William W. Hay

Understanding and Modeling the Sedimentary System

Zusammenfassung

Das sedimentäre System bezieht natürliche Prozesse der Gesteinszerstörung, des Transports, der Ablagerung und der Lithogenese ein. Obwohl die Prozesse gut bekannt sind, weiss man wenig über die Geschwindigkeit ihre Abläufe. Das Ziel der Modellierung sedimentäre Systeme ist es, die Prozesse so sehr zu vereinfachen, dass man sie mit mathematischen Termen beschreiben kann. Erfolgreiche Modelle erlauben die Vorhersage der Ergebnisse von Verwitterung, Erosion, Transport und Diagenese. Vergleiche der Ergebnisse der Modellierung mit geologischen Daten können helfen, die Geschwindigkeiten abzuschätzen, unter welchen die Prozesse bei verschiedenen klimatischen und geologischen Bedingungen ablaufen.

1 Introduction

The sedimentary system (Figure 1) involves processes that weather rocks and reduce them to soluble and fine-grained particulate components that can be transported, deposited, and transformed back into rock. Most of the processes can be observed today, but the present is an unusual episode in our planet's history. We live in a brief warm interglacial episode in an interval usually characterized by large mid- and high-latitude ice sheets and a much lower sea level. To complicate matters further, few measurements of process rates were made before the significant impacts of agriculture and the industrial revolution altered them. Consequently, the rates at which different processes operate over most of geologic time are not well known. The objective of modeling sedimentary systems is to simplify these processes so that they can be described in mathematical terms. Successful models predict the results of weathering, erosion, transport, depositional and diagenetic processes and allow us to determine process rates from ancient deposits. Modeling can also suggest the kinds of geologic information that can be used for its validation.

2 Sedimentary cycling

Younger sediments are formed mostly from the erosion of older sediments [1]. Only a small fraction of the sediments formed at any given time are the "new" products of weathering of igneous rocks. If erosional and depositional processes were constant with time, the mass-age distribution pattern for sedimentary rocks that exist today would have the form of a decay curve, shown as a red line in Figure 2. The actual mass-age distribution is irregular, indicating that the masses of sediment deposited in the past varied significantly. This implies that there have been significant changes in the rates of sedimentary processes over geologic time [2], and more profoundly, that what happens to the system depends on what happened previously.

3 Weathering

Weathering is caused by temperature changes producing differential expansion of the mineral grains in a rock, and by wet chemical reactions acting to break them down into soluble ions and progressively more insoluble residues [3]. Its global effects are shown schematically in Figure 3. Temperature changes occur between day and night in desert regions and between the seasons at high latitudes and altitudes. Temperature changes are greatly reduced by a mantle of soil; diurnal changes penetrate only a few centimeters, and seasonal changes little more than a meter. Chemical weathering results from rainfall incorporating atmospheric gasses reacting with the mineral constituents of rocks. Soluble minerals are dissolved and others are altered, releasing cations into the groundwater system. The most common weathering reaction involves carbon dioxide combining with water so that raindrops are a weak carbonic acid solution. The carbonation reaction with silicates consumes carbon dioxide, altering the climate. The less soluble residual products of weathering form the mineral components of soil, and much of the actual weathering process takes place within it. Soil provides water and minerals supporting plant life that in turn pro-

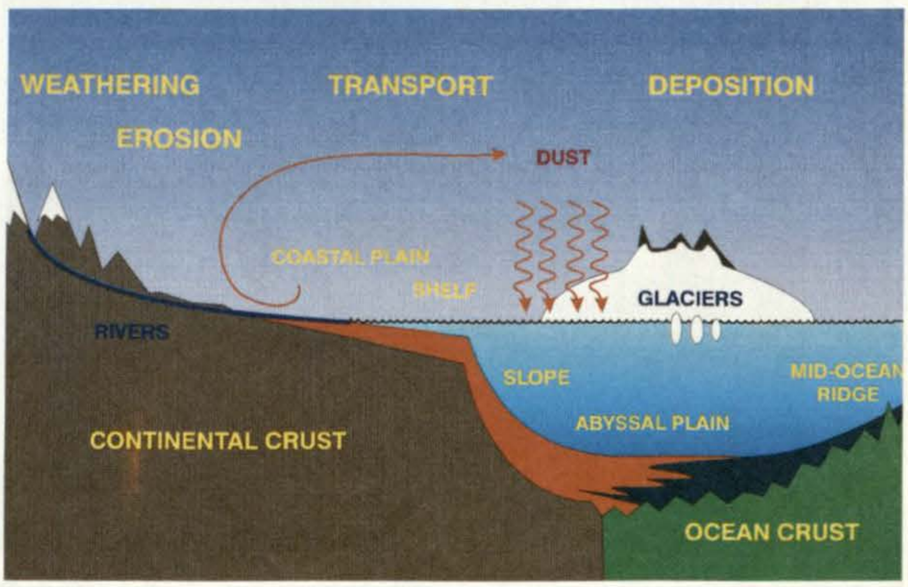

Fig. 1. The earth's sedimentary system.

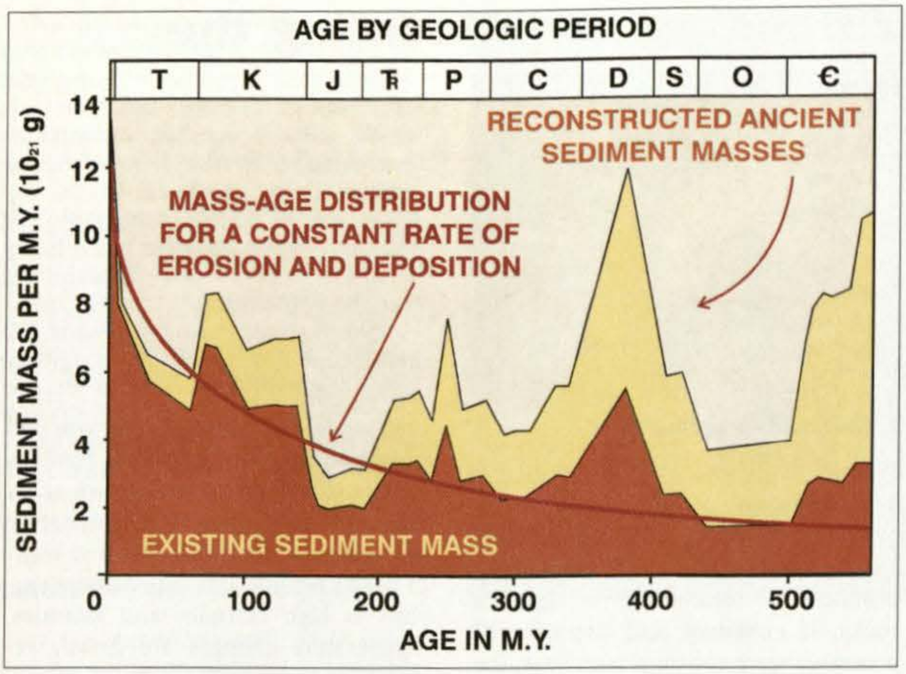

Fig. 2. Mass-age distribution of sediments through the Phanerozoic, showing existing sediments, the sediment masses that existed in the past, and how the distribution would appear if erosion and deposition rates had been constant.

vides decaying organic matter to form the humic components of soil.

Human activity has altered weathering rates. Mining has brought large quantities of sulfides to the surface, where they weather much more rapidly. Acids are also introduced into the atmosphere by automobile exhausts and industrial processes accelerating the decay of stone buildings.

Weathering is the rate-limiting step for the entire sedimentary system because it prepares geological materials for movement. Weathering rates depend on the composition of the rocks (Figure 4), availability of water, and temperature. Present global weathering rates have been estimated from the dissolved loads of rivers [4], but very little is known about weathering rates under the climatic conditions that prevailed over most of the earth's past. Figure 2 suggests that global weathering rates have varied by a factor of four, and that they are presently unusually high [5]. The large increase in the Devonian occurred as plants became established on land and fundamentally altered the nature of soils [6].

The chemical reactions involved in weathering can be examined in the laboratory, but natural rates are too slow to measure directly. In many areas the rates of climate change during the Quaternary have been more rapid than the rates of weathering, so that the weathering products have been formed under changing conditions. Complex processes of this sort are amenable to simulation by modeling calibrated by the geologic record.

Submarine weathering occurs as young ocean crustal rocks are exposed to the circulation of hot solutions derived from seawater. Ions are exchanged and removed from seawater to form clay minerals. Rates and magnitudes of these processes are poorly known.

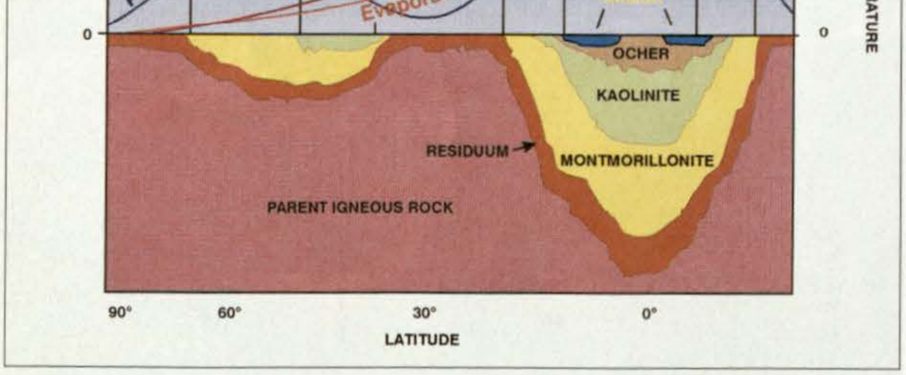

Fig. 3. Weathering products, temperature, precipitation and evaporation as a function of latitude.

4 Erosion

Erosion encompasses the processes by which materials leave the site of weathering and enter the transport system. Under natural conditions, erosion is performed by rain, wind, and moving water or ice [7]. Rainwater flushes the soluble material released by weathering out of the soil and into the groundwater. Where weathered materials are exposed to the atmosphere, erosion is a discontinuous process depending on extreme events – heavy rain and, in dry regions, high winds. In areas where hillside slopes are steep, much of the erosion may take place as mass wasting, either as sudden events, such as rockfalls or landslides, or by slumping and the slow downward creep of materials in response to freeze-thaw or wet-dry cycles. Beneath water or glacial ice, erosion is more continuous but is still influenced by extreme events, such as floods or ice surges. Although the conditions necessary for the lofting of mineral particles into a moving fluid medium are known from laboratory experiments, the long term rates at which materials are eroded and removed from a surface, the denudation rates, are known only from indirect measurements. In individual watersheds, modern erosion rates can be determined by measuring the accumulation of sediments trapped by dams, but it is often not known exactly where the erosion is occurring. Sediments also provide data on long term rates, but time resolution is limited by the stratigraphic record.

The rates at which landscapes evolve are uncertain. The rates at which advancing glaciers transform V-shaped river valleys into U-shaped glacial valleys are not known. The effect of alternating glacial-interglacial cycles on erosion rates remains a mystery.

Today, the most effective agent of erosion is man. The movement of materials involved in preparing land for agricultural production and for urban use, as well as the extraction of materials needed for construction probably exceeds the movement of materials by all natural processes combined. Rates of both chemical and mechanical erosion have at least doubled since the rise of civilization [8].

The only way to understand erosion processes at different time scales is through modeling and comparison of the results with the geologic record.

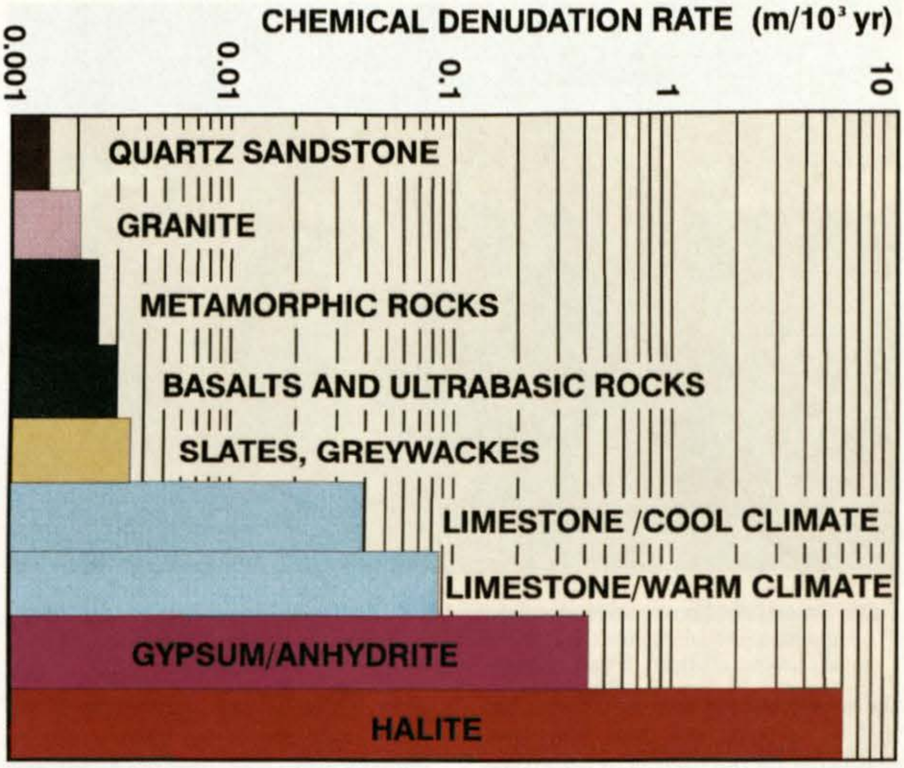

Fig. 4. Chemical denudation rates of major rock types (after [11]).

5 Transport

Transport of material from the site of erosion to the site of deposition is accomplished by the earth's fluid media, water, ice, and air [8]. By far the most important in terms of both dissolved and particulate materials are rivers. Normally, a river course has the shape of a decay curve (Figure 5). Its headwaters are steep, but the slope becomes increasingly more gentle as it approaches the sea. At some point the slope becomes gentle and the water flow such that the river begins to meander, lengthening its course and further reducing its slope. Today many rivers have their source in snowmelt in mountainous regions, others are fed solely by groundwater. The groundwater brings the dissolved material leached from soils and parent rocks. Rivers gain additional water downstream from precipitation and local runoff, and from the additional inflow of groundwater. Rivers lose water to evaporation in arid regions and to percolation into the groundwater system where the water table is low (Figure 6).

The competence of a river to transport detrital particles depends on the slope of the river course, the volume of water, and on the sediment load itself because the suspended sediment increases the density of the water. In many rivers the increase of water volume downstream offsets the lessening of slope so that the river maintains its competence until it reaches the meander belt. There the sudden further diminution of slope causes the river to drop some of its load. Over the annual or longer cycles of waxing and waning of river flows the deposition of sediment results in the formation flood and coastal plains.

Many river systems were modified during the last glaciation. Their downward course is interrupted by lakes that trap sediment. Construction of dams has added many more lakes. The result is that, for many rivers, the amount of detrital material reaching the sea has been reduced even though the erosion rates in the drainage basins have increased [9]. In many areas the dissolved loads were altered by human activity before any measurements were made.

Glacial transport of material is difficult to measure. Sediment loads vary greatly with the nature of the movement of the ice. Normally, most of the movement of the ice takes place above

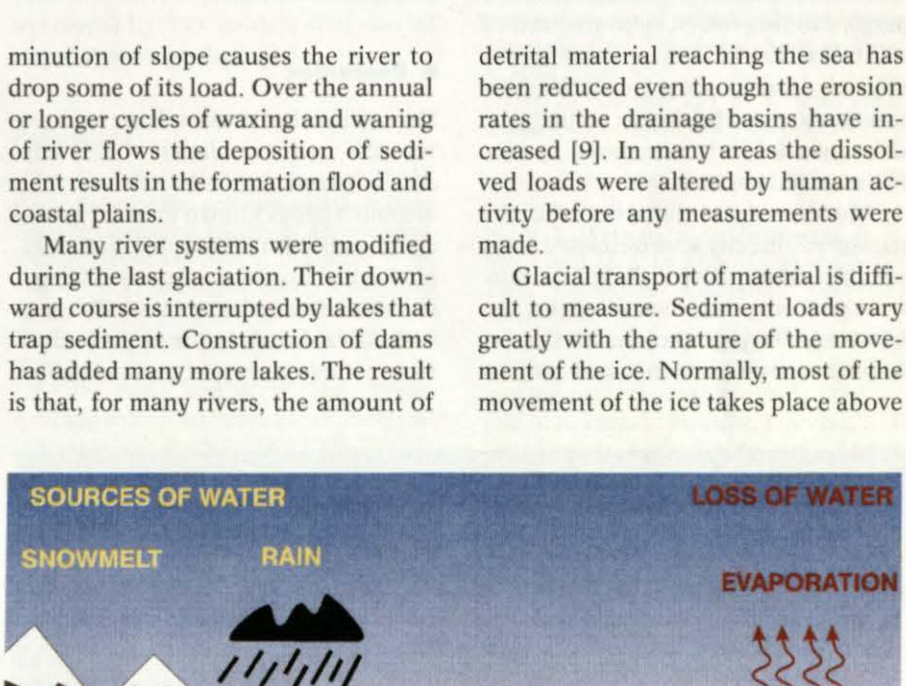

Fig. 5. Factors affecting the competence of rivers to transport sediment, showing sources and losses of water for rivers.

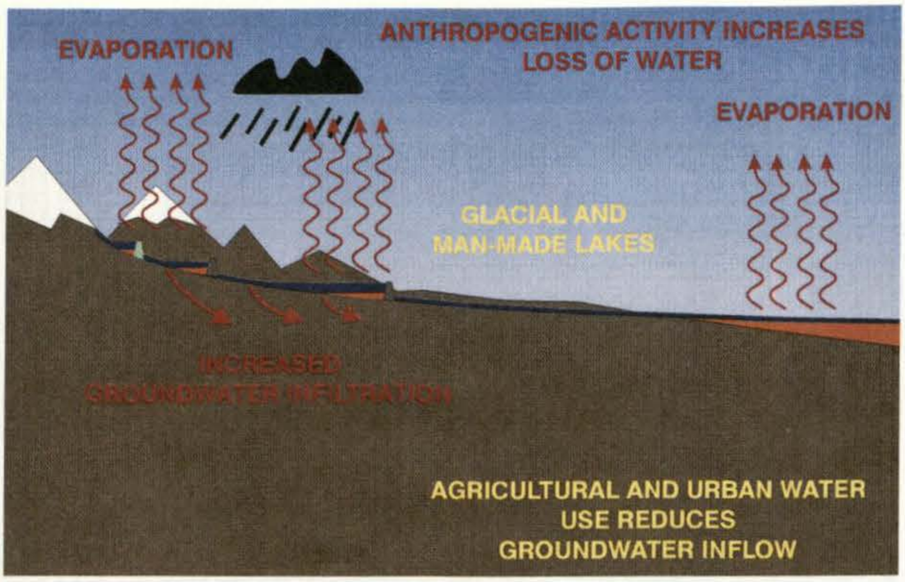

Fig. 6. Natural and human alteration of rivers affecting their ability to transport sediment.

the base of the ice, and transport is limited to material that falls onto or is deposited on the surface of the glacier. However, when the base of the ice reaches the freezing point, the glacier can surge, carrying with it large amounts of sediment frozen into its basal layers. Glacial deposits vary greatly in their distribution and thickness, so that modeling glacial flow is required to evaluate ice transport.

Modern dust transport can be measured directly and estimated from satellite observations. Rates of dust transport are very sensitive to the climate. During the Last Glacial Maximum dust transport rates may be been an order of magnitude larger than they are today [10]. Coupled climate and vegetation modeling may offer insight into the varations in dust transport with time.

6 Deposition

Depositional processes leave a direct record – an accumulation of sediment. As a consequence, sedimentation rates are much better known than are weathering, erosion, or transportation rates. However, in many environments deposition is an irregular and reversible process. Local floods in the upper parts of river courses transport particulate materials a short distance and then redeposit them. The floodplains characteristic of the lower part of the river course are sites of repeated deposition and erosion, responding to changes in the volume of water in the river and its suspended load on seasonal or longer time scales. Coastal plain and shelf sediments are subject to erosion and redeposition as a result of sea level change (Figure 7). Sea level falls result in erosion of detritus from the shelves and its delivery to the deep sea by turbidity currents, forming abyssal plains. Sediment that accumulates on the continental slope may be transported to the abyssal plains by sudden failure resulting in massive slides and/or turbidity currents, or by slow slumping. The relative importance of these processes in transporting material to the deep sea is unknown, as is their frequency. It is also not known whether or how such mass movements are related to sea level changes. It is curious that high-resolution imagery of the continental slopes shows slumping to be widspread, yet few interpreted seismic stratigraphic sections show ancient slump deposits.

Only in the open ocean is sedimentation a more continuous process (Figure 8). The continual rain of cosmic and wind-blown dust combines with a rain of carbonate and opal skeletal particles to produce pelagic sediments. Here too, however, sedimentation rates vary significantly over time.

Although much can be learned from studying sediment cores, sedimentary rocks, and seismic sections, modeling of sedimentary processes plays a major role in developing our understanding of this part of the system. It is particularly important to understand how detrital sediments on continental margins respond to changes in accommodation space, sea level, currents, and waves. As a result, this is currently the most active field of sedimentary process modeling.

7 Diagenesis

Diagenetic changes transform sediments into sedimentary rocks. They involve loss of pore space and chemical alteration of the deposited material. Diagenesis is often termed "reverse weathering" and like weathering, some of its aspects can be examined through laboratory experiment. However, an understanding of large scale diagenetic processes requires hydrogeologic and

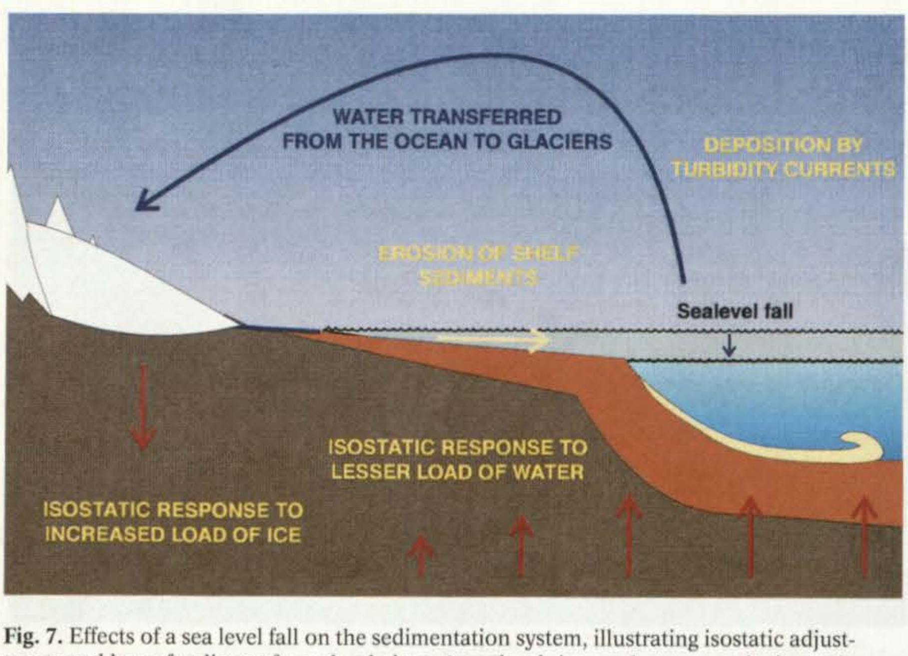

Fig. 7. Effects of a sea level fall on the sedimentation system, illustrating isostatic adjustments and loss of sediment from the shelves. A sea level rise produces opposite isostatic movements, and creates accomodation space trapping sediment on the shelves.

chemical modeling as well as observation of pore fluids and emanations from the sediment surface.

8 Conclusions

Most models describing aspects of the sedimentary system fall into one of three categories: (1) models that describe processes, (2) models that describe the form of the erosional or depositional products, and (3) models that describe fluxes in the system.

Models that describe sedimentary processes involve the physics of parts of the sedimentary system described either by equations satisfying empirical data or by rigorous mathematical treatment. Taken separately, erosional, transport and depositional processes can be treated as open systems and examined independently. However, the sedimentary system as a whole is closed and because it responds to the entire complex of processes involving geologic source materials, relief, climate and vegetation, it remains poorly understood. Today, few if any parts of the sedimentary system are in a steady state. Consequently, the outcome of changing any of the prevailing conditions is difficult to predict. A major problem lies in the lack of baseline measurements that can be used to calibrate the models.

Models that describe the form of the erosional or depositional products are barely two decades old. Two very different advances in geology allowed the success of such models: (1) the development of sequence stratigraphy, in which sedimentary architecture is recognized to be the result of interplay between sediment supply, subsidence, and sea-level change, and (2) the recognition that both erosional and depositional geomorphology can be described in terms of fractal geometries.

Models that describe fluxes in a system and attempt to account for overall mass-balance are in their early stages of development. They have the potential to relate changes in erosion and depositional rates to tectonic uplift and climate change. They can also be related directly to atmospheric and oceanic circulation models. The problem of lack of baseline measurements may be overcome by flux models that can be tested against geologic data.

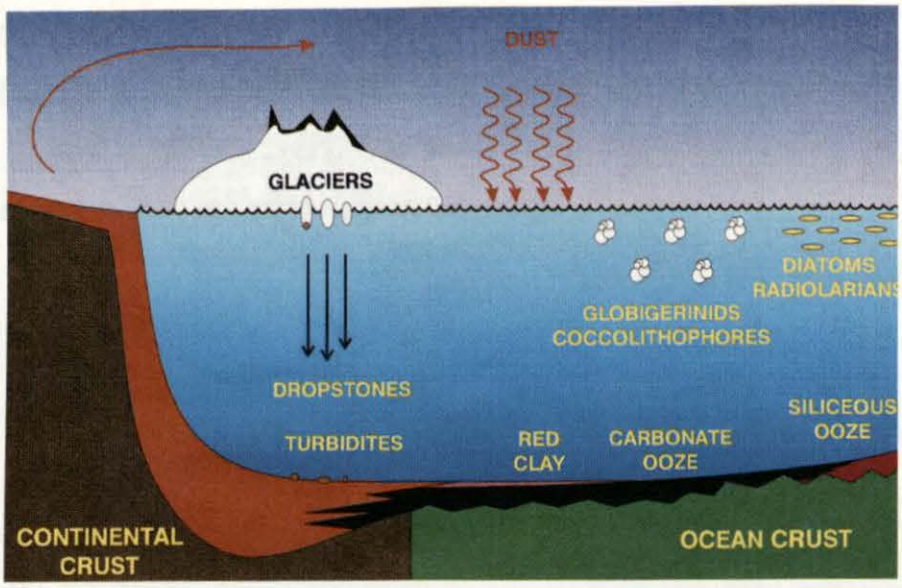

Fig. 8. The oceanic sedimantation system, with terrigenous sediments supplied by turbidity currents to the deep sea floor, and pelagic sediments settling through the water column. Much of the dissolved load brought to the sea by rivers and groundwater is removed by organisms to produce shells that ultimately rain down on the sea floor.

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Author's address:

Prof. Dr. William W. Hay, GEOMAR, Christian-Albrechts-Universität, Wischhofstraße 1–3, D-24148 Kiel, Germany, and Department of Geological Sciences and CIRES, University of Colorado, Boulder, CO 80309, USA.