Origin and Morphology of Ocean Basins 2

2.1 The Depth of the Sea

2.1.1 General Distribution of Elevations

The obvious question to ask about the seafloor is how deep it is and why. The overall depth distribution largely became known through the voyage of *HMS Challenger* in the nineteenth century, and it could then be combined with available information from the land surface (Fig. 2.1). We see that there are two most common elevations on the solid planet: an upper one just above sea level and a lower one centered near the average depth of the ocean. The higher of the two main levels presumably mainly represents the action of erosion to sea level (*base level*), as well as uplift of continental crust. The lower one, one assumes, reflects the volume of seawater along with the availability of space to put the water (i.e., the room that is left after making the continents). The seafloor between the two elevation modalities, that is, the part connecting shelves and deep ocean floor, is a transition consisting largely of the continental slopes and rises. A portion of this intermediate category of elevations also must be assigned to the worldwide mid-ocean ridge and its flanks. In addition, there is a special (small) portion of seafloor that is more than twice deeper than the average: such great depths only occur in narrow trenches, mainly in the subduction ring around the Pacific Ocean.

2.1.2 Notes on the Mean Continental Elevation

The substantial height of the mean continental elevation (several hundred meters; Fig. 2.1) deserves some comment. Apparently it results from uplift, since a general prevalence of erosion would presumably result in lowering the continental surface to sea level, that is, to the *base level of erosion*. For an overall imbalance of rates of uplift and erosion, the mean elevation of continents must vary on geologic time scales; that is, what is being measured geologically are transients, when considering elevations above sea level. A general cooling in the Cenozoic, strontium ratios in marine carbonates, and the onset of ice ages suggest a prominent role for uplift since the beginning of the Eocene and then all through the rest of the Cenozoic. Himalayan uplift in the Neogene supports the suggestion.

2.2 Endogenic and Exogenic Processes

2.2.1 Endogenic Forcing: Tectonics

As is true of all of the face of the Earth in general, the seafloor is shaped by two kinds of processes, those deriving their energy from inside the Earth, the *endogenic* ones (e.g., volcanism, mountain building, and uplift), and those driven by the sun, called "exogenic" (e.g., erosion). In addition, there is astronomic forcing, which is a type of exogenic forcing depending on variations of input of energy from the sun directly, à la Milankovitch.

The forces inside the Earth are responsible for volcanism and earthquakes; we meet them in the eruptions on Hawaii, in the geysirs of Yellowstone National Park, and in the quakes in California. We see their handiwork in the mountain ranges of the Alps, the Sierra Nevada, and the Himalayas and in the gigantic rift of the Rhine Graben and the even larger one of the Red Sea. We shall have to examine tectonic forcing in some detail in this chapter, since the geography of the seafloor largely depends on it.

2.2.2 Exogenic Products Conspicuous

When contemplating questions of biological production (Chaps. 7 and 8), we are obviously in a zone of overlap between ecology and geology. The overlap is prominent in marine geology notably in the portion dealing with

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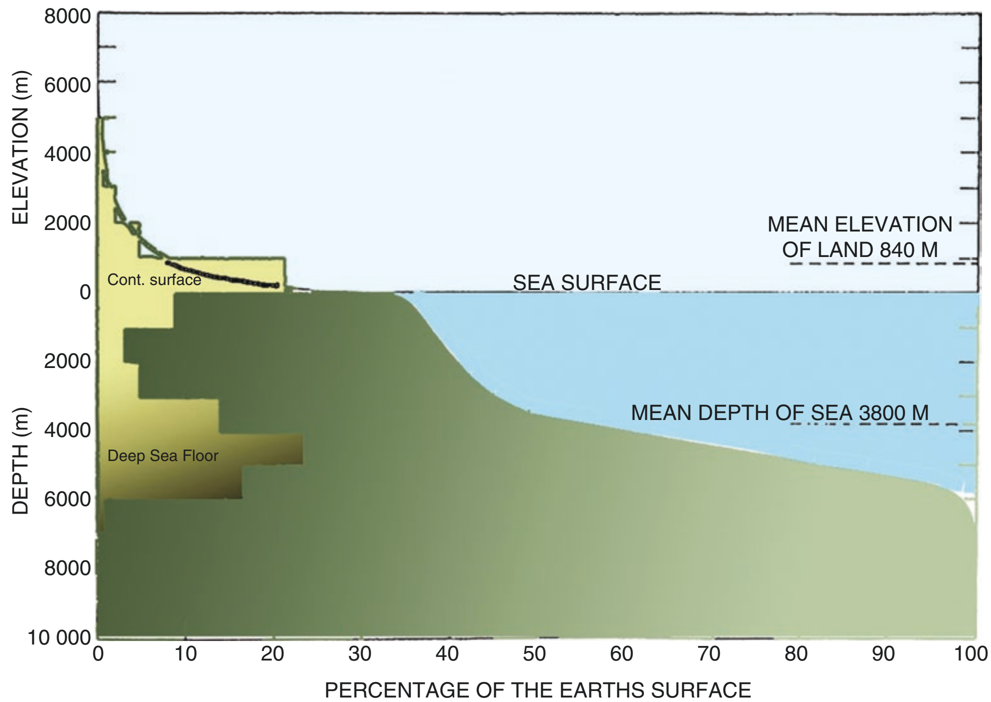

Fig. 2.1 Overall depth distribution of the ocean floor and of land elevations. Buff to *dark gray*: frequency distribution of elevations and depths on the planet. *Greenish gray*: seafloor, more greenish below coastal ocean (After H.U. Sverdrup et al. 1942, modified)

sedimentology and life on the seafloor (rather than with processes related to tectonics). Regarding non-biological sedimentation, there is the origin of turbidites. There is no question that exogenic forces are at work in generating the type of seafloor called *abyssal plain* – incredibly flat areas hundreds of miles in diameter, such as are seen off the MOR in the North Atlantic (Fig. 2.2). On land, the enormous playas that are dried-up lake bottoms in the west of the United States can convey an (somewhat diminished) idea of the extent and flatness of abyssal plains.

The abyssal plains are vast undersea playas collecting fine-grained debris from nearby continents, debris that is produced by the ever-present agents of weathering: rain, wind, and ice. The chippings made by these sculptors that wear down mountains are carried to the ocean by rivers and by winds. Here they build up sedimentary continental margins and abyssal plains beyond some of the continental slopes. The bulk of the mud and sand on the basin floors presumably is brought in by catastrophic events represented by the types of sporadic turbidity currents mentioned in the introduction when discussing Kuenen's contributions (Sect. 1.3).

Most of the sediment accumulating on the deep seafloor away from the continents, however, is not washed off from continents (i.e., it is not *terrigenous*) but arrives at the seafloor as a more or less continuous rain of particles: shells and skeletons of plankton organisms, wind-borne dust, and even cosmic spherules. Through geologic time (here: since the Jurassic), the slowly accumulating pelagic sediments built up a layer a few hundred meters thick on the seafloor of the deep sea, a layer that forms a thin exogenic veneer on the endogenic oceanic crust, which is basaltic. On land, analogous deposits of a pelagic nature are made by snow, albeit at a rate a thousand times greater than sedimentation rates typical for the deep seafloor. It is this thin veneer of pelagic sediments on the deep seafloor that contains a detailed history of the ocean for the last 100 million years or so.

Exogenic processes tend to *level* the Earth's surface by erosion and deposition. However, they also can build mountains, especially within the sea. The outstanding example is the *Great Barrier Reef* off northeast Australia. The reefs covering shelves (and ancient Cretaceous reefs on top of undersea mountains) consist of calcium carbonate secreted by stony corals, coralline algae, mollusks, and small unicellular organisms called foraminifers. The carbonate-secreting algae, as well as the minute algae symbiotic with the coral ("zooxanthellae") and with many of the foraminifers, depend on sunlight for energy, of course. Thus, typically coral reefs grow in shallow, sunlit waters. There are exceptions: some coral species (e.g., of the genus *Lophelia*) do grow at great depth in the dark (obviously they do without photosynthesizing symbionts).

With this briefest of introductions to the opposing effects of endogenic processes (which wrinkle Earth's surface) and

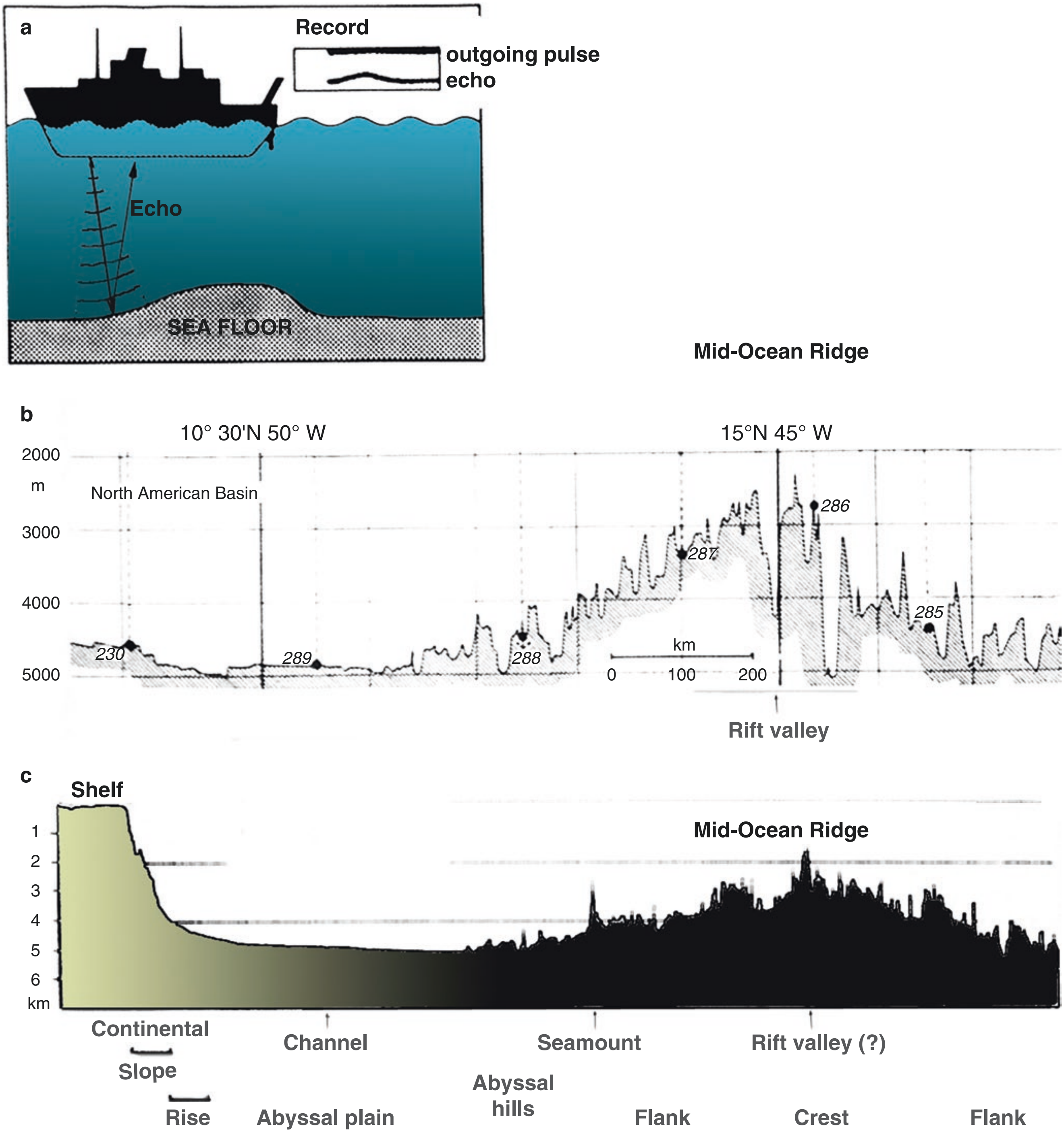

Fig. 2.2 Topography of the Mid-Atlantic Ridge as observed by echo sounding. (**a**) The depth emerges from the time it takes the echo to return and the speed of sound in seawater. The two-way travel time is recorded on the sounding vessel (inset: "Record"). (**b**) Results of echo sounding obtained by the German Meteor Expedition (1925–1927). Numbers refer to sampling stations. Note the prominent central rift. (**c**) Modern topographic profile (after B.C. Heezen et al. 1959; see Geol. Soc. Am. Sp. Paper 65). Labels for physiographic features here added. Note change of scale between (**b**) and (**c**), presumably emphasizing different latitudes

exogenic ones (which mainly smoothen it), let us now return to the nature of the grand morphology of the seafloor, that is, to the endogenic processes that express themselves in seafloor spreading and plate tectonics. Just how do the new concepts bear on the morphology of the mid-ocean ridge and that of the trenches, and how do volcanic island chains fit into the picture?

2.3 Morphology of the Mid-ocean Ridge

2.3.1 Background

On *HMS Challenger*, depth determinations were done by laboriously sending a weight to the ocean floor and measuring the length of the line paid out. When the scattered soundings were connected for drawing depth contours, the ocean floor looked smooth. Despite such difficulties, the fact that a central barrier separates western from eastern Atlantic basins did emerge during the expedition thanks to differences in the temperature of abyssal waters in the eastern and the western trough of the Atlantic. However, only when echo sounding was used routinely (in the twentieth century) did it become obvious that large parts of the ocean floor consist of immense mountain ranges whose cragginess rivals that of the Alps and the Sierra Nevada. Perhaps the most impressive of these ranges is the Mid-Atlantic Ridge, discovered by the famous *Meteor* Expedition (1925–1927) (Fig. 2.2) and subsequently recognized as a portion of the globe-encircling MOR (mid-ocean ridge) by the Lamont geologist Bruce Heezen and his associate Marie Tharp (Fig. 2.3).

Heezen's realization that the Mid-Atlantic Ridge is part of a worldwide phenomenon (the mid-ocean ridge) was a crucial piece of insight. The MOR is continuous and endless, much like the seam on a baseball. Thus, its existence shows a process of planetary dimensions at work.

2.3.2 The MOR a Product of Seafloor Spreading

The mid-ocean ridge is produced by spreading of the seafloor (Fig. 2.4). It is more than 60,000 km long and takes up roughly one third of the ocean floor (the precise value depends on where one puts the outer boundaries of the flanks of the ridge). One third of the seafloor translates a little less than one fourth of the Earth's surface. In the Atlantic and along certain other portions of the ridge, the crest is marked by a central rift, that is, a 30- to 50-km-wide steep-walled valley with a depth of 1 km or more.

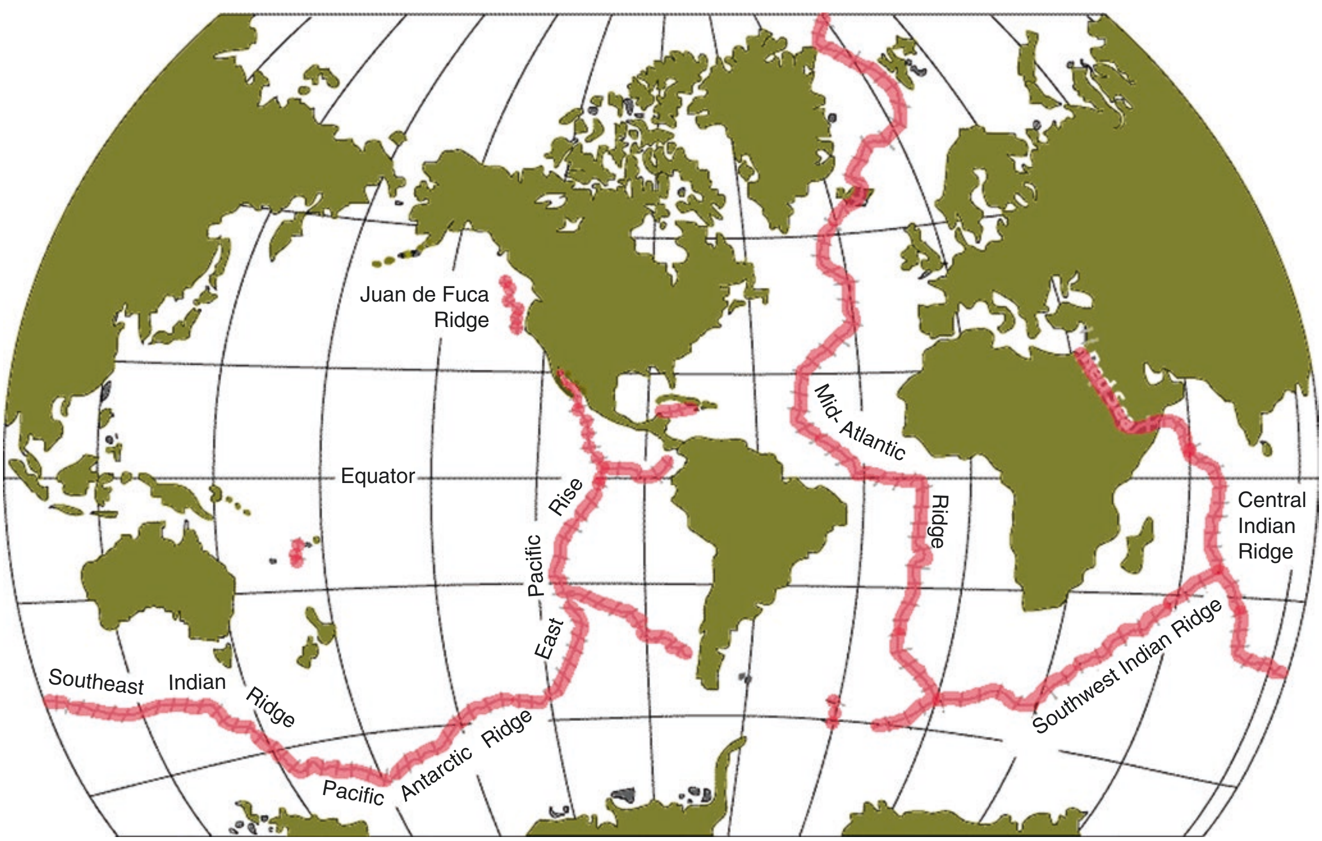

Fig. 2.3 The worldwide mid-ocean ridge, of which the Mid-Atlantic Ridge is a part (From the US Geological Survey)

2.3.3 Open Questions

What proof do we have that the theory of seafloor spreading is sound? The question was raised well into the 1970s. It is no longer asked – seafloor spreading no longer is a crazy idea possibly worth looking into. Instead, it is a fully accepted concept and has become part of textbook science, even at the grade school level. It is now fundamental, much like the insight that a fossil once was part of a living organism, that Earth has an age of 4.6 billion years, that large continental glaciers once covered vast areas of North America and northern Europe, or that biological classification reflects ancestry and evolution. None of these insights got into the textbooks immediately after they arose, being vehemently opposed by "experts" at the time they originated.

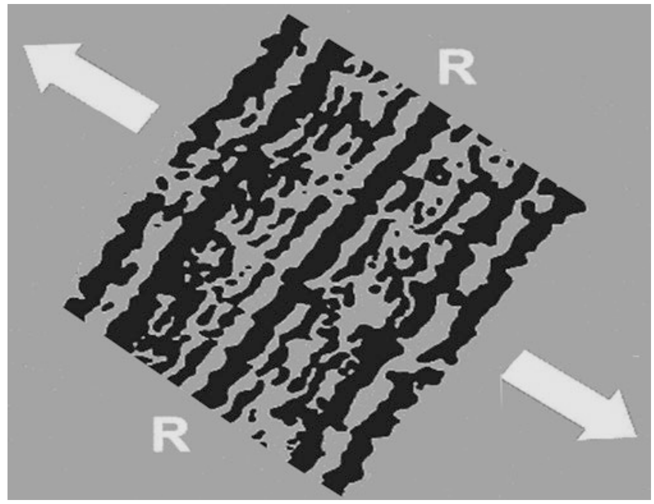

Fig. 2.4 Magnetic anomalies on Reykjanes Ridge according to J.R. Heirtzler et al. [see 1966 Deep-Sea Res. 13: 427] and interpretation in terms of seafloor spreading. The letter **R** (for "ridge", here added, along with arrows) denotes the center of the MOR, which also is a center of remarkable symmetry of the magnetic lineations or "stripes." An earlier (unpublished) report on the 1963 survey became available in 1965. The survey was cosponsored by the US Navy and Lamont Geol. Observatory

2.3.4 The Magnetic Stripes

Seafloor spreading is now treated as a fact. What makes us confident that this is justified?

Our confidence derives from the patterns of magnetic anomalies on the seafloor, notably patterns across spreading centers. As every compass-bearing school kid knows, the planet has a magnetic field, which is linked to the rotation around the Earth's axis (hence, we have "magnetic north" and "magnetic south"). Sporadically, on time scales typically tens or hundreds of thousands of years long (and for reasons unknown), the Earth's magnetic field reverses, so that magnetic north becomes magnetic south and vice versa. The reversals are recorded within the freezing basaltic rock of the new seafloor generated at spreading centers.

When mapping seafloor magnetism, one finds anomalies of magnetic intensity over the seafloor resulting from the combination of the current magnetic field with the one frozen into the basalt when it solidified (the *magnetic stripes*). The stripes were first discovered in the late 1950s. However, their origin remained a complete mystery for several years. One of the problems was that the area where magnetic anomalies were first mapped is geologically complicated, and the symmetry of the patterns about the center of the MOR, which holds the key to the explanation, is not obvious there. It is rather obvious elsewhere, fortunately, such as on the Reykjanes Ridge south and west of Iceland, where the expected pattern was impressively documented by J.R. Heirtzler (Ph.D., New York, 1953) and colleagues, in 1966 (see Fig. 2.4). Much of the original magnetic reversal stratigraphy (including dating) is the work of pioneers A.V. Cox (1926–1987) and his collaborators at the USGS, R.R. Doell (1923–2008) and G.B. Dalrymple (PhD 1963, UC Berkeley).

That there should be these types of magnetic anomalies at a spreading center was proposed by F.J. Vine (then a graduate student at Cambridge University) and D.H. Matthews (his advisor), in 1963. Their suggestion was strikingly simple: put together the ideas on seafloor spreading by R.S. Dietz and H.H. Hess, and combine them with the evidence for periodic reversals in the Earth's magnetic field, as then already in the literature, put there by the USGS geophysicists A. Cox and R.R. Doell, a team later including G.B. Dalrymple. The result is the generation of "blocks of alternately normal and reversely magnetized material 'drifting' away from the center of the ridge and parallel to the crest of it," exactly as documented in subsequent publications.

2.3.5 Fracture Zones and Magma Chambers

The MOR is segmented by fracture zones, as already recognized in the 1960s (Sect. 2.4.3). Thus, the MOR occurs more or less in straight segments that are offset from each other. The consequence of such offset is that a lateral fault must form at the ends of the straight crestal portions. As there is motion along this fault during active seafloor spreading, there are earthquakes on it. These quakes are shallow and define the *active* part of the *fracture zone*, that is, the *ridge-ridge transform fault.* Beyond this active portion, the fracture zone is the frozen trace of the inactive portion of the fault zone. Along this trace, any scarp becomes smaller as the seafloor ages and subsides on both sides of the zone but with the younger and warmer side subsiding faster. Fracture zones tend to have an irregular topography, leaks of magma produce seamounts, and friction and eruptions can result in ridges, troughs, or escarpments.

Each of the ridge segments (typically 300–500 km long) has its own morphology and geologic history. Quite generally, everywhere along the axis of the ridge, there are subtle changes, including elevation changes of a few hundred meters. The changes are in large part a result of the way the central magma chambers along the ridge axis are supplied with molten basalt, from 30 to 60 km below. The supply is discontinuous in time and space and very uneven, with some sections sated with magma, and others starved. Mushroom-shaped magma chambers (some with roofs only 1.5 to 2.5 km below the seafloor) cause local uplift and can generate narrow axial graben structures. Such valleys can then be filled by sporadic lava flows, whose products (pillow basalts and basalt tubes) are ubiquitous evidence of volcanic activity along the ridge. The fast-spreading ridge of the East Pacific Rise has no distinct graben, as mentioned, although in other respects, it may be rather typical of ridge structure (Fig. 2.5).

The molten rock that wells up from the magma chamber forms pillow basalts and lava sheets after contact with the seawater. Seismologists studying the seafloor know the *pillow lavas* and the underlying basaltic dikes as "Layer 2A" and "Layer 2B." The basaltic rocks called *gabbro* ("Layer 3") and the olivine- and pyroxene-rich upper mantle rocks called *peridotite* ("Layer 4") are separated by the discontinuity in sound velocity known as the *Moho* or "Mohorovičić discontinuity" (named after the Croatian seismologist Andrija Mohorovičić , 1857–1936). Below the deep seafloor, the Moho is near 10-km depth. In slow-spreading ridges, much more complicated sequences may obtain.

2.3.6 Crest, Elevation, and Sinking of the Flanks

Generally, the crest of the mid-ocean ridge has a depth of 2500–3000 m below sea level all around the world. From this similarity of elevations, we may conclude that the upwelling material and its temperature are likely rather uniform. In any case, differences are quite subtle.

The crest is characterized by shallow earthquakes (centers are at depths of less than 60 km), by active volcanism, and by high heat flow values. The rift valley is a result of a growing opening of marine crust, with opposite sides pulling apart. It is commonly associated with slow spreading and may be missing elsewhere. The rate of spreading tends to show values between 1 and 10 cm per year (low rates are found in the Atlantic, high ones in the Pacific). The new hot material filling the central gap is light relative to common mantle material, because of thermal expansion. As a result, the ridge stands high above the most common seafloor. Away from the crest, the flanks sink because the basalt becomes denser as it ages and seeks a lower elevation, therefore. The sinking slows exponentially; that is, the sinking is more or less predictable, being linked to 1/square root of time of cooling.

In numbers, the sinking is by about 1000 m during the first ten million years. The subsequent 1000 m of sinking takes about 26 million years. The relationship follows this rule (approximately):

$$\text{Depth added to original depth (in m)} \\ = 320 \text{ times square root of age in millions of years.} \quad (2.1)$$

Using this equation, we can calculate the average age of the deep seafloor from its average depth (after correcting for sediment cover). The result is 60 million years,

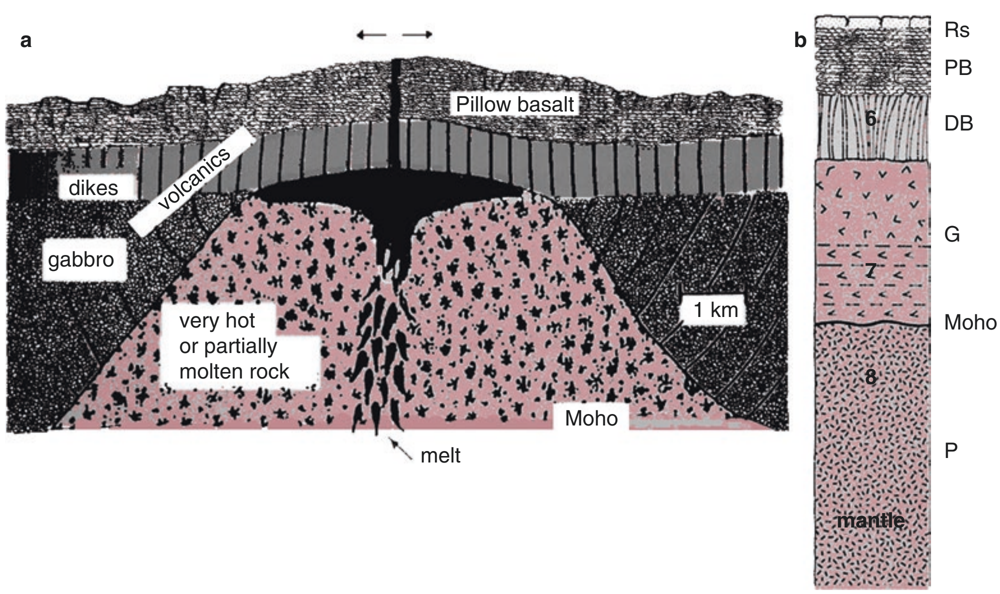

Fig. 2.5 (**a**) Comparison of the internal structure of the East Pacific Rise with (**b**) field observations on an ophiolite sequence on land. (Mainly after sketches by K.C. Macdonald et al., Nature 339, 178; and C. Allègre, 1988, modified) The numbers indicate rough estimates of typical speed of sound in km/s. The "Moho" (base of the crust) represents a jump in sound velocity. Letters in **b** refer to rock types: *RS* radiolarite (chert), *PB* pillow basalt, *DB* basaltic dikes, *G* gabbro, *P* peridotite (mantle rock)

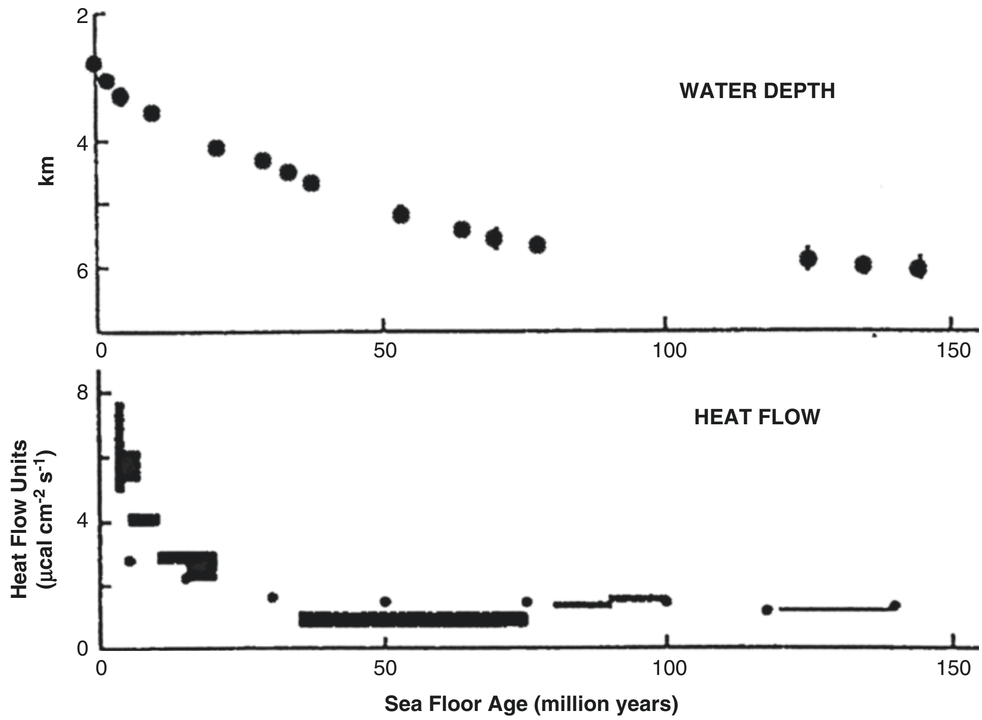

Fig. 2.6 Sinking of the flanks of the MOR (J.G. Sclater et al., 1971) and associated heat flow according to J.G. Sclater and J. Francheteau (1971; dots) and to Sclater et al. (1976; bars) (From E. Seibold et al., 1986. The Sea Floor, Japanese edition. Springer, Heidelberg & Berlin)

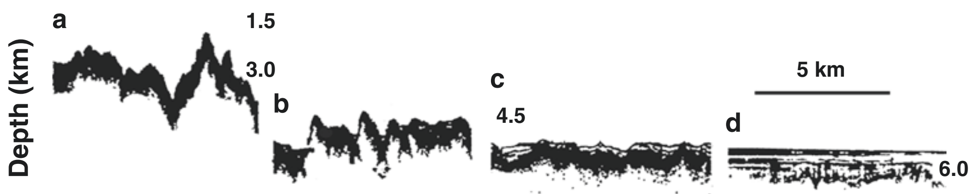

Fig. 2.7 Portions of continuous profiling records, from Mid-Atlantic Ridge (leftmost panel, **a**) to Hatteras Abyssal Plain (rightmost panel, **d**). Note the smoothing of the seafloor by sediment, with increasing distance from the crest. The sediment making the flat abyssal plain is likely to be largely terrigenous mud (After T.L. Holcombe 1977, GeoJournal 1: 25; simplified)

which is indeed close to the observed average age of the seafloor. The evidence linking sinking to cooling is excellent (Fig. 2.6).

The sinking starts commonly near 2500 m, at the average elevation of the crest. There are, however, exceptions to the general rule of ridge elevation. The ridge is much shallower than average in the North Atlantic, where it has, not so coincidentally, one of the most active "hot spots" associated with it, namely, Iceland. Iceland has volcanoes and "geysirs," that is, hot vents fed by locally available water. In fact, the word "geysir" is of Icelandic origin. Evidently, geysirs cool the rocks that make them.

2.3.7 Overall Morphology from Crest to Abyssal Plain

The morphology at the crest commonly is very rugged and complicated, while the flanks tend to be smoothed by sediment and (in the Atlantic) covered by turbidites at the low end (Fig. 2.7). During the sinking of the spreading seafloor, the rough topography produced by volcanism and faulting moves down the ridge flanks, being gradually smoothed by the sediment cover. However, abyssal hills with a relief in the range of 50–1000 m and with slopes between 1° and 15° remain as expressions of the underlying basement morphology over enormously large regions. *Abyssal hill* morphology provides for the most common type of landscape on the face of the Earth: in the Pacific Ocean, about 80% of the seafloor belongs into the category, that is, almost one third of the planet's surface.

2.4 Morphology of the Ring of Fire

2.4.1 The Shrinking Basin

For the Atlantic to grow while the planet retains its size, the Pacific basin has to be shrinking. The chief evidence that it does so is provided by the trenches rimming the basin, trenches being the manifestation of tectonic destruction of seafloor by subduction. The logic demanding a shrinking basin may be somewhat surprising, given the fact that seafloor spreading on the East Pacific Rise has values defining the fast end of the range, while spreading in the Atlantic is comparatively slow. But the demands of the balance notion are rather modest: the rate of subduction in the Pacific should just somewhat exceed the sum of seafloor production by Pacific spreading and the spreading in the Atlantic.

The length of the trench zone in the Pacific is comparable in magnitude to the MOR (Fig. 2.8). In fact, it is the only feature on the seafloor which achieves that particular distinction. Also, the *Ring of Fire* (which is, in essence, the trench zone with associated volcanoes) is a prominent source of deep earthquakes in contrast to the shallow-quake MOR. The MOR and the trenches are linked to the chief plate boundaries. There is no surprise in their great extent and in the occurrence of earthquakes along their boundaries. The boundaries mark zones of friction.

2.4.2 Morphology of Trenches

Trenches, of course, were described well before subduction became a textbook item (Fig. 2.9). The transition between oceanic and continental crust was a complete mystery to begin with. Problems are now regional and local, as the nature of the contact zone changes along and behind the trenches. Strong contrasts in mineralogy, fluid chemistry, and physical properties must be considered when dealing with this zone in any detail.

Trenches are abundant all around the margin of the Pacific basin, notably where continents meet ocean. It is not obvious why there are not more mid-ocean trenches. To answer this question, we would need to focus on processes within the mantle, that is, on largely unknown processes. What we do know is that trenches are narrow, being roughly 100-km wide (in their shallower part) and they are long (hundreds to thousands of kilometers). For example, the Alëutian Trench is 2900-km long. The cross-section is commonly V shaped (inset in Fig. 2.8), except that the deepest part may be flat due to sediment ponding. Sediment at the bottom of trenches commonly shows plain horizontal layering – an observation that

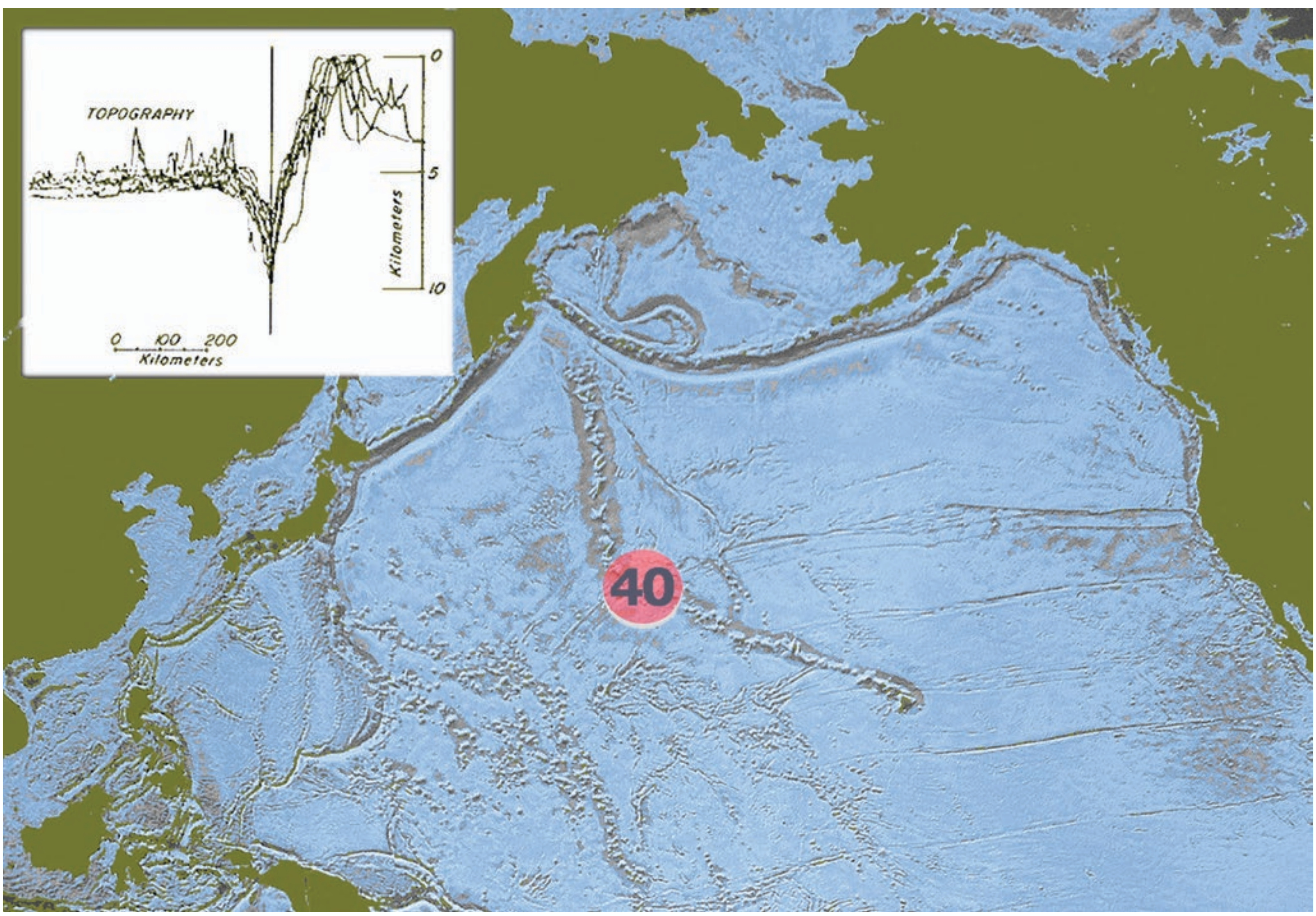

Fig. 2.8 Gravity-based morphology of the seafloor in the North Pacific. Trenches show minimum gravity (Map courtesy of D. Sandwell, S.I.O.; color here added) *Inset*: topographic profiles across trenches in various places in the ocean (M. Talwani 1970, in The Sea vol. 4 (1): 282). **40**, approximate age of the bend, in millions of years

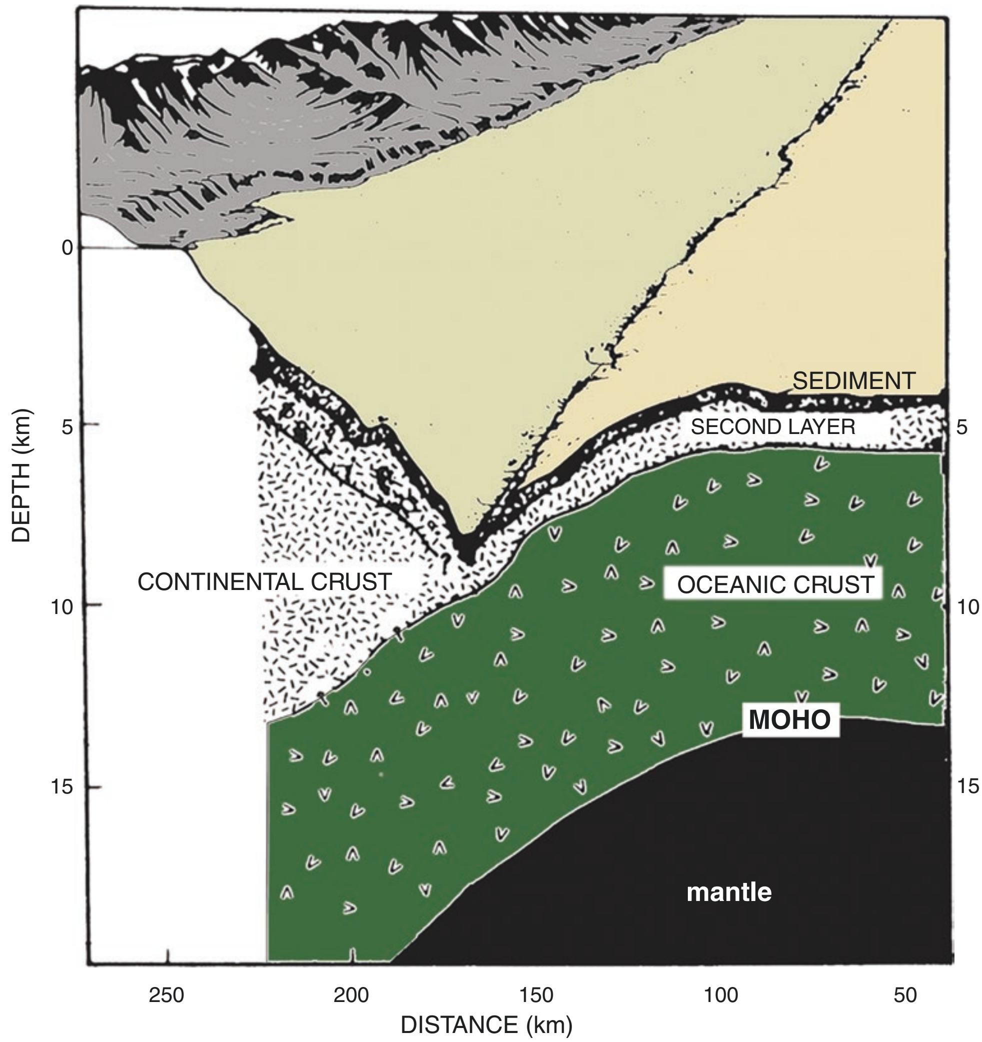

Fig. 2.9 An early version of a trench structure, based on pre-plate-tectonic interpretation of seismic refraction studies, and showing trench morphology off Chile (R.L. Fisher and R.W. Raitt, 1962. Deep-Sea Res. 9: 423. Shading and color here added). The down-going slab of the rigid upper mantle (the lithosphere) is roughly ten times thicker than the oceanic crust it carries. The "Moho" (here added) marks a sudden increase in sound velocity. The second layer actually has rocks that are different from the continental crust

was used on occasion as an argument against subduction when plate tectonic concepts were in their infancy. (However, as geologically young phenomena horizontally layered, turbidites in many trenches are not diagnostic of origins of regional morphology.) The trench walls usually have slopes between 8° and 15°. However, very steep sides (up to 45°) as well as steps also have been mapped. In cases, outcrops of basalt have been discovered by dredging and by deep-sea photography, notably on the inner wall (the side away from the deep ocean floor).

The greatest depths are in the western Pacific, in sediment-starved trenches off island arcs: Mariana Trench (maximally 10.915 m deep), Tonga Trench (10.800 m), Philippine Trench (10.055 m), Japan Trench (9.700 m), and Kermadec Trench (10.050 m). As locally measured features, depth values are not precise. Besides, they were determined from echo soundings affected by temperature and salinity of waters traversed by the sound. The resulting uncertainties, however, cannot mask the similarities in the maximum depths observed. As in the similarity of ridge-crest elevations noted above, the coherency points to the action of similar processes involving similar materials in each of the trenches of the western Pacific. Elsewhere, trenches tend to be shallower: Puerto Rico Trench about 8.600 m; South Sandwich, 8.260 m; and Sunda, 7.135 m. The eastern Pacific basin has trenches directly adjacent to continents, without intervening island arcs. Such trenches are being filled with continental debris.

2.4.3 The Zone of Deep Earthquakes

The ring of trenches girdling the Pacific is the site of deep earthquakes and volcanic activity (Fig. 2.10). Shallow quakes are abundant on the MOR, as mentioned. Within the subduction zones (landward of the trenches), when the depths of the quake centers are plotted below their *epicenters* (nearest point to the quake on the surface), they are seen to occur on dipping planes, presumably the contact planes between oceanic and continental crust. The planes intersect the surface near the trenches in typical arc fashion. They dip underneath the adjacent island arc or continent to a depth of about 700 km, within the mantle.

It seems reasonable to conclude that the earthquakes are largely caused by friction between the down-going slab of seafloor and the surrounding lithosphere and that the friction ceases when the rising temperature at depth becomes high enough to permit ductile deformation and flow. That the trenches are part and parcel of the new global tectonics was recognized by seismologists in the 1960s, based on the interpretation of earthquakes outlined (Fig. 2.11). In fact, the main features of plate tectonics all are well recognized in the seismic environment. Depending on the type of subduction at issue, volcanoes and mountain building proceeds on the landward side of the trench system. Much of such growth apparently also depends on the accretion of *terranes* (sometimes referred to as "exotic terranes"). These are pieces of real estate of various sizes coming from elsewhere with plate motion and refusing to partake in subduction, being less dense than oceanic lithosphere. Thus, they become part of the active margin. A trench clogged by a terrane must move seaward. Much of the West Coast of the USA is thought to consist of "terranes" that moved in with eastward plate motion in the Pacific.

2.4.4 Snake Rock

"Ophiolite sequences" are rocks of seafloor material that incorporate altered basaltic seafloor. In California, one sees "serpentinites" in certain coastal mountain belts, rocks that represent hydrated basalt (Fig. 2.12). "Ophiolite" and "serpentinite" both denote "snake rock" (the first in Greek, the second in Latin). The names are owing to the surface appearance of certain altered basaltic rocks; glossy and green and black and evoking the image of certain snake skins.

With few exceptions, the volcanic rocks forming the oceanic crust on the MOR (mid-ocean ridge basalt or MORB) are olivine-rich tholeiites (a basaltic rock, named after ancient basalt in Tholey near Saarbrücken in Germany). In addition to the minerals olivine (pronounced oly-veen) and pyroxene, MORB (mid-ocean ridge Basalt) has abundant plagioclase, that is, feldspar rich in calcium. (Basalts of island arcs may contain material from continental crust, which has relatively high sodium and aluminum content.)

Quite generally, the different types of basalts are characterized by differences in trace element content (e.g., rubidium, cesium, barium) depending on the history of the original melt. Interpretation of the chemical information is quite difficult and many problems arise when attempting to explain the (nonuniform) composition of the mantle material in terms of different types of basalt and their alteration products found at the surface of the seafloor and in continental margins.

Fig. 2.10 Ring of Fire. Deep earthquakes are common along the Ring of Fire. Very deep and powerful ones are associated with subduction (Fig. 1.2). The photo (Courtesy Taryn Lopez, University of Alaska) shows earthquake country near Fairbanks, Alaska (note the active volcano in the background to the right)

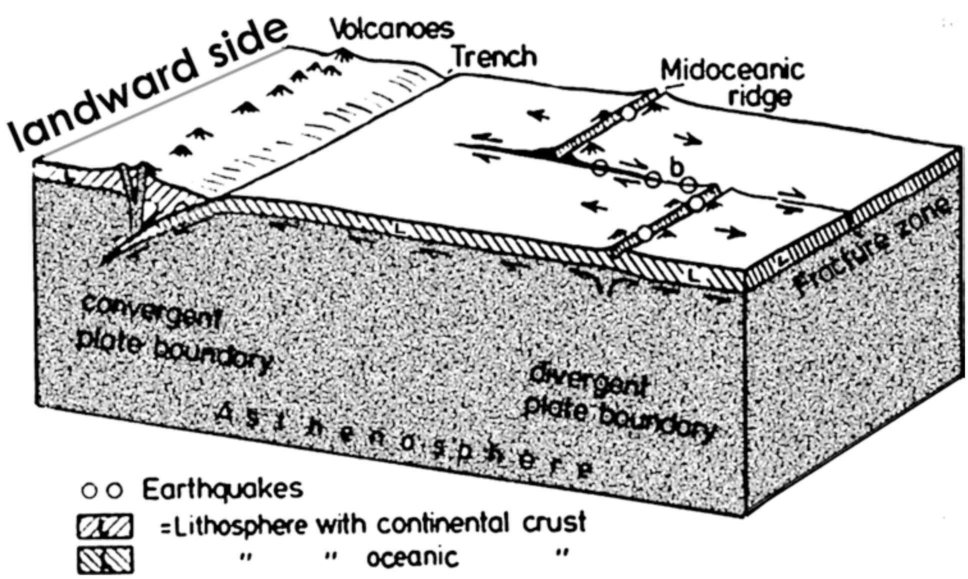

Fig. 2.11 Sketch of trench as an integral part of plate tectonics, based on a 1960s earthquake interpretation (After a famous diagram by B. Isacks, J. Oliver, and L.R. Sykes, 1968. J. Geophys. Res. 73: 5855; here modified for clarity) *L*, lithosphere (traveling toward trench, where it is subducted, accompanied by deep earthquakes)

2.5 Plate Tectonics, a Summary

2.5.1 Discovery

The features defining plates are the boundary-forming mid-ocean ridge (MOR), the trench zone, and *transform faults* connecting the MOR to a trench. These boundaries had to be explained in terms of spreading (Heezen, Hess, Dietz, Vine, Heirtzler, Bullard), subduction (Vening-Meinesz, Hess, Dietz, Isacks, Oliver, Sykes), and appropriate fault motions (Wilson, Vine, Morgan, Vacquier, Menard) to have "plate tectonics" emerge. While spreading and subduction are the central items, fracture zone activity is important. Fracture zones connect the end of a ridge crest portion to a trench. Such zones constitute the third type of plate boundary. Their importance was early recognized by the Canadian geophysicist J.T. Wilson (in the mid-1960s). First motion studies of earthquakes showed which way the slabs tend to move. Each of the plates, it turns out, has its own particular motion, whose long-term aspects can be read from the magnetism of the seafloor (A.V. Cox, J.R. Heirtzler, V. Vacquier). The quantitative development of these concepts was initiated in the late 1960s by pioneer geophysicists such as W.J. Morgan, D.P. McKenzie, R.L. Parker, X. LePichon, B. Isacks, I. Oliver, and L.R. Sykes (see A. Cox, 1973; listed in suggested readings).

Fig. 2.12 Serpentinite (hydrated basalt) found along the coast of California. (Here: Big Sur road cut) The rock glistens and commonly is *green* and *black* in color. A *bluish* tint is seen in places. Large rock lens (ca 1 inch diameter) for scale (Photo W.H. B)

2.5.2 Theory and Observations

"Plate tectonics" takes its name from great pieces of moving real estate on the planet, plates that are perched on uppermost mantle and carry crust and continents (Fig. 2.13). The thickness of the plates, which is typically near 100 km, varies significantly. A great variation in thickness also is typical for the crust that makes up continents (ca. 15 to more than 30 km) – in contrast, the ocean's crust is relatively uniform and is only some 10-km thick. The motions of the plates (lithosphere and crust) are parsimoniously described as rotations on a sphere, each uniform motion being linked to a pole of rotation as required by Euler's theorem. The fracture zones provide traces for the latitudinal circles around the respective pole of rotation (which can be close to, but need not coincide with, a pole of the daily rotation of Earth). Spherical geometry requires that spreading rates must increase away from a pole describing the separation of two plates, toward a maximum value. Remarkably, a given plate can contain both oceanic and continental lithosphere (but does not have to).

The kinds of rock dredged from deep clefts in the mid-ocean ridge and those recovered by drilling into the deep basaltic crust at sea presumably most closely resemble the material within the uppermost mantle and involved in plate motions. It may differ from the original rock, however. It is surely altered, with exposure on the surface of mantle and crust, especially through reaction with seawater.

Fig. 2.13 Sketch of the major plates (and a few minor ones). The subduction edge of the Pacific Plate makes up more than one half of the "Ring of Fire" around the Pacific (a zone of volcanoes and earthquakes). *Arrows* show the general sense of plate motion for two of the largest plates; the letter **R** denotes the mid-ocean ridge, the site of spreading. Direction of relative motion reverses across MORs (Graph courtesy of S.I.O. Aquarium, modified)

The heat that drives the motions in the mantle most probably comes from the decay of radioactive elements. Another possible source is the gravitational segregation of heavy and light material, which produced the onion structure of the Earth in the first place (heavy stuff in the core, light stuff in the crust). To decipher the *messages from the mantle*, that is, information about processes in the interior, geologists use seismic signals. Also, they study the patterns of magnetic and gravity fields. This activity is in the realm of geophysics. Mineralogists and petrologists investigate the behavior of rocks under high pressures and temperatures, and geochemists collect indirect evidence on the interior, in part by studying elemental abundances in the solar system. All this information is used in the reconstruction of the history of plate tectonics, a most difficult subject.

An especially important aspect of plate tectonics, to geologists, is the way mountain chains form in the trench zone. Continental accretion takes place here. It is one way in which the endogenic forces oppose the wearing down of continents by exogenic agents. Thus, the continued existence of continents that rise well above the sea is intimately linked to the processes associated with seafloor spreading.

2.6 Seamounts, Island Chains, and Hot Spots

2.6.1 Hot Spots and Plate Tectonics

Hot spot phenomena are routinely linked to processes deep in the mantle. What we see on the seafloor are edifices apparently resulting from volcanism, including hot spot volcanism. Hot spots on land have been invoked when contemplating certain major eruptions such as those of volcanoes in Wyoming and Idaho. Hot spots in the sea are thought responsible for some island chains, such as the one including the Hawaiian Islands. With very few exceptions, oceanic islands are made of volcanic rock, with or without a crown of reef carbonate. Coral reefs (or rather the algae thereof, symbiotic or coralline) depend on sunlight and grow only in shallow water, therefore. Thus, if a seamount is found with a top of reef carbonate and deeply submerged below the present sea level, it must have sunk from the sunlit zone. Such seamounts are common in the western Pacific. They usually have flat tops and they are roughly 100 million years old. It has been suggested that the mid-Cretaceous was a time of intense hot spot activity, possibly intense enough to elevate the seafloor elevation significantly.

No rocks older than Cretaceous have been found on flat-topped seamounts (or “guyots”). It is in fact unlikely that all the guyots identified have a similar history. There are thousands of seamounts in the Pacific basin, at various depths, so there is plenty opportunity for different signs of development.

2.6.2 The Hawaiian Islands

When discussing marine hot spot activity, one usually is faced with the Hawaiian Islands – large volcanoes along a chain suggesting motion of a plate across a hot spot. The volcanic origin is readily verified (Fig. 2.14). Everything else is not certain, even if very plausible.

The striking thing about the Hawaiian Islands is not, of course, that they are of volcanic origin. Practically all oceanic islands are. There are but a few that are not, being broken

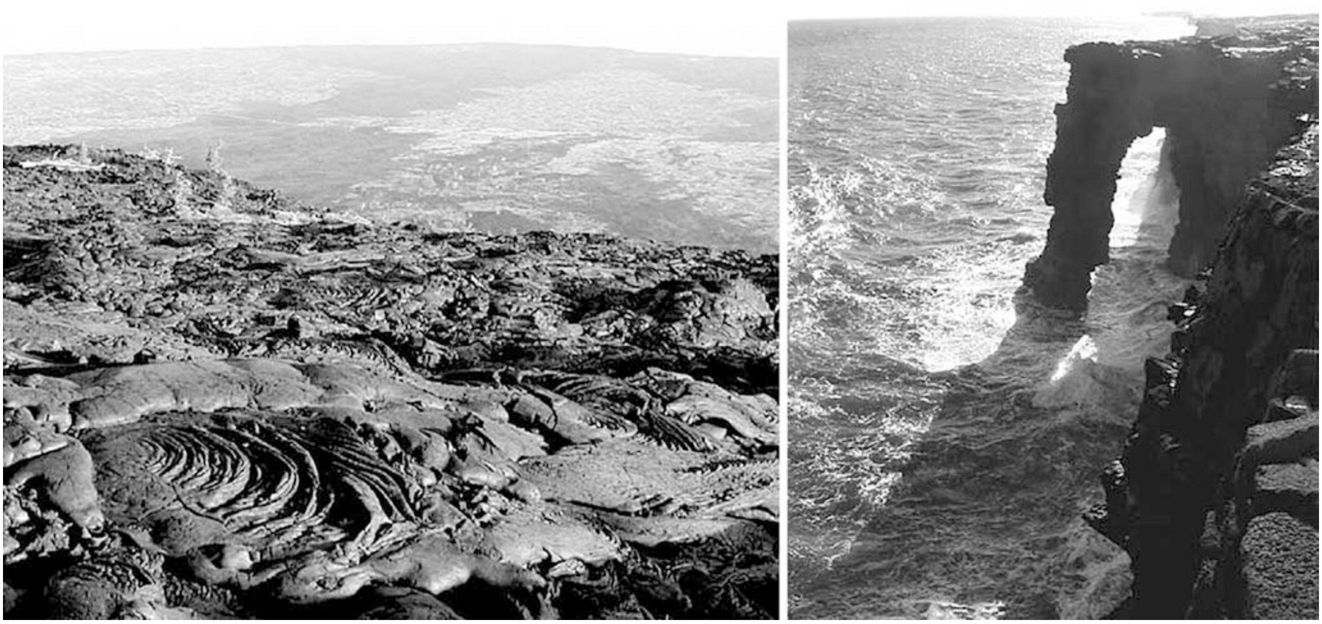

Fig. 2.14 The “Big Island” of Hawaii is an active volcano. Lava can be seen flowing into the sea, as well as frozen into rock on the flanks of Mauna Loa and at the shore (Photos W.H.B., the one to the right also is in the book “Ocean”, UC Press, Berkeley, 2009)

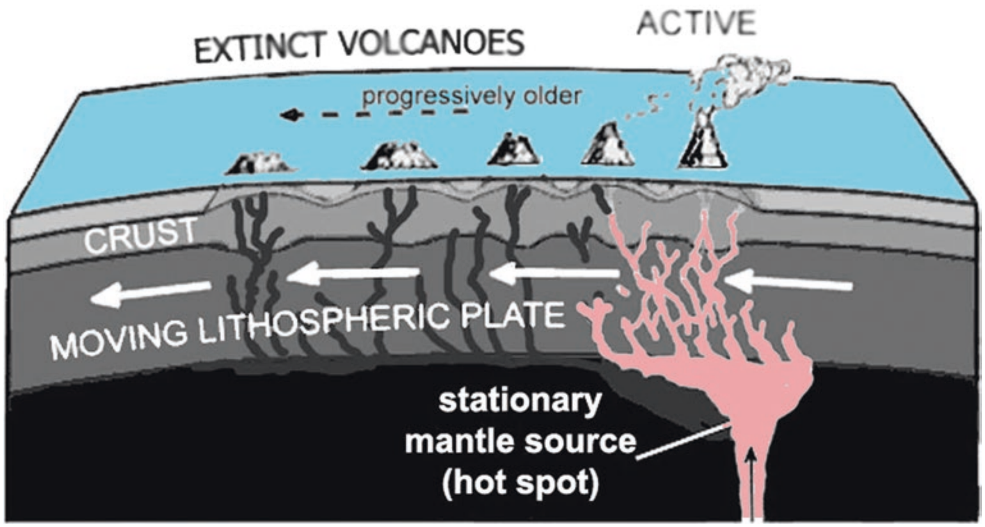

Fig. 2.15 Hypothesis concerning the origin of the Hawaiian island chain (After ideas of J.T. Wilson)

off from continents. What is interesting about the Hawaiian and some other island groups is that they occur in a chain and that commonly a chain in the middle of the Pacific has a kink connecting two linear segments (Fig. 2.8).

One possible explanation for the arrangement is to assume that the volcanoes making the chain lie on a long zone of weakness in the crust, a deep propagating fracture along which magma can rise to form volcanic structures. For the Hawaiian chain, where there is a progression from geologically young high and large active volcanoes in the southeast to sunken older islands with extinct volcanoes in the northwest, the movement of a plate over a hot spot has been postulated. The concept was put forward by J.T. Wilson (in 1965) and elaborated by J.W. Morgan (in 1968). In the view of these geologists, volcanoes built up on top of the oceanic crust over a "hot spot," a stationary source of melt deep in the mantle (also referred to as "plume"). As the plate moved over the hot spot, thus the hypothesis, a series of volcanoes formed, with the older ones cut off from the source and going extinct (Fig. 2.15). Along the Hawaiian chain, the knee between two distinct linear arrangements (circle in Fig. 2.8) has been dated near 40 million years. Within the framework of the Wilson-Morgan concept, a change in direction of plate motion is indicated on approaching the late Eocene. If this is correct, we must assume major reorganizations of upper mantle motions at that time. What we do know for sure is that major changes in sedimentation were going on toward the end of the Eocene.

2.6.3 Open Questions

Textbook assertions are not commonly ended on a question mark. Perhaps they should be in the case at hand. We are relatively ignorant of the mantle processes that drive plate tectonics and hot spot activity.

Regarding hot spots, what we can do is make some reasonable guesses. Large hot spot plumes are commonly thought to originate from the lower mantle and to contribute significantly to convection in the mantle. Basalts from this source are said to differ from basalts of the MOR in having a greater abundance of so-called *incompatible elements* (potassium, rubidium, cesium, strontium, uranium, thorium, and rare earth elements). Presumably, the upper mantle was stripped of these elements in its long history of making continents, so that high values are now only preserved in the lower mantle. However, the distribution of hot spots on the surface of the planet is as yet unexplained, emphasizing a lack of knowledge with regard to these phenomena.

Suggestions for Further Reading

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