important horizontal and vertical components (Fig. 2c, d;

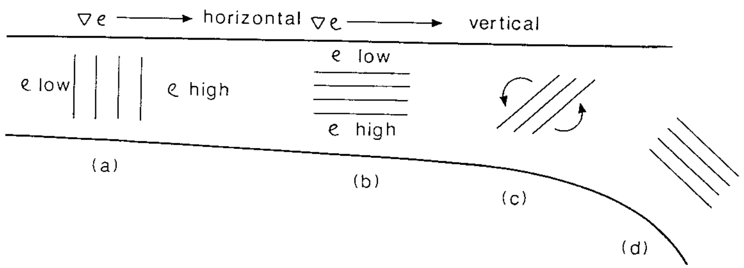

Fig. 2—Schematic view of vertical and horizontal density gradients (ρ is density).

Blanton, this volume). Mixing along and across isopycnals occurs to different extents in these different density regimes.

Inputs of buoyancy tend to stratify the system horizontally. The more obvious processes that increase buoyancy include solar radiation, freshwater runoff, rainfall, and melting ice. The time scales of variation are on the order of one day to annual.

Work by frictional and convective processes at the surface and sea bottom redistribute buoyancy (Fig. 3) and, if the work is sufficiently strong, horizontal stratification is destroyed. Simpson and Hunter (1974) have derived a stratification model which synthesizes the opposing work done by buoyancy fluxes versus work done by mechanical energy. In the absence of advection of buoyancy and neglecting buoyancy fluxes from lateral boundaries, such as ice melt at the shore or river runoff, a *minimum* set of variables for a given margin can be incorporated in a dimensionless stratification number (SN), defined as

$$SN = \frac{BH}{KU^3}$$

where B = buoyancy flux (L^2T^{-3}), H = water depth (L), U is a velocity scale (LT^{-1}), and K is a dimensionless constant which includes an efficiency factor for the proportion of mechanical energy that is used to mix buoyancy. With constant buoyancy flux and technical efficiency, the ratio H/U^3 can be used to define the stratification regime. In shallow water (H small), and using reasonable values of U, SN is small and stratification could be weak or even destroyed at suitable levels of U^3. For large H, constant B, and U^3, SN is large and would represent a stronger degree of stratification.

Sources of mechanical work include friction by bottom currents generated by tides and winds and surface friction resulting from wind stress and surface waves. The time scales here range from seconds to days, considerably shorter than time scales of buoyancy generation. Convection is also an

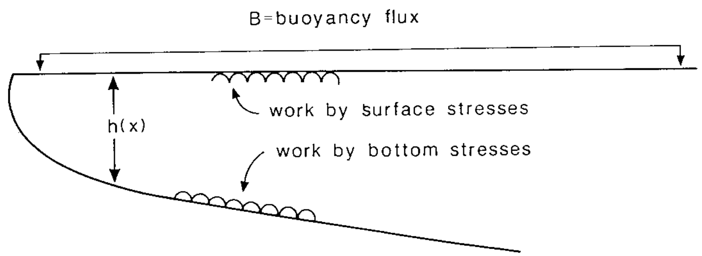

Fig. 3—Hypothetical margin where water depth is a function of offshore width.

within ocean margins, but this retention can be destroyed by extreme events such as hurricanes. A further factor is that physical forcing often acts to resuspend sediment continually, which introduces sites for the adsorption of materials to and remobilization from suspended solids and reduces light penetration.

Biota

Physically driven water exchange with the open ocean imposes constraints on phytoplankton systems. Ocean margins offer environments rich in nutrients that can be highly productive, but this requires that the phytoplankton be retained within the margin and within the euphotic zone in that margin. Since light penetration is a function of depth and suspended solid concentration, the persistence of phytoplankton on a margin interacts with both sediment transport and physical forcing. While many plankton are passive to transport processes, there is evidence that some are active in attempts to remain within a system. Examples are dinoflagellate and zooplankton migrations. The question of sustaining a plankton boom is considered in the next section, but here the group noted the strategies of retaining a relic overwintering population in temperate shelves to provide a seed population for the spring bloom. This usually involves the deposition of resting cells (diatoms), resting cysts (dinoflagellates), or eggs (copepods) in sediment or ice, thus preventing cells being flushed out with the water. These strategies have risks, since it is possible that the resting phases could become deeply buried and hence unable to escape from the sediments or buried in anoxic sediments (and hence killed). However, the success of these strategies is evident from the regular seasonal succession of algal populations seen in many areas. The risk is undoubtably mitigated by the strategy of releasing very large numbers of the resting stages. In tropical latitudes where overwintering is unnecessary, there are suggestions that plankton operate strategies to retain themselves in the coastal zone by sinking from outflowing surface water into onflowing deep waters; however, these communities are much less well studied. A similar strategy employed by *Euphausids* in the Southern Ocean of Antarctica is relatively well understood (Steidinger and Walker 1984).

In some areas where light penetration is great enough, benthic primary production is also important. In addition, there are highly productive margin edge communities which actively modify the physical environment, as in the case of mangroves, marshes, sea grasses, and coral reefs. They occupy physical locations which optimize their productivity by allowing accumulation of sediments (mangroves/marshes) or a location where light and nutrient supply is optimal (coral reefs, sea grasses). The controls on these communities are physical, i.e., light and habitat. All are under threat from coastal development, eutrophication, or disturbance. The margin edge communities may not always be of global importance as material reservoirs, but they are of great socioeconomic value as nurseries for fisheries and coastal protection. Such communities are likely to be affected to a considerable extent by sea level change.

HOW DO THE FACTORS WHICH LIMIT PRIMARY PRODUCTIVITY VARY WITHIN AND BETWEEN OCEAN MARGINS?

The factors controlling primary productivity have been reviewed in an earlier Dahlem Workshop Report (Berger et al. 1989) and in a background paper for this conference (Smetacek et al., this volume). Thus, the group simply listed the major factors of importance such as light, temperature, nutrients (N, P, Si, Fe, and possibly other trace metals), mixing, and grazing without debate. It was noted that the limiting factor on autotrophic biomass must ultimately be chemical when considering large enough spatial and temporal scales for which quasi-steady state is a reasonable assumption, e.g., in the context of global biogeochemical budgets. The term "regulating factor" was adopted as more useful in the context of shelf water, where physical as well as chemical factors are important on shorter time scales.

Differences between Ocean and Ocean Margin Primary Productivity

It is evident from global compilations of phytoplankton primary production rates that margin areas are generally productive in comparison to open ocean areas (e.g., Berger 1989). It was accepted that this characteristic of margin phytoplankton systems derives from the physical setting in which they operate. In comparison to ocean systems in general, much greater nutrient supplies (derived from riverine, atmospheric, and upwelling sources) produce a relatively large nutrient reservoir, and the presence of a shallow sediment boundary to the system allows rapid recycling to the euphotic zone. In many systems this benthic recycling is sufficiently rapid to allow inclusion of the upper few cm of sediment as essentially part of the water column.

There are other distinct characteristics of shelf systems. In addition to high average primary productivity, the formation of intense blooms terminated by nutrient exhaustion appears to be characteristic of shelf systems, though it was recognized that observations in the open ocean could be sufficiently infrequent as to miss such blooms there. Another characteristic appears to be different plankton community structures. These, in part, reflect the increased nutrient supply favoring certain classes of phytoplankton; in addition, however, the availability of a sediment boundary allows margins where seasonal water column stratification occurs. The effect of stratification on the formation and sequence of plankton blooms depends on the meteorological forcing in a nonlinear manner (Radoch and Moll 1990). The transition from one system to another occurs during the spring, from a diatom-dominated system driven by the nutrients regenerated over winter to a flagellate community that recycles nutrients very efficiently. In autumn there may be another transition to return to a system dominated by diatoms. The transitions are forced by the availability of light, nutrients, and mixing. In this case, Si is a potential controlling nutrient because of its requirement by diatoms. The timing of the shift from one system to another and whether there is an autumn bloom or not depends on the latitude in which the area is situated and on the topography of the shelf. For example, during a stratification period in summer, when the flagellate system has established itself, erosion of the nutracline (pycnocline) due to storms or increased bottom friction can occur. This introduces nutrients regenerated below the seasonal thermocline into the upper mixed layer, and populations of diatoms can build up again. The two systems are clearly distinguishable by their dominant organisms. Understanding how continental margin primary production communities switch from one state to another is of critical importance in the case of potentially harmful blooms (e.g., toxic dinoflagellates, *Phaeocystis pouchetii* [Smetacek, this volume; Smetacek et al. 1984]).

Although we have been able to identify several factors that influence primary productivity in margin areas, the data base for areas apart from those close to U.S. and European coasts is very limited. Productivity studies of margin areas of various types over at least annual cycles, and preferably long time series, are an urgent research priority. In addition, the importance of benthic vs. phytoplankton primary productivity requires evaluation, as does the relative importance of $CaCO_3$ and organic carbon production.

Macro and micro benthic primary production and coastal marsh or mangrove communities are unique, diverse, and complex communities within margins; they are of major importance for the functioning of the whole ecosystem. Their quantitative role in margin biogeochemistry is poorly understood and requires evaluation, particularly because of the sensitivity of these environments to global change over the near future.

WHERE DOES REGENERATION OCCUR?

High rates of particulate organic matter (POM) and carbon (POC) production are found in ocean margins. Since not all of this POM is buried (Wollast, this volume), it follows that rates of regenerative processes will also be high in these zones. Upon production (and death for biological particles), sinking will begin to transport the produced material to the sediments (Fowler, this volume). An important control on the rates and type of particle formed and its subsequent fate is the biological community in which it is formed since, as noted earlier, certain biological communities favor the production and settlement of particles while others favor intense water column recycling. Following production, biogenic particles whether primary or secondary aggregates (Fowler, this volume) will undergo regeneration of their component elements and compounds by such processes as microbial degradation, physical destruction through grazing or particle solubilization, element desorption, and zooplankton and bacterial metabolic excretion. The rates associated with these processes will be controlled to a large extent by parameters such as temperature, salinity, energy, and the redox chemistry of the surrounding waters. These parameters vary widely in coastal margins. In addition, regeneration rates, and hence where regeneration occurs in the water column, will be a function of POM composition and the degree to which it is labile since breakdown rates of different organic components vary, as do rates of dissolution of mineral phases such as different carbonates and silica.

From open ocean sediment trap flux profiles it has been demonstrated that the majority of POC and PON (particulate organic nitrogen) regeneration in sinking detritus occurs in the upper few hundred meters, i.e., at depths which often bracket the entire water column in a margin zone. However, recent sediment trap work has suggested that the regeneration rates derived from such particle flux experiments can be grossly overestimated if all living POM which actively entered the collector (i.e., zooplankton "swimmers") is not removed from traps in the upper water column (Fowler, this volume). Furthermore, in high energy margin systems, mass and POM flux do not always follow the classical pattern of exponential decrease with depth seen in the open ocean, because the vertical flux of sinking particles is often confounded by an input of laterally advected particles originating from the margin. Thus, it may be far more difficult to derive element regeneration rates from particle flux profiles in margin waters. The development of new techniques to determine net fluxes to the sediments in margin areas uncorrupted by lateral advection and resuspension is a priority.

Because ocean margins are relatively shallow compared to the open ocean, biogenic particles sinking at speeds of tens to hundreds of meters per day have a greater probability of reaching the sediments with much of their organic matter intact. The alternative fate of a particle being transported off the shelf is dependent on the flushing rate of the shelf in comparison to this particle lifetime of a few days within the water column. Thus, regenerative processes, such as aerobic oxidation and sulfate reduction in or on sediments, will play a major role in resupplying nutrients and trace elements to the overlying waters as well as carbon (Wollast and Blackburn, both this volume). That the benthic boundary layer in margins is an active

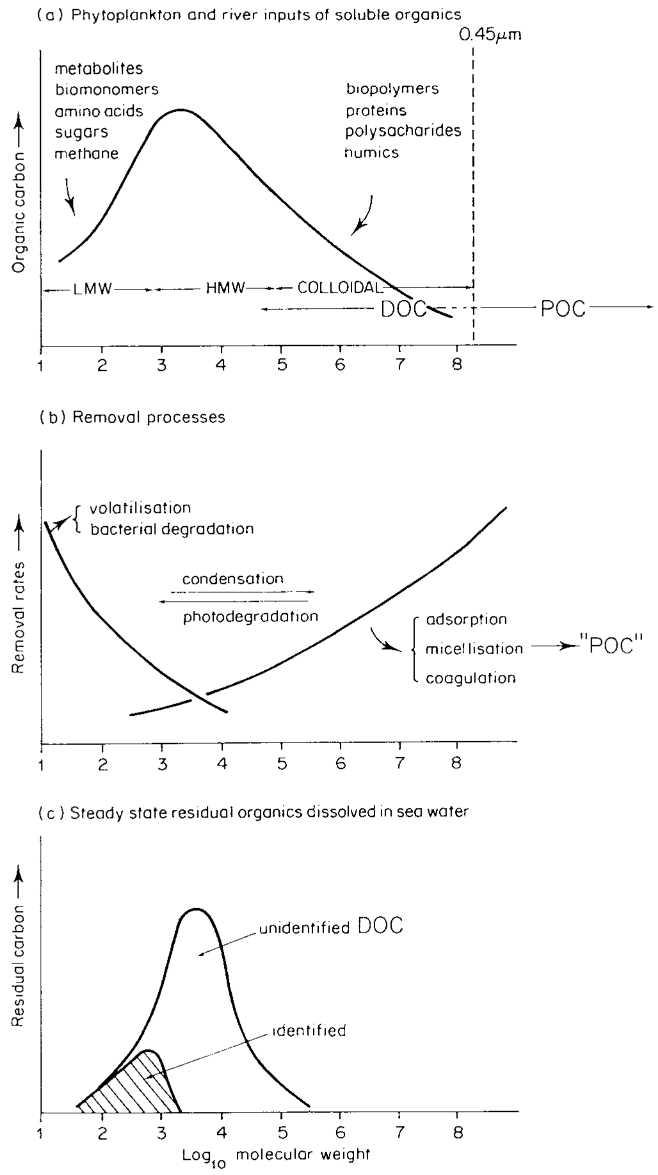

Fig. 7—(A) Hypothetical molecular weight distribution of DOC. (B) Molecular weight dependence of removal processes acting on DOC. (C) Hypothetical resultant residual molecular weight distribution of DOC.

LMW and HMW compounds is potentially complete, except for a residual ensemble (Fig. 7c) of intermediate molecular weight organics which we hypothesize to escape the LMW and HMW removal processes.

As the new high temperature catalytic oxidation (HTCO) technique (Suzuki and Tanoue, this volume) becomes widely available, priority research should include molecular size and biodegradability studies of DOM in contrasting ocean margins. By linking such studies to isotope studies (^{13}C, ^{15}N, and ^{14}C dating), it should be possible to constrain the sources, cycling, and fate of DOM and POM in ocean margins. However, much innovative chemical research focusing on biopolymer chemistry of DOM is needed, and this should be possible following recent advances in chromatographic and spectrophotometric techniques.

Unpublished riverine DOC results (Suzuki et al.) using the HTCO technique suggest previous measurements underestimate DOC by 25–30%. However, this additional (25–30%) DOC fraction appears to be removed nonconservatively in estuaries, unlike the DOC determined by previous techniques. Thus the net effect on the carbon budget of ocean margins may be modest, though the effect on CO_2 budgets may be significant.

At ocean margins there is a steep gradient in salinity, light, ventilation, and bacterial activity; these regions are therefore expected to be areas of degradation of DOM from terrestrial and marine sources, as suggested by data presented in Suzuki and Tanoue (this volume). If further studies confirm these patterns, ocean margins may be globally significant sinks for DOM from both sources. In addition, HTCO–DOC and DON studies (Suzuki, unpublished) indicate that the C/N ratios of surface marine and riverine DOM is 7.6 and 25, respectively. Thus the degradation of this material should result in the release of nitrogen, which will serve to increase the primary productivity on margins. Photolysis of DOM may be efficient in transforming refractory molecules into bioavailable products, though the mechanism and magnitude of these processes is poorly known.

Geological evidence suggests fluvial sediments are efficiently trapped in nearshore sediments and deltas (Milliman, this volume); however, the extent to which the more buoyant finer POM is trapped is uncertain. The large Asian river systems, which discharge most particulate material (Milliman, this volume), require further study. The biodegradability of fluvial POC in ocean margins is unknown. Mass balances suggest that organic carbon deposition on margins is of a similar order of magnitude to fluvial inputs. However, carbon isotope data suggests that sediment carbon on the shelves is predominantly of marine origin. This suggests that either the fluvial POC escapes offshore or is degraded over relatively rapid time scales compared to sediment processes, i.e., tens and hundreds of years.

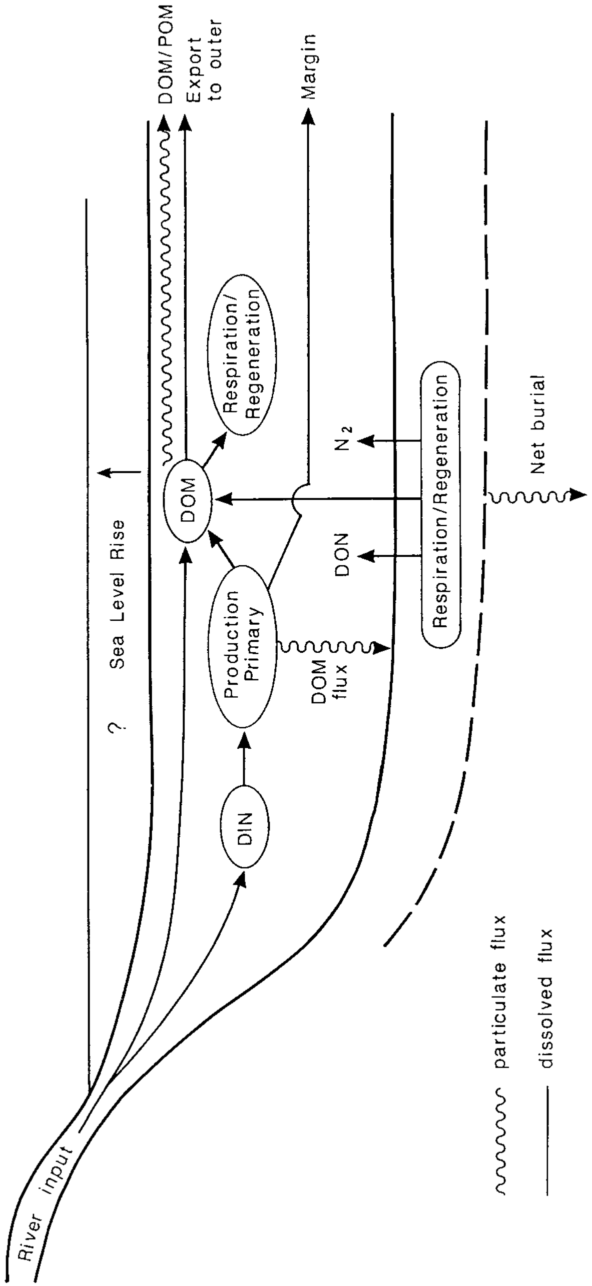

Fig. 8—Key processes of the inner margin requiring further study.

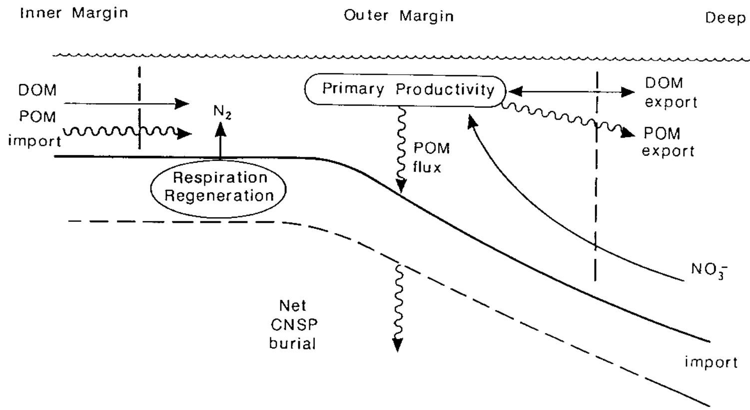

Fig. 9—Key biogeochemical fluxes at the outer margin.

DISTINGUISHING NET FROM GROSS FLUXES: HOW CAN WE LINK INSTANTANEOUS FLUX MEASUREMENTS WITH MASS BALANCES?

The problem of distinguishing net from gross fluxes arises at all boundaries. Examples include the recycling of components between marine water and the atmosphere, the recycling of carbon and nitrogen between the water column and the sediments, "new" and gross primary productivity, and net and gross water and material fluxes across the boundary between the margin and ocean. The problem of distinguishing the fluxes depends on the boundaries considered. If there is a clear physical boundary, such as the sediment–water or water–atmosphere interface, the determinations are relatively straightforward. Where there is no simple boundary, as in the case of margin–ocean exchange in many cases, it is difficult to distinguish the net fluxes from the gross. For example, the flow of water on and off a margin may occur in different places and over different time scales even at a steady state; the importance of rare extreme events complicates the matter further. This example is of interest because the group identified the ocean–margin exchange process as a critical determinant of shelf processes. It is possible to define boundaries in a computer model and to predict water and material exchanges; however, the physical verification of these estimates is an extremely difficult task. Measurements must be made at specific sites and times, and it is rarely obvious if these are the relevant space and time scales in which measurements are needed. The development of strategies to make these types of exchange measurements, particularly at the outer margin boundary, is clearly a high priority but will require the development

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Fractal Theory and Time Dependency in Ocean Margin Processes

K.J. Hsü

Geological Institute, ETH-Zentrum
8092 Zürich, Switzerland

Abstract. Long-run records of temporal variation of magnitude of natural events show a fractal geometry: there is a common tendency of clustering the extremes (Joseph's effect of Mandelbrot), and there is inevitability of the improbable (actualistic catastrophism of Hsü, or Noah's effect of Mandelbrot). This time-dependent probability renders the common practice of assuming Gaussian probability in evaluating magnitude/frequency relationship obsolete. Fractal geometry is a new statistical method, devised by Benoit Mandelbrot on the basis of evaluating long-run records, to predict non-Gaussian probability of natural perturbations. Assessment of responses of ocean-margin processes to natural or anthropogenic perturbations should take into consideration such fractal geometry as indicated by long-run paleoceanographical and geological records.

INTRODUCTION

Several years ago I was on a panel of interdisciplinary experts to discuss the safety (or lack of it) of disposing atomic wastes in seabed. I was astonished to learn, from a colleague who claimed, that ocean-bottom water could never be carried back to the surface by a physical process; only living organisms could overcome gravity and transport radioactive contaminants from deep to shallow waters. The expert is a mathematician, and his far-reaching conclusion is based upon sophisticated and expensive mathematical modeling. In blind admiration for the so-called "exact science," the conclusions were greeted with enthusiasm by delegates to the London Dumping Convention of the International Marine Organization. It seemed that dumping of atomic wastes should be harmless, except for the rare deep-swimming animals.

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