1 Introduction

1.1 The Great Geologic Revolutions of the Twentieth Century

1.1.1 General Background Information

There were an enormous number of striking geologic discoveries made and geologic theories created in the twentieth century. All of these bear importantly on marine geology. Four findings stand out: (1) *plate tectonics* (linked to continental drift and based largely on the geomorphology of the seafloor, geomagnetism surveys, heat flow patterns, and earthquakes at sea), (2) *Orbital Ice Age Theory* (informed by solar system astronomy and confirmed by the study of deep-sea sediment), (3) *stepwise Cenozoic cooling* (based on results from deep-sea drilling), and (4) *confirmation of the impact theory for the end of the Mesozoic* (clinched by stratigraphy of pelagic sediments on land). The respective widely recognized pioneers are (1) a number of largely US American and British geologists, geophysicists, and geomagnetists (e.g., Lamont's marine geologist Bruce Heezen (1924–1977), the US Navy's Robert Dietz (1914–1995) and Harry Hess (1906–1969), the UK geophysicist Fred Vine (Ph.D. 1965, Cambridge)), and also the German meteorologist Alfred Wegener (1880–1930); (2) Milutin Milankovitch (1879–1958), Serbian astronomer and civil engineer, and two astronomers (John Stockwell and Urbain Leverrier) delivering input to his calculations (The leading contemporaneous proponent of orbital forcing is André Berger, Belgian astronomer and climatologist.); (3) contemporaneous pioneers are the NZ-US marine geologist James P. Kennett (Ph.D. 1965, Wellington), the British geophysicist Nick Shackleton (1937–2006), the isotope chemist Sam Savin (Ph.D. 1967, Pasadena), and the geologist Robert Douglas (Ph.D. 1966, U.C. Los Angeles); and (4) the impact pioneers are the German-Swiss geologist and paleontologist Hanspeter Luterbacher, the Italian geologist Isabella Premoli Silva, and the Californian physicist Luis Alvarez (1911–1988) and his geologist son Walter (Berkeley) and their associates F. Asaro (1927–2014) and H. Michel (Berkeley). The crucial papers and books were published (1) in the 1920s and 1960s (*Continental Drift* and *Plate Tectonics*), (2) in the 1920s and 1980s (Orbital Ice Age Theory, proposed and verified), (3) in the 1970s (microfossils and oxygen isotopes), and (4) in the 1960s and 1980s (sudden end-of-Cretaceous mass extinction documented in pelagic sediments on land surveyed and iridium maximum found, respectively).

What, if anything, do the four great revolutions have in common?

They emphasize the control of geologic history by outside forcing, either "endogenic" (processes driven by mantle convection) or "astronomic" ones controlled by solar system phenomena and a call on "positive feedback" for amplification ("negative feedback" stabilizes).

The discovery of the great importance of outside forcing (including the unpredictable and highly variable factors of earthquakes, volcanism, and collisions in space) has resulted in some discrimination against regular surficial Earth processes, which have considerably damaged the perception that the pronouncements of the British lawyer Charles Lyell (1797–1875) regarding uniformitarianism (a long bastion of textbook geology) hold water. His central concept, that the present is the key to the past, became suspect as a dominating rule in the interpretation of the geologic record, especially in an ice age. The same is true for the reverse assertion that the past is the key to the present (or to the future). "Endogenic forces" are difficult to observe, being generated in the mantle of the planet. While regular astronomic forcing can be calculated with great precision, it is not necessarily well understood in its applications to a complicated Earth response.

In system analysis (which started as a concept in engineering), "negative feedback" drives a system toward original conditions during episodes of change. Negative feedback favors the *status quo*. The idea of negative feedback of a chemical system is the backbone of "Le Chatelier's Principle," proclaimed many decades ago by the French pioneer chemist Henry Louis Le Chatelier (1850–1936) and

© Springer International Publishing AG 2017

E. Seibold, W. Berger, *The Sea Floor*, Springer Textbooks in Earth Sciences, Geography and Environment,
DOI 10.1007/978-3-319-51412-3_1

soon after elaborated for the Earth system by the Russian-French geochemist Vladimir Vernadsky (1863–1945). The “daisyworld” model of the UK chemist James Lovelock (Ph.D. 1948, London) beautifully illustrates the negative feedback concept. “Positive feedback,” in contrast, increases any change and eventually leads to blowout if not checked. As a corollary, when positive (“non-Gaian,” K.J. Hsü) feedback is at work, relatively modest forcing can result in enormously large changes. In a very general way, negative feedback supports Lyell and Gaia and traditional geologic thinking going back almost two centuries, while positive feedback does not: it produces unexpected results and abrupt change and tends to be rather hazardous, therefore.

1.1.2 Plate Tectonics and Endogenic Forcing

A little more than half a century ago, it was still possible to think that sediments on the deep seafloor offer information for the entire Phanerozoic, that is, the last half billion years. In fact, some geologists thought the deep-sea record might lead us back even into the Precambrian, into times a billion years ago, or more. Today, it is no longer possible to harbor such thoughts. The deep seafloor is young, geologically speaking. The most ancient sediments recovered are about 150 million years old, that is, less than 5% of the age accorded to ancient rocks on land. Deep-sea deposits older than Jurassic presumably existed at some point, but it is thought that they vanished, entering the mantle by subduction in trenches.

The main relevant activity providing for the forcing of plate tectonics is in the mantle of Earth (Fig. 1.1). It is not known just how the mantle operates in the context of plate tectonics.

“Seafloor spreading” is responsible for the world-encircling mid-ocean ridge and for the Atlantic. Volcanic activity associated with subduction (Fig. 1.2, lower panel) is rampant all around the Pacific Basin (hence, the label “Ring of Fire” for the Pacific margin). It is especially evident in South America (Fig. 1.3) but also on the northern West Coast of the USA, in Alaska, and in Japan. Earthquakes generated in the subduction belts can and do produce “tsunamis,” that is, waves that travel on the surface of the ocean at the speed of jet aircraft and that grow to enormous size in shallow water.

1.1.3 Northern Ice-Age Cycles

Unlike his predecessors, the ice-age pioneer Milutin Milankovitch supposed that it is forced melting of ice in high northern latitudes that holds the answer to the cycles and not the pulsed making of ice (which is the question that was traditionally addressed). According to Milankovitch, what matters is whether the sun’s warmth is strong in northern summer or not. The influx of solar heat is controlled by the changing tilt of the Earth’s axis (the “obliquity”) studied quantitatively by the French astronomer Pierre-Simon de Laplace (1749–1827) and by the changing Earth-Sun distance, a topic tackled by Johannes Kepler (1571–1630) some four centuries ago. Milankovitch’s proposition, worked out mathematically, is now known as “Milankovitch Theory,” reflecting its

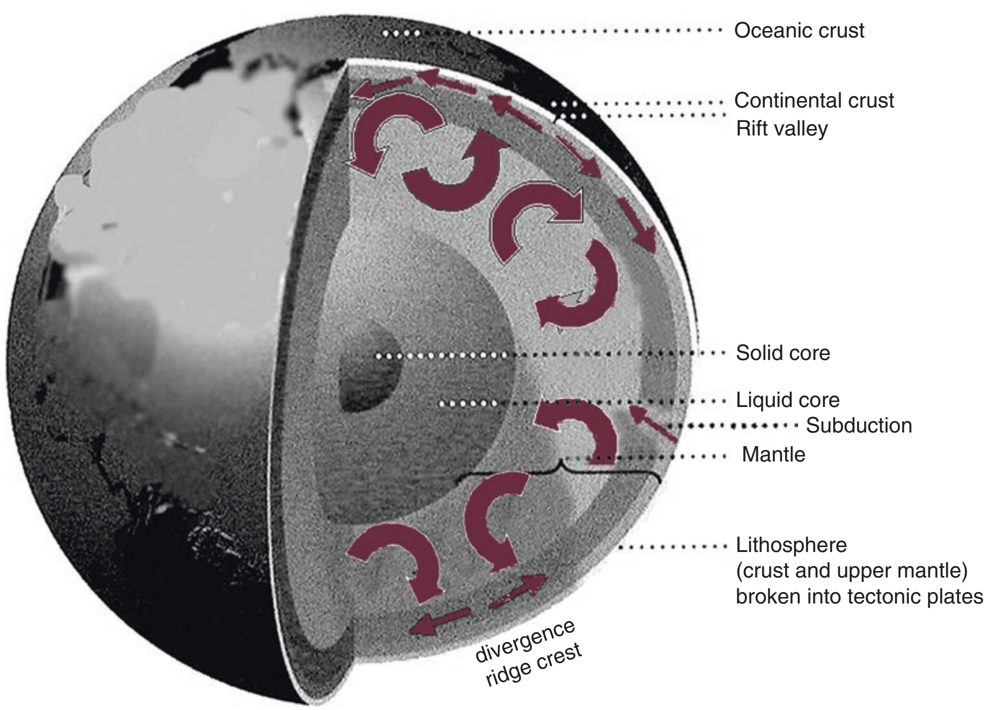

Fig. 1.1 The main elements of the planet’s structure, not to scale and hypothetical regarding mantle motion. Roughly one half of the Earth is mantle; crust is negligible by volume, in comparison. The mantle convects, largely in unknown ways. Alternatively to the picture shown, fast convection may be restricted to an upper layer, while convection in the lower mantle is much slower. The lithosphere (the stiff uppermost part of the mantle) is roughly 100 km thick. Together with the crust, it defines the “plates” (Background graph courtesy of S.I.O. Aquarium Education Program, here modified)

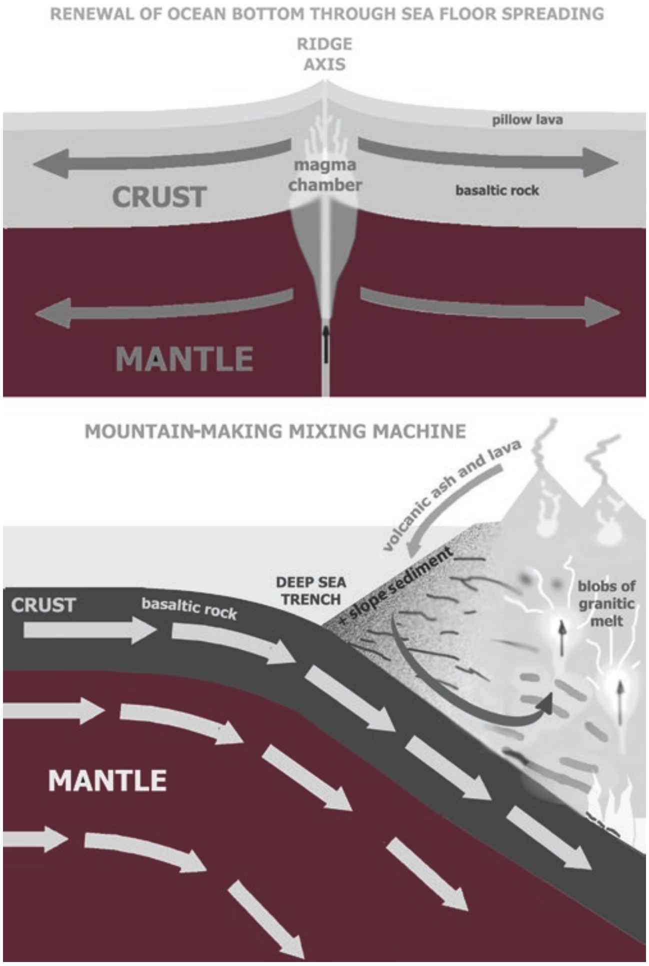

Fig. 1.2 The crux of modern global tectonics involving the seafloor. *Upper panel*: seafloor spreading; *lower panel*: seafloor subduction. The latter involves the making of mountain chains. The assumption is that creation and destruction of seafloor are balanced, so that Earth does not change its size. The downward-going lithospheric slab (about 100 km thick) eventually dissolves within the mantle. Drawing is not to scale (After W. H. Berger 2009, Ocean. U. of California Press, Berkeley, with some minor modifications)

great power in explaining ice-age cycles (and earlier climate cycles on a multi-millennial time scale).

Milankovitch Theory employs seasonal effects as influenced by Earth's orbital variation. Right now Earth is closest to the sun early in January, so according to Milankovitch, ours would not be a good time to melt snow and ice with the help of astronomic forcing. Ten- or twelve-thousand years ago, the Earth was closest to Sol in high northern summer, and melting of the great northern ice sheets proceeded at a rapid clip. Sea level rose rapidly (as far as is known from marine sediments), the average exceeding a rate of 10 m per millennium. Apparently, after having been around for more than 50,000 years (among other things depressing the land it sat on, lowering elevations), large ice masses were ready to go away. The degree of eccentricity of Earth's orbit varies on

Fig. 1.3 Volcanic eruption linked to subduction "Ring of Fire": Turungahua, Ecuador, in 2003 (Photo courtesy of Chung Luz, UCSD). The volcano ("the Black Giant") has frequently erupted in recent years, causing evacuations. On the positive side, volcanic ash acts as fertilizer

a time scale of a hundred thousand years, so that a 100,000-year natural oscillation could conceivably lock on to an orbital energy cycle of similar length (such as eccentricity), even if not closely related. The tilt of the axis (that is, the deviation from an idealized vertical position) varies with a period of 41,000 years. As far as can be ascertained, overall, the Milankovitch mechanism matches observations quite well, although the nature of the match varies with geologic time (Fig. 1.4) for reasons poorly understood.

Correct dating of the cycles seen within a reliable sedimentary record was necessary to support Milankovitch's proposition. Once it is realized that the evidence simply was not available (e.g., no records from long deep-sea cores), it becomes much more understandable why Milankovitch Theory did not prevail earlier. It is not that geologists are uncommonly obtuse, it is that they are skeptical, as are almost all well-trained scientists when examining the hypotheses of colleagues. Verification of Milankovitch Theory required much effort and a challenging list of information. Even today there are obstacles to an unfettered acceptance of Milankovitch Theory. One of these arose toward the end of the twentieth century and became prominent. Milankovitch studied but the last one third of the ice ages, a time period when 100,000-year cycles dominated ice-age history. He did not, however, consider fluctuations of that length. Instead, Milankovitch focused on the effects of "precession" and of "obliquity" (changes in the season of perihel and changes in tilt of Earth's axis). The matter of the dominant 100,000-year cycle is still unresolved and is being discussed. Many scientists believe that Milankovitch-type forcing alone cannot resolve the issue.

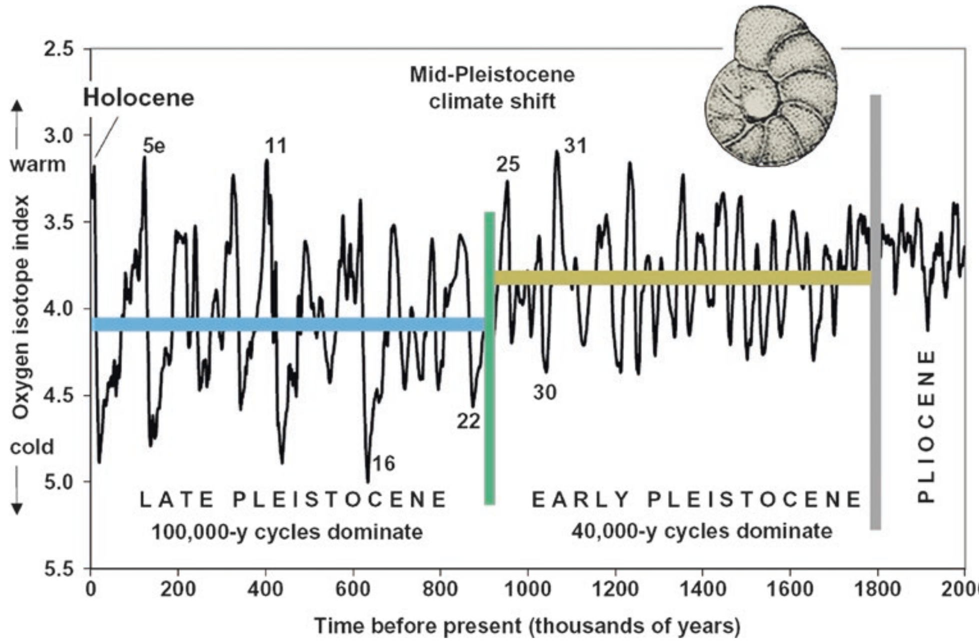

Fig. 1.4 Ice-age record in deep-sea sediments (oxygen isotopes in benthic foraminifers, a proxy for temperature and ice mass) (Data interpolated from Zachos et al. 2001, Science 292:686). The benthic foraminifer (closely related to the benthic signal carriers, genus *Cibicides*) is after a drawing by Jan Drooger. Numbers are MIS designations (marine isotope stages) following Cesare Emiliani – odd for warm stages. The last prominent MIS (25) in the warmish early Pleistocene occurred about a million years ago. Horizontal bars denote average conditions; vertical ones are climate boundaries. Note the changes in dominant cycles. Such changes are not explained by Milankovitch Theory

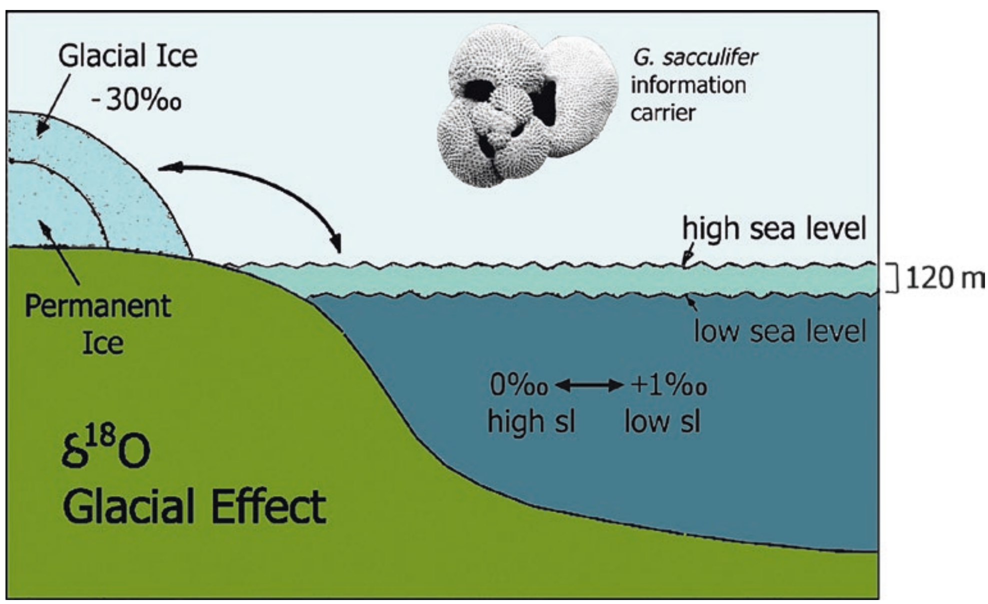

Fig. 1.5 Oxygen isotope ratios as a proxy for polar ice mass according to the Italian-American paleontologist and physical chemist Cesare Emiliani (1922–1995). The ice differs in composition from seawater. Thus, as the ice waxes and wanes, the ocean changes isotopic composition, which is reflected in the shells of foraminifers. Ratios are expressed as deviation from a standard, in permil (equal to ten times the value of percent). There also is a temperature effect, which was emphasized by Emiliani. The signal carrier shown (*Globigerinoides sacculifer*) is a warmwater planktonic species

1.1.4 Deep-Ocean Drilling: Discovering New Worlds

The rise of the new tectonic paradigm greatly encouraged the launch of a major venture in marine geology: the exploration of the deep seafloor by drilling. In fact, perhaps the most celebrated result of deep drilling was the support garnered for plate tectonics during Leg 3 of the Deep-Sea Drilling Project (DSDP). Drilling provided for long sequences. As a result, changes in the environment of the sea could be reconstructed for the last 100 million years in some detail. Thus, the other important result of drilling was the establishment of long-term deep-ocean history focused on environmental change.

Long-term ocean history had been addressed before, of course, based on shelf sediments. It was part of general geologic knowledge that there was a great cooling of the planet in the last 40 million years culminating in the northern ice-age cycles that started not so long ago, geologically speaking. However, the history of cooling was first clearly documented by drilling into Cenozoic sediments on the deep seafloor and the cycling of ice by using oxygen isotopes (Fig. 1.5). The drilling vessels were the *Glomar Challenger* and later the *JOIDES Resolution* (Fig. 1.6). The record on land is patchy

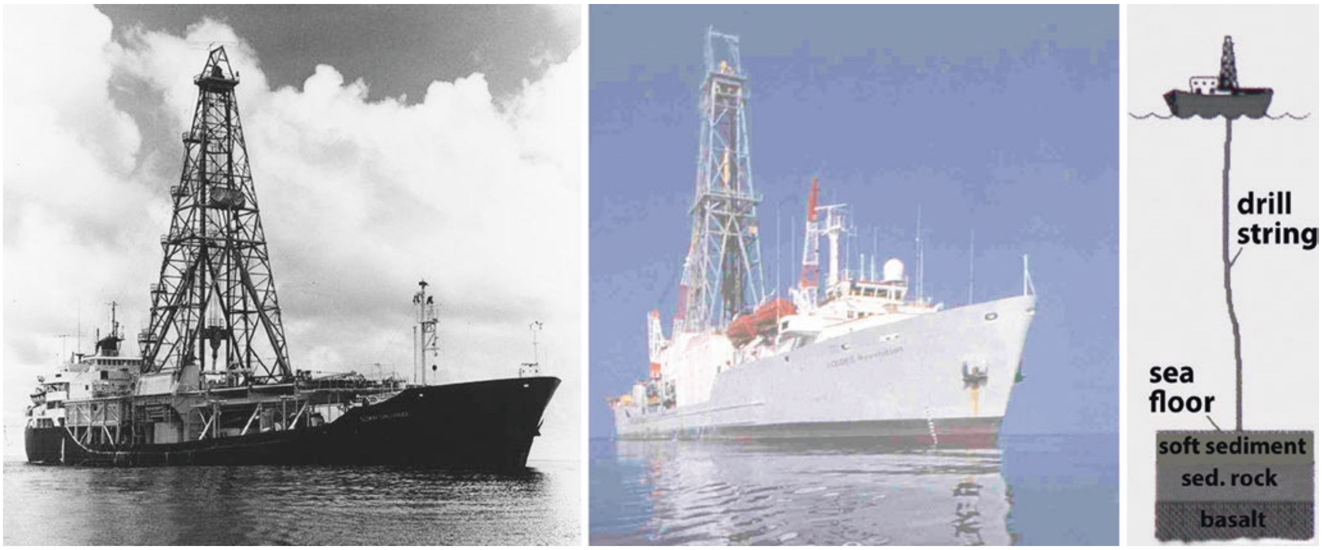

Fig. 1.6 The two drilling ships that explored the deep seafloor between 1968 and 2003. In essence, these were floating platforms for derricks such as used in drilling for oil. In each case, the drill string is lowered through a central hole in the bottom of the vessel (Photos courtesy DSDP, S.I.O., and ODP, Texas A&M; graph from M. Kastner et al., 1995, S.I.O. Ref. 95-15, simplified)

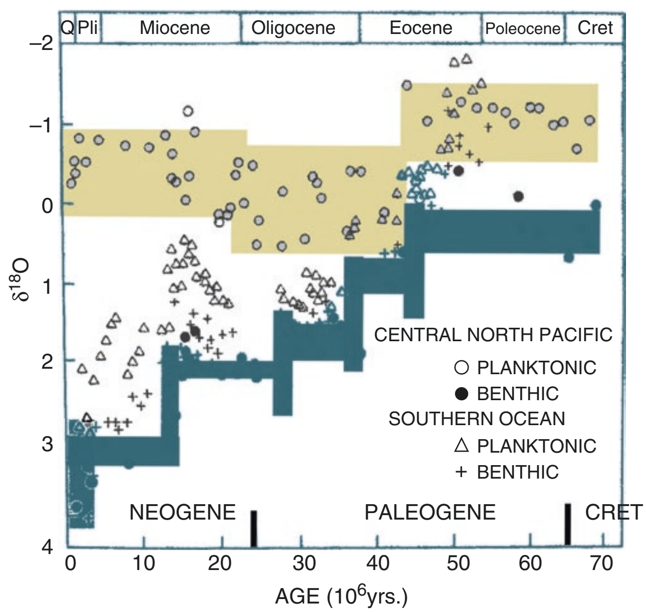

Fig. 1.7 Evidence for stepwise cooling in the Cenozoic (the proxy for temperature – and ice on land – is the δ-value for oxygen isotopes plotted as y-value). Note that the general cooling trend is most obvious in the high-latitude and in the benthic data, not in the low-latitude pelagic ones (Graph after H.R. Thierstein and W.H.B. 1978, Nature 276: 461, modified; one step added in the late Eocene; data from R. Douglas and S. Savin (1975; DSDP Leg 32) and from N. Shackleton and J. Kennett (1975; DSDP Leg 29), as well as from S. Savin (1977, Rev. Planet. Sci. 5, 319–355)). A reliable scale is necessary to put rates of evolution and other items of geologic history into perspective (Fig. 5)

and incomplete by nature – land is eroded and delivers sediment to the sea. This renders suspect all land-based arguments about the pace of evolution, as already by Darwin pointed out. Only the record in the deep ocean can promise complete sequences, and even here gaps (called "hiatuses") proved to be quite common, frustrating much effort at reconstruction.

As a result of the drilling (and associated investigations), the stepwise cooling that characterizes the nature of sediment deposition since the Eocene (Fig. 1.7) was discovered by early DSDP participants in the 1970s. The Eocene itself, the longest of the three periods making up the early part of the Tertiary (called the "Paleogene"), is seen to be dominated by a general cooling. The step toward the end of the Eocene may be considered the culmination of the preceding trend. It is widely assumed that this step and the various others (marked as vertical-shaded rectangles in the graph) reflect positive feedback from albedo changes on ice and snow in high latitudes, including sea ice. Of course, such feedback becomes very strong rather suddenly, at critical temperature levels. The steps quite possibly indicate a sudden drop in carbon dioxide in the air as well. A trend toward lower CO_2 values in the Cenozoic is widely assumed.

The general trend of high-latitude and deep-water cooling has been ascribed to the rise of mountains (that is, to endogenic or mantle-based forcing involving plate tectonics). Mountain building changed the wind field (and thereby heat distribution) and the albedo of the planet. Also, it likely increased weathering rates and hence decreased carbon dioxide concentrations in the air. The same agents based on mountain building, by extension of the argument, were presumably responsible for starting the northern ice ages. Ways to decrease atmospheric carbon dioxide and to increase albedo from causes other than uplift also are being discussed.

1.1.5 The Gubbio Event

The discovery of relatively high iridium concentrations within a layer of indurated clay initiated another major geologic revolution. The clay layer separates Cretaceous rocks from the following (somewhat similar) Cenozoic limestone layers in an exposed marine sediment section in Italy. Chemical analysis and interpretation were by Luis and Walter Alvarez and associates. Walter Alvarez sampled this section (near Gubbio) because it was well documented for foraminifer content by the paleontologists Hans Luterbacher (German-Swiss) and Isabella Premoli Silva (Italian). They had found (as had others earlier and elsewhere) that tropical planktonic forms (i.e., creatures of a warm and sunlit zone in the sea) became extinct at the end of the Cretaceous, followed by new forms, small, inconspicuous, and presumably initially largely nontropical.

The high iridium concentration at the level of the striking change in planktonic foraminifers is thought to have been caused by a "bolide" coming in from space, a large rock, perhaps around 10 km in diameter. Its impact on Earth (a huge crater with the right age was later found in Mexico) presumably created the havoc that produced the extinction of many creatures and thus ended the Cretaceous (and thereby the Mesozoic, the so-called Age of Reptiles). An even larger crater of the right age is said to have been identified near Mumbai, India. This Mumbai crater, suggested to have been made by a bolide 60 times bigger than the Mexican one, may be contemporaneous with the Deccan lava flows in India and thus presumably involved in releasing volcanic gases.

Victims of the end-of-Cretaceous mass extinction included the dinosaurs and in the marine realm the ammonites and the dolphin-like reptiles called ichthyosaurs. Other well-known victims included the reef-forming bivalves called "rudists" and a host of large reptiles such as the fearsome mosasaurs (lizards longer than large crocodiles but with equally awful teeth and with a snakelike expandable lower jaw). Mammals presumably benefited from the demise of the giant reptiles, which had dominated Earth for millions of years. In any case, mammals soon took over in the vertebrate world.

It has been known for decades that minute missives from space are hitting Earth all the time. Amounts arriving are measured in tens of thousands of tons. But only rarely is one of those missives several km in diameter, in which case it is called "bolide," and produces a crater on the surface of the planet. That impacts by bolides from outer space are not all that rare in geologic history was established by the NASA geologist Eugene Shoemaker (1928–1997), who had studied the great meteor crater in Arizona for his Ph.D. thesis. He and his associate (the chemist Edward Chao of Caltech in Pasadena, California) recognized the Miocene Ries crater in Bavaria as an impact feature, in 1960, providing an unusually large and impressive case study. Details of the story can be studied in the local museum at Shoemaker-Platz 1 in the City of Nördlingen in Bavaria. The crater is more than 20 km in diameter, that is, it is considerably larger than the meteor crater in Arizona. The impact is of middle Miocene age. It is said by many geologists to have had very little or hardly any effect on Earth history. Whatever the truth is, it is an interesting and instructive feature and well known to most geologists for the impact rock "suevite," the name a play on the local (German) dialect.

1.2 Great Revolutions in Geobiology and Geochemistry

1.2.1 Hot Vents, Cold Seeps, and Prokaryotic Microbes

The four major geologic revolutions identified in the previous sections concern mainly geophysics, although, of course, there are effects on organisms, as well. In addition to the geophysical phenomena, there are several very important revolutions related mainly to the biology and chemistry of Earth and its ocean. They include the discovery of hot vents and the nature of their fauna on ridge crests (Figs. 1.8 and 1.9), along with chemical reactions between hot basalt and seawater. Pioneers were the geoscientists Jack Corliss, Richard von Herzen, Clive Lister, Peter Lonsdale, John Edmond, and others. Marine biologists included Holger

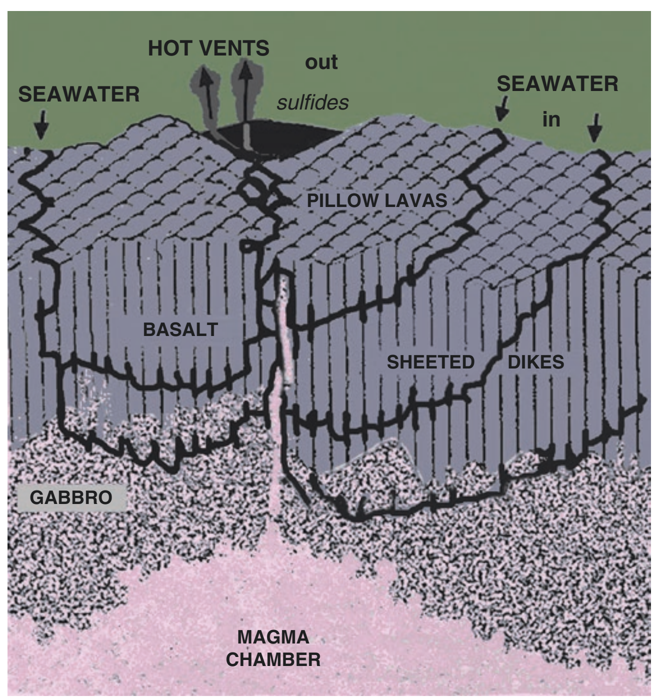

Fig. 1.8 Hot vents accompany the flow of hot seawater through freshly formed basalt in settings involving seafloor spreading. "Pillow lava": basalt with very small crystals and with pillow-shape structures; "gabbro" – basalt with large crystals, commonly "olivine" (*greenish*) and "pyroxene" (*dark gray*). Seawater percolating through cracks acquires heat from the basalt and changes its chemistry, thanks to reacting with the hot rock (Graph after schematic drawings by Enrico Bonatti and Peter Herzig)

Fig. 1.9 Tube worms at a hot vent in the Pacific, as seen from the Woods Hole scientific submarine ALVIN (Photo courtesy of Robert Hessler, S.I.O., here modified)

Jannasch, Robert Hessler, Cindy Lee van Dover, and many others, commonly using *ALVIN*, the scientific submarine of Woods Hole Oceanographic Institute. The discovery of cold seeps in certain continental slope areas also belongs into the category of fluids from the seafloor changing seawater chemistry (see next section). Pioneers were Erwin Suess, Gerhard Bohrmann, Miriam Kastner, Lisa Levin, and many others. A third geobiological revolution also concerns microbes, specifically bacteria and archaea. The discovery of such prokaryotic microbes, by drilling, deep within continental margins in marine sediments millions of years old, represents a major puzzle.

The vent setting (Fig. 1.8) in many places harbors the famous tube worms (Fig. 1.9) that rely on the oxidation of sulfide for sustenance, via the activity of microbes that live within the worms in symbiosis. Outstanding pioneers include Jack Corliss (Ph.D. 1967, La Jolla), who first saw the worms, and Scripps geophysicist Fred Spiess (1919–2006), who provided means to locate the first vent discovered. Woods Hole pioneer biologist Holger Jannasch (1927–1998) is among a long list of users of the Woods Hole scientific submarine *ALVIN*, platform of observations and for obtaining biological samples.

1.2.2 Cold Seeps

In addition to the "hot vents" and their unique fauna, we have "cold seeps" along many of the active margins, also with organisms relying for sustenance on microbe symbiosis (studied by Erwin Suess, Gerhard Bohrmann, Miriam Kastner, Lisa Levin, and many others). The cold seeps are commonly associated with methane-rich ice ("burning ice"; Fig. 1.10). The methane ice ("hydrate" or "clathrate") is being intensely studied for the associated fauna but also for possible retrieval as an energy source and as a potential hazard. Methane clathrates generate concern because of the potential for methane release during global warming. Methane is a powerful greenhouse gas. Also its release can facilitate large submarine landslides and thus generate large tsunamis.

Fig. 1.10 "Burning ice," that is, ice rich in methane ("clathrate"). It is commonly found in regions where interstitial waters are expelled from the seafloor, in continental slope areas bearing "cold seeps" (Photo courtesy G. Bohrmann, now MARUM Bremen, and E. Suess, GEOMAR Kiel)

1.2.3 Bacteria and Archaea

Ever since the end of the ninteenth century, evidence has been accumulating that prokaryotic microbes are intimately involved in the geochemistry of the planet (e.g., see the documentation of microbe activity in soils by S. Winogradsky in 1949). Recently, vast and impressive evidence for living microbes at great depths below the seafloor has emerged from drilling in continental slope sediments.

What, if anything, do these various geobiological revolutions have in common? They are intimately associated with the discovery of strange bacteria-like organisms, the archaea. These microbes define a new biological kingdom, proposed by the biologist Carl Woese (1928–2012) of the University of Illinois and his associates. Their proposal results in three domains of life, rather than just the traditional two (the "prokaryotes" lacking a well-defined nucleus and the "eukaryotes" which possess one). The traditional prokaryotes contain the familiar bacteria, while the eukaryotes cover everything else, including foraminifers, people, and plants. Presumably, the bacteria and archaea found by drilling well below the seafloor (Fig. 1.11) have a strangeness of their own – they must be able to survive for enormously long time spans. Their mass is said to be a substantial fraction of the mass of living things on the planet. The Ukrainian-French

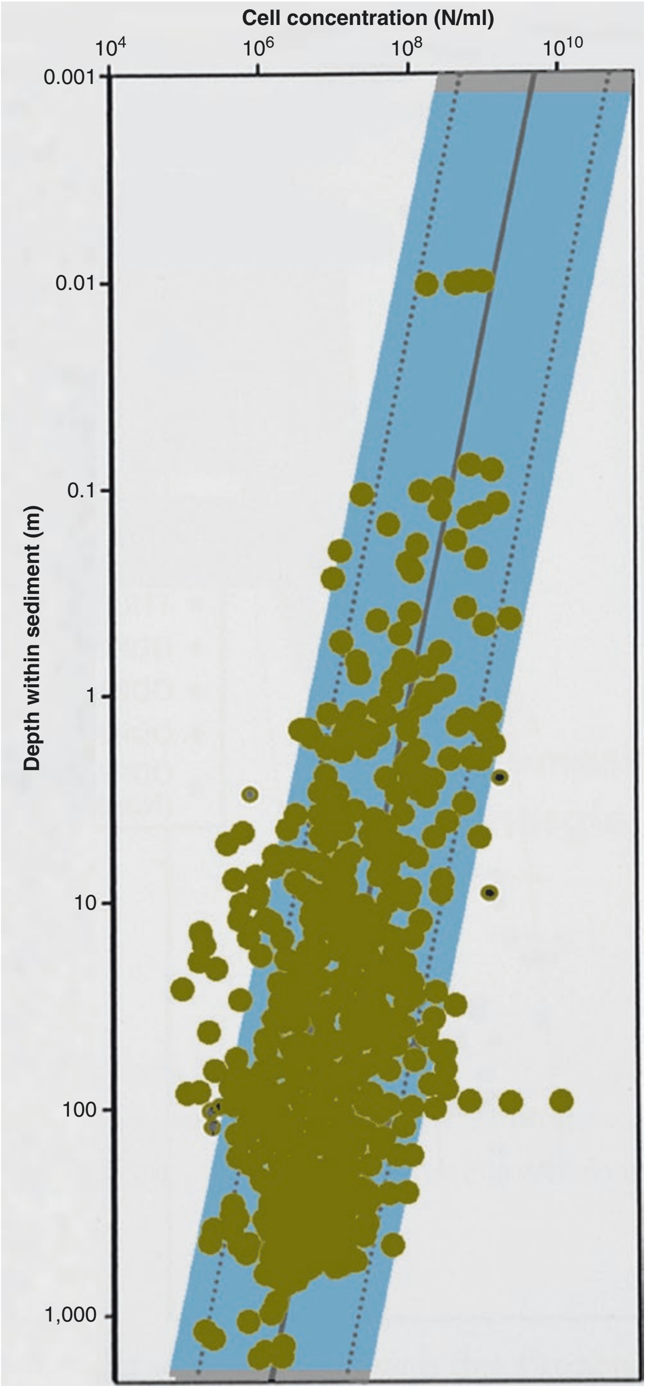

Fig. 1.11 Abundance of microbes within marine sediments (by volume of sediment) (After Hinrichs et al., 2010. In: Expedition Erde (3rd ed.), MARUM Bremen, ed. by G. Wefer and F. Schmieder, p. 144. Data (here simplified; leaving off area of origin): R.J. Parkes et al. (2000), S. d'Hondt et al. (2004), B. Engelen et al. (2008), E.G. Roussel et al. (2008), G. Webster et al. (2009))

microbiologist pioneer Sergei Winogradsky (1856–1953) had been right in surmising that microbial life is pervasive in its effects on the planet, being intimately involved in the cycling of carbon, of sulfur, of iron, and of nitrogen, among other things.

1.3 More on Pioneers Who Identified Basic Questions in Marine Geology

1.3.1 Johannes Walther and Persons in P.D. Trask's Book

Marine geology, as a discipline in geology, started well before the various revolutions listed, of course. It began with geologists noting the processes that helped produce the marine rocks which they saw on land. The German geologist Johannes Walther (1860–1937), known for "Walther's Law," was a pioneer in these types of studies. ("Walther's Law" asserts that vertical sequences of marine sediments reflect originally neighboring types of deposits.)

In his book, *Bionomy of the Sea* (Jena 1893, in German), Walther gave an account of marine environments and the associated ecology of shell-bearing organisms (and the pertinent literature of the time). Research on marine sedimentation in the four decades that followed is summarized in the volume *Recent Marine Sediments* edited by the USGS geologist P.D. Trask (Tulsa 1939). The symposium spans the range of sedimentary environments from beach to deep sea, and many of the articles were written by famous pioneers in marine geology of the time, geologists from various countries.

1.3.2 John Murray and the *Challenger* Expedition

As marine geologic studies progressed and moved farther out to sea, there was a gradual change of emphasis in the set of problems to be solved. The seafloor itself became the focus of attention, not for the sake of the clues it could yield for the purposes of geology on land but for the record it has for its own evolution and its role in the present processes relevant to the Earth's environment. The new emphasis is first obvious in the works of the Scotsman John Murray, naturalist of *HMS Challenger* on her world-encircling expedition (1872–1876). John Murray's chief opus, *Deep Sea Deposits* (written with the Belgian geologist A.F. Renard and published in 1891) laid the foundation for the sedimentology of the deep ocean floor, that is, of the sediments that cover most of the planet.

1.3.3 Philip H. Kuenen, B.C. Heezen, M. Natland, and Turbidites

Some of the great volumes of deep-sea deposits are nothing but shallow-water sediments that moved down to rest on the deep seafloor. This was proposed (in 1950) by the Dutch geologist Ph.D. Kuenen (1902–1976), who demonstrated that sediment clouds could rush downslope from shallow areas to great depth, due to the fact that muddy water is heavier than the clear water surrounding it. The Canadian-born geologist R. A. Daly (1871–1957) (Prof. at Harvard), the Lamont geologist D.B. Ericson (curator of the core collection), and the Californians Manley Natland (1906–1991), E.L. Winterer (Ph.D. 1954, U.C. Los Angeles), and Chicago-trained F.P. Shepard (1897–1985) came to similar conclusions at the time. The sediment thus transported settles out of suspension at the site of deposition, large grains first, fine grains last. The resulting layer (called a "*turbidite*") is *graded*. Graded layers are common in the geologic record (e.g., in the Alpine *flysch* deposits and in the Neogene sequences of sedimentary rocks in the Californian Transverse Ranges) suggesting that Kuenen's concepts are indeed important for all of geology. The Lamont geologist B.C. Heezen (1924–1977), together with Lamont's founding director M. Ewing (1906–1974), offered evidence (in 1952) that turbidite-producing flows race down the slope off the US East Coast occasionally. Similar events are now postulated for the origin of much of continental slope sediments everywhere, and to explain the origin of sea valleys within them, and for the origin of the flatness of *abyssal plains*, which are among the most extensive features on the planet.

1.3.4 *Meteor* and *Albatross* Expeditions and *Vema* Collections

Studies in marine sedimentation led into ocean history when geologists started to take cores. The pioneering expeditions were those of the German vessel *Meteor* (1925–1927), whose participant W. Schott (1905–1989) first proposed rates of deep-sea sedimentation at around 1–2 cm per thousand years, and the one of the Swedish vessel *Albatross* (1947–1948), led by the Swedish physicist and oceanographer Hans Pettersson (1888–1966). The several meters long Albatross cores established the presence, in all oceans, of cyclic sedimentation, which documented evidence for climate fluctuations during the last million years, including several ice ages (see Chap. 11). Enormous collection efforts followed, led by Lamont's research vessel *Vema (*also *R.V. Conrad)*. Several Lamont scientists would have to be mentioned as pioneers, foremost the geophysicist M. Ewing (the founding director) and the geologist Bruce Heezen, already mentioned in connection with the turbidite discovery but also prominent in numerous others.

1.3.5 Deep-Ocean Drilling: *GLOMAR Challenger* and *JOIDES Resolution*

The last (and biggest) effort in the line of deep-sea expeditions elucidating matters of marine geology is the various programs for deep-ocean drilling, including the Deep-Sea Drilling Project (head office at S.I.O.), the Ocean Drilling Program (head office at Texas A&M), and the Integrated Ocean Drilling Program (core repositories in Texas [US Gulf Coast], in Bremen [Germany], and in Kochi [Japan]). Countless samples became available for the study of ocean history, thanks to the drilling expeditions. Together, the various drilling programs recovered hundreds of kilometers of core sections from the deep sea. The main results from drilling in the seafloor concern stepwise cooling within the Cenozoic (Chap. 12) and the shortage of oxygen in the Cretaceous (Chap. 13). Important pioneers are J.P. Kennett, N.J. Shackleton, S. Savin, and R. Douglas, as mentioned above in Sect. 1.1.1.

1.3.6 Morphology (Landscapes)

While the drilling ventures attracted a large amount of attention in the second half of the last century, traditional investigation of the seafloor proceeded unabated. Coastal landforms are the most accessible of the marine environments, and considerable information concerning them had been accumulated early in the twentieth century. Much additional work on these topics was subsequently done by the Scripps geologist Francis P. Shepard (1897–1985), who took his observational skills to sea. In France, it was the geologist Jacques Bourcart (1891–1965) who was able to test theoretical concepts against field data collected in shallow waters. Shepard's textbook *Submarine Geology* (first published in 1948) summarized the results of this and other early works. In the same year that Shepard's first marine geology text was published (1948), M.B. Klenova's textbook *Geology of the Sea* was printed, with ample coverage of Russian work. Among several outstanding Russian pioneers, there were many who made crucially important contributions to the understanding of deposition on the seafloor. For example, N.I. Andrusov (1861–1924) studied deposits in the Black Sea, and N.M. Strakhov (1900–1978) explored the origin of marine rocks in general.

The marine geomorphologist *par excellence* was B.C. Heezen (Fig. 1.12, inset). His physiographic diagram of the seafloor (produced together with his collaborator Marie Tharp, 1920–2006) now is in many or most textbooks. It was republished by the US Navy as a memorial to Heezen. Much of Heezen's work is summarized in the beautifully illustrated book *The Face of the Deep* (New York, 1971), written with C.D. Hollister (1936–1999).

1.3.7 Alfred Wegener (1880–1930)

It is perhaps no coincidence that a geophysicist first formulated a global hypothesis for the overall geography of the

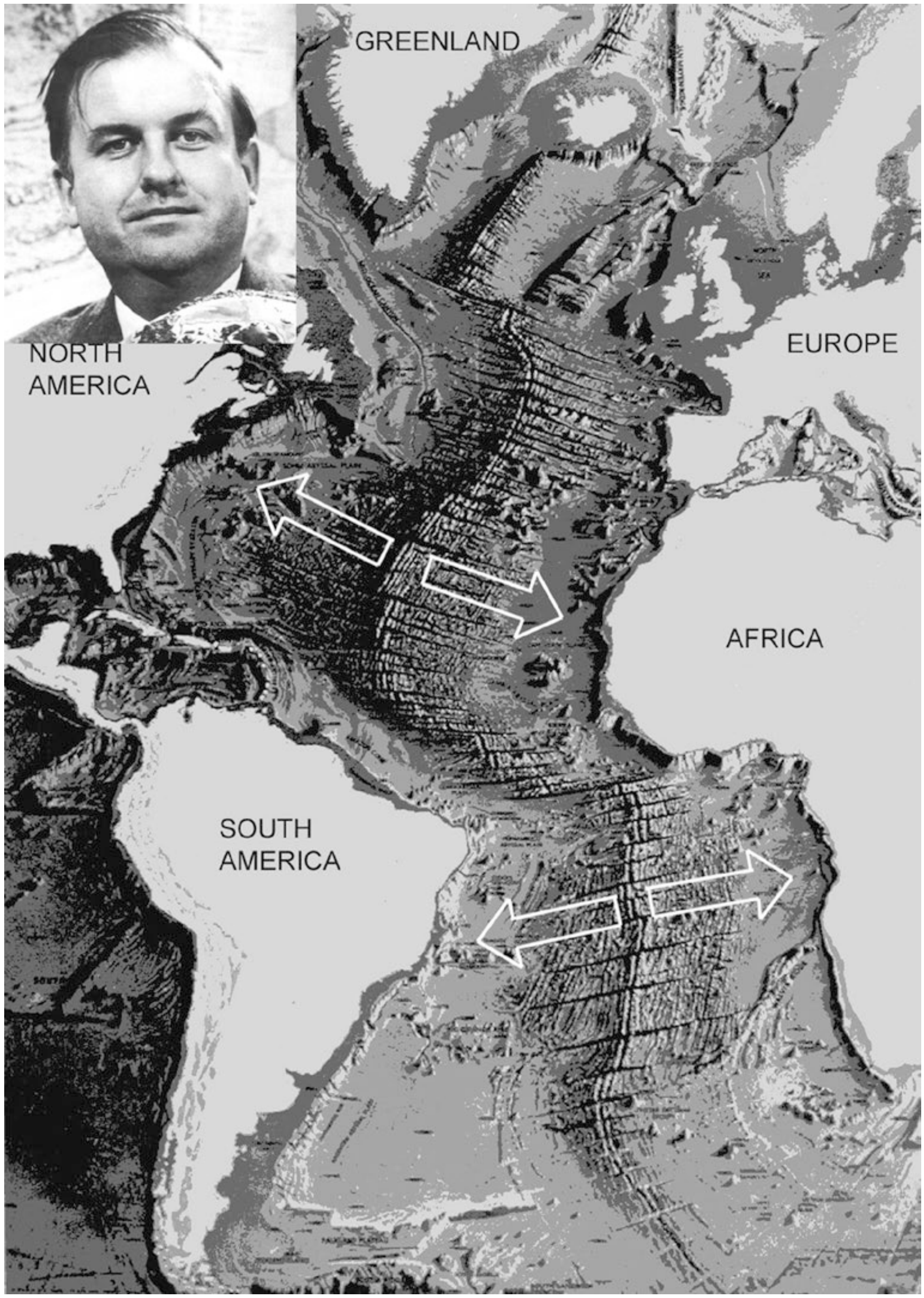

Fig. 1.12 Physiographic diagram of the Atlantic Ocean floor according to Bruce Heezen and Marie Tharp, Lamont, Columbia University, as repainted by H. Berann (National Geographic Society). Rendered here with omissions and additions with a portion of the memorial map of the US Navy. Insert portrait of Bruce Heezen: courtesy of the Lamont–Doherty Earth Observatory

planet that proved to be viable: the proposition regarding continental drift, by the meteorologist Alfred Wegener (1880–1930). Wegener was intrigued with the fact that the coast lines bordering the Atlantic Ocean are parallel. (The observation was widely known. It had been made decades earlier by the naturalist and explorer Alexander von Humboldt, 1769–1859.) Wegener rejected the land bridges proposed by leading paleontologists of his time to explain striking similarities of Paleozoic land fossils on both sides of the Atlantic. Instead, he postulated that the continents were once united. With this hypothesis, he started the "debate of the century" in geology. He proposed his hypothesis in an article in 1912 (in the journal *Geologische Rundschau*) and again in his book *The Origin of Continents and Oceans* (Braunschweig, 1915, in German; later translated into English). He envisioned granitic continents floating in basaltic mantle magma like icebergs in water (Fig. 1.13) and drifting about on the surface of the Earth in response to unknown forces linked to the rotation of the planet.

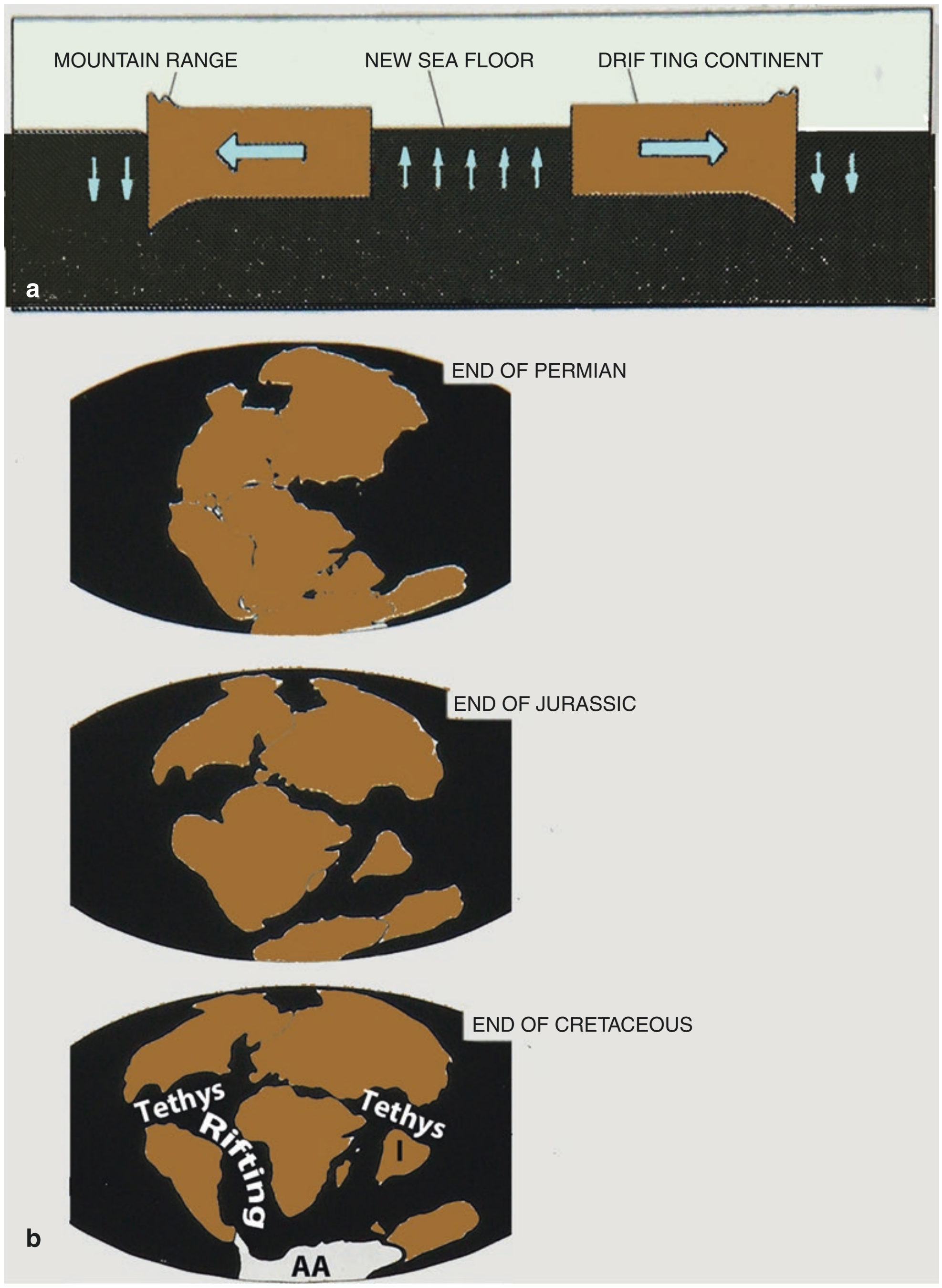

Fig. 1.13 Diagrammatic representation of the hypothesis of continental drift of Alfred Wegener. (**a**) Continental blocks made of rocks rich in silicon and aluminum float iceberg-like in the heavier mantle material rich in silicon and magnesium. As the continental blocks drift apart, mountain ranges form at the bows of the drifting blocks (the "active" margins), while new seafloor forms between the slowly sinking "passive" margins. (**b**) The breakup of the ancient continent of "Pangaea," as envisaged by A. Wegener, in a modern reconstruction by R.S. Dietz (US Navy) and J.C. Holden (1970; J. Geophys. Res. 75: 4939, simplified and with addition of labels). *AA* Antarctica, *I* Indian subcontinent, moving northward toward the ancient seaway called "*Tethys*" (erstwhile, part of a tropical connection between a growing Atlantic and the Pacific, now closed; color here added)

When mentioning Alfred Wegener in connection with plate tectonics, one might assume that "continental drift," the main brain child of Wegener, initiated the thinking that led to the final concept. This was actually not the case: Wegener's ideas were long rejected. It was the magnetism frozen into seafloor basalt solidifying from mantle melt during seafloor spreading that clinched the new concept, a concept that has many parents (see Chap. 2).

1.3.8 E.C. Bullard (1907–1980) and M. Ewing (1906–1974)

Wegener's hypothesis, in modified form, is now an integral part of *plate tectonics*, the ruling theory explaining the geomorphology and geophysics of the ocean floor. It was the work of sea-going geophysicists which eventually led to the acceptance of seafloor spreading and plate tectonics.

The pioneering efforts of the British geophysicist E.C. Bullard (1907–1980) on earth magnetism, heat flow, and seismic surveying must be mentioned, as well as those of the US geophysicist M. Ewing at Columbia University. Although M. Ewing may not have believed that plate tectonics describes reality correctly, he and his associates were of central importance in the development of the new paradigm. Both scientists caused enormous amounts of relevant observations to be made. Of course, there are many others who contributed as well (see Chap. 2). Ewing's and Bullard's studies were important to traditional geology in that they included the nature of continental margins, a region of prime interest in the study of marine layers on land (see the book edited by C.A. Burk and C.L. Drake).

1.3.9 H.H. Hess (1906–1969) and R.S. Dietz (1914–1995)

The turning point in the scientific revolution that shook the Earth sciences and which was culminated in *Plate Tectonics* is generally taken to have been the seminal paper by the former Navy officer and Princeton geologist Harry H. Hess (1906–1969), entitled *History of Ocean Basins* and published in 1962. It is probably fair to say that the paper was widely ignored when first published and for a few years afterward. Hess started his distinguished career working with the Dutch geophysicist F.A. Vening Meinesz (1887–1966) on the gravity anomalies of deep-sea trenches. The investigations resulted in the hypothesis that trenches may be surface expressions of the down-going limbs of mantle convection cells (which is similar to today's explanation). As a naval officer, Hess discovered and mapped a great number of flat-topped seamounts (which he called "guyots") during WWII, in the central Pacific.

Stimulated by the discoveries concerning the mid-ocean ridge (extent, morphology, heat flow, and other items), Hess proposed that seafloor is generated at the center of the mid-ocean ridge, moves away from the ridge and downward as it ages, and finally disappears at trenches. The term *seafloor spreading* was coined by the US Navy geologist R.S. Dietz (1914–1995) in San Diego and published in 1961. B.C. Heezen published on the nature of the Mid-Atlantic Ridge (that is, on rifting) in 1960, leaning on his work with the cartographer Marie Tharp (1920–2012). Years later some discussion ensued about priorities, documenting the importance of the new ideas (but not necessarily their first appearance). The fact that the Austrian geologist Otto Ampferer (1875–1947) and the British geologist Arthur Holmes (1890–1965) published ideas reminiscent of plate tectonic motions decades before others did may render the gist of such discussions moot.

1.4 Seafloor Spreading and Plate Tectonics: The New Paradigm

1.4.1 New Paradigm Accepted, Wegener's Hypothesis Triumphant

The new hypothesis of seafloor origin and mobility was generally accepted around 1970. Deep-sea drilling (Leg 3) probably had a role in it, by showing that micropaleontology agreed with geophysical assessment. This was an important demonstration for many geologists. Of course, many leading *geophysicists* (physicists doing geology) had already signed on to the new paradigm, relying on evidence from paleomagnetics. The plate tectonics theory recognizably starts with thoughts of A. Wegener, who argued from geography, paleontology, and crustal geophysics (Fig. 1.13). In other words, it took more than half a century for Wegener's ideas to prevail. A reluctance to accept new ideas, among geologists, also is obvious for the related propositions of Heezen, Hess, and Dietz. It took one decade for them to succeed (with insights largely based on a plethora of the US Navy data and confirmed by seismic and paleomagnetic information). The amount of information available had grown immeasurably, removing doubt more rapidly than before.

1.4.2 Euler's Theorem

Shortly after Hess published his provocative article on postulated seafloor spreading, E.C. Bullard and associates introduced "Euler's Theorem" to global tectonics (Fig. 1.14). The theorem, generated by the Swiss mathematician Leonhard Euler (1707–1783), states that uniform motion on a sphere is uniquely defined by the rotation about an appropriate point, called a "pole." The path of migration of any point on a plate in uniform motion appears as a portion of a circle about that pole. Bullard and collaborators used Euler's Theorem, in 1965, to produce a new "fit" of the continents bordering the Atlantic. Shortly after, the geophysicist and geologist James W. Morgan of Princeton University realized that fracture zones in the eastern North Pacific run parallel to small circles of Euler poles, thus cementing the connection between plate motions and Euler's Theorem.

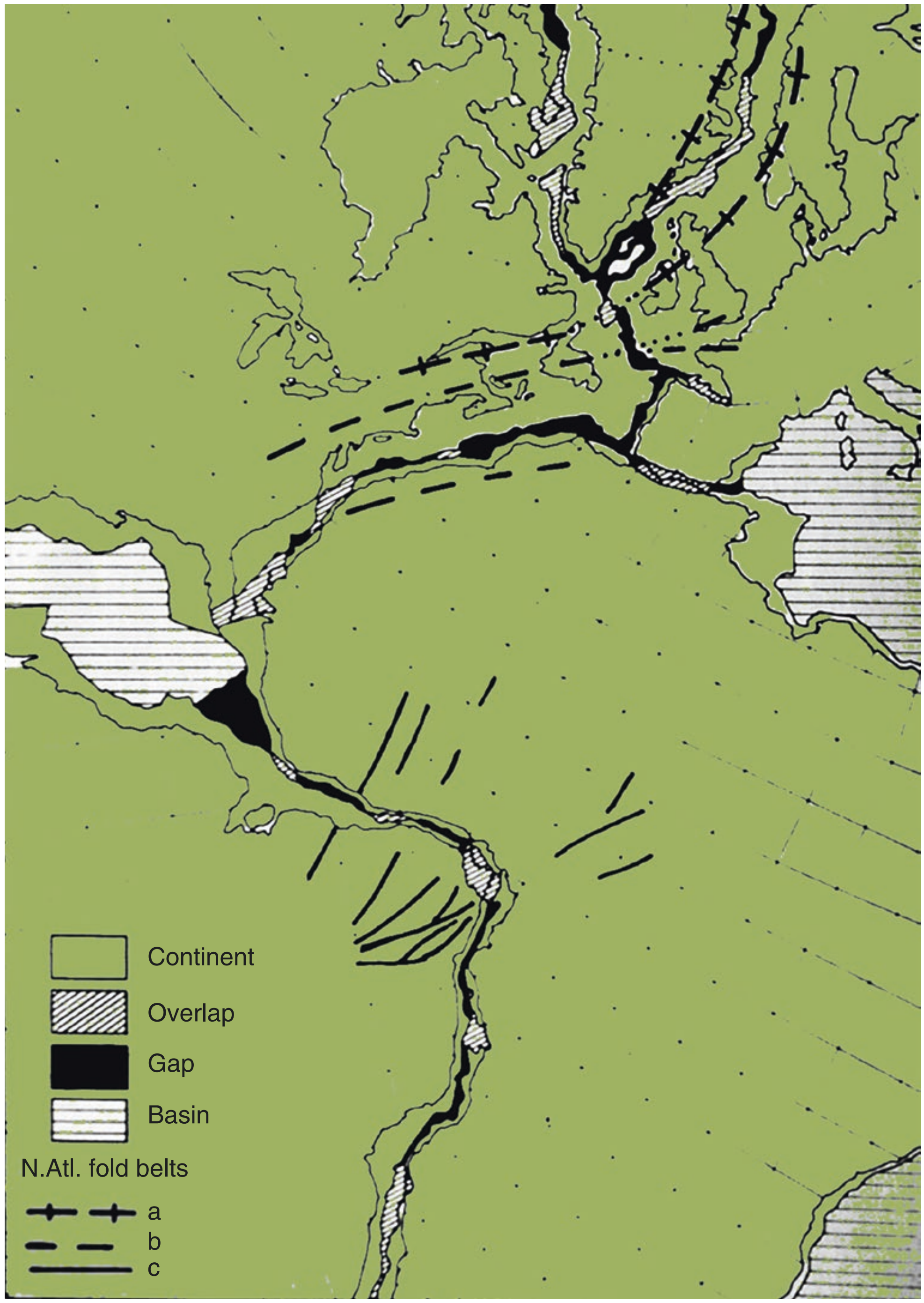

Fig. 1.14 The fit of the continents bordering the Atlantic, as proposed by E.C. Bullard et al., (in Blackett et al., eds., 1965. A Symposium on Continental Drift. Phil. Trans., Royal Soc. London, 258:41). Note the Niger Delta overlap, which is expected since the delta is geologically young, and the Bahamas overlap, which is unexplained. The alignment of the Paleozoic fold belts in North America and Europe and in South America and Africa is striking. (**a**) Caledonian fold belt (Norway-Scotland), (**b**) Hercynian fold belt, and (**c**) Pan-African fold belt (The latter is adapted from C.J. Archanjo and J.L. Bouchez, 1991. Bull. Soc. Géol. France 4: 638. Color here added)

Suggestions for Further Reading*

Holmes , A., 1945. Principles of Physical Geology. Nelson, London.

Kuenen, Ph.H., 1950. Marine Geology. Wiley, New York.

Heezen, B.C., M. Tharp, and M. Ewing, 1959. The Floor of the Oceans. 1. The North Atlantic. Geol. Soc. Amer. Spec. Pap. 65.

Sears, M. (ed.) 1961. Oceanography – Invited Lectures Presented at the International Oceanographic Congress Held in New York, 31 August – 12 September 1959. AAAS Publ. 67.

* A full reading of the references offered is not recommended. The prime intent is to provide a short list of tomes worth perusing for relevant information. Another is to provide access to books that preserve the historic context of the most remarkable revolutions in marine geology within the last century.

Turekian, K.K. (ed.) 1971. The Late Cenozoic Glacial Ages. Yale Univ. Press, New Haven.
Funnell, B.M., and W.R. Riedel (eds.) 1971. The Micropalaeontology of Oceans. Cambridge Univ Press.
Imbrie, J., and K.P. Imbrie, 1979. Ice Ages – Solving the Mystery. Enslow, Short Hills, N.J.
Kennett, J.P., 1982, Marine Geology. Prentice-Hall, Englewood Cliffs, N.J..
Berger, A., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B. (eds.), 1984. Milankovitch and Climate: Understanding the Response to Astronomical Forcing, 2 vols. Reidel, Dordrecht.
Hansen, J.E., and T. Takahashi (eds.), 1984. Climate Processes and Climate Sensitivity. American Geophys. Union, Geophys. Monogr. 29.
Berger, W.H., and L. Labeyrie (eds.) 1987. Abrupt Climatic Change - Evidence and Implications. Reidel, Dordrecht .
Berger, A., S. Schneider, and J.-C. Duplessy (eds.) 1989. Climate and Geo-Sciences. Kluwer Academic, Boston, Mass.
Mountain, G.S., and M.E. Katz (eds.) 1991. The Advisory Panel Report on Earth System History. Joint Oceanographic Institutions, Washington, D.C.
Emiliani, C., 1992. Planet Earth – Cosmology, Geology, and the Evolution of Life and Environment. Cambridge University Press, Cambridge and New York.
Hsü, K. J., 1992. Challenger at Sea: A Ship That Revolutionized Earth Science. Princeton University Press.
Van Dover, C.L., 2000. The Ecology of Deep-Sea Hydrothermal Vents. Princeton Univ Press, NJ.
Houghton, J.T., et al. (eds.) 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
Oreskes, N. (ed.) 2001. Plate Tectonics – An Insider's History of the Modern Theory of the Earth. Westview, Boulder, CO.
McGowran, B., 2005. Biostratigraphy – Microfossils and Geologic Time. Cambridge Univ Press, UK.
https://books.google.com/books?id=obv_AwAAQBAJ&pg=PA3&lpg=PA3&dq=marine+geology+ revolutions&source=bl&ots=A9oc2VYyh&sig=VKPZiCioseC4sd899SpplMJnkmI&hl=en&sa=X&ved=0ahUKEwiB8pnZzrLNAhUDxWMKHZgTBqwQ6AEINzAD#v=onepage&q=marine%20geology%20revolutions&f=false

The web-site panels at the end of "suggested readings" were selected from the list offered when entering prominent chapter topics into the "Google" search engine, a selection based on estimated usefulness. Note that resulting sites could possibly be unsafe, being Internet products. Access to sites was verified in June 2016.