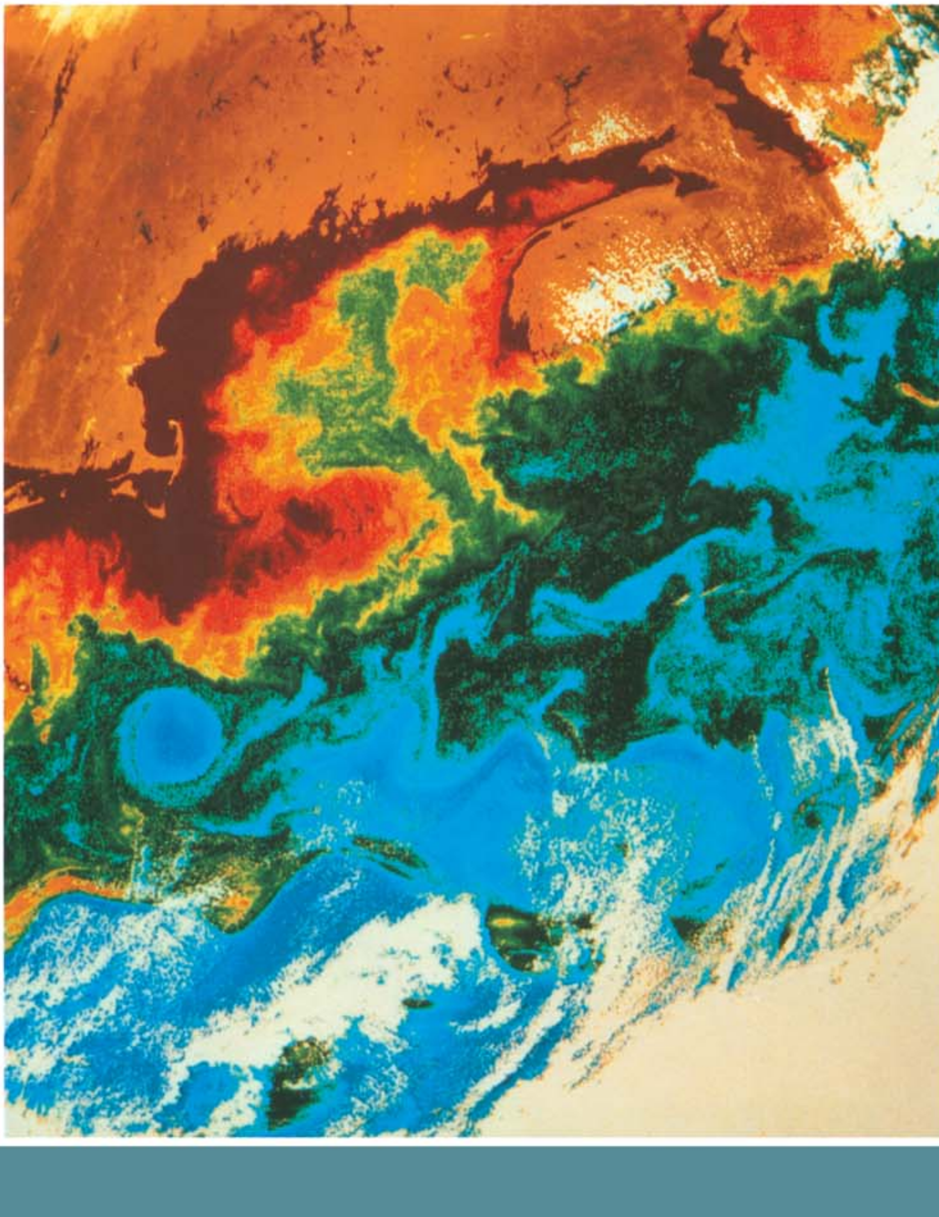
THE OCEAN BASINS: THEIR STRUCTURE AND EVOLUTION

SECOND EDITION

PREPARED BY AN OPEN UNIVERSITY COURSE TEAM



The Open University

THE OCEAN BASINS: THEIR STRUCTURE AND EVOLUTION

THE OCEANOGRAPHY COURSE TEAM

Authors
Evelyn Brown (*Waves, Tides, etc.; Ocean Chemistry*)
Angela Colling (*Ocean Circulation; Seawater (2nd edn); Case Studies*)
Dave Park (*Waves, Tides, etc.*)
John Phillips (*Case Studies*)
Dave Rothery (*Ocean Basins*)
John Wright (*Ocean Basins; Seawater; Ocean Chemistry; Case Studies*)

Designer
Jane Sheppard

Graphic Artist
Sue Dobson

Cartographer
Ray Munns

Editor
Gerry Bearman

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Cover illustration: Satellite image showing distribution of phytoplankton pigments in the North Atlantic off the US coast in the region of the Gulf Stream and the Labrador Current. (*NASA, and O. Brown and R. Evans, University of Miami.*)

THE OCEAN BASINS: THEIR STRUCTURE AND EVOLUTION

PREPARED BY JOHN WRIGHT AND DAVID A. ROTHERY FOR THE COURSE TEAM
SECOND EDITION REVISED FOR THE COURSE TEAM BY DAVID A. ROTHERY

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ABOUT THIS VOLUME

This is one of a Series of Volumes on Oceanography. It is designed so that it can be read on its own, like any other textbook, or studied as part of S330 *Oceanography*, a third level course for Open University students. The science of oceanography as a whole is multidisciplinary. However, different aspects fall naturally within the scope of one or other of the major 'traditional' disciplines. Thus, you will get the most out of this Volume if you have some previous experience of studying geology, geochemistry or geophysics. Other Volumes in this Series lie more within the fields of physics, chemistry and biology (and their associated sub-branches).

Chapters 1 to 4 describe the processes that shape the ocean basins, determine the structure and composition of oceanic crust and control the major features of continental margins. Today's ocean basins are geologically ephemeral features, and these Chapters show why. Chapter 5 deals with the 'hot springs' of the deep oceans that result from the circulation of heated seawater through oceanic crust. This phenomenon was not even suspected until the mid-1960s and was not confirmed by observation until some years later. Since then, many people have seen the striking photographs of 'black smokers' at ocean ridges. Chapter 6 summarizes the main patterns of sediment distribution in the ocean basins and shows how sediments can preserve a record of past climatic and sea-level changes. Finally, Chapter 7 considers the role of the oceans as an integral part of global chemical cycles.

You will find questions designed to help you to develop arguments and/or test your own understanding as you read, with answers provided at the back of the Volume. Important technical terms are printed in **bold** type where they are first introduced or defined.

ABOUT THIS SERIES

The Volumes in this Series are all presented in the same style and format, and together provide a comprehensive introduction to marine science. *Ocean Basins* deals with the structure and formation of oceanic crust, hydrothermal circulation, and factors affecting sea-level. *Seawater* considers the seawater solution and leads naturally into *Ocean Circulation*, which is the 'core' of the Series. It provides a largely non-mathematical treatment of ocean–atmosphere interaction and the dynamics of wind-driven surface current systems, and of density-driven circulation in the deep oceans. *Waves, Tides and Shallow-Water Processes* introduces the physical processes which control water movement and sediment transport in the nearshore environment (beaches, estuaries, deltas, shelves). *Ocean Chemistry and Deep-Sea Sediments* is concerned with biogeochemical cycling of elements within the seawater solution and with water–sediment interaction on the ocean floor. *Case Studies in Oceanography and Marine Affairs* examines the effect of human intervention in the marine environment and introduces the essentials of Law of the Sea. The two case studies respectively review marine affairs in the Arctic from an historical standpoint, and outline the causes and effects of the tropical climatic phenomenon known as El Niño.

Biological Oceanography: An Introduction (by C. M. Lalli and T. R. Parsons) is a companion Volume to the Series, and is also in the same style and format. It describes and explains interactions between marine plants and animals in relation to the physical/chemical properties and dynamic behaviour of the seawater in which they live.

CHAPTER 3 THE EVOLUTION OF OCEAN BASINS

IMPORTANT: In this Chapter you will find frequent reference to the divisions of the geological time-scale. This is shown in the Appendix.

The Earth's oldest rocks – around 3850 Ma old – include both water-lain sediments and evidence of ancient oceanic crust. It follows that oceans have been forming since the beginning of the geological record, and probably before that. However, the shape of most past ocean basins has to be worked out from observations of remnants preserved in continental areas. That is because ocean basins are relatively short-lived features of this planet: no oceanic crust older than about 180 Ma is known from the present oceans.

If we take the life cycle of a large ocean basin to average about 200 Ma, how many times could such basins have been formed since 3800 Ma ago?

The exact answer is 19, but because our figure of 200 Ma is only a crude guess and we do not know how rates of plate-tectonic processes in the distant geological past compared with those of the present, it is wiser to give an approximate figure of 15–20 times. This is probably a minimum, for the Earth's interior was a good deal hotter in the past than it is now, and the turnover of oceanic lithosphere could have been more rapid.

That simple calculation was designed only to give you a feeling for the time-scale of evolution of individual ocean basins, and it is obviously somewhat artificial. In the past, as one ocean basin expanded, another must have contracted, just as the Atlantic and Pacific are doing today. Thus, there is always some overlap in the history of different basins. Continents and ocean basins are continually changing their shapes and relative positions at rates that are geologically very rapid and are not slow even on human time-scales. The speed of sea-floor spreading has been compared with that of growing fingernails. Since the compilation of the first maps to cover any appreciable area of ocean, around five centuries ago, the Atlantic coasts have drawn apart from each other by about 10–20 m. This is a substantial movement, even though it represents only 0.0003% of the width of the ocean. Spreading rates in parts of the Pacific are several times greater than in the Atlantic.

3.1 THE EVOLUTION OF OCEAN BASINS

An individual ocean basin grows from an initial rift, reaches a maximum size, then shrinks and ultimately closes completely. Stages in this cycle are summarized in Table 3.1 (overleaf) and briefly reviewed below.

Whether or not the East African rift valleys really are an incipient ocean basin (Stage 1) and eastern Africa will eventually be split apart is debatable. Nevertheless, such rift valleys must develop along the line of continental separation. When separation does occur, sediments from the adjacent continents soon begin to build out into the new basin and will become part of the eventual continental shelf–slope–rise zone. As the spreading axis migrates away from the marginal areas, the continents become increasingly distant and so the sediment supply dwindles (Stage 2). The ocean floor between the spreading axis and the continent subsides by thermal contraction of the underlying lithosphere (Figure 2.13), abyssal plains form, and the continental shelf–slope–rise zone becomes fully developed. The continental margins are more or less parallel to the central spreading ridge, as in the Atlantic (Stage 3).

Table 3.1 Stages in the evolution of ocean basins, with examples.

Stage	Examples	Dominant motions	Characteristic features
1 embryonic	East African rift valleys	crustal extension and uplift	rift valleys
2 young	Red Sea, Gulf of California	subsidence and spreading	narrow seas with parallel coasts and a central depression
3 mature	Atlantic Ocean	spreading	ocean basin with active mid-ocean ridge
4 declining	Pacific Ocean	spreading and shrinking	ocean basin with active spreading axes; also numerous island arcs and adjacent trenches around margins
5 terminal	Mediterranean Sea	shrinking and uplift	young mountains
6 relict scar	Indus suture in the Himalayas	shrinking and uplift	young mountains

Stage 4 involves the development of one or more destructive plate margins. The reason for the formation of new destructive margins probably lies in changing circumstances in another part of the globe, such as continental collision or the initiation of new continental rifting. If (as seems certain) the Earth is neither expanding nor contracting, the net rates of spreading and subduction over any great circle on the Earth must be equal, and the pattern of plates and plate motion must adjust to keep this so.

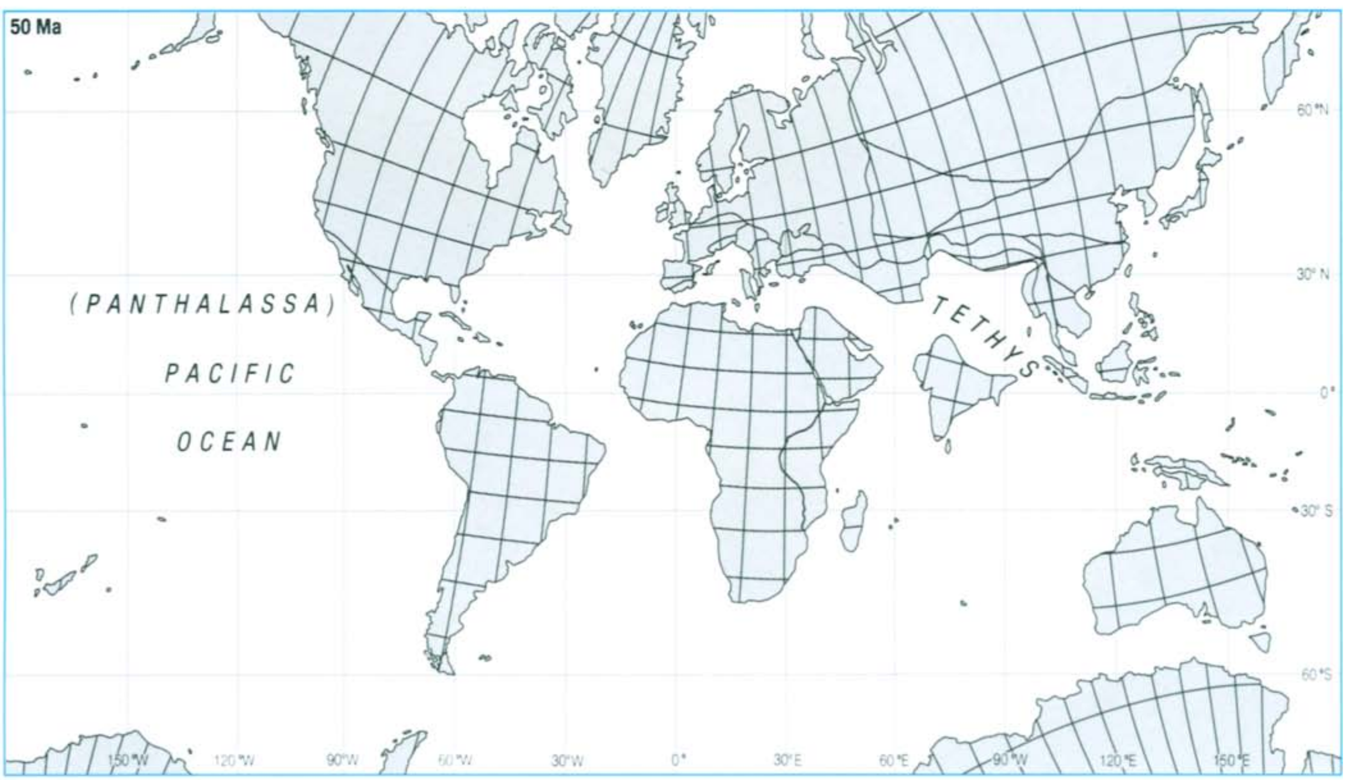
The Mediterranean is an ocean in the final stages of its life (Stage 5), with the African Plate being consumed under the European Plate. Unless the world system of plates changes so as to halt the northward movement of Africa relative to Europe, the continental blocks of Europe and Africa will eventually collide, and new mountain ranges will form (Stage 6).

(a)

Figure 3.1 Palaeogeographic reconstruction, compiled from topographic, palaeoclimatic and palaeomagnetic data. Panthalassa was the huge ocean that dominated one hemisphere. Pangea was the supercontinent in the other hemisphere, of which Eurasia and Gondwanaland were two components. (a) Jurassic, about 170 Ma ago. (b) Cretaceous, about 100 Ma ago. (c) Eocene, about 50 Ma ago. The maps show *present-day* coastlines for ease of reference. Ancient coastlines did not coincide with these.


100 Ma
PANTHALASSA
OCEAN
TETHYS
60°N
30°N
0°
30°S
60°S
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E

(b)


50 Ma
(PANTHALASSA)
PACIFIC
OCEAN
TETHYS
60°N
30°N
0°
30°S
60°S
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°W
120°E
150°E

(c)

QUESTION 3.1 Study Figure 3.1.

(a) Tethys was a major ocean basin, a branch of Panthalassa, that once separated Eurasia from the southern continent, Gondwanaland. How have its shape and size changed over the past 170 Ma and what are its present-day marine remnants?

(b) How long ago did the Atlantic Ocean start to open?

(c) When did the Indian Ocean start to open?

(d) Was the period from 170 to 100 Ma or the one from 100 to 50 Ma more significant in terms of the fragmentation of Gondwanaland?

(e) What were the major changes between 50 Ma and the present day?

3.2 THE BIRTH OF AN OCEAN

Figure 3.2 summarizes the development of a new ocean basin. During crustal extension, the ductile lower part of the crust is stretched, but the brittle upper

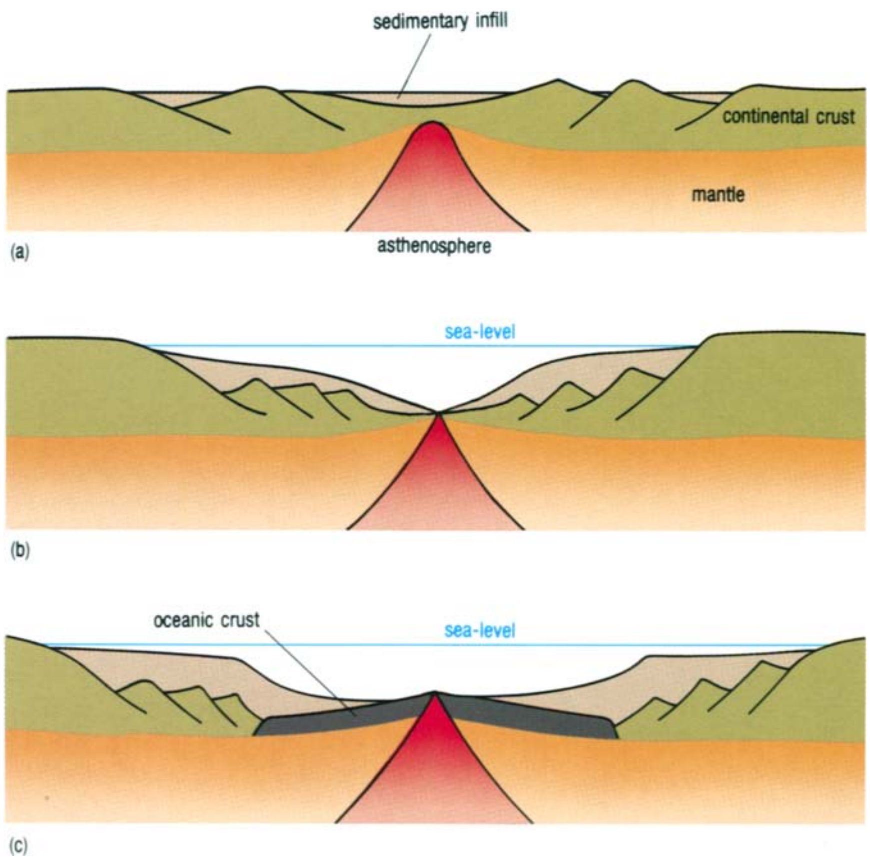


Figure 3.2 Diagrams illustrating how a new ocean basin may form.
(a) The surface of the stretched and rifted region is still above sea-level and may even be uplifted as a result of thermal expansion because of a heat source at the site of the future spreading axis. Terrigenous sediments (i.e. those derived from erosion on land) occupy the rift valley.
(b) The future continental margins have thinned enough to subside below sea-level and marine sedimentation has begun. Sediments thicken away from the new spreading axis.
(c) Separation is complete, a new spreading ridge has developed, and a shelf–slope–rise zone is forming (cf. Figure 2.6).

part is rifted. Blocks of crust slide down fault planes, and sediments accumulate in the lakes and valleys which occupy the resulting depressions. When separation occurs, basaltic magma rises to fill the gap between the two continental blocks. Because the resulting new oceanic crust is both thinner and denser than continental crust, it lies below sea-level. The remainder of the lithosphere, below the crust, is composed of upper mantle material.

Initially, the young marine basin is fairly shallow. If repeated influxes of seawater become wholly or partly evaporated, salt deposits (**evaporites**) will accumulate. Otherwise, there will be normal marine sedimentation of muds, sands and limestones, depending on local conditions. One of the clearest examples of a young ocean basin is the Red Sea.

3.2.1 THE RED SEA

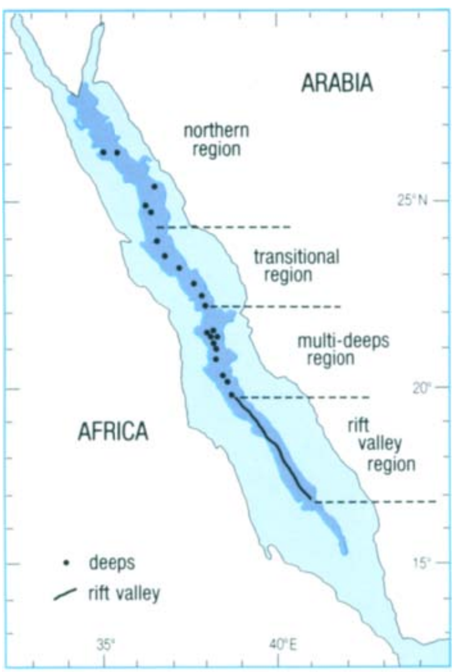
In the Red Sea, a narrow deep axial zone is flanked on either side by a broad shallow area of shelf sea (Figure 3.3(a)). Evaporites of Miocene age (deposited between about 20 and 5 Ma ago) that are over 4 km thick in places underlie the shallower waters of these flanking regions. They obscure the nature of the crust beneath, which appears to be thinned and stretched continental crust (Figure 3.3(b)).

The evaporites were deposited at a time when the only marine connection to the Red Sea was with the Mediterranean by an intermittent, shallow, seaway. Evaporite deposition ended about 5 Ma ago at the end of the Miocene when this seaway was finally broken and a new connection with the Indian Ocean was opened in the south. Open water conditions were established, in which planktonic organisms flourished, especially in the southern Red Sea. High rates of biogenic (biologically derived) sedimentation caused bathymetric features to be smothered, and they become much less obvious south of about 16° N.

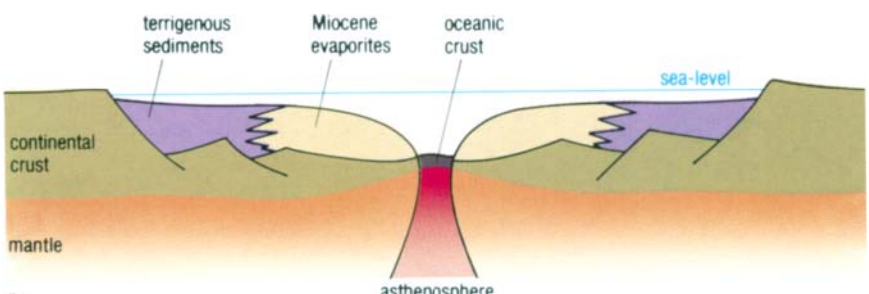
Further north, the post-Miocene biogenic sediments give way to a thinner sequence of terrigenous (land-derived) clays, sands and gravels, produced by erosion of the flanks of the basin. Similar terrigenous sediments can also be found interbedded with the Miocene evaporites, especially near the margins.

Only in the axial zone, which represents that part of the Red Sea generated since the end of evaporite deposition, do we find true oceanic crust produced by sea-floor spreading. On the basis of seismic and magnetic surveys, submersible observations and side-scan sonar mapping, the axial zone can be subdivided into several regions along its length (Figure 3.3(a)) as described below.

Figure 3.3 (a) Outline map of the Red Sea, with the axial zone (dark blue) defined by the 500-fathom isobath and subdivided into four main sections, described in the text (1 fathom = 6 feet = 1.83 m).
(b) Highly schematic cross-section through the Red Sea.



(a)



(b)

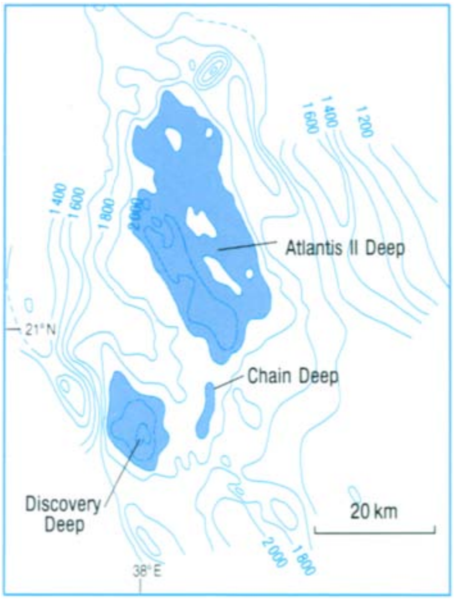


Figure 3.4 Bathymetric details of some major 'deeps' in the multi-deeps region of Figure 3.3(a). Hot, metal-rich brines are found in them, and metalliferous muds are being deposited there. Depths are given in metres.

Rift valley region

The southern part of the axial trough is now known to have a well-developed straight central rift (similar to that on the Mid-Atlantic Ridge; Figure 2.12), which is offset by 3–10 km about every 30–50 km. These discontinuities may be either transform faults or some sort of non-transform offset.

High-amplitude linear magnetic anomalies occur throughout this region, though they become weak and irregular at the offsets. Measurements of the magnetic anomaly stripes indicate that spreading has proceeded at a rate of about 0.8 cm yr^{-1} for the past 5 Ma.

Multi-deeps region

North of about 20° N, the straight axial rift loses its identity and is replaced by a complex series of axial deeps, distributed partly in an *en echelon* fashion, perhaps because of offsets by transform faults. The deeps are best developed between about 20° N and 22° N and they have attracted commercial interest on account of the metal-rich hot brines and muds which some of them contain (Figure 3.4). Individual deeps have a rift-valley type structure with strong magnetic anomalies, but between the deeps the anomalies are much weaker and the axial region is sediment-covered.

Transitional and northern regions

Beyond about 22° N, the deeps become progressively narrower and less well developed, and the associated magnetic anomalies suggest that the oceanic crust in them may be only 2 Ma old or less. North of about 25° N, only isolated deeps are found, the high-amplitude magnetic anomalies characteristic of oceanic crust which occur further south have virtually disappeared, and the region appears to have a more or less continuous sediment cover.

In summary, then, only about 80 km width ($2 \times 5 \times 10^6 \times 0.8 \times 10^{-2}$ m) of new ocean floor up to 5 Ma old can be demonstrated to have formed in the southern part of the axial zone; further north, ocean floor has formed only in the deeps and is 2 Ma old or less.

All of this suggests strongly that the axial zone of the Red Sea is a northward-propagating zone of separation between adjacent plates of continental lithosphere. The fracture began to open properly about 5 Ma ago in the south but has yet to do so in the north. This is consistent with the end of evaporite deposition in the Red Sea about 5 Ma ago, when a link with the Indian Ocean was established via the Gulf of Aden.

But what about the crust outside the axial region of the Red Sea? Figure 3.5 shows magnetic anomalies in the southern Red Sea. The well-defined axial anomalies that are characteristic of true oceanic crust give way to an irregular and much weaker pattern in the flanking regions. This is consistent with thinned and stretched continental crust, injected by thin vertical sheets of basaltic rock (dykes).

From a variety of geological evidence, it is clear that this stretching and subsidence of the continental crust pre-dates the sea-floor spreading in what became the Red Sea. It seems likely that the first stage, about 35 Ma ago, was the propagation of a crack from the Arabian Sea westward through the Gulf of Aden. By about 25 Ma ago, east–west extension had begun to be felt across the entire area of the Red Sea (from its junction with the Gulf of Aden northwards as far as the Gulf of Suez), and was manifested by the development of a rift system within the continental crust. A new fracture

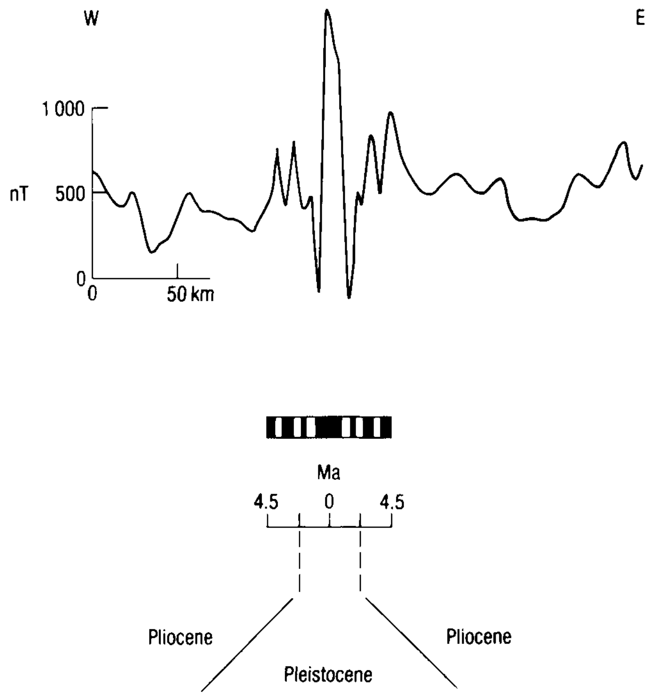


Figure 3.5 Magnetic anomalies for the southern Red Sea, showing the contrast between the strong central pattern over the axial trough and the subdued pattern on either side. For this profile, correlation with the magnetic reversal time-scale (black = normal polarity; white = reverse polarity) gives an average full spreading rate of 1.5 cm yr^{-1} over the past 4.5 Ma. The magnetic field is measured in nT (nT = nanotesla = 10^{-9} T).

developed in the north along what is now the Gulf of Aqaba/Dead Sea line, running towards the north-north-east. Transcurrent (lateral) movement along this line accompanied further widening of both the Gulf of Aden and the Red Sea as Arabia moved away from Africa. Oceanic crust formed in the Gulf of Aden. About this time there was widespread extension-related volcanism in the western parts of what are now the Yemen, Saudi Arabia, Eritrea, and northern Ethiopia.

Along the Red Sea rift, the continental crust continued to stretch and subside, and evaporites were deposited on top of it. About 5 Ma ago the system was reactivated when movement was renewed along the Gulf of Aqaba/Dead Sea line. The continental crust was already so fully stretched that rather than thinning and stretching even further it was pulled apart, and sea-floor spreading began here for the first time, while continuing in the Gulf of Aden.

The opening of the Red Sea as a new ocean was clearly a drawn-out and complicated affair, and we should bear in mind that the opening stages of other ocean basins are likely to have been similarly complex. However, we must now move on to consider larger ocean basins that have reached Stage 3 or 4 of Table 3.1, bearing in mind that in the early stages of formation, they probably resembled the Red Sea.

QUESTION 3.2 Roughly where would you expect to find the pole of relative rotation (see Figure 2.14) about which the African and Arabian Plates are moving to form the Red Sea?

3.3 THE MAJOR OCEAN BASINS

Figure 3.6 summarizes the age distribution of oceanic crust beneath the world's oceans, as determined from magnetic anomaly patterns. The virtually symmetrical pattern of ages about the ocean ridges is visible everywhere, and it is clear that (apart from the Caribbean area and in the extreme south-west) the Atlantic has had the least complicated evolution of any of the three main ocean basins. The Pacific and Indian Oceans display more complex histories, partly because of the development of major subduction zones along one or more boundaries and partly because of adjustments in spreading direction.

QUESTION 3.3 With reference to Figure 3.6, determine the relative order in which sea-floor spreading began in these three parts of the Atlantic:
(i) northernmost Atlantic, between Greenland and north-west Europe;
(ii) northern Atlantic, between North America and north-west Africa;
(iii) southern Atlantic, between South America and southern Africa.

From Figure 3.6, it is relatively easy to reconstruct stages in disruption of the continental jigsaw puzzle that led to the present-day Atlantic. It is simply a matter of moving the continents back along the transform faults to determine the positions of their margins at any particular time, as represented by the age of the ocean floor magnetic stripes.

The Pacific and Indian Oceans are more difficult to 'close up'. The Pacific is almost surrounded by subduction zones, so much of the evidence of its older history has disappeared. The widths of the ocean floor age strips increase northwards along the line of the East Pacific Rise in a way that is consistent with increasing spreading rates from south to north. However, the East Pacific Rise runs into the North American continent, beneath which its northern end is being subducted.

You have already seen evidence of changes in spreading direction in the north-western Pacific (Figure 2.22), and more evidence is to be seen in the pattern of ocean floor ages in Figure 3.6.

The Hawaiian Chain is oblique to the spreading trend indicated by the age strips for 0–43 Ma Pacific Ocean floor in Figure 3.6. What does that tell you about the movement of the East Pacific Rise? Bear in mind that hot spots can be regarded as effectively stationary with respect to the Earth as a whole.

The East Pacific Rise must have been moving relative to the frame of reference provided by the Hawaiian and similar chains (the 'hot-spot reference frame'). It is important for you to realize that magnetic anomalies, and the sea-floor age strips which can be mapped using them, record only the motion *relative to the spreading axis at which the sea-floor was formed*. It is quite possible for the spreading axis itself to be migrating relative to the deep Earth. In fact, it is impossible to have several spreading axes on a sphere and keep them all stationary, unless the plate motion at each one is individually and exactly compensated for by nearby destructive plate margins. Thus, a spreading axis can migrate across an ocean basin, and will be destroyed if it gets carried into a subduction zone. Figure 3.7 (overleaf) shows how the global plate boundaries are thought to have evolved over the past 61 Ma based on the types of data you have read about in this and the previous Chapter, especially hot-spot traces and magnetic anomaly patterns.

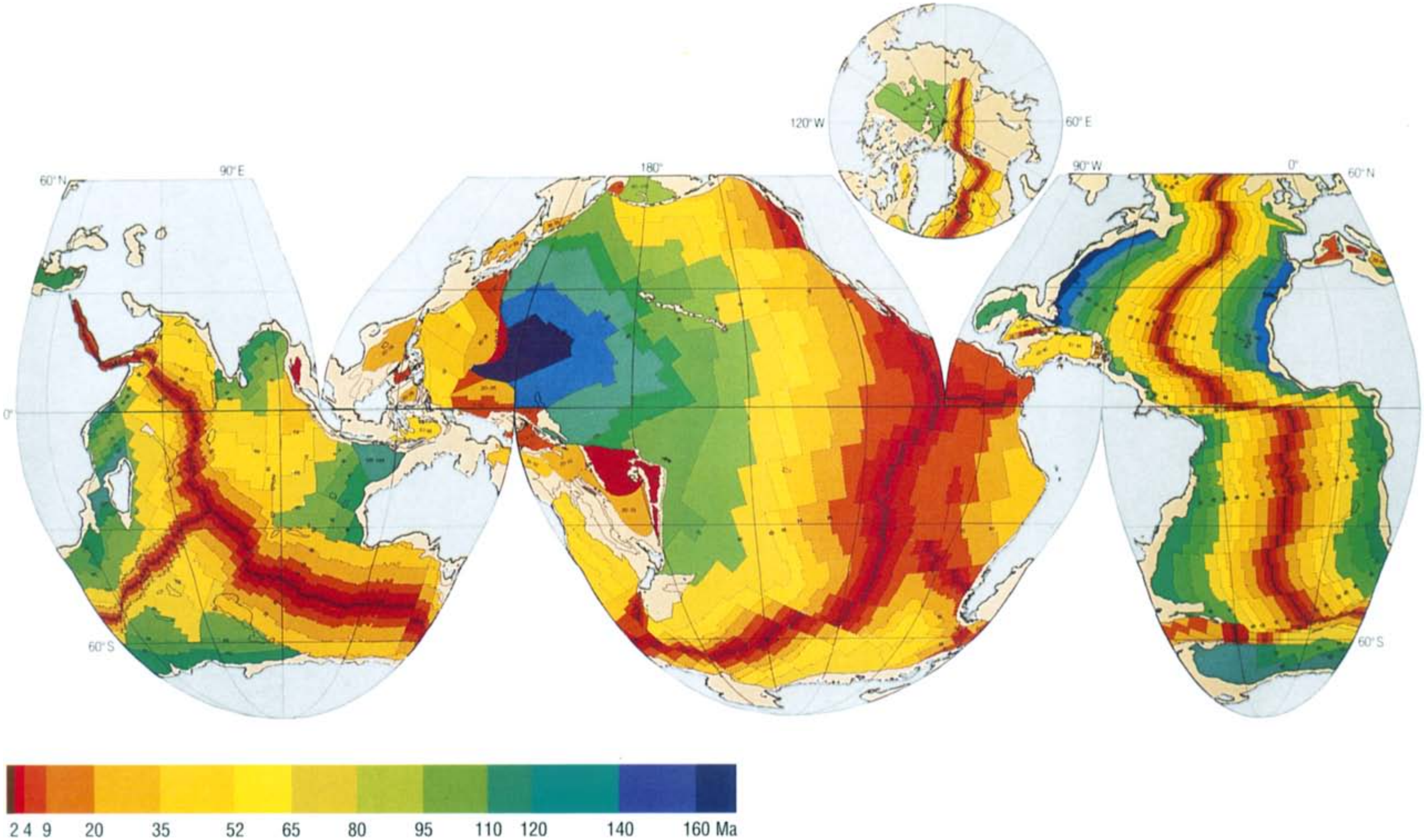


Figure 3.6 The age of the ocean floor, showing strips of floor of different ages derived mainly from measurements of magnetic anomaly stripes. Boundaries are drawn at 2, 4, 9, 20, 35, 52, 65, 80, 95, 110, 120, 140 and 160 Ma intervals in a colour scheme that runs from dark grey (youngest) through red, yellow, and green to blue (oldest). Pale brown areas are the continental shelves.

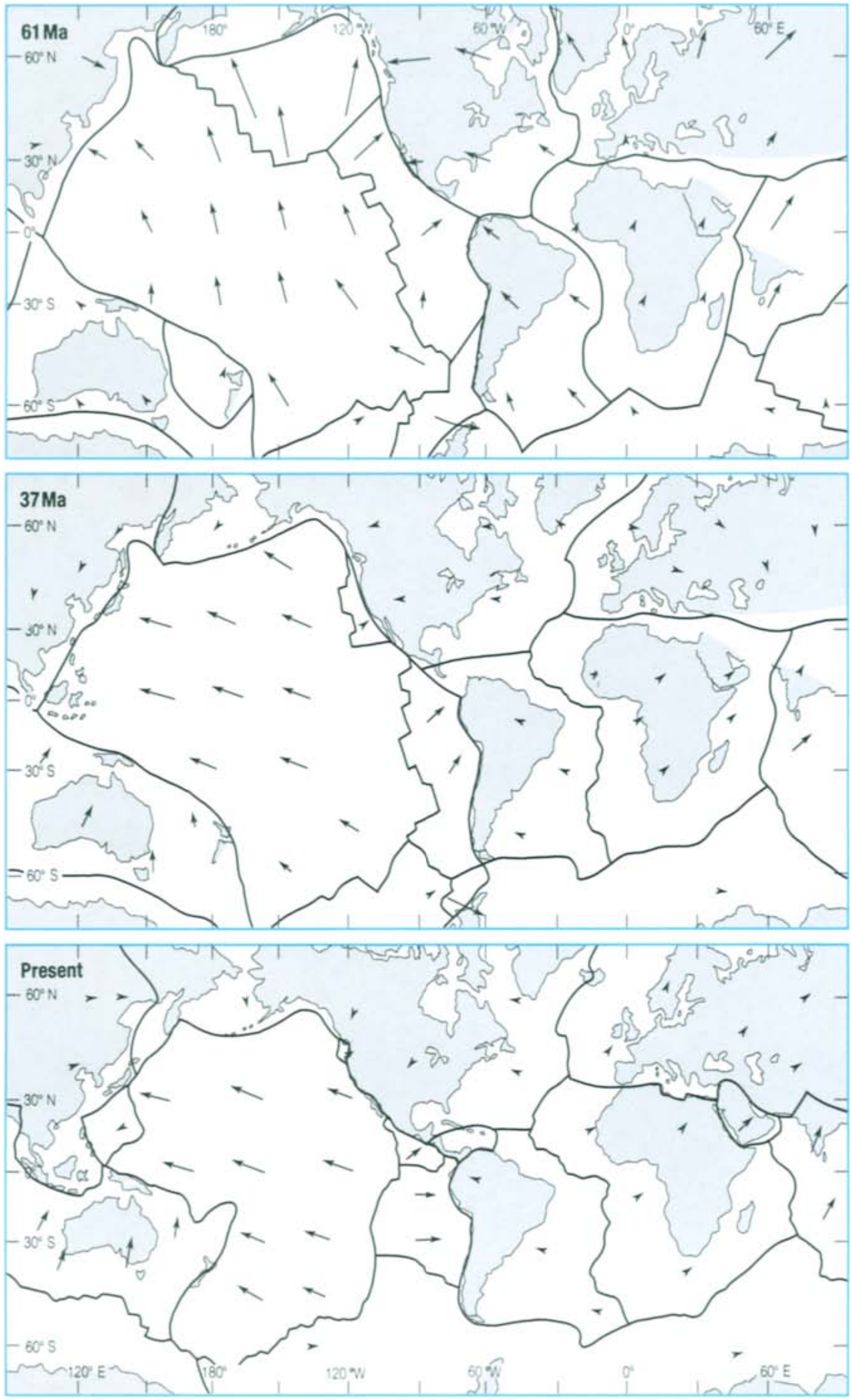


Figure 3.7 Evolution of plate boundaries over the past 61 Ma. The arrows show the directions and relative rates of motion of the plates.

The oldest oceanic crust in the Pacific is found in the north-west, but the western Pacific as a whole is an area of great complexity. This is because of the generation of new oceanic lithosphere at various spreading axes above subduction zones, where island arcs are being built and then split apart, and back arc basins are forming, as outlined in Section 2.2.2 and illustrated in Figure 3.8. These events occur independently of sea-floor generation at the East Pacific Rise.

In the Pacific, there is an added complication when it comes to reconstruction of the continental jigsaw puzzle. Palaeomagnetic, geological

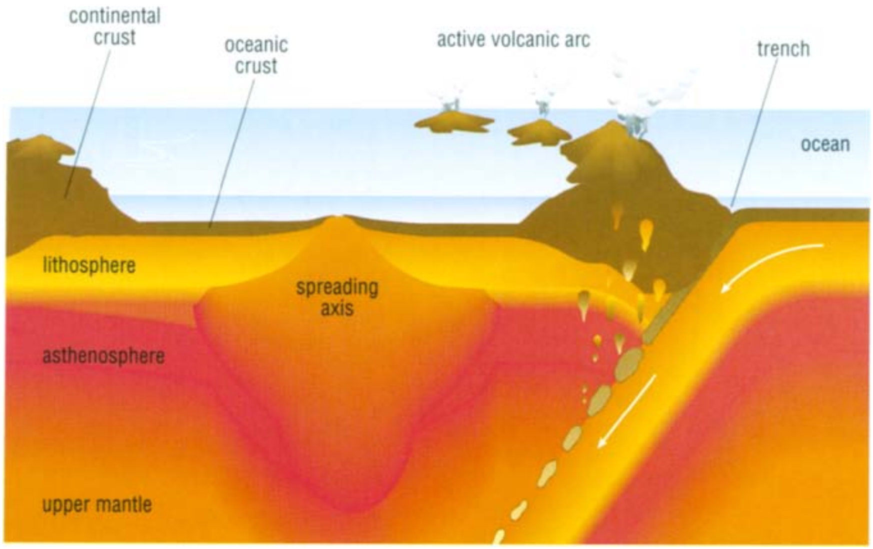


Figure 3.8 A schematic cross-section through a typical western Pacific continental margin. A small spreading axis has generated new oceanic crust behind the island arc. In some places, an even more complex series of island arcs and back arc basins separates the deep ocean trench from the continental margin.

and palaeontological evidence have demonstrated that substantial tracts of western North America are 'exotic terranes'. These are blocks of continental crust – microcontinents – that have been transported by plate movements for great distances across the Pacific to become accreted onto North America.

The Indian Ocean has several features of interest, too. Its northern boundary is a major complex subduction zone, represented by the Himalayan belt and the Java Trench system. South of India, the spreading direction changed from north–south to north-east–south-west about 50 Ma ago when the present South-east Indian Ridge became established.

The aseismic Ninety-east Ridge (Section 2.5.4) must lie on the line of an old major transform fault, for the age of the crust changes in opposite directions on either side of it, as can be seen in Figure 3.6.

QUESTION 3.4

(a) In what directions do crustal ages change on either side of the Ninety-east Ridge?

(b) Were these areas of oceanic crust generated before or after development of the present South-east Indian Ridge?

(c) What happened to the spreading axis which generated the crust immediately east of the Ninety-east Ridge?

You can find other examples of changes of spreading rate and direction, and development of new spreading axes and subduction zones, displayed in Figure 3.6. You may also have noticed that many of the ocean floor age strips are oblique to subduction zones, e.g. in the north-east Indian Ocean and parts of the western Pacific. Oblique subduction of ocean floor is by no means exceptional, and it means that continent–continent or continent–island arc collision does not necessarily occur head-on, and so major transcurrent faulting may result.

In the major ocean basins, irrespective of whether they are classified as Stage 3 or 4 in Table 3.1, there is no indication that increasing age is correlated with any decline in the intensity of sea-floor spreading activity. The Pacific basin is the oldest, for instance, but it has the fastest spreading rates. When we come to Stage 5, we find that even in the latest stages of evolution, there is little diminution of vigour.

3.3.1 THE MEDITERRANEAN

The Mediterranean can be classified as an ocean in the final stages of its life cycle, the only major remnant of the once-extensive Tethys Ocean (Table 3.1, Stage 5; Figure 3.1). The Mediterranean is shrinking as the African Plate continues to thrust its way northwards beneath the European Plate. We might therefore expect that the Mediterranean would be floored by oceanic crust dating back perhaps as far as Jurassic times, which would be consistent with its being the remnant of an old ocean, and that it would have an obvious major trench. It turns out, however, that the Mediterranean region has been broken into many small plates, whose boundaries may be delineated partly by analysis of earthquakes (which are sporadic and scattered in this region), and partly by drilling. The deep basins contain several kilometres of sediments, including evaporites (see Chapter 6), and this hampers geophysical investigations into the nature of the underlying crustal layers.

The eastern Mediterranean is floored by crust of Cretaceous age (*c.* 110 Ma), bordered by an area of middle Tertiary (25 Ma) crust south of Italy, possibly the result of back-arc spreading. There is a collision zone running south of Cyprus, where the African Plate meets the Eurasian Plate, and there is some evidence of subduction there. Miocene and younger (10–2 Ma) oceanic crust in the western Mediterranean is generally believed to have formed in a back-arc setting, associated with the subduction that removed older ocean floor from this region. Active volcanism and frequent earthquakes in and around the Mediterranean show that this ocean basin is still evolving.

QUESTION 3.5 Can you explain the correlation between crustal age in the eastern and western Mediterranean (Figure 3.6) and the geoid anomaly in these two areas (Figure 1.18)?

Apart from the eastern Mediterranean sea-floor, ocean crust older than about 70 Ma is represented in the Mediterranean region by slivers of oceanic crust and upper mantle which have been tectonically removed from the ocean floor and emplaced over a continental margin, usually during a collision event. A piece of ocean floor which has been preserved in this way is called an **ophiolite** or **ophiolite complex**. Ophiolites are too small and fragmentary to preserve magnetic stripes, but they can be dated by other methods (e.g. radiometrically or by examining the fossils in the oldest sediments associated with them). The ophiolite forming the Troodos mountains in Cyprus is one of the most intact and best-known. This is one of many ophiolites of mostly late Cretaceous age (*c.* 80 Ma), preserved in collisional mountain chains along the north side of the Mediterranean in the Balkans and Asia Minor. This belt runs eastwards all the way through the Himalayas and represents the remains of the Tethys Ocean. Older ophiolites tend to occur near the western Mediterranean, particularly in the Alps, and range in age back to the Triassic (*c.* 220 Ma). These may represent the oldest ocean floor of the Mediterranean–Tethys region.

Reconstruction of the evolution of ocean geometry is more than just an academic exercise. Combined with information from the sediments on the ocean floor, it can be used to reconstruct past climatic and circulation patterns. Compilations such as Figure 3.6 are continually being up-dated as less well-known areas are surveyed in greater detail, sometimes with the help of satellite bathymetry data. The more we understand about fluctuations in past oceanic cycles, the better we shall understand the present-day oceans.

We shall look at this with particular reference to sea-level in Chapter 6, but next we turn to the mechanisms of generation of new oceanic crust.

3.4 SUMMARY OF CHAPTER 3

1 Oceanic crust is much younger than most continental crust. Oceanic lithosphere must have been generated at spreading axes (ridges) and destroyed at subduction zones many times since the formation of the Earth. Ocean basins form initially by stretching and splitting (rifting) of continental crust, and the rise of mantle material and magma into the crack to form new oceanic lithosphere.

2 The Red Sea is an embryonic ocean that appears to be opening progressively from the south, where the axial region is underlain by oceanic crust and has a rift valley. Further north are isolated deeps – with metal-rich muds – but there is less evidence of oceanic crust in the axial region. The thick evaporites bordering the axial region rest on thinned continental crust.

3 Among the major ocean basins, the Atlantic has the simplest pattern of ocean-floor ages. Subduction is confined to relatively small island arc systems in the Caribbean and the extreme south-west. Successive stages in the shape of the Atlantic basin are therefore fairly easy to reconstruct, by moving the continents back along a direction at 90° to the magnetic anomaly stripes and parallel to the transform faults.

4 In contrast, both the Pacific and Indian Oceans (which have major subduction zones) are characterized by changes of spreading rate and direction and the development of new spreading axes. Because of these complications, it is difficult to work out how the shapes of these ocean basins have changed with time. The occurrence in western North America of 'exotic terranes', which in some cases are believed to have originated as microcontinents in the south-west Pacific, make the task of such reconstruction even more complicated.

5 The Mediterranean represents an ocean in the final stages of its life cycle, contracting as Africa pushes northwards into Europe and western Asia. However, no *in situ* oceanic crust older than the Cretaceous is known from the Mediterranean basin, and crust as young as 2 Ma has been found there, demonstrating that there is no inverse correlation between age of an ocean basin and the vigour of sea-floor spreading and plate-tectonic activity.

Now try the following questions to consolidate your understanding of this Chapter.

QUESTION 3.6 'India moved northwards at rates of between 10 and 20 cm yr^{-1} from about 135 to about 45 Ma ago. For the next 25 Ma or so, it moved more slowly at about 5 cm yr^{-1}.' Are the relative widths of the age bands south of India in Figure 3.6 consistent with these statements?

QUESTION 3.7 According to Figure 3.6, what is the approximate ratio between the average spreading rate over the past 52 Ma for the East Pacific Rise at the Equator and that of the Mid-Atlantic Ridge at 30° S over the same time (52 Ma is in the middle of the yellow field in Figure 3.6)? If the average spreading rate in the Atlantic was 2 cm yr^{-1} over this period, what was it for the East Pacific Rise?