SEDIMENTARY ROCKS

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Contents

Summary

Sedimentary rocks include all unconsolidated or consolidated natural materials deposited in an environment having some potential for preservation. Environments suitable for sediment preservation are found in sedimentary basins—topographically lower areas on Earth's surface, whose type and configuration largely depend on the geotectonic setting.

The character of the sediment is largely controlled by the type and intensity of weathering in the source area, which are, in turn, governed by the interplay between

climate and local tectonics. Detrital sediments consist of fragments of older rocks, minerals, or organic remains, while chemogenic and biogenic sediments form by precipitation from solution. Sediment dispersal paths and the shapes of the resulting sedimentary bodies are closely linked with the transport mechanism and depositional environment, which can be deciphered from structures and textures preserved in the sediment.

The concept of sedimentary facies—bodies of sediment sharing specific features—has been adopted for the purpose of correlation within a basin or between basins. The distribution of facies in a basin is controlled by changes in accommodation space and sediment supply.

Mechanical and chemical changes of sediments after their deposition include compaction (loss of pore space) and cementation, connected with crystallization of secondary minerals. These processes, called diagenesis, usually result in a transformation from loose, soft material into a consolidated rock. Diagenetic processes are also responsible for maturation of coal, crude oil, and gas, which are the principal sources of energy now in use.

1. Sediments and Methods of Their Study

The perpetual interplay between exogenous and endogenous forces taking place on Earth's surface involves, among other processes, gravity-induced redistribution of huge amounts of material from elevations to areas lying at lower altitudes. This process can be described in terms of the composition and disintegration of the original rock, size, and character of transported particles, transport medium and environment of deposition, and the geometries and internal architectures of the newly formed bodies of accumulated material. Once deposited, such natural material is considered a sedimentary rock.

Sedimentary rocks, although much less in volume than igneous or metamorphic rocks in the Earth's crust, are more accessible to study and exploitation as they cover 72% of the land surface and 99% of the ocean floor. They have a special position among life support systems as they hold most of the world reserves of groundwater. Moreover, they host all of the world deposits of fossil fuels either formed *in situ* or entrapped in favorable structures after migration through the rock massif. It takes millions of years for oil and natural gas to form in natural conditions because their maturation requires temperatures and pressures connected with deep burial. Similar intervals are needed for the formation of other industrial-use sedimentary rocks, such as limestone and sandstone. Many types of sediments originated under conditions that no longer exist on Earth. This is why sedimentary rocks truly represent a nonrenewable element in the development of the human race on Earth.

It is, therefore, not surprising that much attention is given to the study of sediments, the principles of their distribution and possibilities for their utilization. The first sediment studies were carried out with the purpose of extraction of fossil fuels and engineering projects such as tunnel construction. Some of the fundamental observations appeared in Charles Lyell's *Principles of Geology* in 1830. In 1893–1894, Johannes Walther wrote

his *Einleitung*, where he successfully applied the processes observed in modern sedimentary systems to the study of ancient sediments. This approach, which proved to be indispensable in modern sedimentology, motivated the development of models of sedimentary environments much later.

In the 1950s, P. H. Kuenen introduced laboratory modeling of sedimentary processes. Experiments in hydraulic tanks (flume experiments) filled with sediment of a defined grain size were carried out. This allowed explanation of the origin of such phenomena as turbidites and tempestites, which can barely be studied in natural conditions. A relation was found for subaquatic sediments between flow characteristics, particle size of the sediment, and the type of bedforms on the bottom, and hence also for sedimentary structures preserved in the sedimentary record.

Hydraulic experiments in the 1960s with particle entrainment and settling considerably improved the interpretation of grain-size parameters of detrital sediments. This knowledge, however, also led to the false concept that the genesis of detrital sediments can be determined using only data from sieve analyses, such as particle size, sorting, and skewness.

At the same time, descriptive characteristics of sedimentary rocks were improved, using modern laboratory and analytical techniques. A structural classification of limestones was proposed by R. L. Folk in 1959 and became very popular among petrologists. Its wide applicability motivated others to come up with their own subdivision of other types of sedimentary rocks: tens or even hundreds of classifications were proposed for detrital sediments, mostly based on the proportions of their components plotted into ternary diagrams. However, the high natural variability of such sediments accounts for the continuing absence of a universally accepted subdivision system for them. Still, it was not until the early 1980s that the fashion of "describe and classify" finally converged to the original concept of "describe, analyze, explain."

The publications of *Sedimentary Environments and Facies*, edited by H. G. Reading, in 1978 and *Facies Models*, edited by R. G. Walker, in 1981 triggered the complex use of different models for sediment accumulation in different environments, sediment supply conditions and tectonic settings (see section 4), and their testing on a wide range of fossil examples. Gradually, after the progress in stratigraphy in the 1980s, these models were extended by incorporating the time factor, and spatial distribution of sedimentary bodies as products of different depositional environments started to be modeled using computers.

Sedimentary rocks in general are undoubtedly the most explicit products of the processes on Earth's surface. Sedimentology and stratigraphy (Figure 1) are the sciences studying sedimentary rocks in order to recognize such processes in the past, and investigating the sedimentary record so as to decipher changes in these processes through time. The bad news is that the sedimentary record is extremely incomplete from the viewpoint of individual areas of deposition, with periods of erosion and nondeposition observed in vertical sections accounting for much longer time periods than the sediments preserved. Studying the sedimentary record is like reading a book badly damaged by a careless infant, with only every tenth page left in its place.
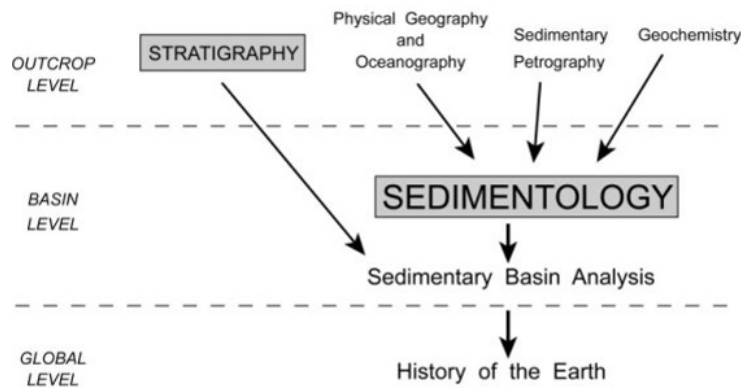
Figure 1. Position of different sciences studying sedimentary rocks in the process of understanding Earth's history, with indicated levels of observation
Although stratigraphy can be performed both at outcrop level and basin level, it is most indispensable in the description and analysis of individual vertical sections.

The preservation potential of sediments deposited at different settings varies widely, being generally higher in low-energy, low-relief areas: for example, deltaic sediments and sediments of meandering rivers have a better primary preservation potential than sediments of braided rivers, and offshore muds have a better primary preservation potential than sand locked in tidal bars and barrier islands. The completeness of the sedimentary record is also significantly jeopardized by subsequent tectonic uplift and erosion, largely depending on the regional plate–tectonic setting. A complete reconstruction of the depositional history of a specific area is, therefore, impossible, and attempting to disclose Earth's history from such fragmentary evidence is nothing but a jigsaw puzzle.

Sedimentary rocks, if preserved, provide evidence of (1) the provenance of the material deposited and the possible source rock, which may reveal areas subjected to erosion (see Section 2, this article); (2) physical, chemical, and/or biological processes effective during the deposition, and the depositional environments (Sections 3 and 4, this article); (3) deposition at the given place, indicating the distribution of topographic lows (Section 5, this article); (4) climatic conditions; and (5) where the rocks contain fossil remains, the character of organisms inhabiting or transported to the site of deposition. As all of these data refer to the time of deposition, the age of the sediment is of primary interest (see *Time in the Geological Past of Earth*). It has to be noted that only the presence of a temporal framework allows us to define the rate of environmental change and to correlate events between remote areas of sediment deposition.

Now, why are sedimentary rocks studied so extensively worldwide? And why are the different stratigraphic concepts so fiercely debated? The most important practical implication of sediment study lies in its ability to predict: to predict the possible presence of a coal seam in a certain horizon, to predict the distribution of ores confined to a certain lithology, and so on. Prediction of the geometries of sand bodies from limited outcrop and borehole data is a common practice in exploration for both hydrocarbon reservoirs and aquifers, thereby saving unnecessary expenses and preventing environmental damage related to extensive technical works. In addition,

much of the record preserved in ancient sedimentary rocks and its interpretation gives us a powerful clue for prediction of climatic and environmental changes to come in the near future.

2. Erosional Processes

The set of processes responsible for source rock disintegration and transport to the site of deposition is known as erosion. The outcome of erosional processes largely depends on the source rock composition and resistance, the intensity and type of weathering and the available transporting medium and its potential to carry clasts. While the effect of erosional processes on landform evolution is discussed elsewhere, the text below is intended to explain their effect on the character of sediments deposited.(See *Plate Tectonics and Landform Evolution*.)

2.1. Weathering

Erosion starts with the process of weathering: *in situ* disintegration and decomposition of rocks on exposure to atmospheric agents. Since air and surface water may reach to considerable depths along fractures, weathering is by no means restricted to the land surface. Weathering involves physical, chemical, and biological processes which closely interact. Physical weathering results in rock fracturing. Fracturing enlarges the area of rock surface exposed thus promoting chemical weathering. Chemical weathering, on the other hand, makes the rock more brittle and vulnerable to fracture. Biological weathering, rendered by microorganisms, plant roots, insects, and other burrowing animals, usually accelerates rock disintegration by combined physical and chemical action. All these types of weathering occur simultaneously, affecting sediment particles in the source area, during their transport, and even at their site of deposition.

Some of the most effective tools of physical weathering in temperate and polar climates are freeze-and-thaw processes. When water in cracks and pores freezes, it expands by ~9%, tearing the rock apart. Pieces of rock are separated and accumulated at the bases of slopes in the form of talus. Pressure release occurs in rocks uplifted from deeper parts of Earth's crust and exposed to the surface. The excessive energy of the rock is released by expansion and "peeling off" of slabs along fractures roughly conformable with the rock surface. Growth of secondary salt crystals acts in the same way as ice expansion. As a weathering mechanism, it is particularly effective in porous rocks in arid regions.
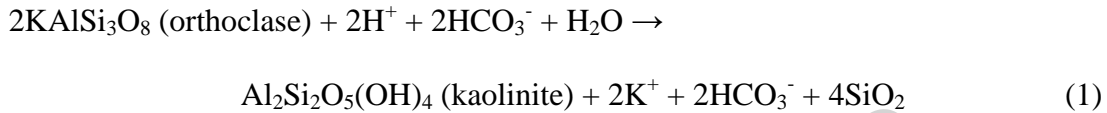
Figure 2. Granitic Half Dome in the Yosemite Valley (Yosemite National Park, California, USA). This is an example of an exfoliation dome formed in response to pressure release. It was half eroded by a valley glacier in the Pleistocene. The sheer wall thus created is 660 m high and 960 m wide.

The rate of weathering is significantly affected by intrinsic features of the rock itself: physical parameters of rock particles, rock structure, and texture. For example, rocks with wide contrast in clast size or crystal composition are more prone to weathering than equigranular rocks. This is due to the different response of the individual particle constituents to temperature variations of diurnal and seasonal periodicity. For the same reason, rocks showing more complex structures are more easily disintegrated than homogeneous rocks of the same type. Differential weathering occurs where neighboring rocks weather at different rates. It can be recognized by specific, often bizarre landforms.

The process of chemical weathering is connected with the effect of surface waters on minerals, either by direct dissolution (evaporites) or by chemical alteration. Chemical weathering brings rocks that originated at different temperature and pressure conditions nearer to equilibrium with a new set of environmental conditions. Minerals formed earlier from the melt (at higher temperatures and pressures) are generally less stable at atmospheric conditions and decompose more easily. Therefore, a difference can be seen between weathering patterns of igneous rocks: lower-temperature felsic rocks and higher-temperature mafic rocks. Ferromagnesian mafic minerals such as olivine, biotite, hornblende, or pyroxene are easily altered by oxidation of iron into red hematite (Fe_2O_3)

or brown limonite ($FeOOH.nH_2O$), while silicon is carried away in solution. Reddish weathering profiles, so common in the tropics, are produced by reaction of iron-containing minerals with oxygen contained in water.

Felsic rocks, on the other hand, are dominated by quartz, feldspars, and muscovite. Feldspars are altered by hydrolysis, the replacement of positive ions in minerals by hydrogen ions. Some released ions from feldspar are incorporated in the newly formed clay mineral as shown in the following equations.

$$2KAlSi_3O_8 \text{ (orthoclase)} + 2H^+ + 2HCO_3^- + H_2O \rightarrow$$

$$Al_2Si_2O_5(OH)_4 \text{ (kaolinite)} + 2K^+ + 2HCO_3^- + 4SiO_2 \qquad (1)$$

This is why granitic rocks tend to produce quartz sandstones with clay admixture and only few or no feldspar grains. Feldspar may, however, become a prominent component of some sedimentary rocks, such as arkoses, under conditions of weak chemical weathering in the source area and rapid burial at the site of deposition.

Most minerals are not soluble in pure water. Calcite ($CaCO_3$) becomes dissolved only in the presence of carbon dioxide, which is available from rainwater and from decaying organic matter in soils. Carbon dioxide reacts with water to produce weak carbonic acid, in which calcite dissolves according to the following formula.

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \qquad (2)$$

In sediment study, the relationships between source rocks and their weathering products led to the development of a set of methods suggesting the provenance for particular sediments. It has to be noted, however, that most sedimentary rocks consist of particles derived from a number of source rocks, and that some of these particles may have undergone several phases of erosion and redeposition. The best provenance indicators are fragments of the source rock itself. Quartz grains and pebbles may be studied under a polarizing microscope to see whether they are composed of one or more crystals: monocrystalline quartz grains are typical for granites while polycrystalline grains with "shingle" structure indicate metamorphic rocks. Among heavy minerals (those with specific gravity >2900 kg·m^{-3}) staurolite, disthene, sillimanite epidote, or garnet (almandine) indicate a metamorphic source; and apatite, monazite, zircon, and tourmaline usually come from acid magmatic rocks; while pyroxene, amphibole, and garnet (pyrope) are derived from basic magmatic rocks.

2.2. Transport

Weathering products which remain in their original place may be further modified to form a soil. Most of them are, however, redeposited into basinal areas. The principal transport medium is water, usually in its liquid form, along with wind. Soluble materials are transported in solution, while solid particles are transported by the mechanisms of traction (in bedload) and suspension (in suspended load). The moment of particle entrainment by flow generally depends on the gravity force and the shear stress exerted by the flow. Particles carried by traction are swept across the bottom by rolling or

dragging in downcurrent direction. With increasing values of bed shear stress, the particles start to move along the bottom by making more or less regular jumps (saltation). When the bed shear velocity exceeds the settling velocity of a particular particle, the particle may go into suspension. Flow velocities necessary for the entrainment of quartz particles of different sizes were experimentally determined by Hjulström in 1935 (see Figure 3).
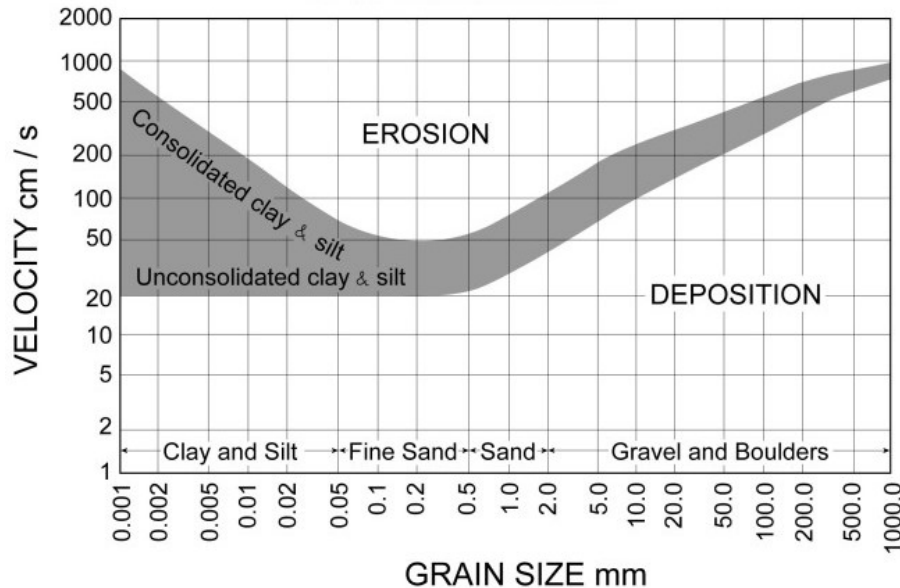

Figure 3. Hjulström's diagram showing the necessary flow velocity for moving particles of different sizes in an aquatic environment (flow depth = 1 m)
Note that the flow velocity necessary to erode silt- and clay-sized particles is higher than would be expected. This is due to electrostatic forces between these particles, which increase cohesion in consolidated mud. Gravel can be moved only at flow velocities exceeding 100 cm·s^{-1}. In slower currents, gravel forms a lag deposit, which protects the underlying sediment from erosion.
Diagram from Hjulström F. (1935). Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bulletin of the Geological Institute of the University of Uppsala* **25**, 221–527.

Among flow parameters, the most important for sediment deposition is the dimensionless Froude number, which controls the type of flow:

$$Fr = U(gh)^{-2} \tag{3}$$

where U is the mean flow velocity, g is the gravity acceleration, and h is the flow depth. Subcritical values of the Froude number ($Fr < 1$) create hydraulic conditions known as the "lower flow regime" while supercritical values ($Fr \geq 1$) are referred to as the "upper flow regime." Each of the two regimes is characterized by the formation of specific bedforms (see section 3.2. and Figure 6), giving rise to the respective sedimentary structures.

Transport by wind (eolian transport) is characterized by a large population of grains in saltation and by the formation of residual gravel pavements. Prior to the formation of vegetation cover after Pleistocene glacial periods, large amounts of silt particles were blown out from glacial and fluvial sediments and desert surfaces. They were transported in suspended load over long distances and deposited in numerous accumulations in the temperate climatic zone in the form of loess.(See *Soils*.)

3. Depositional Processes and Sediment Types

Much like all other rocks, sediments are composed of individual constituent elements, or particles in the broader sense, whose character, size, patterns of arrangement, and mutual relationships are indicative of the essential rock type. In some sediments, such elements are so small that they can only be studied under a microscope. Particles deposited by a physical process involving the action of water, wind, or ice, produce detrital sediments. In contrast, chemogenic sediments originate either by chemical deposition from natural waters on Earth's surface or precipitation from pore fluids after sediment burial. The category of biogenic sediments refers to those sediments whose deposition is mediated by living organisms. Biogenic sediments also include accumulations of bodies or skeletal parts of organisms on condition that these were deposited purely by gravitational settling. In this respect, accumulations of particles of biogenic or chemogenic origin redeposited by streams should be viewed as detrital sediments as the mechanism of deposition was of physical nature.

The problem of finding a strict dividing line between these three genetic types of sediments has led some authors to simply distinguish between intrabasinal and extrabasinal sediments, depending on whether the sediment particles come from the sedimentary basin itself or from an area outside the basin. Sedimentary material in marine basins which was produced by erosion of rocks on dry land is called terrigenous material.

It will be shown in the paragraphs below that detrital sediments definitely bear a more distinct imprint of the source area than chemogenic or biogenic sediments. Owing to their sedimentary structures, they provide fair evidence of the physical processes during deposition, and of their dynamics. As such, they are indispensable in paleogeographic and paleoenvironmental reconstructions. The character of chemogenic sediments, on the other hand, is closely linked with climatic conditions.

3.1. Features of Detrital Sediments

Detrital sediments (Latin *detritus*, a rubbing away) are also called clastic sediments as they are composed of clasts: redeposited rock or mineral particles. Detrital sediments composed almost exclusively of quartz and silicates are often referred to as siliciclastic rocks, as opposed to those composed of carbonate clasts, pieces of carbonized wood, or other intrabasinal particles. Limestones dominated by gravel- and sand-sized clasts are sometimes called calcirudites and calcarenites, respectively. As seen in the diagram in Figure 4, detrital sediments represent by far the most common category of rocks deposited throughout Earth's history. Gravels, sandstones and mudstones can be found in a number of terrestrial settings as well as in lakes and marine basins. In all settings,

the particle size of the sediment deposited generally decreases from high-energy environments to low-energy environments. This way, the upper reaches of rivers deposit gravel while finer sand and mud are transported further downstream. Also, beaches and river deltas are dominated by sand whereas offshore settings are characterized by mud. As the coarser basin margins are usually subject to earlier erosion than basin centers, the amount of quartz sands, arkoses and graywackes relative to mudstones in Figure 4 is possibly still underestimated.
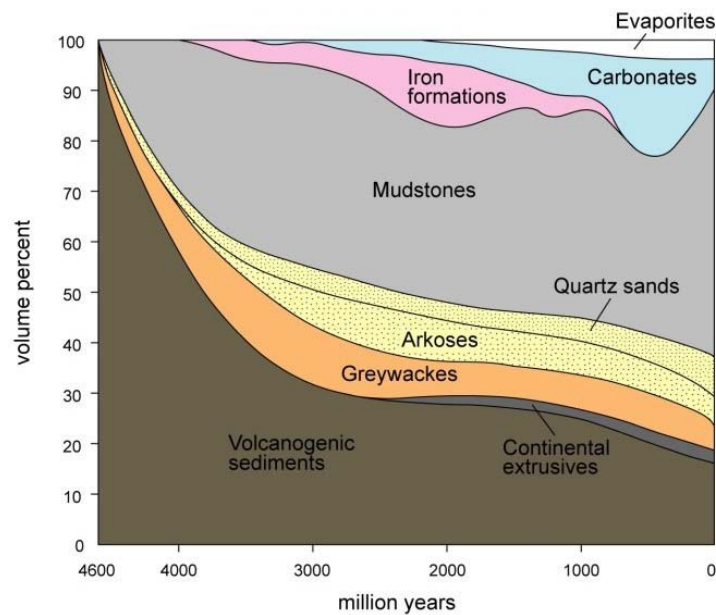

Figure 4. Relative proportions of different types of rock deposited in cratonic regions of Earth in the course of geologic time. Obvious is the increase in volume of iron-rich sediments after a shift towards oxidizing atmospheric conditions some 2.109×10^9 y BP, and the increase in volume of carbonate rocks in the Phanerozoic. Modified from Stanley S.M. (1989). *Earth and Life Through Time*, second edition, 689 pp. New York: W.H. Freeman and Company.

Although clasts in a general sense may be of all different sizes, a common practice in describing textures of a particular sediment sample is to distinguish between coarser "clasts" and finer matrix in each rock sample. This usage, based on relative size contrast between particles, parallels the phenocrysts–groundmass dichotomy in igneous rocks. Sediment particles are classified by their size into gravel-sized psephitic particles, sand-sized psammitic particles, silt-sized aleuritic particles, and clay-sized pelitic particles. Size ranges and synonyms for the individual categories are shown in Table 1. Particles of the prevailing size range determine the name of the detrital sediment (see section 3.5).

Particle size (mm)	Names of Greek origin	Names of Latin origin
>2	psephitic	ruditic
2– 0.063	psammitic	arenitic

0.063–0.004	aleuritic	lutitic
<0.004	pelitic	

Table 1. Size classification of sediment particles

Clasts are typically derived from rocks beyond basin margins, which became uplifted and subjected to the effect of external forces. With ongoing transport, clasts become fractured and abraded (worn out), which results in a reduction in their size in the downstream direction. Interactions between larger clasts smooth their sharp edges and corners, transforming angular clasts into rounded clasts. Therefore, roundness is a function of the distance of transport and energy of the environment during transport. The means of transport also determines sediment sorting, which is the degree of homogeneity of particle size in a sediment sample. For example, eolian and beach sands are well sorted while sediments of alluvial fans are poorly sorted.

3.2. Bedforms and Sedimentary Structures

Unconsolidated sediment lying on a flat surface, such as a river bed, coastal plain, or sea bottom, and exposed to flow-induced shear stress, tends to form a series of shifting bodies: bedforms. In areas with positive accommodation and sufficient material available, such bedforms may be preserved in the form of sedimentary structures. In the lower flow regime, bedforms whose crests run transverse to the flow direction are current ripples, dunes, and sand waves, reaching 1–10 cm, 10–50 cm, and over ~1 m in height, respectively. The largest sand waves exceed 20 m in height. All these bedforms travel downstream with their upstream faces, or stoss sides, being eroded and their downstream faces, or lee sides, experiencing accumulation of avalanching particles. In contrast, anti-dunes are bedforms of a dune size formed in the upper flow regime, traveling upstream by lee side erosion. They are formed at higher flow velocities or lower flow depths (effective flow thickness) than the other bedforms. This implies that anti-dunes are more commonly found in streams than in shallow seas.
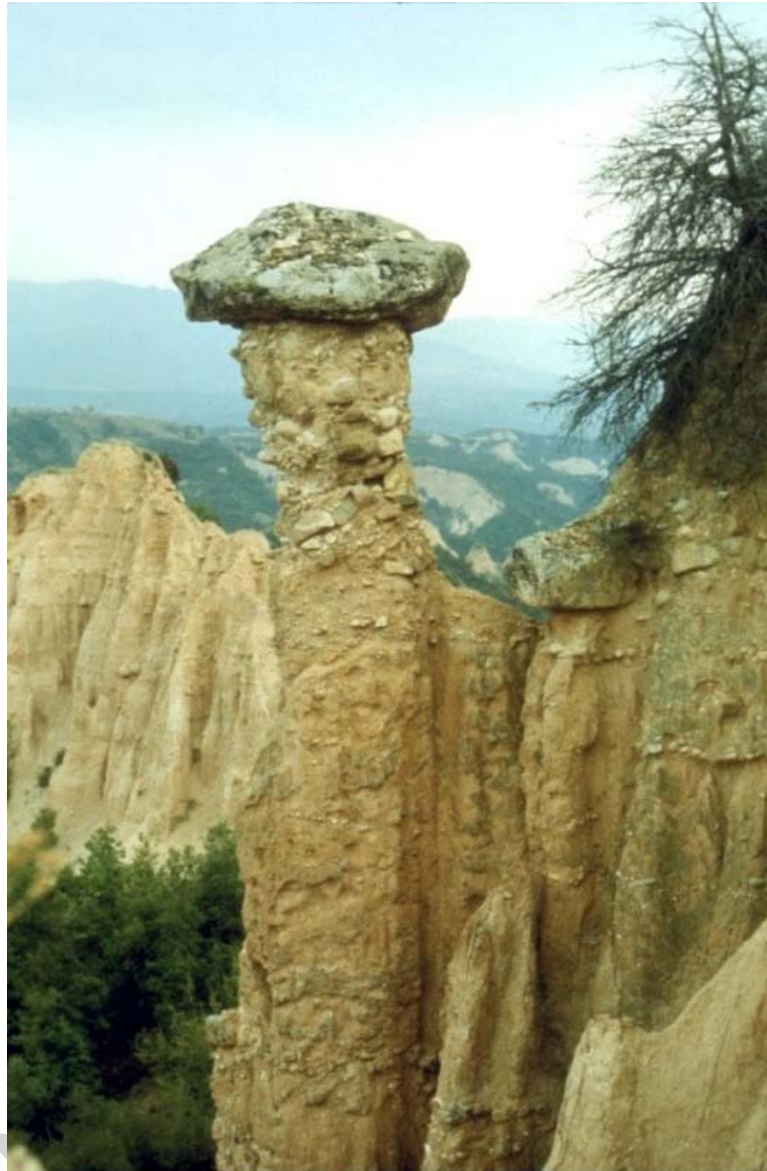
Figure 5. Selective erosion of unsorted detrital sediments by rainwater may produce earth pinnacles. The pillar in the photo was sculpted in Tertiary alluvial fan deposits near Melnik, Bulgaria.

Planar cross bedding and trough cross bedding are probably the most frequent current-generated sedimentary structures. The former is produced by bedforms having straight crests (two-dimensional dunes) and the latter by bedforms with sinuous crests (three-dimensional dunes; see Figure 6). As dune-crest undulation is a feature associated with turbulent flow, two-dimensional dunes change into three-dimensional dunes at the moment when the flow velocity exceeds a critical value (0.8 m·s^{-1} for subaquatic dunes at flow depths >1 m).
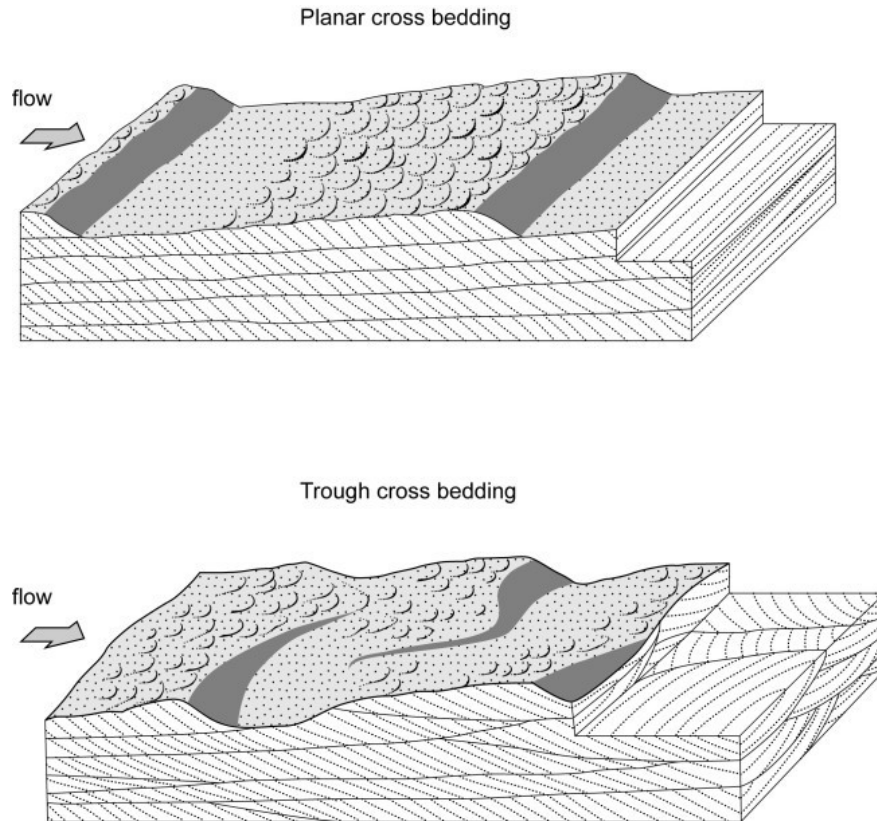
Planar cross bedding

Trough cross bedding

Figure 6. A comparison between planar cross bedding and trough cross bedding with the types of dunes that produce them. Troughs are generated by turbulence ahead of migrating dunes with sinuous crests.

Flow-parallel, longitudinal bedforms in shallow seas are represented most commonly by linear sand ridges or offshore bars and barrier islands. Such bodies are roughly shore-parallel, several meters high and several tens of kilometers long. They form in shallow seas where tidal currents or waves approach the sand-dominated shore at an oblique angle and become deflected to a shore-parallel direction as longshore currents. The internal architecture of linear sand ridges is characterized by lateral accretion surfaces—mostly landward-dipping, low-angle (<10°) surfaces—and superimposed cross-bedded sets indicating shore-parallel flow. Analogous large-scale but low-relief longitudinal bedforms are point bars developed in meandering rivers and longitudinal gravel bars in braided rivers. Longitudinal sand ridges in arid environments are known as seif dunes. These bedforms, common in the Sahara Desert, Africa, and the Gibson Desert, Australia, are typically 10–30 m high and several tens of kilometers long. Their internal architectures are rather complex as they typically result from a combination of two different wind directions.

Subaquatic wave ripples develop in places affected by waves, with no steady unidirectional flow. With increasing water depth, orbital motion of water mass is transformed into bi-directional oscillatory motion. Wave ripples are therefore roughly symmetrical. Their internal structures are either conformable with the ripple contour where aggradation prevails over migration, or similar to those of current ripples at

higher migration rates. Wave ripple cross-lamination is a typical sedimentary structure of some lake sediments.

Strong unidirectional currents in shallow seas may occasionally be combined with an oscillatory component, such as during storm events. Such circumstances generate a series of low-relief shifting mounds and troughs on the sea bottom at depths unaffected by wave action in normal weather. These bedforms are associated with a sedimentary structure known as hummocky cross-stratification (see section 4.4, Figure 15A). A variety of sedimentary structures are produced by specific hydraulic conditions, dragging and bouncing of larger clasts on the bottom, or by processes taking place after sediment deposition, such as compaction or water escape.

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Biographical Sketch

Jiří Adamovič graduated from the Charles University, Prague, in 1989. For the next eight years, he was employed with the Czech Geological Survey, working on a series of geological maps and environmental issues related to geology, with special reference to the Bohemian quartzose sandstones of the Cretaceous Age. As a structural geologist, he was involved in remediation of North Bohemian uranium deposits in 1992–1996. At his present position in the Academy of Sciences (since 1997), his major interests include siliciclastic deposition and sequence stratigraphy, hydrothermal alteration of sandstones, and young tectonic deformations of the Bohemian Massif.