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978-1-107-01752-8 - Mid-Ocean Ridges
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Excerpt
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1 Introduction

1.1 The global mid-ocean ridge system

Mid-ocean ridges (MOR)s are a product of the separation and spreading of tectonic plates, and are a major component of the Earth system. Their role as plate boundaries is discussed in detail in Chapter 4. Back-arc spreading centres are functionally similar, and for many purposes can be grouped together with ridges, although they will not be considered in detail in this book. This chapter introduces MORs, outlines their discovery and the theory of plate tectonics (since ridges form an important class of plate boundaries), and briefly introduces some of the institutions and organisations that have been critical for understanding ridges.

The MOR system spans the world, extending to some 65 000 km in length (Figure 1.1). Plate separation rates range from only a few millimetres per year to some 160 mm a^{-1}, and even faster at some past times (Müller *et al*., 2008; Teagle *et al*., 2012). MORs are characterised by shallow ocean floor, narrow bands of shallow seismicity and high heat flow. Their crests generally lie some 2.6 km below sea level; their flanks may be thousands of kilometres wide and reach depths in excess of 6 km. They contain arguably the largest array of active volcanoes in the world, and host extensive hydrothermal vent fields where unique ecosystems based on chemosynthesis flourish. They are the places where new oceanic lithosphere is continuously generated, and where this newly created lithosphere is flexed, faulted and chemically altered. This book aims to present an overview of all of these processes.

Many aspects of ridges are at least in part related to spreading rate. Strictly speaking, 'spreading rate' is the rate at which each tectonic plate grows, or spreads away from the ridge axis. However, it is sometimes also used to mean the rate at which the two plates diverge (which for symmetric spreading is twice the spreading rate). To avoid confusion, the two rates should be identified by different names. Although not entirely accurate, the custom has developed of using 'half spreading rate' for the rate of plate growth and 'full spreading rate' for the rate of plate separation. Alternative uses would be 'plate accretion rate' and 'plate separation rate'.

Because ridge characteristics tend to depend on spreading rate, ridges are often grouped into broad classes as a function of this rate (Table 1.1). Nevertheless, spreading rate varies continuously, and the given class boundaries are approximate and may vary between authors. Other factors, particularly mantle temperature and fertility, may also control ridge morphology, structure and processes.

Table 1.1 Spreading rate categories of mid-ocean ridges

Class	Total opening rate, km Ma^{-1}	Reference	Example
Superfast	>130 –150	Sinton *et al*. (1991)	East Pacific Rise 20° S
Fast	90–130	Lonsdale (1977)	East Pacific Rise 13° N
Intermediate	50–90	Lonsdale (1977)	Juan de Fuca Ridge
Slow	20–50	Lonsdale (1977)	Northern Mid-Atlantic Ridge
Ultra-slow	<20	Grindlay *et al*. (1998)	Southwest Indian Ridge, Gakkel Ridge

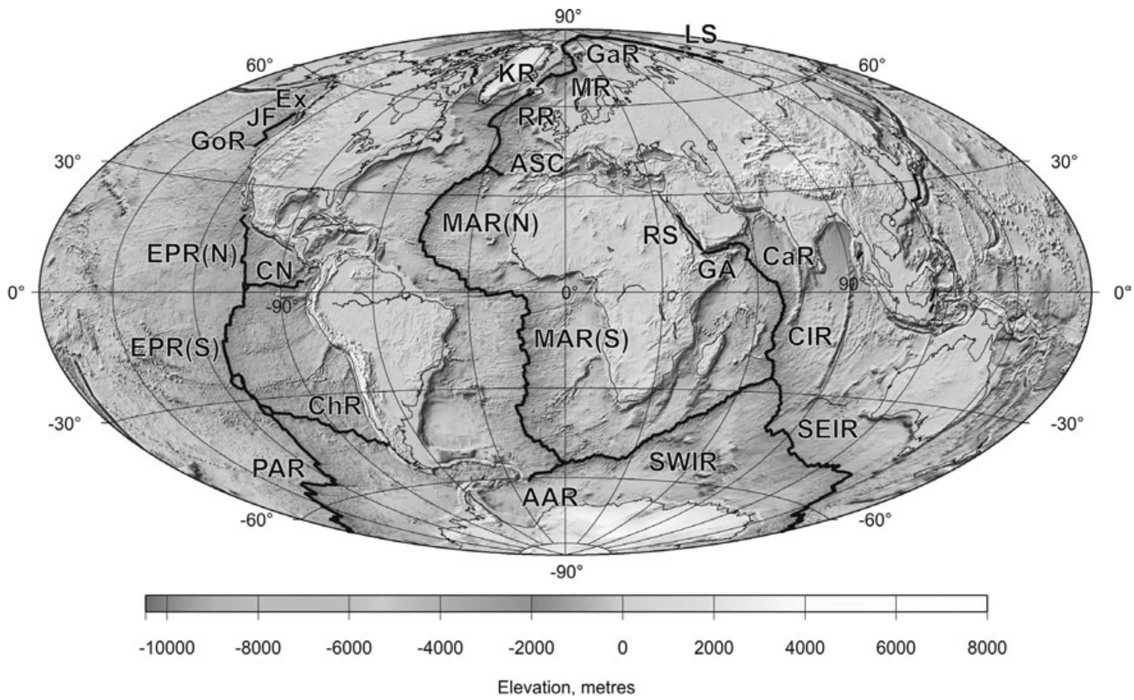

Figure 1.1 World topography with mid-ocean ridges superimposed (heavy black lines). Back-arc spreading centres have been omitted for clarity. AAR, American–Antarctic Ridge; ASC, Azores Spreading Centre; CaR, Carlsberg Ridge; ChR, Chile Rise; CIR, Central Indian Ridge; CN, Cocos–Nazca Spreading Centre; EPR, East Pacific Rise (north and south); Ex, Explorer Ridge; GA, Gulf of Aden; GoR, Gorda Ridge; GaR, Gakkel Ridge; JF, Juan de Fuca Ridge; KR, Kolbeinsey Ridge; LS, Laptev Sea Rift; MAR, Mid-Atlantic Ridge (north and south); MR, Mohns Ridge; PAR, Pacific–Antarctic Rise; RR, Reykjanes Ridge; RS, Red Sea; SEIR, Southeast Indian Ridge; SWIR, Southwest Indian Ridge. For colour version, see plates section.

Each ocean contains an MOR (Figure 1.1). Most are named for the ocean they are in (e.g., Mid-Atlantic Ridge – MAR), but some have specific regional names (e.g., Gakkel Ridge in the Arctic Ocean), and some are named for the plates they separate (e.g., Cocos–Nazca Spreading Centre). The fast-spreading East Pacific Rise (EPR) and Pacific–Antarctic Rise are called ‘rise’ because their morphology is gentler than that of the slower-spreading

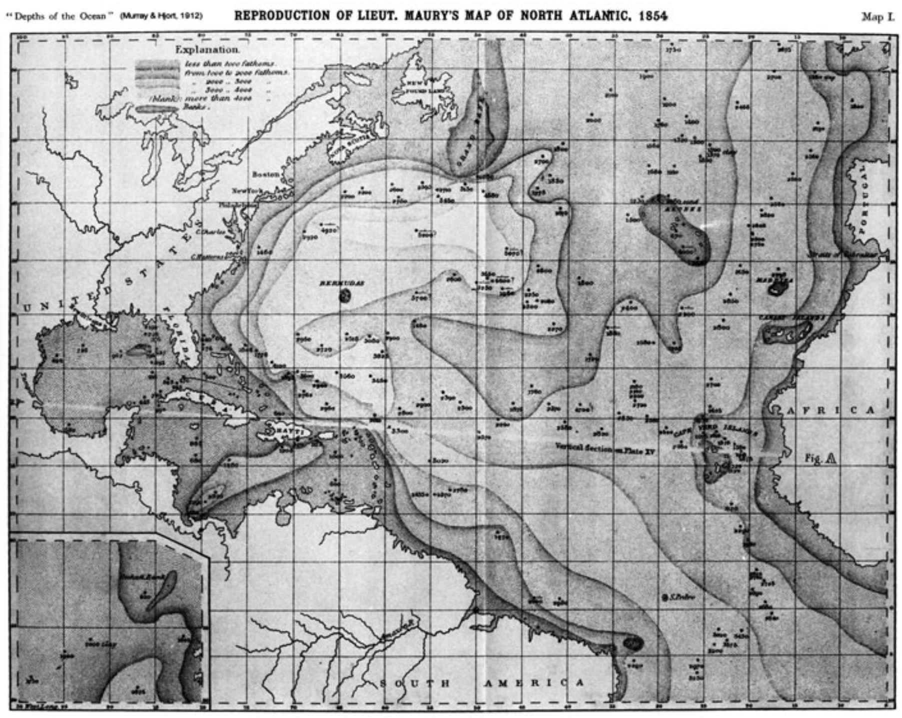

Figure 1.2 The first map of the North Atlantic, showing the position of the MAR after Murray and Hjort (1912), reproduced from Maury (1860).

'ridges'. Some ridges are not centred in their ocean, having come about by rifting of a pre-existing oceanic basin rather than of the bounding continent, so are not 'mid-ocean' in the strict sense; however, their structures and processes are common to the MORs *sensu stricto*.

1.2 The discovery of MORs

Mid-ocean ridges were discovered in the nineteenth century. The American hydrographer Matthew Fontaine Maury developed improved methods of deep-sea sounding, and produced the first map showing the varying depth of the North Atlantic Ocean (Maury, 1860). His Plate VII shows a broad, shallow region in the position of the MAR between 20° N and 52° N (Figure 1.2). The northernmost part of this was called Telegraphic Plateau, and was discovered by surveys for the first trans-Atlantic telephone cables. The rest of this broad rise, south of 45° N, was known as 'Middle Ground'.

The first systematic oceanographic expedition was the circum-global cruise of HMS *Challenger* from 1872 to 1876 (Thomson, 1877). The *Challenger* expedition's studies

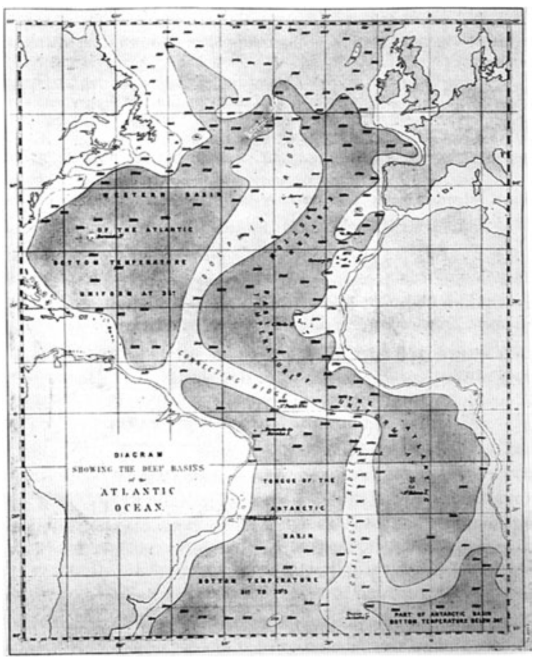

Figure 1.3 Map of the MAR, after Tizard (1876).

included both depth soundings and measurements of water temperature. On the basis of a difference between the deep-water temperatures between the western and eastern Atlantic, Tizard (1876) inferred the existence of a topographic ridge separating the two basins. His Plate 6 shows the existence of this ridge, named ‘Dolphin Ridge’ in the North Atlantic and ‘Challenger Ridge’ in the south (Figure 1.3). They are joined by ‘Connecting Ridge’ which comprises what are now known as the equatorial Atlantic fracture zones.

Early in the twentieth century, Murray and Hjort (1912, p. 135) produced a map showing many of the world’s MORs, although only one, the MAR, was yet named as such. In the Pacific, the US ship *Albatross* had discovered the Albatross Plateau (now known to be part of the EPR) between 1880 and 1905. Thousands of soundings had been made world-wide by 1923, when electronic echosounding began to be introduced (Shepard, 1959). The German ship *Meteor* ran 14 echosounding lines across the south Atlantic in 1925–1927 (Marmer, 1933), clearly revealing the southern MAR in detail (Shepard, 1959, pp. 162–163). These were the only detailed profiles available prior to World War II (Heezen and Menard, 1963). At about the same time, the Danish vessel *Dana* (1928–1930) discovered the Carlsberg Ridge in the Indian Ocean (Tharp, 1982). Following World War II, continuously recording precision echosounders came into widespread use (Section 2.2.2), and by the middle of the twentieth century the general outline of the global MOR system was well established (Shepard, 1948; Figure 1.4).

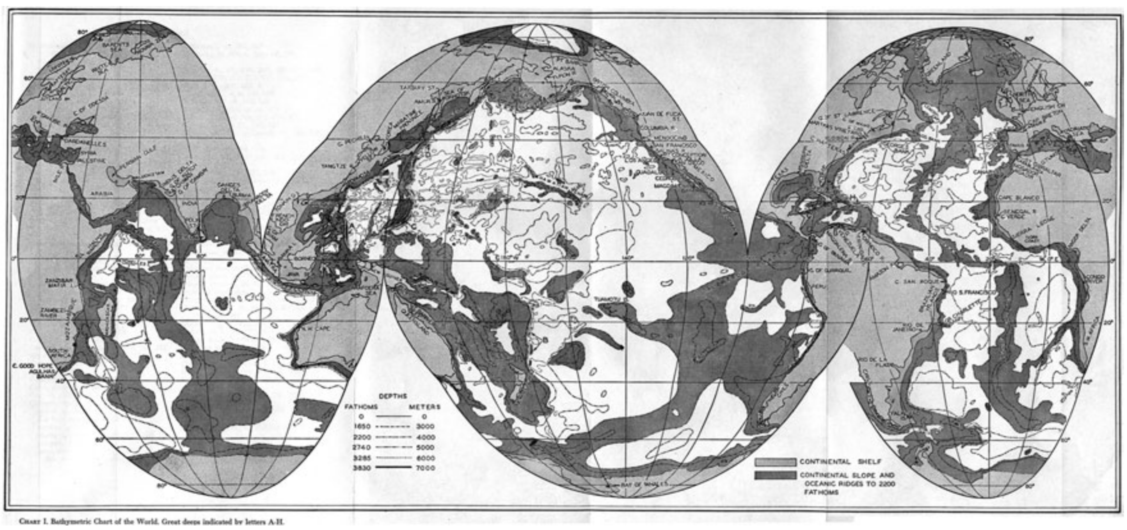

Figure 1.4 Bathymetric chart of the world's oceans, after Shepard (1948).

1.3 Sea floor spreading and plate tectonics

The theory of sea floor spreading views tectonic plates as being created at MORs and then 'spreading' away from them on either side. The theory developed from the ideas on continental drift proposed by Wegener (1912, 1966), based on the matching coastlines and geological features, and the divergence of evolutionary trends, on either side of the Atlantic. Dietz (1961) proposed that oceanic seismic layer 3 (the lower crust, see Chapter 5) and the uppermost mantle are chemically the same, and introduced the term 'lithosphere' to describe the outermost, rigid part of the Earth (Chapter 3). Importantly, he suggested that the sea floor represents the tops of convection cells; the MORs mark the up-welling sites and the trenches are associated with down-welling. This contains the essence of sea floor spreading and plate tectonics as now understood. Hess (1962) also accepted mantle convection, and suggested that the MAR is spreading at about 1 cm a^{-1} half-rate. He proposed that ridges' elevations reflect their thermal expansion, and that their low seismic velocities are partly due to raised temperatures. Crucially, he suggested that continents ride passively on the convecting mantle rather than having to plough through oceanic crust, providing a more acceptable mechanism for continental drift.

Critical evidence for sea floor spreading came from detailed marine magnetic surveys. Detailed surveys by Scripps Institution of Oceanography in conjunction with the United States Coast and Geodetic Survey off the west coast of the USA and Canada (Mason, 1958; Mason and Raff, 1961; Raff and Mason, 1961) revealed extensive, parallel, linear magnetic anomalies (Figure 1.5) in the region of the Gorda, Juan de Fuca and Explorer Ridges (though these ridges were not recognised at that time). Subsequent studies elsewhere

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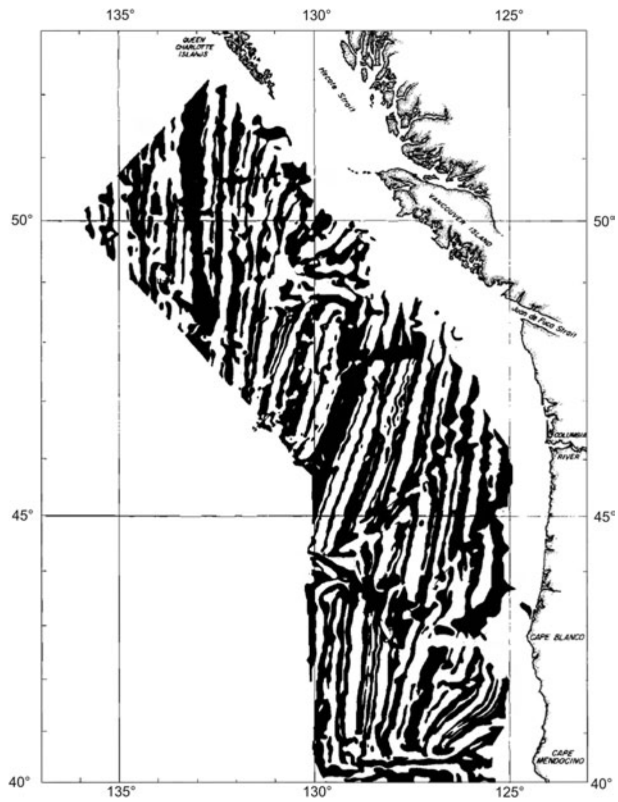

Figure 1.5 Magnetic lineations in the northwestern Pacific, after Raff and Mason (1961).

showed the remarkable symmetry of magnetic lineations about ridge axes (e.g., Heirtzler *et al.*, 1966; Figure 1.6).

Vine and Matthews (1963) of Cambridge University conducted a small but very detailed survey over part of the Carlsberg Ridge. They demonstrated that the observed magnetic lineations could be explained if approximately 50% of the sea floor was underlain by normally magnetised material and 50% by reversely magnetised material. By combining this observation with the recognition of periodic reversals of the Earth's magnetic field (Cox *et al.*, 1963) they were able to explain the magnetic lineations in terms of sea floor spreading. A much greater body of supporting evidence was later published by Vine (1966). Essentially the same interpretation had been put forward more or less simultaneously by Lawrence Morley, who was unable to get his ideas published immediately (Glen, 1982) but did so later (Morley and Larochelle, 1964).

In summary, the theory of sea floor spreading states that tectonic plates diverge from MOR axes, at separation rates ranging from <10 km Ma^{-1} (Dick *et al.*, 2003) to >160 km Ma^{-1} (Naar and Hey, 1989). This causes the underlying ductile mantle to rise and, at higher spreading rates, to partially melt producing magma that solidifies to form a volcanic crust (Figure 1.7); at slower spreading rates, the mantle is extruded directly onto the sea floor (Chapter 7).

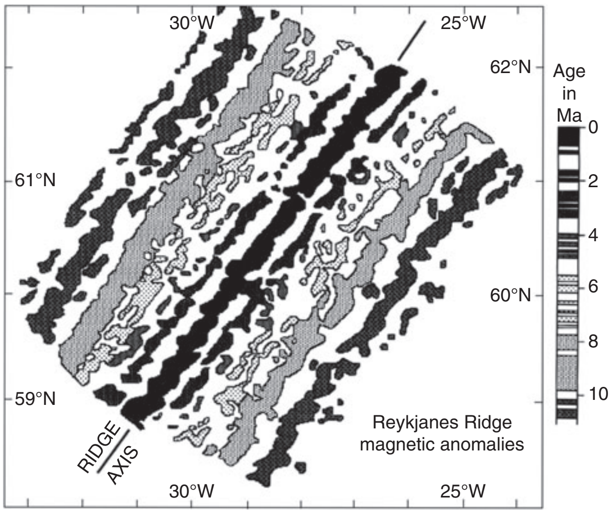

Figure 1.6 Magnetic anomalies over the Reykjanes Ridge, reprinted from Heirtzler *et al.* (1966), © 1966, with permission from Elsevier.

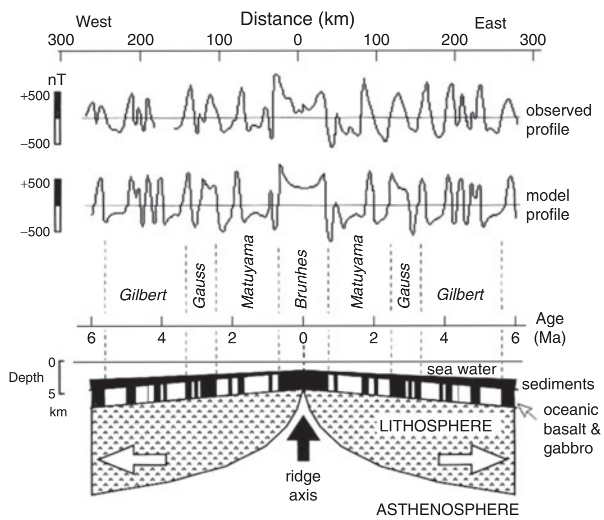

Figure 1.7 Diagram of sea floor spreading, after Lowrie (1997).

The recognition of the origin of lineated magnetic anomalies, coupled with radiometric dating of the field reversals (Cox *et al.*, 1963), provided a means of both dating older sea floor and determining spreading rates. A detailed magnetic reversal timescale is now available back to the late Cretaceous (118 Ma; Cande and Kent, 1995). The most prominent positive magnetic anomalies have conventionally been numbered from 1 (axial anomaly, zero age) to 34 (83 Ma, end of Cretaceous magnetic normal epoch), with a separate numbering scheme for older anomalies. Periods of constant field direction (normal or reversed) are called ‘chrons’, and have been numbered to fit in with the pre-existing

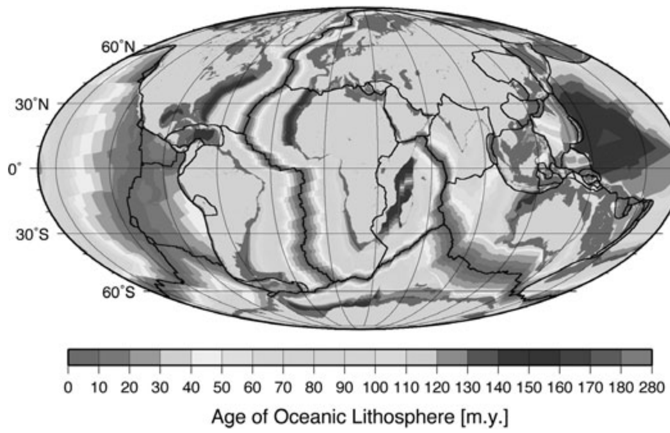

Figure 1.8 Age of the ocean floor, after Müller *et al.* (2008). For colour version, see plates section.

anomaly numbering scheme (e.g., Cande and Kent, 1995). Global measurements of marine magnetic anomalies, coupled with plate kinematic modelling, has allowed the age of the ocean basins to determined (Müller *et al*., 2008; Figure 1.8).

1.4 Oceanographic institutions

Marine research is unusual, and possibly unique, in being extremely multi-disciplinary, involving geologists, geophysicists, geochemists, physicists, biologists, engineers, mathematicians and others. This may partly reflect the hostile medium in which they all work, the need to share expensive vehicles and platforms, and perhaps the youthfulness of these sciences where the inter-relations of sea floor rock, water motion, chemistry and biology are still being worked out. As a result, specialised multi-disciplinary oceanographic research institutions have played an important role in developing MOR studies.

Early on, several nations developed oceanographic institutions, and these gave impetus to the new oceanographic sciences by concentrating funding and effort. In the USA, Scripps Institution of Oceanography, Woods Hole Oceanographic Institution and the Lamont–Geological Observatory (now Lamont–Doherty Earth Observatory) were all founded in the first half of the twentieth century. They have provided important technological support, including developing the first deep-towed geophysical instrument (SIO), developing manned and unmanned submersibles (WHOI) and maintaining the world's only academic research ship with a fully 3D-seismic capability (LDEO), as well as making major advances in MOR and other marine science.

Britain's National Institute of Oceanography (now renamed the National Oceanography Centre, Southampton) was founded in 1950, has carried on important investigations of MORs since its founding, and has played a particularly important role in the development and use of side-scan sonars. Many other nations have developed regional or national oceanographic research centres, for example IFREMER in France, GEOMAR and the

Institut für Meereskunde in Germany, and the Japanese Marine Science and Technology institute (JAMSTEC). There are numerous university and a few independent research centres around the world, including the Monterey Bay Aquarium Research Institute (MBARI), founded by David Packard in 1987. It focusses on the development of instruments and research systems, and has made important contributions to, for example, understanding its neighbouring Gorda, Juan de Fuca and Explorer ridges.

1.5 Dedicated MOR research programmes

The study of MORs increasingly requires the use of pooled resources to provide expensive ships and instruments, and focussed approaches to make rapid progress and engage funding bodies. It is more of a global enterprise than many science disciplines, and this has encouraged high degrees of international collaboration.

Recognising a need for focussed research, the US Ridge initiative began in 1987, with the aim of understanding the 'geophysical, geochemical and geological causes and consequences of energy transfer' along the global spreading centre network (Delaney, 1989). It was extended into the RIDGE 2000 programme, and funded focussed research on a small number of selected sites, supported by the National Science Foundation. Several other national programmes, including the British BRIDGE (Cann *et al*., 1999), French Dorsales, and German D-Ridge were developed along a similar model (Anonymous, 1993).

It was recognised that there was also a need for an international organisation to coordinate MOR research around the world. As a result, InterRidge (www.interridge.org) was founded in 1990. It aims to promote interdisciplinary, international studies of oceanic spreading centres by creating a global research community, planning and coordinating new science programmes that no single nation can achieve alone, exchanging scientific information, and sharing new technologies and facilities. It operates by means of a number of working groups, by convening workshops, acting as an information exchange, publishing a newsletter, and maintaining a web page. Notable achievements have included focussing research interest onto the remote and poorly studied ultra-slow spreading South West Indian Ridge and Arctic Gakkel Ridge. InterRidge is dedicated to reaching out to the public, scientists and governments, and to providing a unified voice for ocean ridge researchers worldwide. For example, it has recently sponsored the 'InterRidge statement of commitment to responsible research practices at deep-sea hydrothermal vents' (http://www.interridge.org/IRStatement).

Another important international organisation involved (in part) in MOR research is the Integrated Ocean Drilling Program and its predecessors, the Ocean Drilling Program and Deep Sea Drilling Project (http://www.iodp.org/). IODP provides a vital facility for drilling deep into the oceanic crust (Section 2.13.4).

1.6 Outline of this book

In order to allow readers from different disciplines to use the book easily, I have tried to make each chapter as self contained as possible, with cross-referencing where appropriate.

In addition, the appendices include a glossary of terms and a directory of place names used. Because the history of ridge science is intimately bound up with the development of technology, Chapter 2 provides a brief historical review of the relevant major developments in instruments and techniques. Chapter 3 describes the deep foundations of ridges in the oceanic lithosphere. Chapter 4 looks at ridges as tectonic plate boundaries. In Chapter 5, I focus on the structure of the oceanic crust. This leads to the description of the magmatic construction of the crust in Chapter 6. Chapter 7 describes the deformation of the newly formed crust by tectonic processes such as faulting. Chapter 8 covers hydrothermal vents, and finally Chapter 9 provides a summary and synthesis, and attempts a unified model of sea floor spreading.