

THE OCEANIC LITHOSPHERE

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Summary

This chapter provides an overview on the structure and composition of the oceanic lithosphere, both at the axis of mid-ocean ridges, and off-axis. Studies carried out in the last 10 years have resulted in a review of the 'standard' model of a layered, continuous oceanic crust of ~6 km, composed of gabbro, diabase and basalts, and extending over most ocean basins. Instead, geological observations have shown that this magmatic crust is absent in many areas, particularly along slow-spreading ridges, where mantle rocks outcrop at the seafloor. The structure and processes operating at the spreading centers that create these two end-member oceanic lithospheric types also differ substantially, and depend primarily on the magma supply to the ridge axis. Further variability in lithospheric structure is introduced by hot spot volcanic activity, responsible for the formation of over-thickened crust, and by the rifting of continental lithosphere leading to the onset of seafloor spreading and the formation of oceanic basins.

The oceanic lithosphere is composed primarily of mantle peridotites and magmatic rocks that are the result of the melting of these mantle rocks: gabbro, diabase and basalt.

Other rock types are present but in smaller quantities, such as secondary alteration products of these rocks (serpentinites), or hydrothermal deposits. The oceanic lithosphere is structured and emplaced at the axis of mid-ocean ridges, where magmatic, tectonic and hydrothermal processes operate and interact in response to plate separation. With ongoing plate separation the lithosphere is moved away from the narrow active axial zone. In some instances it can be modified by off-axis processes such as off-axis volcanism (hot spots), and recycled into the mantle after subduction. This simple tectonic history and limited number of rock types present in it make the structure and composition of the oceanic lithosphere a simple object to study when compared to that of continents. Most of the knowledge acquired on lithospheric processes is obtained from combined geological and geophysical observations, primarily seismic imaging.

One key aspect to understand the dynamics of mid-ocean ridges that shape the oceanic lithosphere is the rheology. The mechanical properties of the rocks and their mode of deformation control the nature of faulting and seismicity, shapes the porosity structure of the crust that allows water to penetrate and establish hydrothermal systems, or determines the mode of melt propagation in the mantle and crust. Lithospheric rheology is also strongly affected by the presence of fluids (water and other volatiles, and melt). The distribution and quantification of these fluid phases is poorly constrained by seismic methods, but electromagnetic studies, but additional electromagnetic studies are required as they are still scarce and only available at a limited number of sites.

1. Background: Mid-Ocean Ridges and the Oceanic Lithosphere

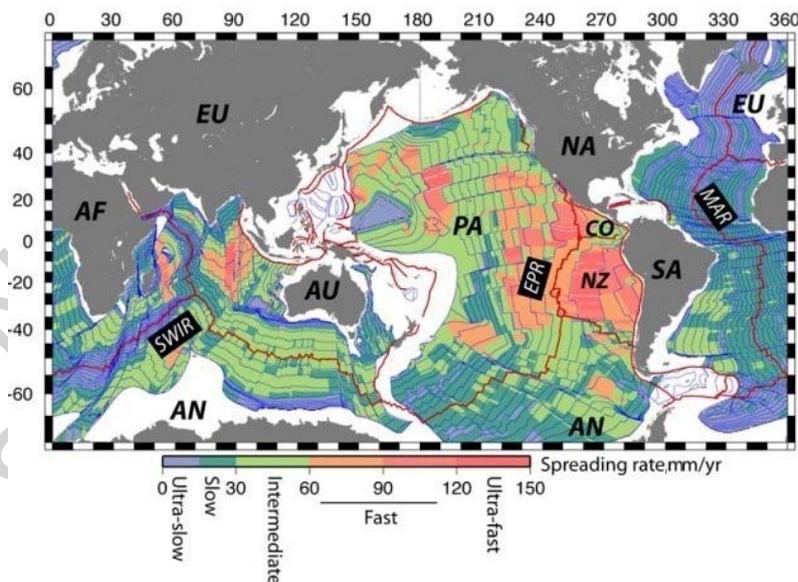


Figure 1: Map of seafloor spreading rate (colors) and seafloor age (contours), showing the main tectonic plates. The oceanic lithosphere (white and colored areas) covers >65% of the Earth's surface. Digital seafloor data compilation from Müller *et al.* [1997].

Ridges are often classified according to their spreading rate, as marked. Plate boundaries are marked in red, and correspond to zero age crust along ridges; 10 Myr age contours are also indicated (thin blue lines). Plates: EU: Eurasia; SA: South America; AF: Africa; PA: Pacific; AU: Australia; AN: Antarctica; CO: Cocos; NZ: Nazca; NA:

North America. The East Pacific Rise (EPR) Mid-Atlantic Ridge (MAR) and South-West Indian Ridge (SWIR) are also indicated for reference.

The oceanic lithosphere, which accounts for more than 65% of the Earth's surface, is formed along a narrow band of seafloor at the summit of mid-ocean ridges. Owing to its mode of formation and relatively simple history after formation, it differs substantially from the continental lithosphere (see *Continental Crust*). The mid-ocean ridges correspond to divergent plate boundaries, which have a total length of more than 60000 km and an elevation of 2 to 3 km above adjacent ocean basins. They are a consequence of mantle convection and upwelling driven by plate separation, and are initiated after rifting and break-up of continents. Most of the world's magmatism and seismicity concentrates along the axis of ridges, where a complex interaction between magmatic, tectonic, hydrothermal and biological processes takes place. The rate of plate separation is one of the main parameters that determine the architecture and composition of the oceanic lithosphere and associated active processes, and varies between near-zero cm/yr at the American-European plate boundary close the North pole, and >10 cm/yr at the East Pacific Rise between the Nazca and Pacific plates (Figure 1).

The separation of plates induces passive mantle flow under ocean basins and the ridge axis, and the resulting mantle upwelling controls the depth of ocean basins. Hot mantle material brought up under the axis is cooled from the top, and the isotherms deepen with age as the lithosphere moves away from the axis. The overlying seafloor bathymetry reflects this thermal structure by a gradual deepening away from the axis at the summit of mid ocean ridges. For seafloor ages younger than 70 Myr, the average global seafloor depth d is a function of time t :

$$d=2.5 + 0.35 t^{1/2}$$

with d in km and t in Myr. For seafloor ages older than 70 Myr the mean seafloor depth increases more slowly:

$$d=6.4 - 3.2 e^{-t/62.8}$$

Slightly different depth-age relationships are observed at different sites and ocean basins, reflecting variations in the temperature of the underlying mantle, or different thermal histories such as the presence or absence of hot spots. Further complications are introduced by lateral shifts of the position of the ridge axis, which are common throughout the history of ocean basins.

A second consequence of plate separation is pressure-release melting of the mantle during its ascent under the ridge axis. Mantle cools at a rate of 1-2° per ~3 km (1 kbar) of adiabatic ascent and crosses the mantle solidus at a depth that depends on the mantle temperature. As mantle continues to upwell, it melts ~1-2% per ~3 km of ascent. The total amount of melt produced under the ridge axis depends then on the thermal structure beneath the axis, that determines the shape of the melting regime and the thickness of the melting zone; larger amounts of melt are produced from a hotter mantle (Figure 2). Melt, which is lighter than the residual mantle, is collected and focused towards the ridge axis. The mode of emplacement of the melt depends on the shallow thermal structure of the oceanic lithosphere; at fast-spreading ridges all melt appears to

gather and form a continuous, layered oceanic crust, while at slow spreading ridges the melt is emplaced in a discontinuous manner throughout the thickness of the lithosphere ($T < 750^{\circ}\text{C}$). This dependence of melt production on the thermal structure is most noticeable along 15-20% of the total length of the mid-ocean ridge system that is thermally influenced by hot spots (i.e., Galapagos or Iceland). Hot spots, which are generally considered zones of active mantle upwelling due to thermal anomalies in the mantle that are relatively fixed, also result in off-axis volcanism and formation of large oceanic plateaus and volcanic islands.

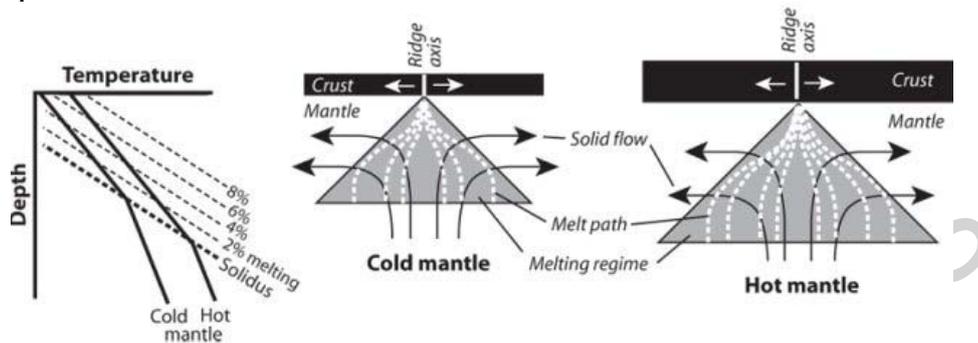


Figure 2: (Left) Mantle temperature decreases during adiabatic ascent under mid-ocean ridges. When the mantle temperature intersects the melting temperature (solidus, which is a function of pressure), melting initiates. Hotter mantle intersects the solidus at deeper levels, and undergoes more melting, than colder mantle. (Right) The melting regime is a function of the thermal structure of the lithosphere under the axis, and can be assimilated to a tent-shaped area in vertical cross-section. Lighter melt ascends and focuses to the ridge axis, decoupled from the passive solid flow. The collected forms a thicker crust in the case of a ridge with over hotter mantle (i.e., near hot spots). White arrows indicate the plate separation that drives passive mantle flow and upwelling under the axis. After *Langmuir et al.* [1992].

The oceanic lithosphere is defined the outer shell of the Earth, that behaves as mechanical layer limited in depth by the brittle-to-plastic transition ($T \sim 750^{\circ}\text{C}$). The crust has a compositional connotation, and in oceanic basins it is assimilated to a layered succession of gabbro, diabase and basalt, resulting from the mantle melting, which is emplaced above the Moho (mantle-crust transition). Discussion and description of the oceanic lithospheric structure also requires us to differentiate between the axial lithospheric structure, where magmatism and other processes are actively constructing and shaping the upper lithosphere, and the resulting off-axis, inactive lithosphere. In this chapter we will first discuss the structure and composition of different types of common oceanic lithosphere away from the ridge axis, as inferred from both geological and geophysical observations. As active processes operate at the axis, the structure and composition of the lithosphere in these areas is substantially different from that of mature lithosphere, the characteristics of both magmatic and amagmatic ridges are discussed separately. Recent geological data demonstrate that in some environments, particularly along slow-spreading segments, there is no continuous crust, and instead a heterogeneous mixture of mantle (peridotite) and magmatic rocks are exposed instead. As the crust cannot be defined as such in some geological environments, we will refer to the composition and structure of the oceanic lithosphere, as it encompasses both typical 'oceanic crust', heterogeneous lithosphere, zones of transition from continental to

oceanic lithosphere, and the hot spot influenced areas.

2. Methods of Study of the Oceanic Lithosphere

Geological observations. Geological observations both at the seafloor and at exposed pieces of oceanic lithosphere tectonically emplaced in continents (ophiolites) provide information on composition, structure and evolution. Seafloor observations include dredging, drilling, and ROV and submersible sampling. Seafloor imagery (video and photography) has become a powerful tool to map seafloor features and tectonic structures.

Petrology and geochemistry. Mineral assemblages and chemical compositions of basalts, peridotites, gabbros and other oceanic rocks provide clues on the processes that operate during and after the formation of the mantle lithosphere. These studies provide constraints on mantle composition and temperature, melting, magma accumulation and crystallization in the lithosphere, eruption of basalts, fluid circulation and water-rock interaction, chronology of volcanic events, among other processes.

Bathymetry and seafloor structure. Bathymetry and acoustic images (sonar) provide information on the tectonic structure, distribution of lava flows and other geological features, thermal subsidence, etc. Ship-mounted systems allow for surveys of large areas of the seafloor, but near-bottom instruments mounted on deep-tow systems, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) provide high-resolution images to study in detail volcanic and tectonic processes at the ridge axis. Global bathymetric information is now also available from combined global shipboard bathymetry and satellite-derived sea surface gravity (see below).

Gravity and magnetic studies. Gravimetric and magnetic measurements provide information on the density and magnetic structure of the oceanic lithosphere. Potential data requires correction for navigation, vehicle and topography effects to obtain anomalies that are then inverted to obtain information on the internal structure of the lithosphere. Magnetic anomalies are particularly useful to determine the seafloor age and the history of plate movements. Satellite altimetry data is also used to obtain global sea-surface gravity maps. Near-bottom studies with AUVs and ROVs provide high-resolution information on the detailed structure of the upper lithosphere.

Electromagnetic studies. Both passive and active-source electromagnetic experiments provide images of the conductivity structure of the oceanic lithosphere. These methods are particularly important to map the presence of electrically conductive fluids such, as magma or water from hydrothermal fluids below the ridge axis.

Seismic methods. The most used methods to infer the structure and composition of the oceanic lithosphere are seismic reflection and refraction. Ocean bottom seismometers and active sources are commonly used to infer the velocity (P- and S-wave) structure of the oceanic lithosphere that can be interpreted in terms of lithology. Active sources are normally deployed at the sea surface, but sources at the seafloor allow for high-resolution seismic studies. Seismic reflection data provide higher-resolution images of the reflectivity structure of the lithosphere, and have been particularly useful to map the

thickness of extrusives, the presence of magma chambers, or the presence or absence of Moho reflections. Other parameters such as the Poisson's ratio, the attenuation, or the anisotropy provide also information on the structure and processes. A more recent technique, seafloor compliance, can be used to infer the S-wave structure of the oceanic lithosphere. Ocean bottom seismometers and underwater hydrophones can also be used to monitor seismicity, and study both magmatic and tectonic activity at mid-ocean ridges.

Permeability. The permeability of the lithosphere is a critical component of fluid circulation and cooling with age. ODP drill holes are used to study the permeability structure of the lithosphere near mid-ocean ridges by sealing sections of drilled wells, monitoring of pressure changes, and pumping water to study pressure variations in adjacent wells.

Rock mechanics and rheology. The mechanical properties of the oceanic lithosphere (rheology) are determined based on geophysical observations and rock deformation experiments at elevated pressures and temperatures. Results of laboratory experiments are extrapolated to geological scales and conditions (pressure, temperature, strain rate,...) to construct models of strength and mechanical behavior of the lithosphere. Predictions from these rheological modes are compared to and tested with observations (i.e., distribution of seismicity, textures of naturally deformed rocks, tectonic structures, etc.).

Laboratory measurements of physical properties. Interpretation of geophysical data (gravity, magnetic, seismic...) requires laboratory measurements of different rock types under natural temperature and pressure conditions. Measuring physical parameters (seismic velocity, density, electrical properties, permeability,...) is required to properly interpret the geophysical images and discriminate among rock types. As some rock types have very similar properties (i.e., the seismic velocity of gabbro and partially altered peridotite), determination of several physical properties of the lithosphere may be required to properly constrain its composition (e.g., combined seismic and electromagnetic studies).

Heat flow and hydrothermal studies. Heat loss is an important factor on the evolution and thermal structure of the oceanic lithosphere and underlying asthenosphere. Conductive heat loss can be measured with probes equipped with thermistors in areas where sediments blanket the seafloor. These probes can measure both the temperature distribution with depth (temperature gradients) and the thermal conductivity of the sediments, from which the heat flow can be calculated. These measurements provide information on convection cells in the sedimentary cover of the oceanic lithosphere, in addition to the Earth's heat loss. A large proportion of the heat is lost through fluid flow through the crust at the ridge axis, through hydrothermal vents and diffuse flow. Mapping of water signals associated with this hydrothermal activity and temperature measurements of vent temperatures provide information on the distribution and dynamics of such systems, but provide no accurate quantification of the heat loss associated with hydrothermal venting.

Study of active processes. Mid ocean ridges are the center of active magmatic,

tectonic, hydrothermal and biological processes that interact. To understand this complex system, an integrated approach has been adopted by the scientific community in recent years to study selected portions of the mid-ocean ridge system to concentrate all types of studies (seismicity, geodesy, mapping and bathymetry, microbiology, ecology...) over extended periods of time (>10 years). These studies include the deployment of seafloor instruments, and, in some cases, lay out of cables or buoys to transmit real-time data from the seafloor.

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Biographical Sketch

Javier Escartín Guiral, was born in Huesca, Spain, and graduated from the Facultat de Geologia of the University of Barcelona, Spain, and the Université de Perpignan, France, in 1990 with a B.Sc. in Geology and Oceanography. In 1990 he joined the WHOI/MIT Joint Program in Oceanography, where he conducted his PhD research between the Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology (USA). He graduated in 1996 with a thesis entitled 'Ridge segmentation: Tectonic evolution and rheology of slow-spreading oceanic lithosphere'. From 1996 to 1998 he was a Post-Doctoral Researcher between the Universities of Durham (England) and the University of Edinburgh (Scotland). In 1998 He moved to Paris for an InterRidge Post-doc position, followed by a Post-Doc appointment at the Institut Jaume Almera of the Spanish National Research Council CSIC, in Barcelona, Spain. Since 1999 Javier Escartín holds a Research Scientist position at the French Centre Nationale de la Recherche Scientifique (CNRS), and holds also a three-year (2003-2006) appointment as an Adjunct Scientist at the Woods Hole Oceanographic Institution, USA. His scientific career has focused on the study of the oceanic lithosphere, with research on faulting, rock mechanics, geophysics, seismicity, and the study of active processes at mid-ocean ridges. As part of his research he has participated in more than 10 oceanographic cruises, including submersible and ROV surveys of the seafloor. He regularly conducts his research in

France, and with colleagues USA and Spain. He has published more than 20 peer-reviewed papers, in addition to book sections, reports, etc, and presented more than 50 scientific communications at international meetings. He is also the chairman of the Observatories and Monitoring Working Group of the InterRidge program, for the study of active processes at mid-ocean ridges.

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