5 Effects of Waves and Currents

5.1 Sediment Transport and Redistribution

5.1.1 General Remarks

We have seen that the morphology of ocean margins is largely determined by tectonics and sediment supply (Chap. 3), and we have reviewed the various types of sediments involved in building margins in the previous chapter (Chap. 4). We now turn to the all-important role of water motion in determining the distribution of sediments on the seafloor. A first impression of this role can be gained from contemplating Fig. 5.1, which illustrates the redistribution of sediment supplied to the sea by a river in a setting typical for Southern California. To be sure, the water motions indicated in the graph are not the only ones that need to be dealt with, as we shall see.

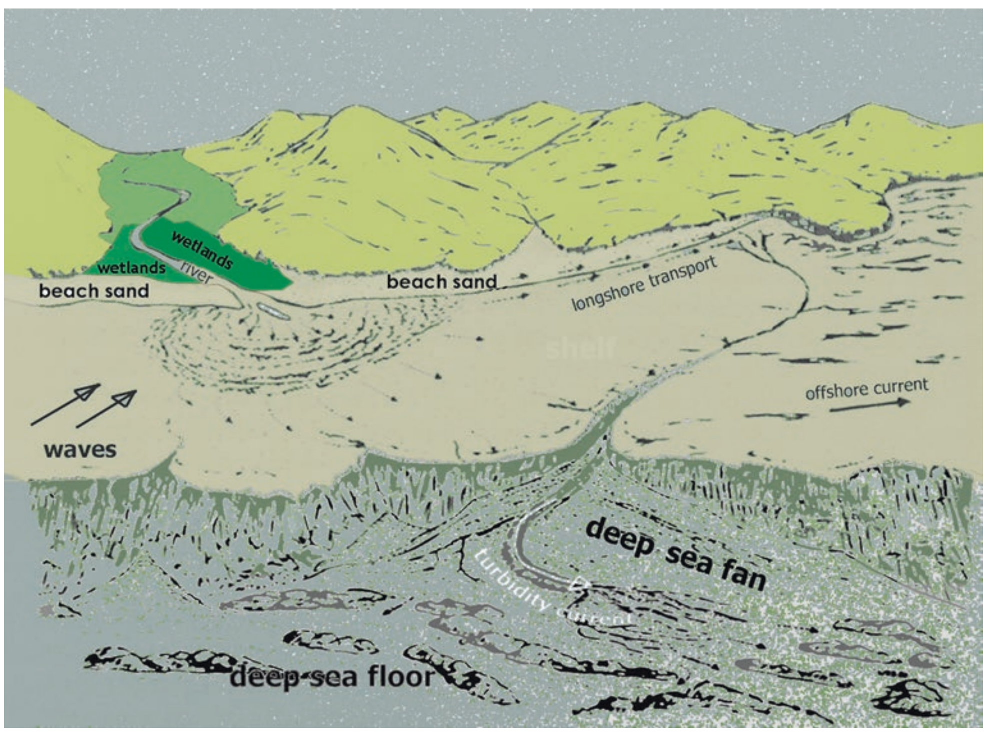

Fig. 5.1 Redistribution of sediment on the continental margin, by water motion. The drawing reflects a La Jolla (West Coast) setting. Note the river bringing material from nearby mountains (*green*), the longshore transport powered by waves, and the interception of the "river of sand" (D. Inman) by a submarine canyon that delivers the sediment to a submarine fan on the continental slope. Also note starved beaches and rocky shelf beyond the canyon. Vertical scale greatly exaggerated (Based on a drawing by D.G. Moore, US Navy Electronics Laboratory, modified; see Geol. Soc. Amer. Spec. Pap. 107: 142 (1969))

E. Seibold, W. Berger, *The Sea Floor*, Springer Textbooks in Earth Sciences, Geography and Environment,
DOI 10.1007/978-3-319-51412-3_5

Fig. 5.2 Evidence for the action of waves and currents. *Left*: ripple marks in the intertidal flats off the mouth of the Weser, northern Germany. *Middle*: ripple marks on the beach of Southern California. *Right*: Large submarine sediment dunes on the continental slope off Baja California, as found by F.P. Shepard, using seismic profiling (Photos **a** and **b**, W.H.B., graph to the *right* (**c**) courtesy of F.P. Shepard, S.I.O., excerpted)

Waves and currents leave their imprint on the seafloor in many ways, as depositional and erosional features. Familiar examples are waveforms on the sediment surface, from the smallest ripple marks to large submarine dune fields (Fig. 5.2). Others are bedding structures within the sediment, from beach laminations to thick graded layers, and also the grain of the sediment, from muddy lagoon deposits to the highly sorted sands on wave-washed beaches. Scour marks, channels, and clean-swept banks and submarine plateaus also are conspicuous evidence for erosion by currents in the sea.

Just how effective are waves and currents as sculptors on the ocean floor? To this question we turn next. Also, we need to examine the clues to be studied if we wish to reconstruct the wave and current regimes of the past from the geologic record. One way to do this is to study ripple marks visible at low tide or in echo-sounding profiles or documented by diving (Figs. 5.2 and 5.3).

5.1.2 Role of Grain Size

The details of the relationships between water motion and sediment response are by no means clear, despite of considerable study of the matter. One problem in trying to capture relationships precisely is the complicated feedback between modified water motion at the interface of water and sediment and the changing character of the seafloor surface. It is difficult to predict what will happen in a given situation based on studies of another one because grain-sized distributions, porosity, and cohesiveness of the sediment may not be precisely the same for any two situations. With a different mix of properties come different interactions.

Fig. 5.3 Measuring ripples. Diver is assessing the inclination of a lee slope of a giant ripple north of Fehmarn Island, Baltic Sea (Photo Diving Group, Kiel)

5.1.3 The Hjulström Diagram

One of the most basic questions one can ask in the context is "how strong does a current have to be to move sediment?" Answers are still being found in the "Hjulström Diagram" (Fig. 5.4).

It is reasonable to expect that coarser grains need more of a push to move than finer ones, and this is indeed what is found by experiment. Also, there is no surprise in consolidated sediment being more difficult to erode than unconsolidated deposits, with consolidated clay being rather resistant. The principles are readily established; details remain somewhat obscure, however. For example, how far above the bottom the velocity should be measured poses a problem, when contemplating the "Hjulström Diagram" (Fig. 5.4).

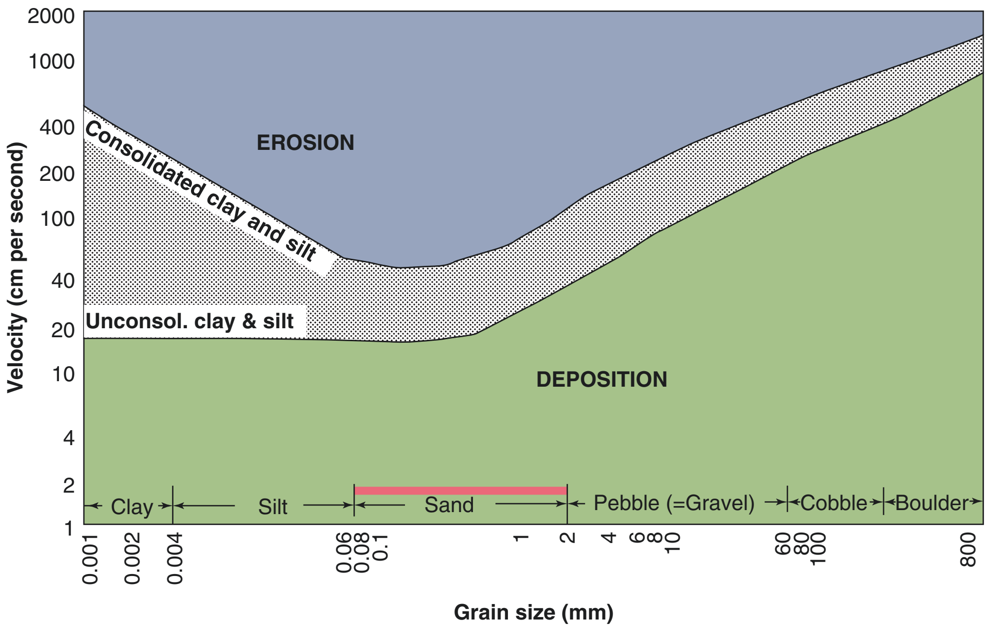

Fig. 5.4 In the Hjulstroem diagram, one might explain the cloth pattern (difference between relating current velocity somewhat above the seafloor to transport of grain-sized particles (well sorted)) (After A. Sundborg, 1956, cited in J. Gilluly et al., 1968. Principles of Geology. W. H. Freeman, San Francisco, modified). Note that 1 mm describes sand size, with 0.063 mm being the lower boundary for the category, and 2 mm the upper one (*solid red line*)

Regarding the principles, the graph of Fig. 5.4, modified from one introduced by the Swedish geographer Filip Hjulström (1902–1982) to illustrate transport by rivers, is easy enough to read. For example, we can see that sand grains of 1 mm in diameter move in a current of around 0.4 m per second (almost one *knot* in oceanographer's lingo) and that boulders are starting to move only at velocities of several meters per second. Note that the diagram is a log-log plot (a plotting method that unfailingly greatly reduces the visual impact of experimental scatter).

According to the diagram, very fine material remains in suspension more easily than material coarser than fine sand. Thus, the fines will be carried farther from the source than the coarser stuff. As a result, grain size will normally decrease in the downstream (or down-current) direction of transport, a clue to motions that can be applied along the coast, on the shelf, or even in the deep sea in places (where shape and fill are very important). However, this simple and obvious relationship between grain size and water velocity is valid only down to sizes of 0.1–0.2 mm. For grain sizes smaller than that (very fine sand and finer), water velocities may have to *increase* again to initiate erosion. Why should this be so?

The chief reason for the aberrant behavior of clay and silt is that when particles settle on the floor, the very fine sediments tend to produce a smooth surface, which reduces turbulence at the interface and thus the opportunity for pulsed pickup of sediment particles by fast water particles. The large surface areas of fine particles also provide for increased cohesion between them. Another reason for resistance to erosion is that *bacterial mats* form on fine sediment layers, mats that likewise reduce the impact of water on sediment particles by smoothening the surface. Also, bacteria increase cohesion between sediment particles.

5.1.4 Role of Water Velocity

How exactly does water move the grains? The average velocity of the current decreases on approaching the bottom and goes toward zero at the interface itself. Hence the values of current velocity given in the Hjulström diagram are applicable for some distance *above* this interface. Because of the difficulties in defining the proper distance for different conditions, modern investigations use *bottom shear stress* produced by the flow regime. Exactly how much effect a current has at the interface depends on the roughness of the seafloor and the turbulence created on the bottom. Turbulence produces sudden changes in the impact of water on a grain sticking out at the surface. Roughness is not part of the diagram, which applies to grain sets of equal size. In the real world, as current velocity increases, the frequency and force of impact pulses increase and some of the smaller grains start to move. This leads to the impacting of grains by other grains and also to a small-scale increase in roughness of the floor. Soon more and more grains start to roll and jump over the floor. The rolling and jumping grains are addressed as *bed load* of a current in contradistinction to the *suspension load,* a term applied to sediment within the water (Fig. 5.5).

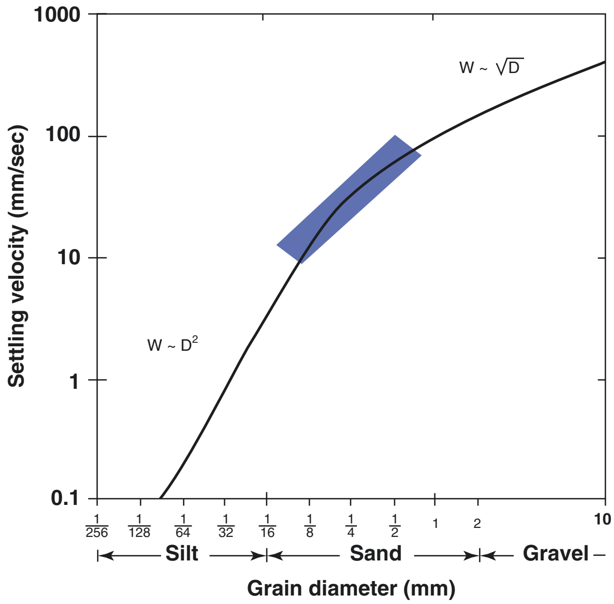

Fig. 5.5 Settling velocities of quartz grains in water. Silt and fine sand settle according to one equation (velocity a function of square of diameter; Stokes' Law) and coarse sand and gravel according to another (velocity a function of the square root of diameter). The transition zone i(*blue*) is shaded (After W.W. Rubey, 1933, as quoted in C.O. Dunbar and J. Rodgers, 1957. Principles of Stratigraphy. John Wiley, New York, modified). Note that sizes are plotted in steps of factor of two

A grain, once moving, greatly decreases contact with the seafloor. Contact vanishes entirely for the *suspended load*. Since fine grains settle rather slowly and turbulence moves many grains upward, they stay in the water for some time, once brought into suspension. Bed load and suspension load tend to go parallel, therefore. Correlations depend on grain-sized distributions and turbulence. The bed load particles, which impact each other, experience abrasion, which therefore increases with the length of transport especially for pebbles, which are thought to be 300– 400 times more sensitive to abrasion than sand grains. Below a size of 0.25 mm rounding and length of transport have no simple relationship. In fact, rounding may *decrease* down-current as the sands become finer and hence more irregular.

As is evident from Hjulström Diagram, the values for current velocities at which the sediment comes to rest are considerably lower than the values for erosional velocities. Clearly it is easier to keep sediment moving than to set it in motion from rest. One implication of the behavior of sediment captured in the Hjulström Diagram is that any current activity will tend to separate clay-sized from sand-sized material. The clay-sized particles stay in suspension long after most of the sand has settled out, as is evident in the top layer of graded beds. For the suspended load, there is no minimum velocity for transport. *Settling* dominates the scene (Fig. 5.5) and not conditions at the interface.

We have presented the processes involved in erosion, transport, and deposition of detrital sediments in a very simplified and mostly qualitative manner. The information given in the Hjulström Diagram, for example, which might be taken to be of a quantitative nature is, in fact, an illustration of a *concept* rather than a nomogram describing observable relationships with some precision.

Quite complicated experiments and theories are necessary when attempting the quantification of the processes involved, processes that are of considerable interest to geologists studying sediments and to coastal engineers who deal with changing beaches and with shore erosion. One difficulty arising is that in many circumstances the condition of the sediment being studied is inherited from the recent past and does not reflect present wave and current dynamics. *Relict* sediments in this category show distribution patterns appropriate for the past conditions. This confusing situation can be very misleading when trying to interpret present sediment patterns in terms of current conditions.

5.1.5 Role of Unusual Events

Events that result in suspension and thereby allow considerable transportation can be rather short. Also, once sediment particles are brought into suspension by currents, even a relatively weak current can keep the material moving. In providing for suspension by waves, mid- and high-latitude events are commonly linked to winter storms, while in low latitudes, hurricanes or typhoons provide common sources of forcing for various events. Effects are widespread and include the action of both waves and currents. Seasonal changes may be very important in providing for the kind of forcing that turns out to be effective. In the Yellow Sea, for example, sediment distribution is entirely dominated by the combined action of strong winter waves and associated currents. All around North America, beach sands move southward, driven by winter waves.

The occurrence of sediment-relevant events may be separated by long time intervals – long, anyway, with respect to the duration of the events. Storms do much of the moving of sediments along the shores and much of the damage observed from cliff erosion and other factors, even though the time intervals of the processes involved are brief. In the record, a geologist dealing with millions of years may see the results of events unheard of in the normal course of history. Especially large storms can rework a relatively thick layer of sediment on the seafloor, a layer subsequently undisturbed. Such layers are identified as *tempestites*, that is, as a record of unusual storm activity.

5.2 Effects of Waves on Sediments

5.2.1 Beach and Shelf

One notes chiefly three kinds of waves (Fig. 5.6) in a nonscientific way: (1) the everyday waves, commonly originating

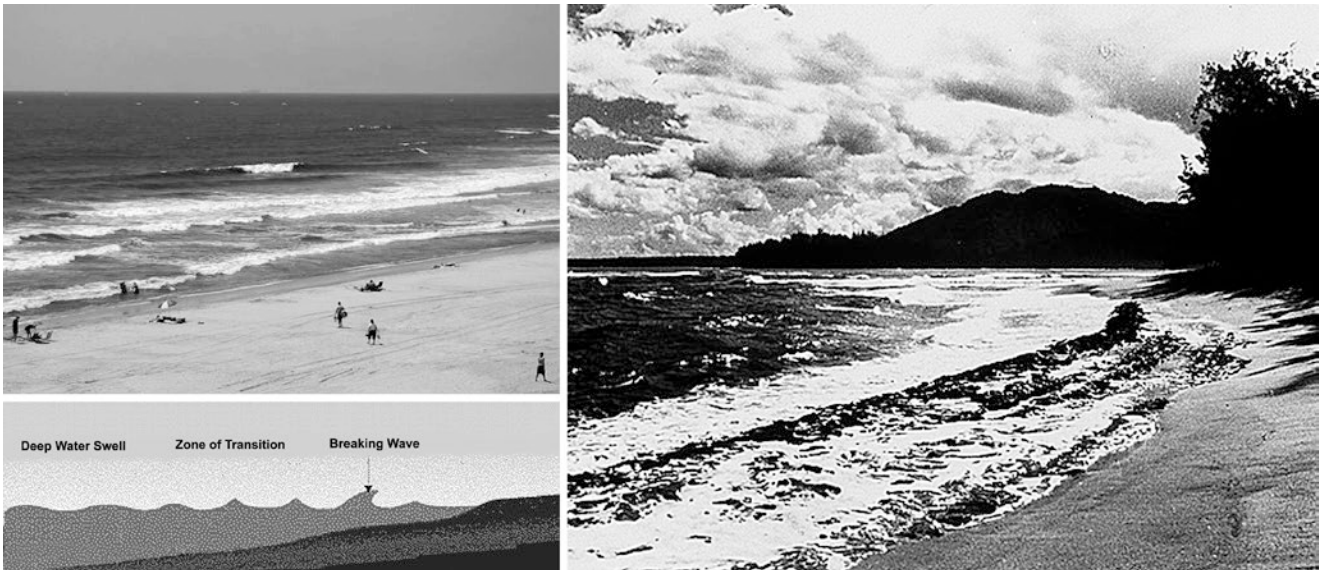

Fig. 5.6 Regular wave climate. *Left*: on a beach in San Diego County. *Right*: in Hawaii. Waves slow in shallow water and steepen. They break when the slowdown of the wave base attains a critical value so that the top of the wave becomes faster than the base (Beach photos W.H.B., graph of breaking wave: NOAA)

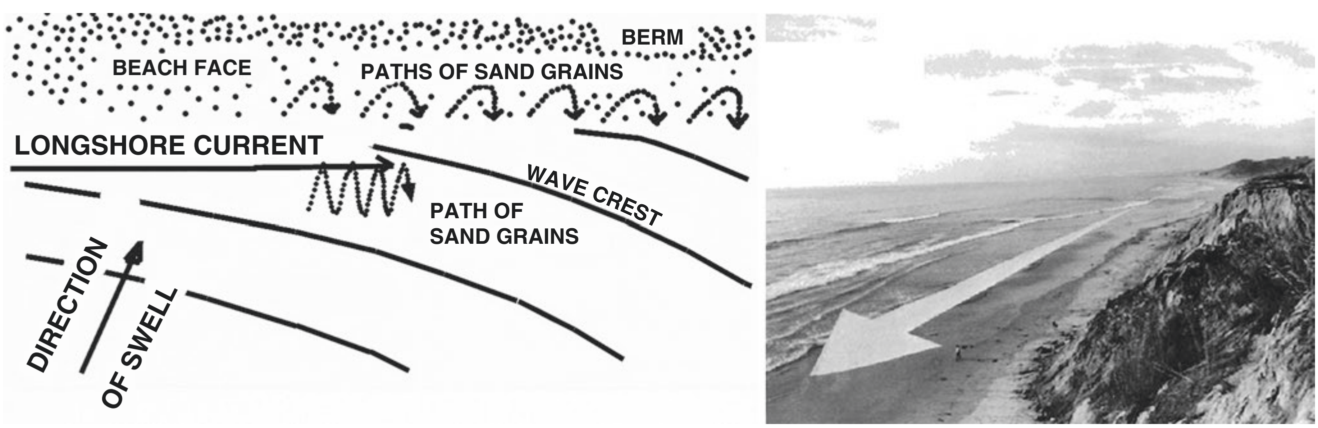

Fig. 5.7 Sand motions on the beach. Overall, sand moves southward on both West and East Coast of North America, driven by waves from northern storms (Graph and image inspired by W. Bascom (*graph on left*) and D. Inman (*image on right*)) see SW. H.B., 1976, Walk Along the Ocean. S.I.O., La Jolla

from storms and traveling many hundreds of miles before arriving at the shore, (2) the long waves that traveled thousands of miles and originated in large southern storms, even storms from off Antarctica, and (3) the winter storm waves, which in California come from northerly regions and make rather choppy surf upon breaking, a surf poorly suited for surfing. Scientifically, the various types of waves are characterized by length and period.

Choppy waves made by local winds are well distinguished from the swells that carry energy from distant storms and typically have a longer period than the chops. All types of waves move sediment after breaking along the shore, as seen in comet marks and other sand patterns on the beach. But the *winter storm waves*, as the most energetic ones, are chiefly responsible for transport of beach material (Fig. 5.7), a transport that ends with filling canyon heads and creates the conditions for turbidity currents running down those canyons (Fig. 5.1).

The energetic winter waves of Southern California, generated by northern storms, move sand out, exposing a rocky beach terrace on occasion (Fig. 5.8). Also, powerful waves can result in the coastal erosion that produces so many problems along many shores (Fig. 5.9).

Not all beaches are chiefly made of sand, of course. In latitudes with morainal debris, one finds pebble beaches and other beaches with coarse material (e.g., in East Anglia and around the Baltic Sea and in the Svalbard archipelago and in Alaska). Also in low latitudes, storms can add plenty of coarse material to the beaches (such as reef debris, e.g., in the Caribbean and in Hawaii). In some places there is pebble-sized volcanic debris.

Fig. 5.8 Seasonal change in sand cover, beaches of La Jolla, California. Summer condition: *far left*. *Middle*: winter condition. *Far right*: wave-cut terrace at sea level near SIO (Photos W.H. B)

Fig. 5.9 Cliff erosion in Oceanside, San Diego, endangering roads on a terrace next to the shore (Air photo W.H. B)

Wave motion quickly decays with depth in the water. At depths greater than one half the wavelength, there is virtually no motion from surface waves. Surface waves involve only the uppermost part of the water column. We can be fairly certain that strong winds were responsible for making the waves in the first place and that wave-driven motion of sediment must be largely confined to the region bordering the beach. *Internal waves* also exist, at the thermocline and at other density discontinuities in the water column. Such waves have been shown to induce currents in submarine canyons, and they may be rather important in pumping nutrients into surface waters above canyon heads. On the whole their origins may vary (the tides apparently are commonly involved) and their effects are not well known. Waves called *tsunamis* can be generated in deep water by earthquakes and associated motions, by submarine landslides, and by volcanic eruptions. Such waves, traveling at the ocean surface, have lengths measured in kilometers and they move at the speed of a jet plane.

In general, the maximum depth to which sand is being moved below a surface wave, the *wave base*, is near 10–20 m. In exceptionally strong storms, wave motions can reach considerably deeper. Evidence is hard to come by, however. Thus, for example, while ripple marks are seen on shelves even out to the shelf break, they presumably formed during glacial times, aided by a drop in sea level. In any case, the relative importance of surface waves, past waves, internal waves, tides, and currents in producing such ripples is not necessarily clear. Some years ago symmetrical ripples were discovered in fine sands of the outer shelf off Oregon at depths to 200 m, with crest-to-crest lengths of 10–20 cm and with the crests parallel to the coast. These oscillation ripples are thought to have been produced by winter storms on a shelf then only thinly covered.

Despite of numerous problems in interpreting extant ripple marks on the shelf, "wave base" is a useful concept. The concept is important not just for wave motions per se but also for the distribution patterns of sediment types and for benthic organisms. The composition of benthic organisms changes greatly across the wave base boundary, presumably in response to changes in sediment motion.

5.2.2 Storm Action and Storm Damage

We already mentioned the ability of strong waves and associated currents to clear a terrace of its sediment and to vigorously erode cliffs (Figs. 5.8, 5.9, and 5.10). At Boomer Beach in La Jolla, the beach forms in summer next to a slightly uplifted (geologically young) terrace made of marine rocks of Cretaceous age (rocks that were made of sediment once deposited well below the shelf edge). The place has become a prime tourist attraction, in part because of the spectacular breaking waves on the rocky point (hence the name "boomer") and in part for the fact that the beach lately is a favorite hangout for harbor seals and their pups at the southern end of its extent, where a man-made barrier calms the waves and sand is present all year. In winter, in response to wave attack, much of the sand along the northern and the middle portions of the (unprotected) beach moves offshore, leaving underlying rocks and gravel exposed. The sand that collects offshore forms bars whose position can be recognized from the shore by observing the breakers that form on top of them. (Very shallow water slows down waves and makes breakers.)

Where beaches are narrow or missing altogether, storm waves can hit the coast with force. Armed with gravel or sand, breakers can dig a deep notch into cliffs, especially in places where the rocks at the base of the cliff are somewhat softer than normal. When the notches and sea caves become large and deep enough, the overlying material collapses and the cliff retreats. This type of cliff erosion (*notch cutting*) makes for wave-cut terraces (Fig. 5.8) as well as for steep cliffs (Fig. 5.9). Also, by grinding up the fallen rocks, storm waves produce additional beach sand while cutting into the land.

An obvious response to wave attack is the construction of defensive walls to protect the shore. However, walls are quite vulnerable to wave attack. Attacking waves remove the support at the base, so that a wall eventually topples over toward the sea. A more effective way to tame a furious sea is to pile up "rip rap" (i.e., large boulders) or "tetrapods" (i.e., man-made concrete structures). Or else one can construct dams with gentle slopes, where breakers can spend their energy

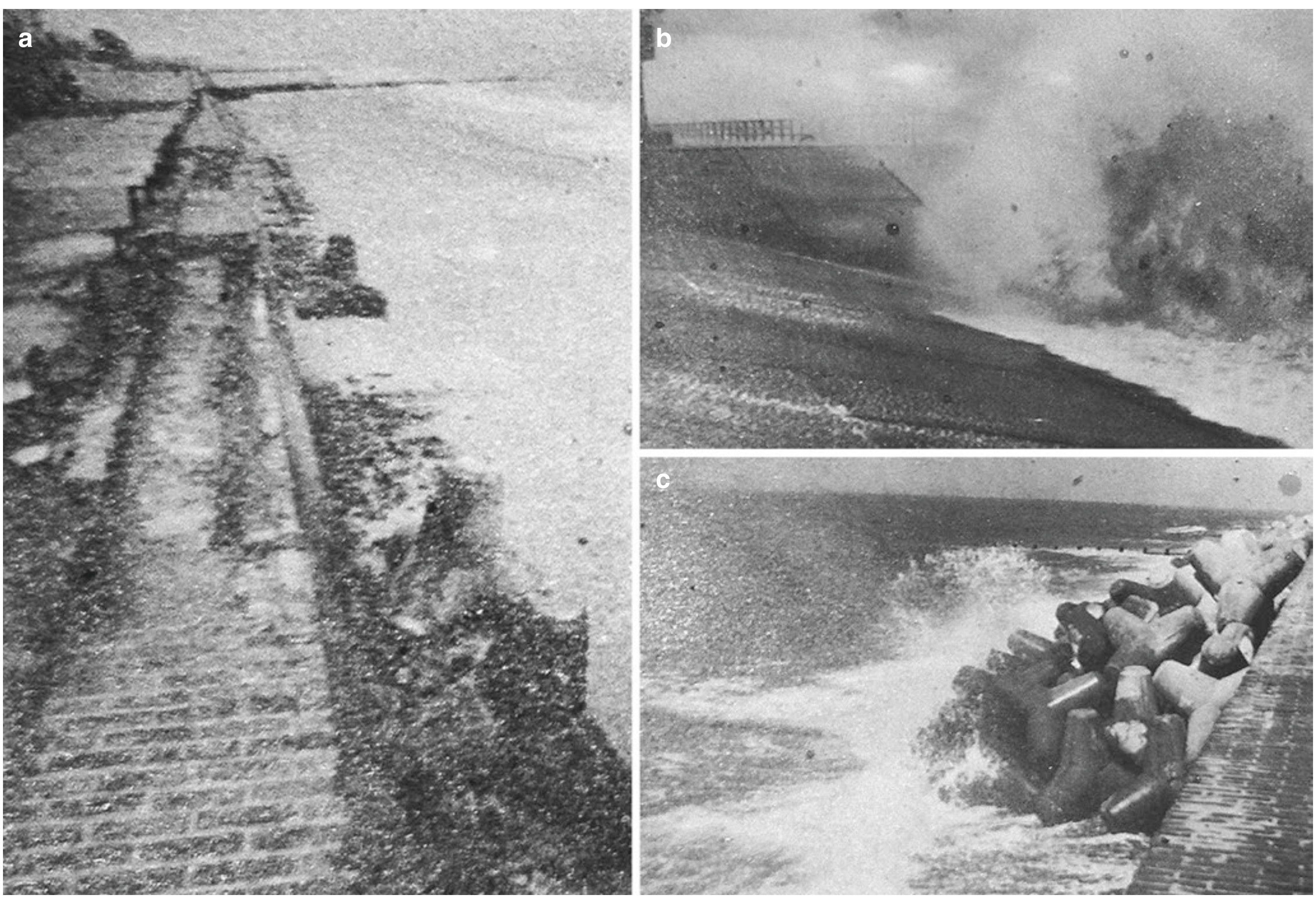

Fig. 5.10 Defense against violent surf action in Westerland, Island of Sylt, German North Sea. (**a**) Damaged beach wall and displaced tetrapods; (**b**) gently sloping wall for breaking the power of storm waves; (**c**) interlocking tetrapods dissipating energy before damage is caused (Photos E.S. (**a**) and courtesy J. Newig (**b** and **c**))

(Fig. 5.10). Also, energy-consuming friction and turbulence can be enhanced by providing for rough surfaces on such slopes.

Whenever dealing with shore defense, or in fact whenever dealing with the dangerous side of nature, it is well to recall the advice of the British Renaissance philosopher Francis Bacon (1561–1626) who believed in scientific observation and experiment: "Who would rule Nature must first obey her."

Bacon thought it is worthwhile to study what actually happens in nature, before trying to steer events.

5.2.3 Tidal Waves

Tidal currents are ubiquitous on continental shelves. They are produced by tidal waves, which owe their existence to the Earth's moon and the interaction of its gravitational field with that of the sun and the tidal forcing of both experienced by Earth. In Southern California, including La Jolla, we have mixed diurnal tides, with one of the two crests per day being somewhat higher than the other. Elsewhere the smaller crest may disappear entirely (*diurnal tide*), or it may reach the elevation of the larger tide (*semidiurnal tide*).

The puzzle for the uninitiated is that some simplified textbook schemes with a water-covered Earth show two similar tidal crests associated with each Earth rotation in an explanation of diurnal tides. Given the sense of gravity, why is there a bulge opposite to the moon? The solution to this puzzle is that the moon does pull a bulge where it is closest to Earth, but it also generates a second one at the opposite side, which reflects the difference between the lunar gravity and the opposing centrifugal force between the moon and the Earth. The forces keeping the moon up there are in balance, but only on average, not locally.

The normal tidal wave has a period of 12 h and 25 min, one half of the length of the lunar day, which is 24 h 50 min long – slightly longer than the rotation period of 24 h. The lengthening of the lunar day relative to the Earth day is due to the fact that the moon moves eastward. Thus it takes slightly more than one Earth rotation (a day) to get the moon to reappear at the same meridian as the day before. Tidal action does depend on the sun as well. When in line (sun-Earth-moon or Earth-moon-sun), the forces add up straight and we have a spring tide, with tidal action at a maximum. But when the celestial bodies are at right angles (with Earth at the point of intersection of the defining lines), the sum of forces is much weaker and we get a neap tide.

Tidal currents are set up especially along the continental margins – typically on the shelves. Whenever there are no shelves during glacial times, most of the tidal energy must be lost elsewhere, presumably in the deep sea. Even at present, we think we see evidence for tidal action on the deep seafloor. However, the most conspicuous evidence at present is on shelves, in shallow water. Effects include the uncovering of burrowing mollusks, as well as ripple marks (Fig. 5.11).

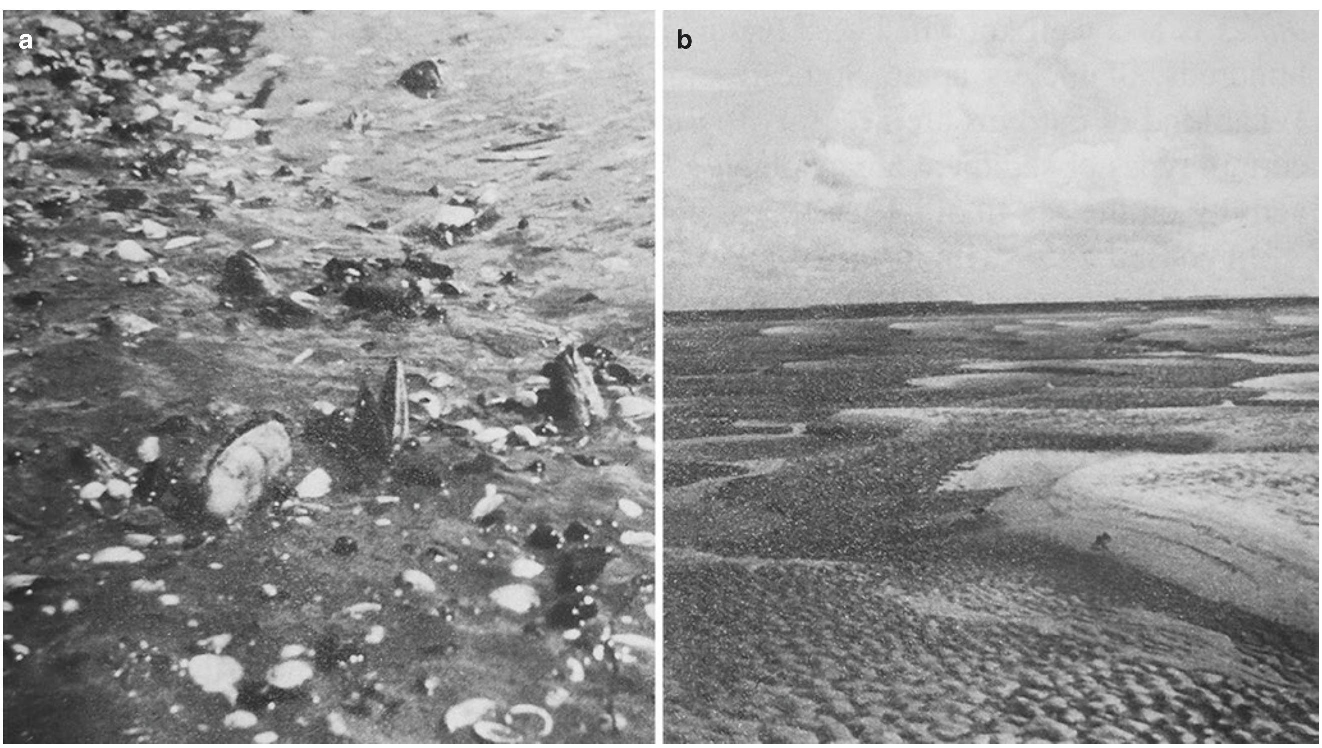

Fig. 5.11 Current action in tidal flats, German Bight, North Sea. (**a**) *Mya arenaria* in life position uncovered by erosion by migrating tidal channel; (**b**) ripples off the Weser, produced by currents of the outgoing tide. Note the presence of both large and small ripples (Photos E. S)

Current ripples tend to be at right angles to the current creating them. Their shapes are controlled by the flow of water over the seafloor that results from the presence of the ripples themselves. Thus, we deal with a complicated feedback system, whereby currents make ripples, and ripples stabilize ripples and make more of them, extending them sideways (hence the washboard aspect of ripple marks).

5.3 Effects of Currents on Sediments

5.3.1 Shelf Currents in General

There are many clues to the direction and strength of past currents at the seafloor, as mentioned when discussing size distributions. Winnowing (the separation of fine from coarse material) is one type of clue; scour marks behind obstacles is another. Responding to density gradients within an almost unconstrained environment, flow in the sea is turbulent. Also, it is influenced by the Earth's rotation. The use of side-scan sonar, both on the shelf and in the deep sea, has greatly increased our knowledge about the nature and distribution of bottom-near currents (Fig. 5.12). The currents are not seen directly on the sonar graphs but are inferred from their effects on sediment patterns on the seafloor. Streaks of coarse material in fine sediments, a result of current action, were discovered at the entrance to the Baltic Sea by such acoustic sensing (Fig. 5.13). In the deep sea, also, current-generated sediment streaks, ripple marks, and other markers have been discovered.

5.3.2 Currents in the Open Sea

Of all ocean currents, the *Gulf Stream* js perhaps the most familiar (Fig. 5.14). It is the largest and most important current of the northern hemisphere, transporting nearly 100 million cubic meters per second of warm water northward into colder regions. Some of this water even reaches the shores of Norway, keeping coastal fjords free of ice all winter. For comparison regarding the volume of transport, extraordinary peak floods of the Mississippi might carry as much water as one half of a thousandth of the usual Gulf Stream transport.

The Gulf Stream is best understood as the western limb of the great North Atlantic gyre, driven by the trade winds in the south and the west winds in the north. The eastern limb is provided by the Canary Current and is associated with upwelling along the coast, a phenomenon of central importance when discussing the productivity of the sea (Chap. 7). The center of the gyre (which marks a desert area of the ocean in terms of production) is near 30°N, in the Sargasso Sea. There are five such great gyres on the globe: North and South Atlantic, North and South Pacific, and southern Indian Ocean. In each case, the west winds and the trades provide the driving forces, and the western and eastern boundary

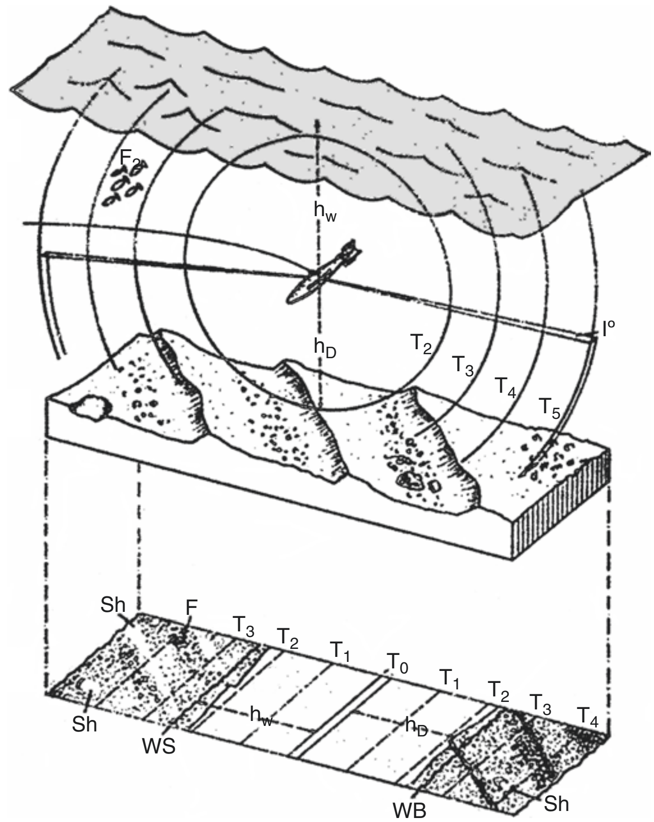

Fig. 5.12 Principle of side-scanning echo sounder. (**a**) Water surface; (**b**) seafloor with ripples and rocks; (**c**) acoustic recording of the area (sonograph). T0, outgoing sound pulse (see in *panel c*); other Ts with subscripts: sound waves emanating from the sound source, the "fish"; Sh, acoustic shadow; F1 and F2, fish schools, and their acoustic image; hw, distance of the sound source to the water surface; hb distance of sound source to seafloor (R.S. Newton et al., Meteor Forschungsergeb. Reihe C 15:55; simplified)

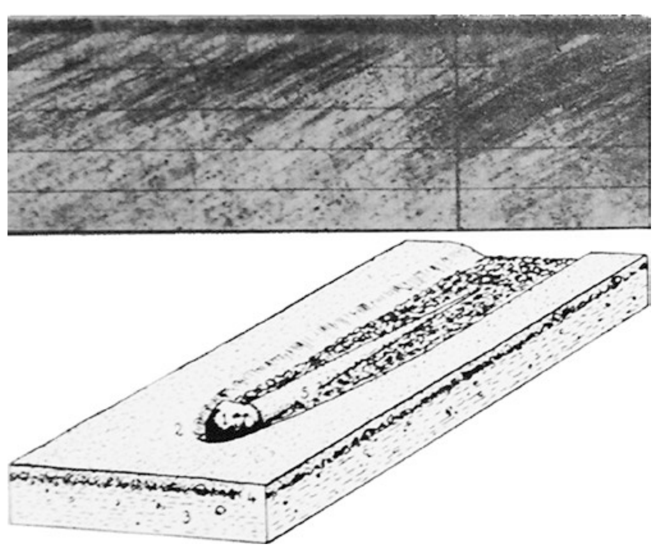

Fig. 5.13 Bottom current indicators in the Big Belt Channel in the Baltic Sea ("Store Belt") between the Danish islands of Langeland and Lolland. *Upper panel*: excerpt of sonograph (one side only). Length of the record is 2 km. Water depth is approximately 12 m (Source: F. Werner, Kiel). A "comet mark" (details by diving) may result from turbulence behind an obstruction interfering with the current. Sediments consist mainly of moraine material (Courtesy F. Werner, Kiel; See F. Werner et al., 1980. Sediment. Geol. 26:233)

currents complete the "gyres" (a term introduced by the physical oceanographer Walter Munk, S.I.O.).

Normally, the surface currents of the open ocean reach down to about 100 or 200 m, and their velocities are low: a fraction of a knot. The Gulf Stream, however, and other fast narrow boundary currents like that (e.g., its sibling off Japan, the Kuroshio) reach to a depth of some 1000 m and have velocities of a couple of knots or so (~100 cm/s). According to the Hjulström Diagram (Fig. 5.4), such fast currents can carry grain sizes beyond the coarsest sand. The Florida Current, which brings Caribbean waters into the Gulf Stream through the Florida Straits, reaches velocities of six knots (300 cm/s).

5.3.3 Northern Heat Piracy

The Gulf Stream is a major means of heat import into high northern latitudes in the Atlantic (*North Atlantic heat piracy*). The North Atlantic heat piracy ultimately results in a large warmwater anomaly in and around the Norwegian Sea, a fact that is reflected in the planktonic shells accumulating on the seafloor in the area. The warm current that starts as the Gulf Stream is intimately linked to the ocean's deep circulation in the Atlantic. Surface waters moving north have a large component of salt-enriched water thanks to enhanced evaporation in the central North Atlantic. Upon cooling in high latitudes, this salt-rich water becomes heavy enough to sink to great depth. In doing so, it starts deep-water and bottom-water southward flow in the region (Fig. 5.15). The resulting stratification pattern in the deep Atlantic reflects anti-estuarine circulation and is an important control on sediment patterns.

Present circulation patterns changed markedly over geologic time, as suggested by the sediment sequences obtained by deep-ocean drilling (Chap. 12). The evolution of an anti-estuarine North Atlantic starting in the middle Miocene

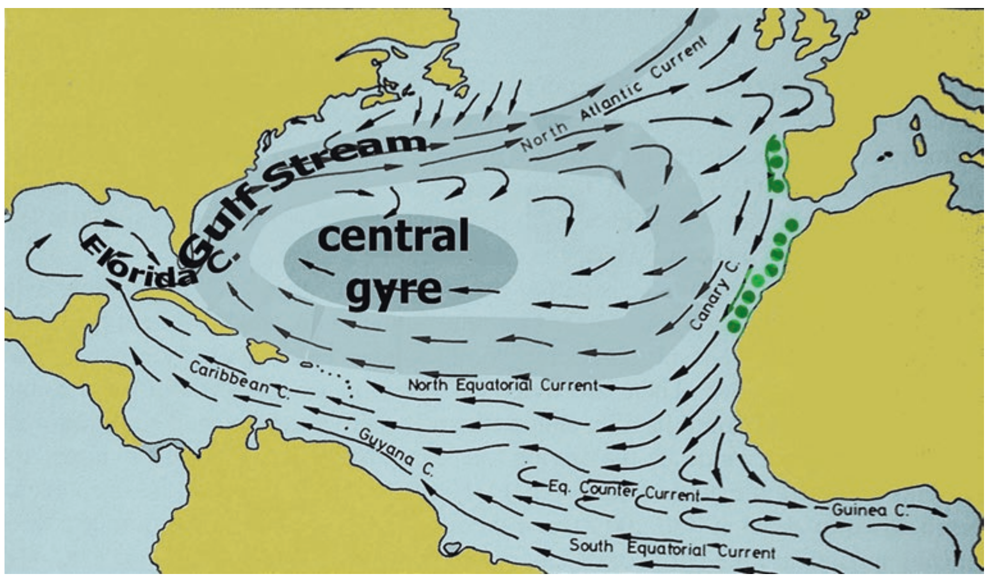

Fig. 5.14 The Gulf Stream off the Atlantic US coast, carrying warm water to the offshore areas of NW Europe. It is fed warm and salt-rich water by the Florida Current (and also by the central gyre). Upon cooling, such water can sink to the bottom. *Green dots*: coastal upwelling (Background chiefly after G. Neumann and W.J. Pierson, 1966. Principles of Physical Oceanography. Prentice-Hall, Englewood Cliffs)

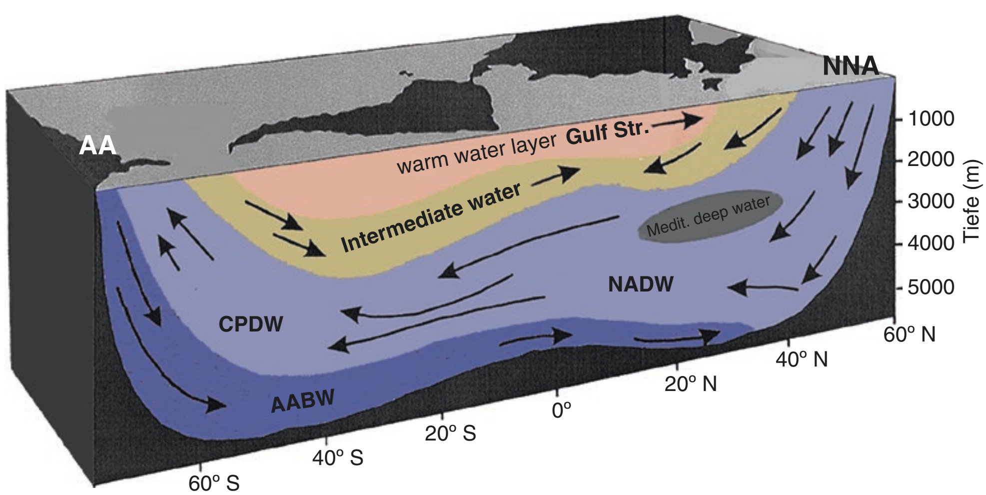

Fig. 5.15 Anti-estuarine nature of deep circulation in the Atlantic. *NNA* northern North Atlantic, *NADW* North Atlantic Deep Water, *AA* Antarctic, *CPDW* circumpolar deep water in the Antarctic ocean, *AABW* Antarctic bottom water (After G. Wefer et al., in G. Wefer and F. Schmieder (eds.) 2015. Expedition Erde. Marum, U. Bremen, p. 329; modified and color added)

implies the development of a balancing estuarine circulation in the deep North Pacific with implications for deep basin-to-basin exchange patterns.

Before the serious cooling of the planet in the Oligocene, heavy bottom waters presumably were not made in high latitudes, but elsewhere closer to the equator. Shelves in the ancient seaway called "Tethys" are attractive candidates, owing to present-day observations in the Adriatic Sea east of the Italian peninsula, where Mediterranean deep water is made by winter cooling of saline shelf water. Salinity effects, of course, are important everywhere when making heavy deep waters. In today's polar regions, the effects from the rejection of salt from freezing sea ice commonly dominate. Evaporation is important in the subtropics, and always was, one assumes.

The North Atlantic deep circulation with its strong link to heat transport represents the most conspicuous portion of the "global conveyor," the inferred worldwide circulation system reproduced in many oceanography textbooks and commonly credited to Lamont geologist and chemical oceanographer W. S. Broecker. The *conveyor* links the motion of surface waters and deep waters and reflects well the heat transport between ocean basins and between hemispheres. The sedimentary record suggests a beginning in this circulation roughly 15 million years ago, in an event that was arguably linked to the buildup of ice masses in Antarctica (the middle Miocene "Monterey Event" in Chap. 12).

5.3.4 Bottom Water Circulation

There was a time, a century ago or even less, when the deep ocean was thought to be a quiet and calm environment with weak currents, currents that were considered rather unimportant as far as shaping the seafloor. The first indication that this concept could be quite wrong came from the calculations of the physical oceanographers Georg Wüst (1890–1977) and Albert Defant (1884–1974) in the 1930s, in the wake of the famous German *Meteor* Expedition (1925–1927) (which also delivered initial data on the stratification of the Atlantic shown in Fig. 5.15). These two scientists showed that the distributions of temperature and salinity seen in the closely spaced profiles of the *Meteor* in the deep central Atlantic implied strong bottom-near flows driven by density differences. Such currents hug the slopes of ocean margins and the flanks of mid-ocean ridges following density surfaces.

The currents at issue are commonly referred to as *contour currents* (by marine geologists) or as *deep geostrophic currents* (by oceanographers). Their effects are clearly seen on deep-sea photographs as streaks or ripples reminiscent of the features in shallow water. Deep currents are strong enough to erode the seafloor in places, especially where confined to passages. Erosion occurs, for example, where abyssal bottom water passes through the Vema Channel off Argentina or through the Samoan Passage in the deep central Pacific.

The NADW (North Atlantic Deep Water) that sinks in the Norwegian Sea falls over shallow passages in the Greenland-Faroe Ridge northwest of Scotland in enormous undersea cataracts. As the NADW moves south in the western trough of the Atlantic toward the Circumpolar Current, it makes the *Deep Western Boundary Current,* which affects the seafloor along the deep eastern margin of North America. Coarsening of silts, alignment of magnetic grains, and the making of mud waves, ripples, and scour marks indicate its presence, forming *contourites*. Deep *contour currents* were investigated in detail during the *HEBBLE* (High Energy Benthic Bottom Layer Experiment) project at 4800 m depth off the US East Coast near Woods Hole. One surprising finding of the study was the discovery of strongly pulsed *abyssal storms* lasting between 2 and 20 days and occurring several times a year. Currents of such "storms" can approach velocities of one knot and carry sand over enormous distances. The origin of the storms is commonly sought in eddy formation within shallow water, eddies whose energy is partially transferred to great depth.

In general, the frictional interaction between bottom currents and the seafloor results in a *benthic boundary layer,* which is on the order of a few hundred meters thick. Compared with the overlying deep water, it has a high content of suspended matter and is characterized by turbulent motion. Also, its chemistry is distinct. This water layer, in combination with the bioturbated layer of sediment on the seafloor, forms a system within which seawater/seafloor interaction is a dominant process controlling benthic life, sedimentation, and geochemistry.

At present the *Antarctic bottom water* (*AABW)* covers vast regions of the deep seafloor. Also, it causes dissolution of calcareous sediment – a process that profoundly affects all of deep-sea sedimentation (Chap. 10). The AABW originates on the shelf of the Antarctic mainly in the Weddell Sea. The processes involved consist of cooling of locally available seawater loaded with salt from the making of sea ice. Being heavier than other water in the deep ocean, AABW sinks and fills abyssal basins. For the filling to proceed in any one basin, of course, there must be access to the basin.

Besides small-scale scour features and ripple marks on the deep seafloor, there are some large-scale features in places, features that likewise indicate the activity of bottom currents. Among these are giant submarine dunes (Fig. 5.16). The deep-side-looking sonar developed in the late twentieth century by the marine geophysicist and engineer Fred Spiess and his colleagues at S.I.O. has revealed an abundance of dunes, sediment ridges, and erosional ravines in many places at abyssal depths, even where deep currents were not suspected. (Of course, one must always keep in mind that any attempts

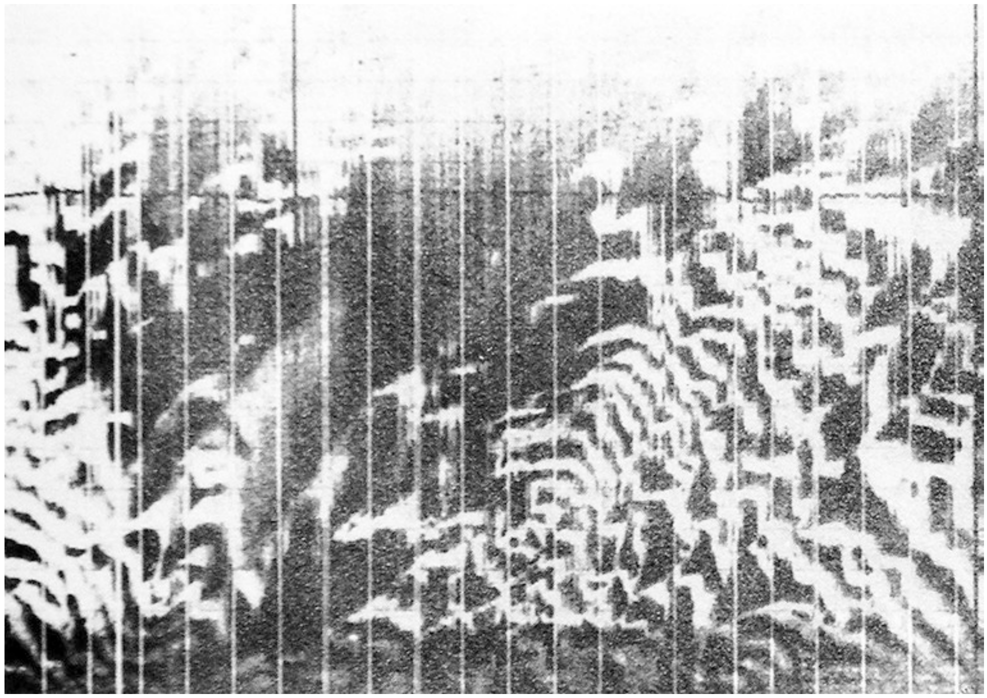

Fig. 5.16 Giant submarine dunes in the Carnegie Ridge area, eastern tropical Pacific. Side-scan sonograph taken at 2.4 km depth. Long edge of the area surveyed roughly 1 km sediment is calcareous ooze (Recording courtesy P. Lonsdale and B.T. Malfait, S.I. O)

to link sediment features to measured currents could be futile if the features seen have nothing to do with present water motions, being inherited from conditions of a distant past. We point out, again, that when shelves are drained during maximum glaciation, tidal action is confined to the deep sea.)

5.3.5 Exchange Currents

The currents that provide for the exchange of waters between marginal semi-enclosed seas and the open ocean are geologically highly significant. The *nature of the exchange* (commonly known as "estuarine" or "anti-estuarine") entirely dominates the chemistry and productivity of a marginal basin through regulation of oxygen and nutrient abundance, with corresponding control on sedimentation.

In arid zones excess evaporation over precipitation produces relatively heavy surface waters in marginal basins, water masses that flow out to the open ocean at depth and are replaced by import of nutrient-poor surface waters of the open ocean. Prime examples for this type of circulation are the Mediterranean Sea and the Persian Gulf. As a result of this *anti-estuarine circulation*, the Mediterranean seafloor has very little diatomaceous sediment and is poor in organic carbon and phosphatic materials, but has abundant calcareous deposits, as does the Persian Gulf. The inverse situation – shallow current out, deep current in – is typical for estuaries and occurs on a large scale in the Black Sea and the Baltic Sea. Excess precipitation over evaporation is necessary to develop this *estuarine circulation* or freshwater inflow, as in estuaries.

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