14 Resources from the Ocean Floor

14.1 Background

14.1.1 Principles and Expectations

The one resource originating in marine deposits and also of prime importance economically at present is *petroleum*. Energy use is basic to a flourishing economy, so that the item has traditionally received much supportive attention both from elected politicians and from other decision makers in the industry and elsewhere. However, in recent decades, it has become obvious that the use of carbon-based fossil fuels involves uninsurable risks. Manageable and insurable risks are largely confined to activities concerning obtaining the resources. The risks with regard to energy waste disposal (mainly carbon dioxide), however, are much larger, involving unwanted climate change, as well as sea-level rise and other associated serious problems.

Generally, when geological services are in demand (including those for marine geology), they increasingly involve dealing with conflicts stemming from the danger of pollution and other topics concerning the public interest. Problems related to climate change have become especially prominent, since the burning of carbon for obtaining energy produces an important greenhouse gas that interferes with the natural radiation balance.

To be sure, a growing demand on carbon-based energy (regardless of any associated downsides) presumably will dominate the economic scene yet for some time. One might assume (based on what is happening) that oil and gas will remain the most sought-after resources from the seafloor, whatever our individual preferences or insights are concerning what the future might be. To emphasize the importance of less-discussed but similar issues, we note that the need for waste disposal likewise will keep growing. Disposal of waste at sea can represent considerable economic benefit to the dumper (and dispersed environmental risk to all others).

Conflicts are common. Geologists involved with conflict resolution are likely to be faced with extremely difficult problems arising from urgent requirements. For example, cities produce waste, and they need to deal with the pileup, preferably in the cheapest possible way. On the other hand, the tourist industry needs clean beaches and a clean ocean for its customers if it is to stay in business.

Getting an acceptable beach in the first place, while simple in principle, may turn out to be rather expensive. Who is to bear the cost? The search for cheap and suitable offshore sand to use for beach replenishment will acquire increasing urgency as sea level rises from the melting of ice on the planet, with considerable impacts on the tourist industry and the safety of nearshore structures.

From an economic perspective, a shallow resource is better than a deep one, because access is better (i.e., cheaper) in shallow than in deep places. Inasmuch as many important resources represent growing biological products, they are linked to shallow (sunlit) waters and hence tend to be rather accessible, that is, they are found largely in certain shelf basins and also on the upper continental slope. The fact that many resources share this property of shallowness increases the likelihood of conflict, of course.

For hydrocarbons, there is a requirement for maturation from the organic matter originally deposited, which implies an abundance of heat and geologic time, that is, special circumstances. Obviously, where tar or other petroleum products ooze out of the ground, such geological requirements are likely to have been met (Fig. 14.1), and the resource may safely be assumed to be abundant in the underground.

14.1.2 On the EEZ

The EEZ is a fact that requires paying much attention to whenever exploring the seafloor anywhere near the shore. The

E. Seibold, W. Berger, *The Sea Floor*, Springer Textbooks in Earth Sciences, Geography and Environment,
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Fig. 14.1 Petroleum in the seafloor of Southern California. *Left*: tar seeping from the beach cliffs at Carpenteria; *right*, offshore production rig off nearby Santa Barbara (Photos W.H.B.)

"exclusive economic zone" has its origin quite obviously in economics. The EEZ denotes a 200-nautical mile zone adjacent to national boundaries. Established by agreement between nations in 1982 (United Nations Convention on the Law of the Sea), it restricts the right of geological exploration and any resource extraction on areas next to national boundaries to the nation owning the EEZ. In essence, since hydrocarbons are the one resource that really matters, the convention assigns the rights to explore for or produce hydrocarbons from the seafloor adjacent to a country. To be sure, fisheries played a role in introducing the concept and are still important in places. But the focus of the EEZ is largely on hydrocarbons.

The EEZ is of interest in all marine geological work that occurs within or close to 200 miles of land, including islands. Permission must be obtained from the EEZ owner for any exploration within the EEZ (including seismic profiling, sampling, and drilling, whether or not for commercial purposes). Permits are obtained commonly well ahead of an expedition. The perception is that geological knowledge is an important economic factor, whatever the intent of obtaining it. Thus, there is a strong motivation for controlling the creation and dispersion of the type of knowledge produced by marine geologists.

For many barren islands, especially small ones, the EEZ seems to be the one item that matters to the owning nation. Presumably, small barren and surf-swept rocks defining the EEZ are of little or no interest by themselves in most circumstances. It is the control of the surrounding seafloor that counts.

14.2 Petroleum Beneath the Seafloor

14.2.1 A Focus on Petroleum

The chief reason for the great interest in petroleum from the seafloor is economic: it is possible to extract petroleum profitably in large amounts (as long as proper safety rules of extraction are followed). Besides, demand on fossil energy sources is rising markedly, decreasing chances that eventually excess supply will depress prices to unacceptably low levels. Also, the earnings by the world's oil production are measured in trillions of dollars. They are in the same category as national incomes even of large nations. Offshore production plays a significant role in this, with revenues in the USA reported in the tens of billions of dollars per year and job creation in the tens of thousands. Demand is generally increasing globally for petroleum, gas, and coal, regardless of expert warnings and of any expressed national preferences for non-carbon energy. The discrepancies between perceived economic necessity (decades) and planetary reality (which includes millennia and centuries and even millions of years) obviously result in confusion and also in conflicts. Commonly, both confusion and conflict interfere with the goals of international climate conferences. Avoidance of tough decisions is another problem. For the sake of clarity, confusion, conflict, and avoidance, so far, have prevented the adoption and execution of the type of economics acceptable to climate scientists (i.e., an economy that avoids carbon-based energy).

The "exclusive economic zone," with resources commonly in shallow waters and hence quite accessible, naturally has been an object of intense scrutiny for hydrocarbon resources over the last several decades in many nations. The payoff sought is measured in terms of supply of energy that is considered economically affordable, in terms of jobs created and of tax monies collected. Economy-based concerns about conflict of carbon-energy use with the tourist business and with regional fisheries have led, in some cases, to significant restrictions on offshore hydrocarbon development in the EEZ. Concerns about undesirable effects on global climate change of carbon-based energy use – although well recognized as an issue by relevant scientists and by many politicians – apparently have had much less recognizable impact on policy.

In 2015, world production was about 5 billion tons of petroleum (up from 3 billion near the end of the last century). Prices were highly variable (they are measured in US dollars per barrel, a unit seven times smaller than dollars per ton). The total value was well in excess of a trillion US dollars (i.e., more than a thousand billion). In addition, there were 3 trillion cubic meters of natural gas production (at a price of around $50 per thousand cubic meters). Around one half of the oil used and more than one fourth of the "natural gas" (mainly methane) came from offshore sources. The discovery that much oil and gas previously unavailable can be extracted from known (and previously exploited) hydrocarbon and carbon deposits by creating new pathways for the movement of fluids and gas underground has changed all assessments for hydrocarbon resources in the ground and their accessibility. For many instances, invoking the possibility of *fracking*, the availability of water may constitute a severe limitation, one that presumably would not apply in an offshore setting. "Fracking," even well offshore, may however result in conflicts with users of potable groundwater close to the shore, largely for similar reasons as apply on land.

14.2.2 Methane Ice and Hydrate

Conventional hydrocarbon energy resources have a new potential partner: methane ice, called methane *hydrate* by geochemists. "Hydrate" is the name for ice that holds large amounts of gas in its structure, which is much more accommodating than would be regular water ice (which contains some air, mainly as bubbles). The gas of interest commonly is methane (CH_4), but other types of gas can be at issue. Thus, hydrate has been discussed in the context of sequestration of carbon dioxide on the deep seafloor. Almost all natural gas hydrate resources in the sea are thought to occur below the seafloor close to continents. (Petroleum reservoirs on land, coal, and permafrost masses have large potential resources of this type, as well.) So far, commercial exploitation of marine methane is not much in evidence, presumably mainly because generating natural gas from hydrates and transporting it to market, while possible, are not sufficiently profitable at this time to spread widely and vigorously.

Finding a way to exploit hydrates for energy use is commercially attractive: many professional geologists concerned with the matter estimate that the abundance of methane in gas hydrates greatly exceeds the volume of known conventional gas resources in coal. Since we do not know how much oil, gas, and coal is in the ground, and how much clathrate is below the seafloor, such comparisons are difficult to make. What we do know is that the burning of natural gas, whether from clathrates or from elsewhere, produces carbon dioxide, which warms the planet and changes the climate. It is true, though, that the production of the greenhouse gas carbon dioxide from methane is considerably less for the same amount of energy than that produced from burning coal or oil (coal, including the so-called clean coal, has the highest output of carbon dioxide per unit of energy produced among the fossil carbon-based energy sources).

14.2.3 Risk Assessment

Exploitation of resources invariably implies economic risks other than the enormous ones linked to anticipated climatic effects of carbon dioxide release and the (largely unknown) consequences of *acidification*. Recovery may fail, or that what is recovered may not bring a profit, or costly damage may accompany recovery attempts or transportation. Such risks are taken very seriously: large amounts of money are potentially involved. The risks addressed (and insured against commercially) are not necessarily the largest ones, however. Insurable risks can be estimated from history and therefore can be handled reasonably well by the insurance industry. Future costs of climate change are not in that category.

Climate risks are widely ignored (although there is plenty of discussion about the subject). A general list of potential problems is daunting and extremely difficult to work with, both for political and for scientific reasons. A scientific focus on one obvious and ubiquitous type of damage (say, involving the rise of sea level) might help in that situation, putting emphasis on an item of great interest and hence useful in education. Educating the public about possible problems ahead is definitely a necessary and welcome activity. But confounding risk and fact in the process would be unhelpful. Such confounding may result in severe discounting of the most important problems faced by humanity.

One source of risk is accidents, especially those that result from failure in safety measures. Much attention has been paid to the danger of oil spills, based on experiences with a blowout off Santa Barbara (Union Oil Platform) in 1969, the Amoco Cadiz running aground off France in 1978, and the Pemex blowout event in Campeche Bay (Ixtoc I; Gulf of Mexico 1979) among others. The Exxon Valdez hits rocks off Alaska in 1989, causing much local damage. In 2010, the extremely expensive Gulf of Mexico Deepwater Horizon accident occurred, involving BP, a major oil company. Damages for the largest spills are commonly measured in hundreds of millions of dollars; for the Deepwater Horizon event, it was billions (many thousands of millions). As a result of that event, whose cost greatly exceeded all others, a focus on progress in technology for the reduction of risk from spillage may have lost much credibility. Instead of a focus on how to drill, a focus on where to drill may be called for. Such an emphasis has produced a perfect safety record for DSDP and ODP. The difficulty regarding general application of the types of safety measure used in scientific drilling to commercial drilling is obvious: scientific drilling explicitly avoids hydrocarbons.

Oil spills, while highly visible, are not the only commercial risk in the resource business, of course. There are many others, even when just concentrating on hydrocarbons. Some risks are related to various political developments, which can impact profitability. Whether such risks are insurable is another question, one that is certainly beyond the scope of marine geology.

14.2.4 Origin of Petroleum

In general, the conversion of organic matter to commercial hydrocarbon is rather inefficient. We have to ask why this is so. A number of items are at issue, beginning with the organic chemistry of hydrocarbons (Fig. 14.2).

The production of commercially important hydrocarbons is a complicated process, as is evident in the listing of requirements that follows. (1) Organic matter captured within marine sediments must be converted to fluid petroleum by thermochemical processes, commonly requiring a thick blanket of sediments (more than 1 km thick) and temperatures of 50–150° Celsius. To be sure, long reaction times can compensate for relatively low temperatures, and high temperatures can compensate to some degree for a thin sediment cover. This is demonstrated, for example, in the *Guaymas Basin* in the Gulf of California, where hydrothermal activity produced oil from sediments less than 5000 years old. At excessively high temperatures, however, some of the reactions do not proceed to make oil, and we get natural gas instead (Fig. 14.2). (2) Petroleum must migrate from organic-rich source rock sediments to porous and permeable reservoir rock such as sandstones or porous limestones if it is to be recovered in conventional ways (Fig. 14.3). (3) Reservoirs must be big enough to be of commercial interest, and they must trap the petroleum with impermeable cover rocks such as shales or evaporates. Otherwise, the more volatile hydrocarbons can escape to the surface and to the atmosphere, which results in pitch lakes and tar accumulations (familiar to Southern Californians from the *La Brea tar pits* in Los Angeles). Tar also occurs in some of the sea cliffs in Carpenteria near Santa Barbara (Fig. 14.1). (4) The several petroleum-forming processes must take place within the correct time

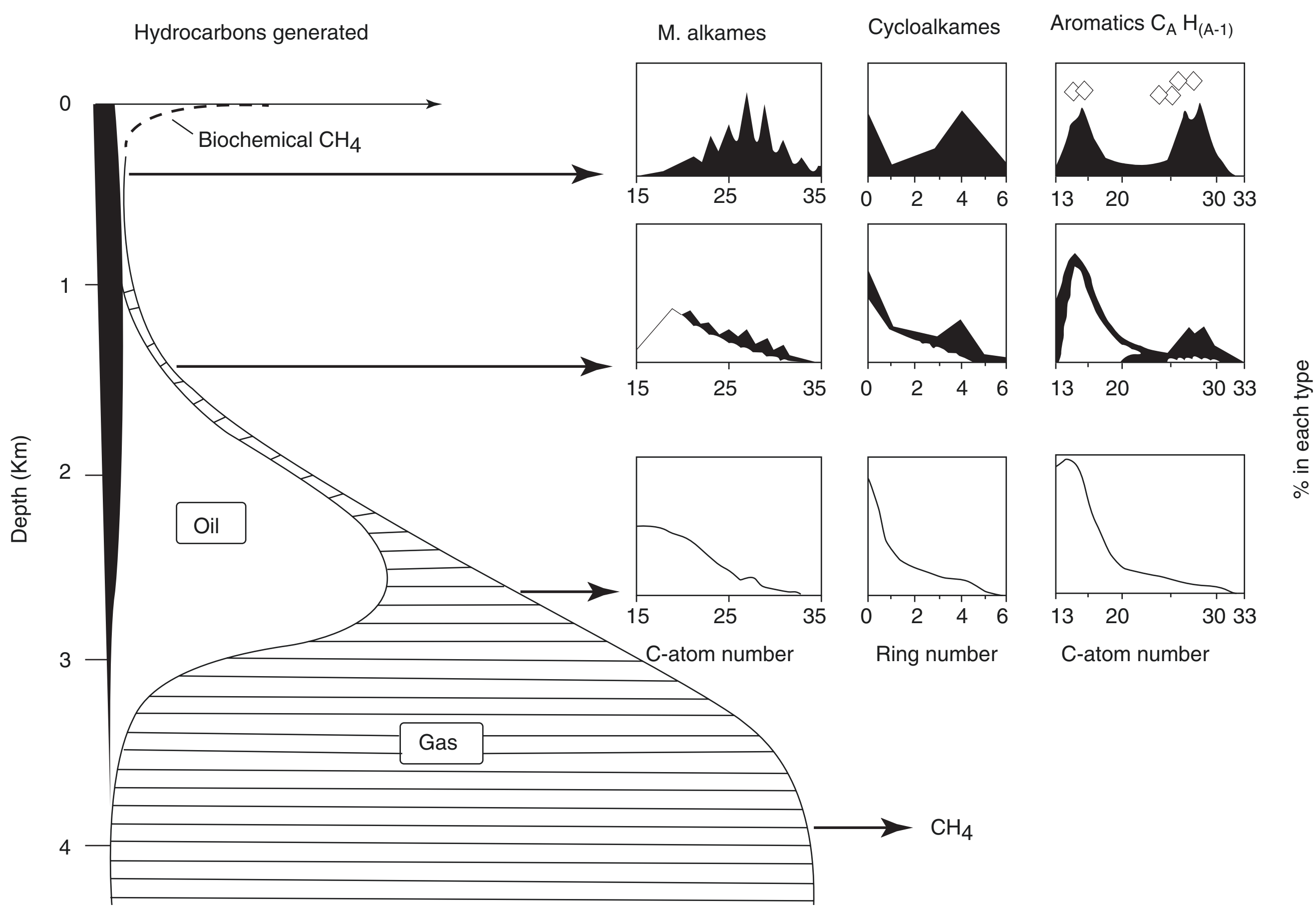

Fig. 14.2 Origin of petroleum. After burial of the source material (*black*), carbon chains and rings are produced. Gas is produced under a large overburden and can help push the oil out during production (After B.P. Tissot and D.H. Welte, 1978. *Petroleum Formation and Occurrence*. Springer, Heidelberg)

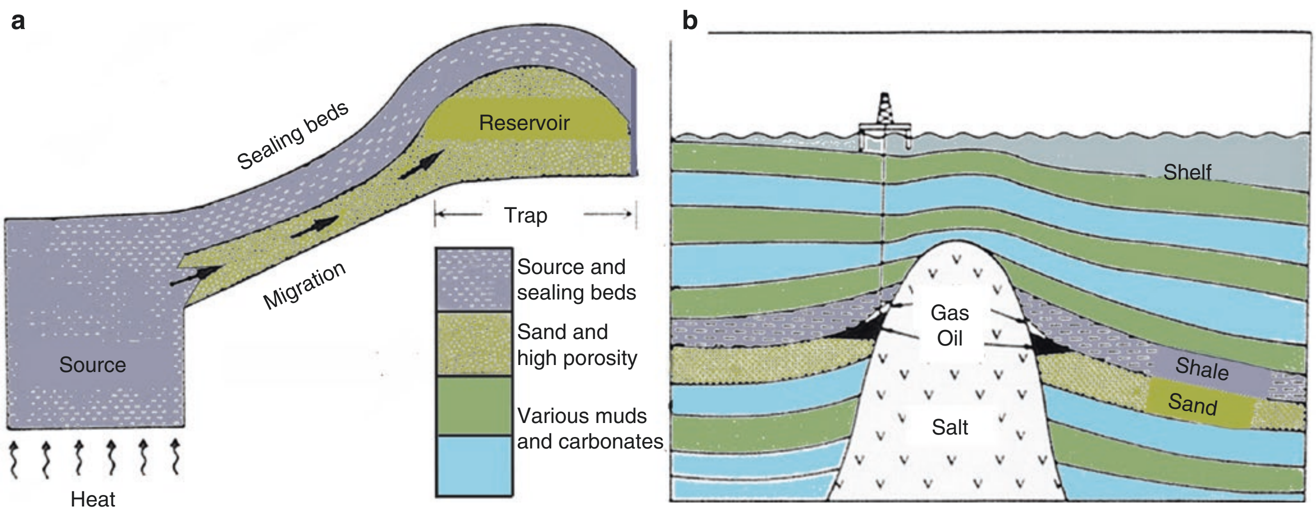

Fig. 14.3 Schematics on hydrocarbon accumulation. (**a**) Basic elements of a petroleum reservoir system, with migration from heated source rocks to a porous reservoir. (**b**) Offshore salt dome tectonics generating trapping conditions

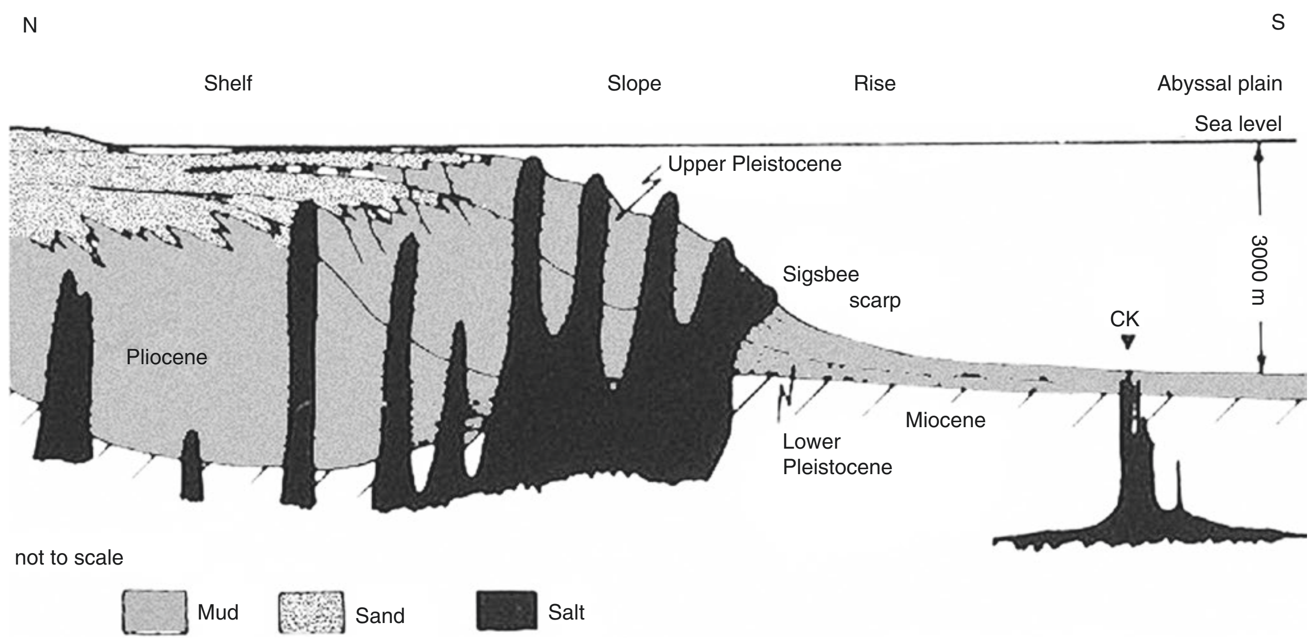

Fig. 14.4 Salt plumes in the Gulf of Mexico: Mesozoic salt intruding Neogene mud (After C.J. Stuart and C.A. Caughey, 1977, *AAPG Geol. Mem.*, 26, modif.; "CK", Challenger Knoll, a salt dome below the continental slope (position from DSDP Leg 1))

frame to result in a usable resource. Each process needs to complete its turn in sequence. A drill hole might be "dry" even though conditions seem right for successful exploitation, because the *timing* in the interplay of the natural processes was wrong.

14.2.5 Where Offshore Oil Is Found

The conditions of entrapment of oil in the marine realm are much like those on land (Fig. 14.3). Marine sediments can overlie salt deposits that are gravitationally unstable, being less dense than the overburden. The salt pushes up in plumes, making a so-called *salt domes*. Such domes are common at depth in the Gulf of Mexico (Fig. 14.4). Upturned sedimentary strata butting against the salt can provide traps for hydrocarbons (as shown schematically in Fig. 14.3b). The label "CK" in Fig. 14.4 denotes the "Challenger Knoll," which was drilled during the first leg of the Deep Sea Drilling Project (Hole 2). In subsequent drilling legs, such salt dome targets were avoided for safety reasons, as were any dome-like structures on the continental slope. In the well seaward of the continental slope, the sediment cover is generally too thin (and productivity too low) to cause serious concern in regard to hydrocarbons.

Offshore oil has been produced from the *Continental Borderland off Southern California*. There, the oil originates from Miocene organic-rich layers originally formed in upwelling areas and under conditions of oxygen deficiency. The oil is trapped in sandy layers ending at faults, which can promote considerable natural seepage into the sea (Fig. 14.1). On the *Arctic shore of Alaska*, there also are highly eligible areas for the recovery of offshore petroleum, and extraction is proceeding in Prudhoe Bay. Climatic conditions are very inclement, however, making exploration and production hazardous.

Thanks to recent technological developments' boosting recovery, the area of the North Sea (including portions of the Norwegian Sea), Europe's chief source of marine hydrocarbons, is still a large potential source, in spite of many years of vigorous hydrocarbon extraction. It has thick sediments, with source rocks common in the Mesozoic, and much storage in the early Tertiary sands. Permian Zechstein salts are involved in producing salt domes (Fig. 14.5). Thus, Phanerozoic sedimentary rocks of all ages combined forces here in generating the resources. Of the various western European nations involved in exploiting the resources, the UK and Norway have had the largest shares. In 1989, production of oil was some 175 million tons (53% from UK concessions, 43% from Norwegian ones) and 150 billion cubic meters of natural gas (30% UK, 21% Norway, 48% Netherlands, including onshore sources relatively close to sea level).

Production has waned since the turn of the millennium, when it may have attained maximum recovery for the oil (*peak oil*). Thanks to new technology, future recovery of hydrocarbons may be of the same order as recovery in past decades. To be sure, the *decommissioning* of existing oil fields has started (abandonment has to follow strict safety rules); nevertheless, projections regarding recovery are optimistic. However, the details of hydrocarbon occurrence in the North Sea region are complicated involving a host of sources and traps. In any case, future production is notoriously difficult to predict accurately.

In the south of the hydrocarbon-rich region, a broad belt of gas fields stretches east-west from Germany to southern England. Gas was once migrated from Carboniferous coal measures to porous Lower Permian sandstones and was sealed by overlying Zechstein (upper Permian) evaporates. Oil fields, in contrast, are concentrated around the north-south rift in the northern North Sea, which is reported to have originated in the first stages of opening of the northern North

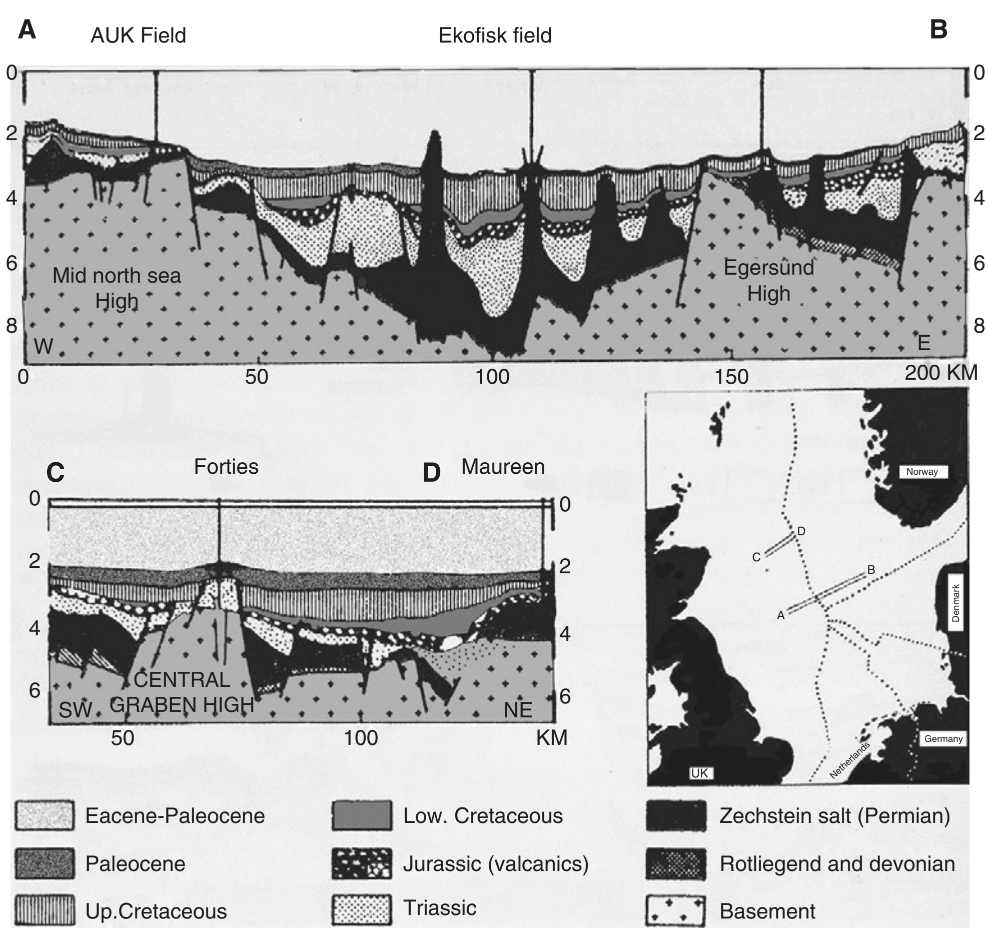

Fig. 14.5 Geological profiles under the North Sea, with hydrocarbon fields. Vertical exaggeration 6.7×. *Insert*: Map with national shelf boundaries (After P.A. Ziegler, 1977, modified for clarity. See *Geol. Journal* 1:7)

Atlantic. In the south, the oil occurs in Cretaceous chalk reservoirs, next to salt domes. Some fields are developed on Jurassic sandstones on the crests of horsts and tilted blocks. The Forties and other fields get oil from reservoirs in basal Tertiary sands.

We see that offshore oil, for reasons having to do with high organic production and thick sediment cover, is most likely found in shallow water close to continents. It is here that one finds thick sediments (Fig. 14.6). The locations are such that heavily populated regions can readily generate issues adverse to untrammeled oil extraction, starting with considerable objection to hydrocarbon exploration from fears centered on oil pollution. Experience shows that such fears are not without justification.

In addition to sediment thicknesses being unimpressive at great oceanic depths and organic matter content relatively low, both the risks associated with drilling and with production and the cost of recovery of hydrocarbons increase greatly with depth of water. In short, in deeper water, successful exploitation is increasingly less likely. Thus, shallow-water regions are and likely will be targets for commercial exploration. Minima of people aggregations (and associated conflicts) are located in icy polar areas. Thus, activities in shallow waters in high latitudes are likely going to define the future of petroleum recovery from the seafloor in the foreseeable future, despite the very palpable risks arising from inclement weather. Of course, concerning the projected damage to climate from hydrocarbon burning, the source regions for the hydrocarbon used do not matter.

14.2.6 Offshore Methane as a New Energy Source?

Much attention is being paid to methane as a new energy source with a reduced output of carbon dioxide upon burning relative to coal and to oil. So far, promises have been slow in being met. Methane is, however, an important risk factor in global warming. Judging from the stability relationships identified by geochemists (Fig. 4.5), a warming of the deep ocean along the slopes might set free much of the methane now safely shut into icy cages. The result of freeing the methane depends on the fraction converted to carbon dioxide by microbes and the rate of such conversion. Methane is much more powerful as a greenhouse gas than the oxidized gas (a factor of 25 has been suggested on the century scale). Presumably, fast release implies less conversion than slow release. Again, the time scale matters. A lack of information on rates of destruction at various temperatures and pressures within slope sediments may contribute to difficulties in predicting likely developments following the release of methane.

We have mentioned clathrates as a type of chemical sediment, gas accommodated in water ice with a very open structure. Much gas is trapped below the clathrate level where temperatures are low enough on the continental slope for clathrate to exist (Fig. 4.5). Thus, much of the gas may be at temperatures too high to make clathrate, that is, a large proportion of the methane in the system may be close to the stability zone, hard to recover but sensitive to disturbance.

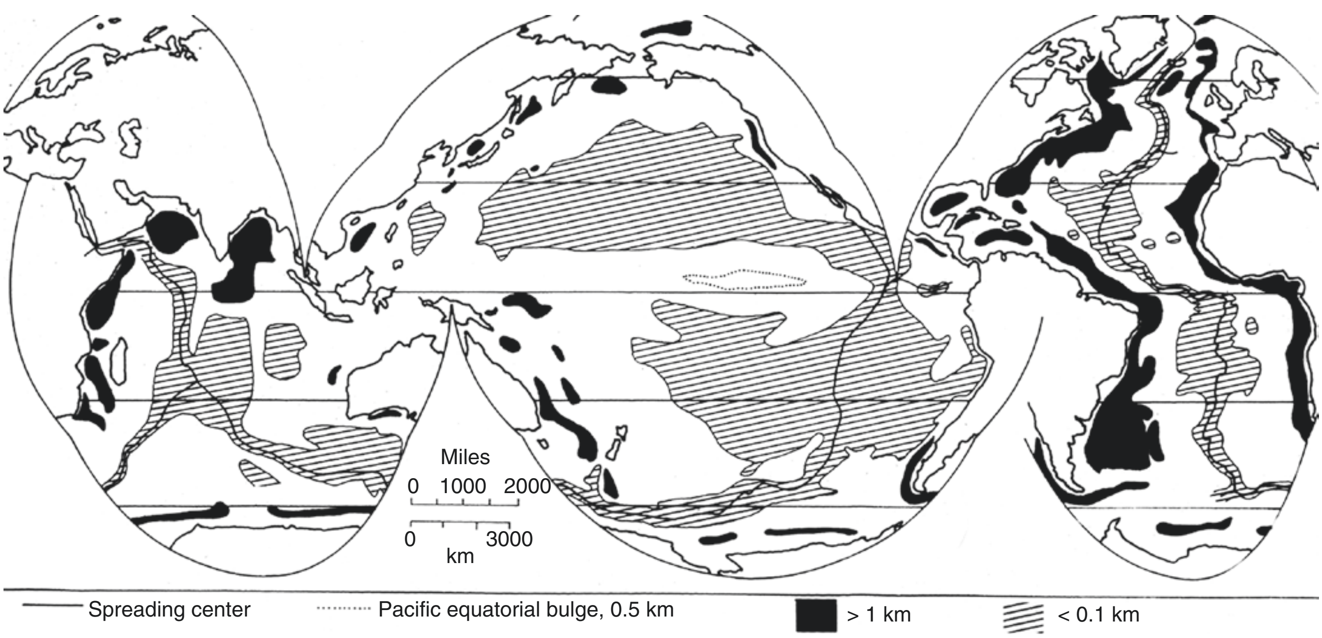

Fig. 14.6 Regions with thick and with thin sediments in the ocean (W.H.B., 1974. In: C.A. Burk and C.L. Drake (eds) *The Geology of Continental Margins*. Springer, Heidelberg Berlin)

Any planned removal of clathrate for commercial purposes has to be assessed with this problem in mind. On the seafloor, one can see places of presumed methane that exits the sediment in so-called mud volcanoes even without any provocation (Fig. 4.6). Presumably, one would not wish to increase the number of such "volcanoes."

14.3 Solid Raw Materials from Shelves

14.3.1 Phosphorites

Ground-up phosphatic rocks and products resulting from reactions with sulfuric acid are used as fertilizer in agriculture. Consumption is measured in millions of tons. Marine sources play a relatively minor part, although much of the phosphorite (*phosphate rock*) mined is marine in origin. Offshore (Neogene) phosphorites typically contain less than 25% of P_2O_5.

Modern marine phosphorites have a general formula containing the elements calcium and the bases phosphate and carbonate. They are, on the whole, fluoride- or hydroxide-bearing apatite rocks. The rocks at issue typically occur in areas of high productivity – off Southern and Baja California, for example, and in other upwelling areas (e.g., off Peru and Namibia, see Fig. 14.7). They occur as black or brown nodules forming pellets with various diameters (up to head size) and as irregularly shaped cakes. In places, they look like replacement products of fine-grained carbonate rock. In other places, they are interpreted as mineralization of preexisting organic matter, as precipitates from microbes filling cavities within carbonates or as direct precipitates from interstitial water.

Marine phosphorites on the present seafloor are typically Neogene in age (i.e., post-Paleogene), with the Miocene strongly represented. They are found in upwelling regions (Fig. 14.7). However, the early Tertiary phosphatic rocks and even Cretaceous ones are commonly associated, even though their origin may differ from the Neogene types. In many cases, it is not clear why phosphates of Neogene age tend to occur together with much more ancient ones. Possibly some of the conditions favorable for the making of Neogene phosphatic rocks (i.e., high productivity) also enhance the chances for preservation of preexisting older phosphates. The origin of phosphates on seamounts is not necessarily obvious. Some of the phosphates may stem from a time when the seamounts were islands and had bird-producing guano and were surrounded by a strong oxygen minimum zone. In any case, ancient phosphatic rocks on seamounts presumably did not form in the conditions in which they are found at present. In Fig. 14.7, only the Neogene and non-seamount phosphates are shown.

The common depth of deposition of phosphatic materials is on the shelf and upper slope. For reasons discussed in Chap. 7, productivity is high here, and oxygen may be in short supply (a condition of phosphorite formation according to a pers. Communication of the marine geochemist Y. Kolodny in Jerusalem). Also, there is a chance for considerable rework-

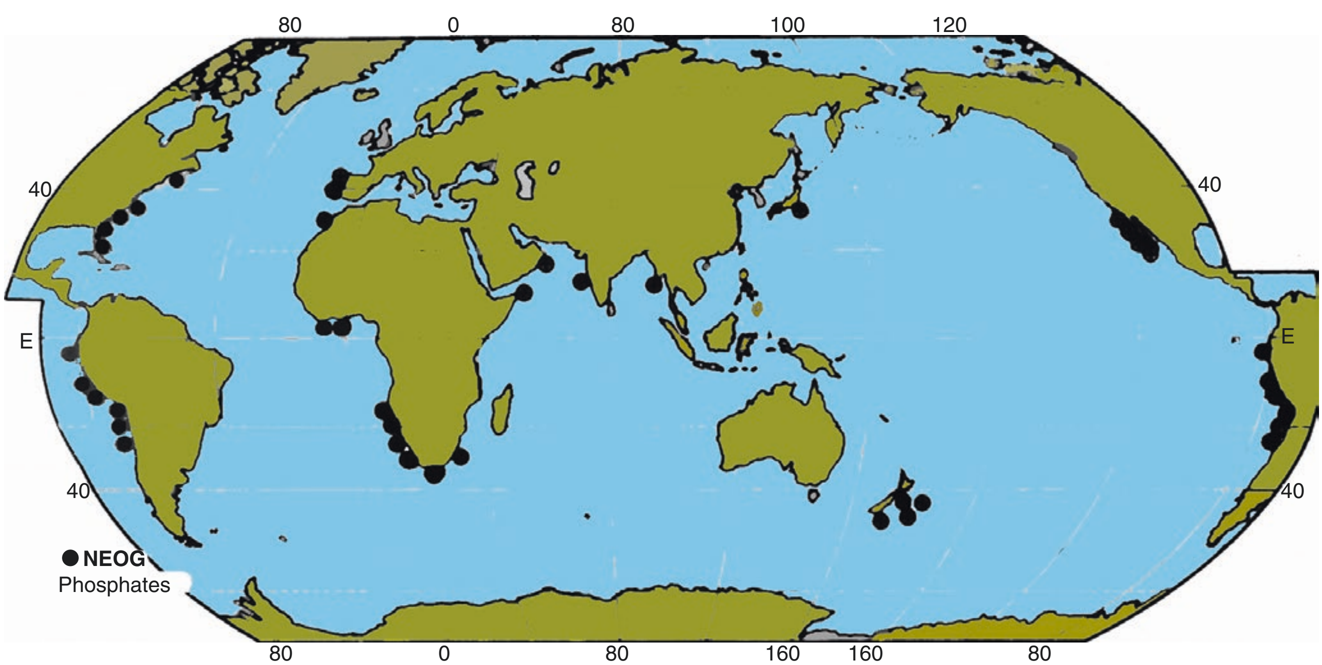

Fig. 14.7 Distribution of Neogene phosphorites according to G.N. Baturin and P.L. Bezrukov, 1979 (*solid circles*). Omitted compared with original graph: phosphatic rocks (regardless of age), phosphate on seamounts, and much of the longitude-latitude grid (Marine Geol. 31:317; modified) (note the importance of upwelling areas in focusing occurrences of Neogene phosphate rocks)

ing (and attendant concentration of the resource) from drastic changes in seawater cover owing to pulsed ice buildup and ice decay. In many places, shallow marine phosphate deposits are accessible on land (e.g., in Florida and in Morocco) where mining is economically inviting. About two thirds of the US production of phosphatic rocks is from Neogene sources in Florida, enriched by weathering processes. The mineral "francolite" (a carbonate-fluorapatite) is the chief carrier of the sought-after phosphorus here. Until recently, the USA mined more phosphate rock than any other country (almost 30 million tons in 2011, satisfying more than 90% of its own demand), but some other large nations have caught up. Morocco is the chief exporter of phosphorite. It has abundant weathering-enriched phosphate rocks of the early Tertiary and Mesozoic age from the ancient Tethys seaway.

The association of geologically young phosphorite deposits with present-day regions of upwelling suggests that the source of the phosphorus is organic matter (and that the relevant upwelling process is geologically young, which agrees with the 10 million-year age commonly quoted for the beginning of strong upwelling). During decomposition of organic debris on the seafloor, phosphate is released and becomes highly concentrated in interstitial waters. Apatite precipitation can then proceed, as well as diagenetic replacement of preexisting carbonate minerals. Off Peru, nodules with diameters of several centimeters grow within soft sediments with a rate of several millimeters per millennium, suggesting upward diffusion of dissolved phosphorus. The resulting phosphatic concretions are resistant to transport by currents; they can be mechanically exhumed and concentrated during periods of sediment reworking. Indeed, concretions are commonly associated within the sediment with hiatuses or other discontinuity surfaces with drastically reduced net deposition rates. Alternatively or in addition, particles can be sorted by size and density. Turbidity currents, in places, have concentrated phosphatic particles in layers in the (Miocene) Monterey Formation, for example.

14.3.2 Calcareous Shell Deposits

Calcareous shell deposits were or are dredged in places as raw material for calcium carbonate and for obtaining road-building material. For example, oyster shells have been mined in San Francisco Bay and in Galveston Bay in the Gulf of Mexico, as well as in Chesapeake Bay. Unfortunately, the large-scale removal of oyster shells apparently damages existing oyster reefs (by removing suitable sites for oyster spat). In addition, the dredging for shells may adversely affect the productivity of the seabed. In any case, conflicts commonly arise where shell dredging and fishery activities overlap.

Pretty shells have become collection items for tourists. With the advent of worldwide souvenir markets and of face mask diving, the gathering and sale of shells and of corals are now an important source of income for many islanders and other coastal peoples. Not surprisingly, attractive and rare species suffer considerable depredation from such collecting. There is safety in looking drab. Hence, according to Darwinian selection, the relative abundance of drab specimens is likely to increase in the years to come, while that of pretty shells is bound to decrease further.

14.3.3 Metals, Heavy Minerals, and Diamonds

Concentrations of heavy minerals and ore particles on beaches and in estuaries are locally mined for metals such as titanium, gold, platinum, thorium, zirconium, and tungsten and for valuable minerals such as diamonds. Some of the material is in uplifted beaches and in dunes. Seventy percent of the world production of zirconium is being extracted from placer deposits off eastern Australia (what is mined here is the Zr silicate). Diamonds are found in beach deposits of Southwest Africa and Namibia, as well as offshore. Magnetite is being mined from beach placers in Japan and New Zealand. Gold has been mined from beach deposits near Nome, Alaska. The big rush was at the very beginning of the twentieth century. Today, tourists wash gold there. Thousands of tons of ilmenite (an iron-rich titanium oxide) were extracted at one time from Redondo Beach, California. Also, titanium minerals were taken from beach sands along the northeastern Florida coast during World War II in "Mineral City" (now Ponte Vedra Beach, a golf resort). The biggest producers at present are Australia, with a million tons, and South Africa, with another million; Canada is third. Beaches in the western Oregon have chromite and other heavy minerals as well as gold and platinum.

14.3.4 Placer Deposits

As mentioned, magnetite is being mined from beach placers in Japan and New Zealand. (Magnetite is conspicuous in many places on beaches in Southern California but is not suited for mining here.)

The mining of black sands supports large operations in several places, including at several beaches in India, Indonesia, and the Philippines (Fig. 14.8). Unfortunately, the removal of sand from beaches, for whatever reason, can have serious consequences, including loss of protection from storm waves. In some places, therefore, mandatory restoration activities are linked to beach-mining permits.

How do placers originate? The process of concentrating heavy particles on the beach has much in common with panning for gold – water motion works on particles with different settling velocities and with different sizes, separating heavy from light and large from small (Fig. 14.9). Thick

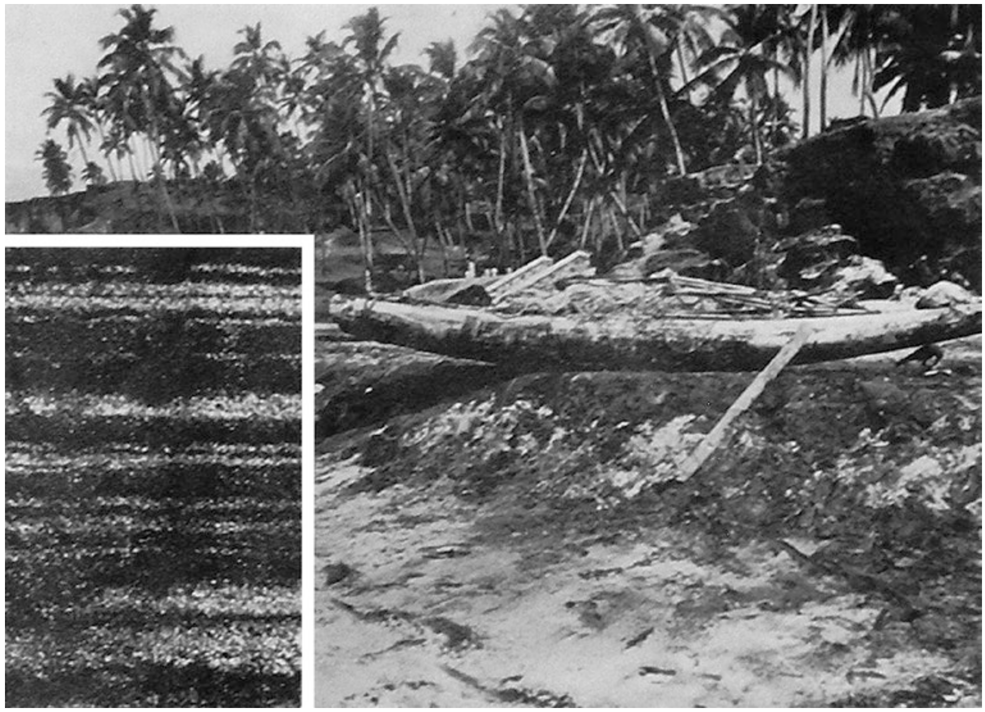

Fig. 14.8 Black sand in beach placers. The beach south of Quilon (southwest India) has a heavy mineral deposit on top of the beach (where the boat rests). During the southwest monsoon, high waves sort the sand into layers of dark and light mineral (*inset*, 20 cm high) (Photos E. S)

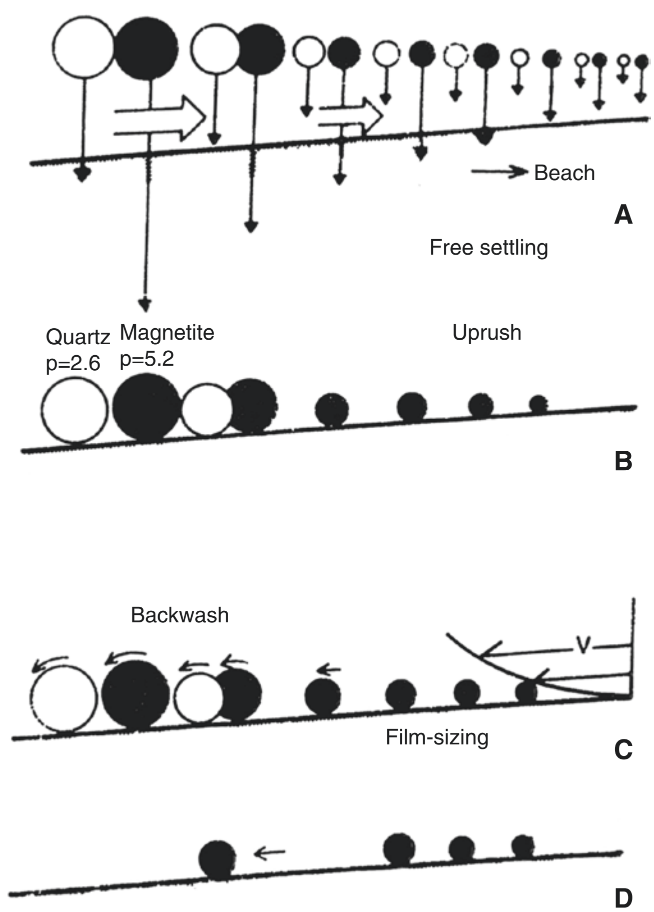

Fig. 14.9 Origin of heavy mineral placers, schematic. (**a**) Suspended sediment particles are washed onshore with incoming waves, large and heavy ones first (*black*). (**b**) Resulting grain association is enriched in grains that settle easily. (**c**) Backwash rolls away large grains preferentially, owing to increase of water velocity off but still close to the floor (note v in *inset*). (**d**) Resulting well-sorted and heavy mineral assemblage (E.S.,1970. *Chem. Ing. Tech*. 42: A 2081)

placers of heavy particles form in the beach zone only. Offshore placers do exist; presumably the ones observed formed when sea level was lower than now. River deposits may contain heavy mineral concentrations also, for example, the cassiterite deposits in Thailand, Malaysia, and Indonesia. In the relevant places, former river beds on the shelf, now submerged down to about 100-m water depth, are of economic interest, and some have been exploited offshore in shallow water for many decades.

14.3.5 Sand and Gravel

Locally considerable amounts of sand may be taken from the beach for building roads and houses, as well as for coastal protection (dams) and for fill. However, the main use of beach sand is indeed for building sand castles and for plain enjoyment. Recreation is one of the most important uses of beaches – by far exceeding mineral extraction in business value. Beaches are commonly eroded by winter storms (Sect. 4.2.2). In some areas, sand may be brought in from offshore to replace eroded material, at considerable expense.

Gravel rarely reaches the sea, unless high mountains are close to the shore or unless we deal with glacial debris. Such debris, when washed by waves or rivers on the exposed ice-age shelves, can readily yield gravel. Around the Baltic and in the North Sea region, for example, gravel is mined as filler for concrete. Taken altogether, the economic importance of sand and gravel and other raw materials from shelves is rather modest. For a high economic impact of marine resources, one must look to hydrocarbons, recreation, and waste disposal, perhaps fisheries.

14.4 Heavy Metals on the Deep Seafloor

14.4.1 Importance of Manganese Deposits

The metal deposits on the deep seafloor have been a popular topic of discussion among marine geologists ever since the *manganese nodules* (better *ferromanganese concretions*) were described by the *Challenger* Expedition more than a century ago (Fig. 14.10) and were shown to be rich in copper, cobalt, nickel, and other heavy metals. The abundances of these metals in seawater are extremely low, largely because their oxides and hydroxides have low solubility. The metals are nevertheless extracted by biological processes and sent to the seafloor with organic matter.

The nodules grow extremely slowly, rates being measured in millimeters per million years. They have growth rings that reflect Cenozoic history with widely spaced events. Both nodules and crusts have been studied. Nodules, some being perfectly spherical, may be subject to (geologically) frequent overturning motion. (Not exactly a dance of the objects on hot springs at depth as visualized by the Bavarian chief geologist W. V. Gümbel more than a century ago. Gümbel was sent some nodules from the *Challenger* Expedition, perhaps by mistake.)

The ferromanganese nodules are quite abundant in places, as seen on photographs of the seafloor (Fig. 14.11). The amount of nodules on the Pacific Ocean floor has been estimated as exceeding one hundred billion tons. However, the economic value of the deposits is not materially greater than zero. It is expensive to mine them and any profits (however unlikely) are at risk: the ownership of the deposits is not clear. While this is not true for certain deposits in the Baltic Sea that are located within the EEZ of various bordering countries, those deposits likewise have little economic value, being not large enough for commercial exploitation and commonly not particularly attractive as concerns associate metals. (In the Baltic region, the Mn and Fe presumably are derived from glacial deposits.)

14.4.2 Origin of Manganese-Bearing Deposits

Where do the ferromanganese deposits occur? How much of the valuable trace metals do they contain? And how did they originate?

Distribution and composition may have some clues to origin. The nodules are generally restricted to areas of low sedimentation rate: they would soon be covered up in regions of high sediment supply. Surprisingly, brown pelagic clay accumulates slowly enough (at 1–2.5 m per million years) to accommodate the nodules (which grow a thousand times

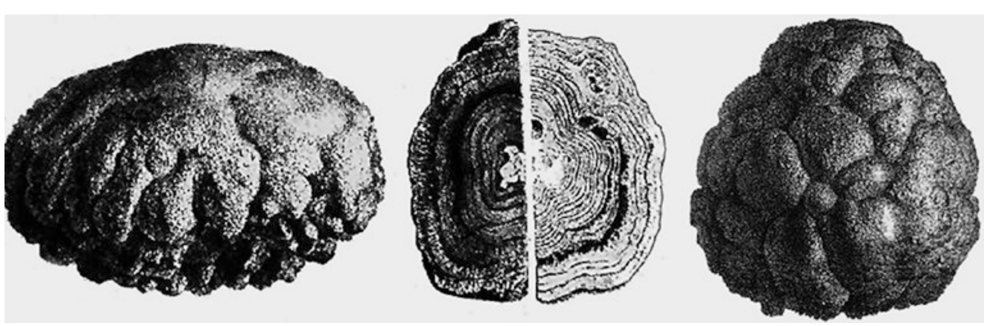

Fig. 14.10 Ferromanganese concretions from the Challenger Reports (The objects shown have diameters of ca. 5 cm). Sectioning of nodules yields growth rings containing information on Cenozoic history

more slowly). Apparently, they are moved about sufficiently by large benthic organisms to stay on top of the clay. In fact, such movement may account for the roundness of nodules and their failure, in many places, to make crust or pavement by coalescing (Fig. 14.11). In places, bottom currents prevent clay deposition or even cause erosion over large areas. It is there that ferromanganese nodules tend to be concentrated. The nodules are more common in the Pacific than in the Atlantic, possibly a result of additional sources in the Pacific and of low sedimentation rates there. Figure 14.11 suggests an important role for sediment cover, regarding the abundance of nodules. Perhaps a temporary covering by slowly migrating sediment waves and by burrowing mounds are more common than is generally realized.

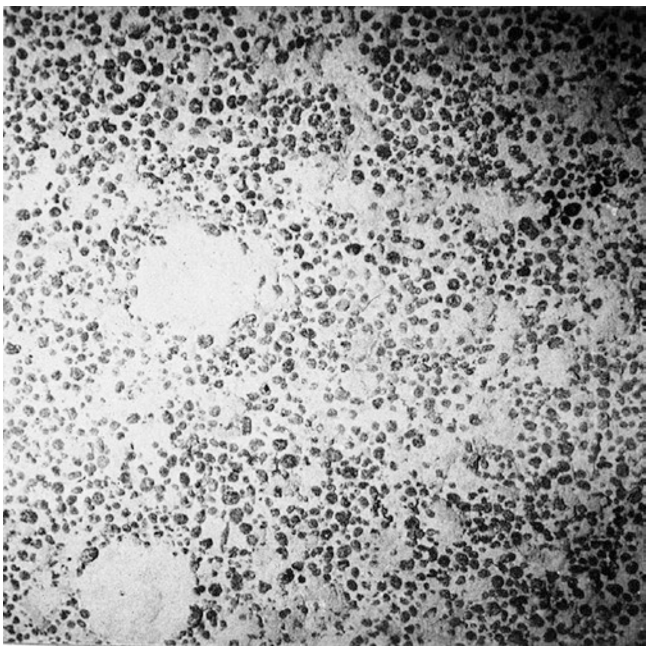

Fig. 14.11 Nodule-covered deep seafloor, central tropical Pacific (Photo courtesy of Metallgesellschaft Frankfurt)

In the various discussions about the origin of ferromanganese concretions (and about their commercial value), the trace element content and the *iron-to-manganese ratio* (its inverse) play an important role. Typical values are listed in Fig. 14.12 in a table. Note that the Mn/Fe ratio is greater in the Pacific than in the Atlantic. Also, the content of trace elements in Pacific sediments is typically considerably larger in Pacific concretions than in Atlantic ones, suggesting differences in origin and in value.

14.4.3 Ores from Spreading Axes

14.4.4 Hot Vents and Black Smokers

For some of the ferromanganese deposits on the deep seafloor, the origin is hardly in doubt: the concretions are located near the crest of active spreading ridges. At the hot vents (and beyond), seawater circulates through cracks in the newly formed crust, reacting with the hot basalt (Fig. 14.13). Precipitation of sulfides (Fe, Mn, Cu, Zn, etc.) originating there may become economically important some day; they are not at present, even though something like a hundred discoveries (among many more) have massive sulfides. Access is difficult and resource volumes are modest, compared with those on land. In recent years, increased interest has been shown by some developing nations in the mining of ridge crest sulfides, especially in back-arc basins where accessibility is enhanced by shallower depths and by the fact that the

%	*Ferromanganese nodules*					FerroMn Crusts	Hydrothermal Oxides	Hot vent sulfides Average	Max.	Min.
	Avg. Pacific	*Indian O.*	*Atlantic*	*Max.*	*Min*					
Mn	17.2	14.9	13.6	34.0	5.4	21.6	27.3	-	-	-
Fe	11.8	14.6	15.5	26.3	4.4	16.5	11.6	19.1	34.0	2.5
Ni	0.63	0.38	0.33	2.0	0.13	-	-	-	-	-
Co	0.36	0.31	0.24	2.6	0.045	0.63	0.0023	-	-	-
Cu	0.36	0.17	0.16	2.5	0.028	-	-	2.9	9.2	0.2
Pb	0.047	0.053	-	0.51	0.046	-	-	0.71	12.1	0.03
Zn								16.9	36.7	4.0
SiO2								10.2	28.1	1.2

Fig. 14.12 Metal contents of manganese nodules, crusts, and hot vent sulfides (Sources: J.S. Tooms, 1972. Endeavour 31:113; F.T. Manheim and C.M. Lane-Bostwick, 1989. *Nature* 335:59; S.D. Scott, 1991. In: K.J. Hsü and J. Thiede (eds.) *Use and Misuse of the Seafloor*. Wiley, Chichester, UK)

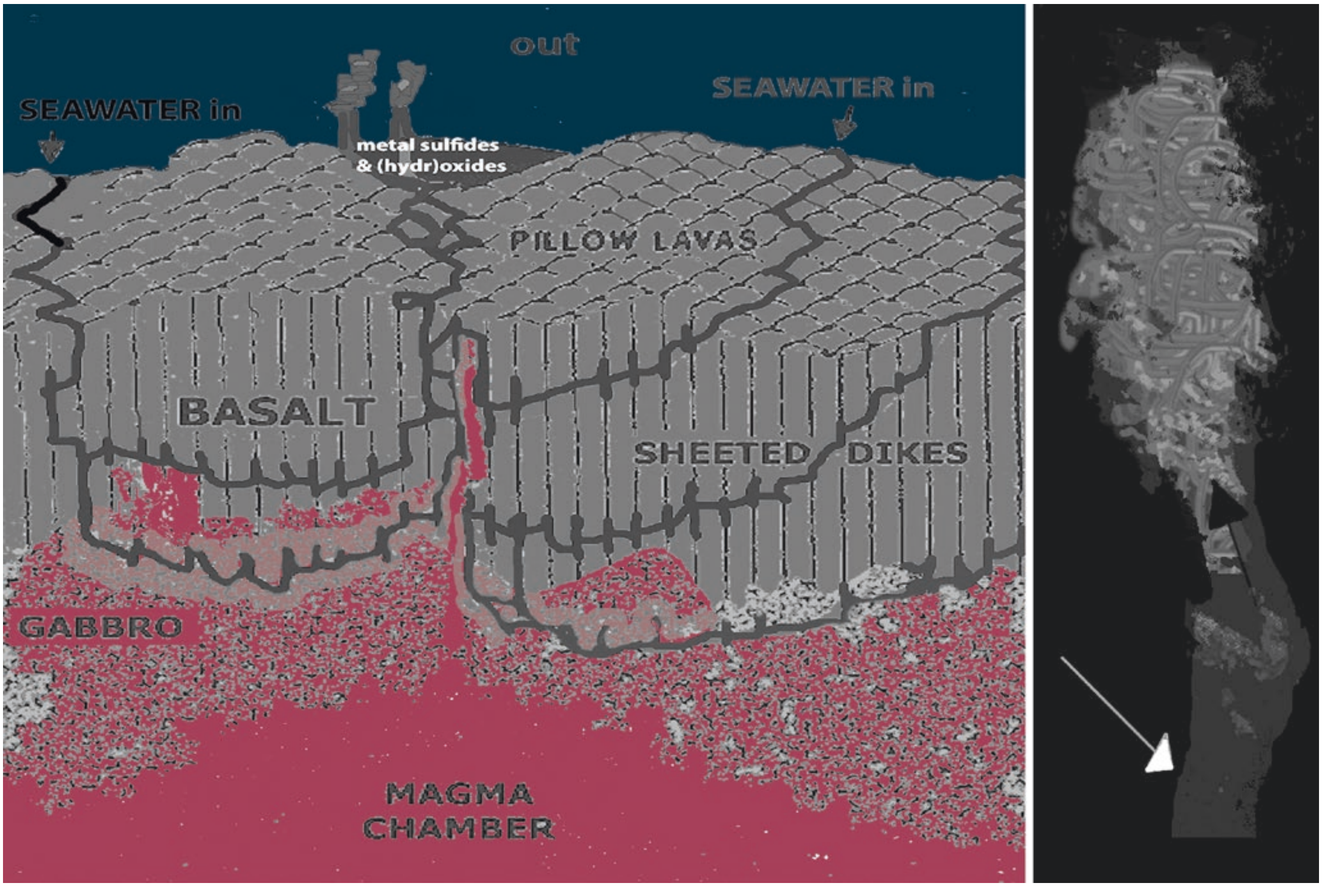

Fig. 14.13 Black smokers as a resource for metals. The smoker has reaction products of seawater with hot basalt exiting from chimneys (*black arrow*). Resources are largely sulfide chimneys (*white arrow*) (*Right*, schematic, using a photo taken from Woods Hole's scientific submarine ALVIN (here redrawn for simplicity); *left*: see Fig. 1.9 for source)

EEZ is involved in many cases. Most discoveries have been in the Pacific. The first notable efforts in mining hot vent deposits were made in 2006.

Many surficial land-based ores are in fact of marine origin and originated in ways similar to known ridge crest deposits, with massive sulfides resulting from stripping seawater sulfate of its oxygen by reactions of seawater with reduced iron within the hot basalt and with (hydr)oxides resulting from reaction of metal-bearing fluids with the oxygen in the cold deep seawater. Depending on how the metal-bearing fluids emerge and mix, mounds, miniature spires, and various baroque edifices can be built, some several meters high. The growth of modern spires may take but years, rather than decades or centuries.

A chimney made of anhydrite in the North Fiji basin (back-arc spreading) was labeled "La Dame Blanche," in reference to its ghostly appearance. The white structure stands in stark contrast to the more common "black smokers," vent fluids shooting from dark chimneys made of metal sulfides and oxides (Fig. 14.13). In a broad zone around the vents, iron- and manganese-(hydr)oxides are precipitated, as the reduced iron and manganese (Fe2+ and Mn2+) meets normal, oxygen-rich seawater and becomes insoluble.

As the various minerals precipitate within the cracks of the basalt, they tend to clog the system and shut it down. Thus, on the whole, the hydrothermal systems are short lived. However, where resources are voluminous in certain mining areas on land systems, there is evidence that the vent system was renewed in many pulses, each presumably ending in a shutdown.

14.4.5 Red Sea Ore Deposits

The "Red Sea" likely gets its name from certain plankton blooms, not from any deposits on the seafloor, which remained unknown till well into the last century, after the "Red Sea" acquired its colorful name. The rift represents a rather specialized case of ridge crest accumulation of heavy metal deposits. The deposits are of considerable economic interest, and the area has been visited by many research vessels, including drilling vessels. The various ships were sampling heavy metal deposits, commonly present as a type of mud in so-called deeps. The deeps were named after the vessels that discovered them.

In the central Red Sea – an active spreading center that opened only a few million years ago and whose axis does not form a ridge yet, therefore – there are several "deeps," that is, enclosed basins. The Atlantis II Deep is more than 2000-m deep and only 6 by 15 km in area. The bottom is filled with brine having a temperature of about 60 °C and a salinity of 25%, seven times that of seawater. The brine is rich in iron, zinc, and copper. The sediment below the brine is incredibly colorful, brick-red layers alternating with ocher, white, black, and greenish layers. A variety of minerals provides the coloring; economically of interest are the sulfides in the dark layers. Trace element contents are high. Zinc is abundant within the fine-grained mud, and copper is present, along with its chemical homologs silver and gold.

The metals are trapped within the brine, which forms water bodies below seawater within the relevant deeps. Brine, being very heavy, does not mix well. The salt presumably comes from older deposits, formed as the rift first opened. While the Atlantic II Deep may contain millions of tons of zinc and thousands of tons of copper and silver (and be quite rich compared with other marine deposits of interest), these metals are still more readily mined on land. For the countries adjacent to the Red Sea, however, mining within their own EEZ might be of interest eventually.

Suggestions for Further Reading

Bolin, B., and R. Cook (eds.) 1983. The Major Biogeochemical Cycles and Their Interactions. John Wiley, New York.
Rona, P.A., K. Boström, L. Laubier, and K.L. Smith (eds.) 1983. Hydrothermal Processes at Sea Floor Spreading Centers. Plenum Press, New York.
Haq, B.U., and Milliman, J.D. (eds.) 1984. Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan. Van Nostrand Reinhold, New York.
Tissot, B., and D.H. Welte, 1984. Petroleum Formation and Occurrence (2nd ed.). Springer, Berlin.
Suess, E., and von Huene (eds.) 1990. Proc. ODP Sci. Results 112.
Hsü, K.J., and J. Thiede (eds.) 1992. Use and Misuse of the Seafloor. Dahlem Konferenzen. Wiley, N. Y.
Kennett, J.P., J.G. Baldauf, and M.Lyle (eds.) 1995. Proc. ODP, Sci. Results 146 Part 2).
Pirajno, F., 1995. Hydrothermal Processes and Mineral Systems. Springer, Berlin.
Van Dover, C.L., 2000. The Ecology of Deep-Sea Hydrothermal Vents. Princeton University Press, N.J.
Wefer, G., D. Billett, D. Hebbeln, et al. (eds.) 2002. Ocean Margin Systems. Springer, Berlin Heidelberg.
Stein, R., and R.W. Macdonald, (eds.) 2004. The Organic Carbon Cycle in the Arctic Ocean. Springer, Berlin & Heidelberg.
Schulz, H.D., and M. Zabel (eds.) 2006. Marine Geochemistry, 2nd ed. Springer, Heidelberg & Berlin.
https://www.elcamino.edu/faculty/tnoyes/Readings/13A_R-Ocen_Resources_Reading.pdf
http://noc.ac.uk/science-technology/research-groups/mg