# MID-OCEAN RIDGE GEOCHEMISTRY AND PETROLOGY

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## Introduction

The most volcanically active regions of our planet are concentrated along the axes of the globe, encircling midocean ridges. These undersea mountain ranges, and most of the oceanic crust, result from the complex interplay between magmatic (i.e., eruptions of lavas on the surface and intrusion of magma at depth) and tectonic (i.e., faulting, thrusting, and rifting of the solid portions of the outer layer of the earth) processes. Magmatic and tectonic processes are directly related to the driving forces that cause plate tectonics and seafloor spreading. Exploration of midocean ridges by submersible, remotely operated vehicles (ROV), deep-sea cameras, and other remote sensing devices has provided clear evidence of the effects of recent magmatic activity (e.g., young lavas, hot springs, hydrothermal vents and plumes) along these divergent plate boundaries. Eruptions are rarely observed because of their great depths and remote locations. However, over 60% of Earth's magma flux (approximately 21 $km^3$ $year^{-1}$) currently occurs along divergent plate margins. Geophysical imaging, detailed mapping, and sampling of midocean ridges and fracture zones between ridge segments followed by laboratory petrologic and geochemical analyses of recovered rocks provide us with a great deal of information about the composition and evolution of the oceanic crust and the processes that generate midocean ridge basalts (MORB).

Midocean ridges are not continuous but rather broken up into various scale segments reflecting breaks in the volcanic plumbing systems that feed the axial zone of magmatism. Recent hypotheses suggest that the shallowest and widest portions of ridge segments correspond to robust areas of magmatism, whereas deep, narrow zones are relatively magma-starved. The unusually elevated segments of some ridges (e.g., south of Iceland, central portion of the Galapagos Rift, Mid-Atlantic Ridge near the Azores) are directly related to the influence of nearby mantle plumes or hot spots that result in voluminous magmatism.

Major differences in the morphology, structure, and scales of magmatism along midocean ridges vary with the rate of spreading. Slowly diverging plate boundaries, which have low volcanic output, are dominated by faulting and tectonism whereas fast-spreading boundaries are controlled more by volcanism. The region along the plate boundary within which volcanic eruptions and high-temperature hydrothermal activity are concentrated is called the neovolcanic zone. The width of the neovolcanic zone, its structure, and the style of volcanism within it, vary considerably with spreading rate. In all cases, the neovolcanic zone on midocean ridges is marked by a roughly linear depression or trough (axial summit collapse trough, ASCT), similar to rift zones in some subaerial volcanoes, but quite different from the circular craters and calderas associated with typical central-vent volcanoes. Not all midocean ridge volcanism occurs along the neovolcanic zone. Relatively small ($<1$ km high), near-axis seamounts are common within a few tens of kilometers of fast and intermediate spreading ridges. Recent evidence also suggests that significant amounts of volcanism may occur up to 4 km from the axis as off-axis mounds and ridges, or associated with faulting and the formation of abyssal hills.

Lava morphology on slow spreading ridges is dominantly bulbous, pillow lava (**Figure 1A**), which tends to construct hummocks ($<50$ m high, $<500$ m diameter), hummocky ridges (1–2 km long), or small circular seamounts (10s–100s of meters high and 100s–1000s of meters in diameter) that commonly coalesce to form axial volcanic ridges (AVR) along the valley floor of the axial rift zone. On fast spreading ridges, lavas are dominantly oblong, lobate flows and fluid sheet flows that vary from remarkably flat and thin ($<4$ cm) to ropy and jumbled varieties (**Figure 1**). Although the data are somewhat limited, calculated volumes of individual flow units that have been documented on midocean ridges show an inverse exponential relationship to spreading rate, contrary to what might be expected. The largest eruptive units are mounds and cones in the axis of the northern Mid-Atlantic Ridge whereas the smallest units are thin sheet/lobate flows on the East Pacific Rise. Morphologic, petrologic, and structural studies of many ridge segments suggest they evolve through cycles of accretion related to magmatic output followed by amagmatic periods dominated by faulting and extension.

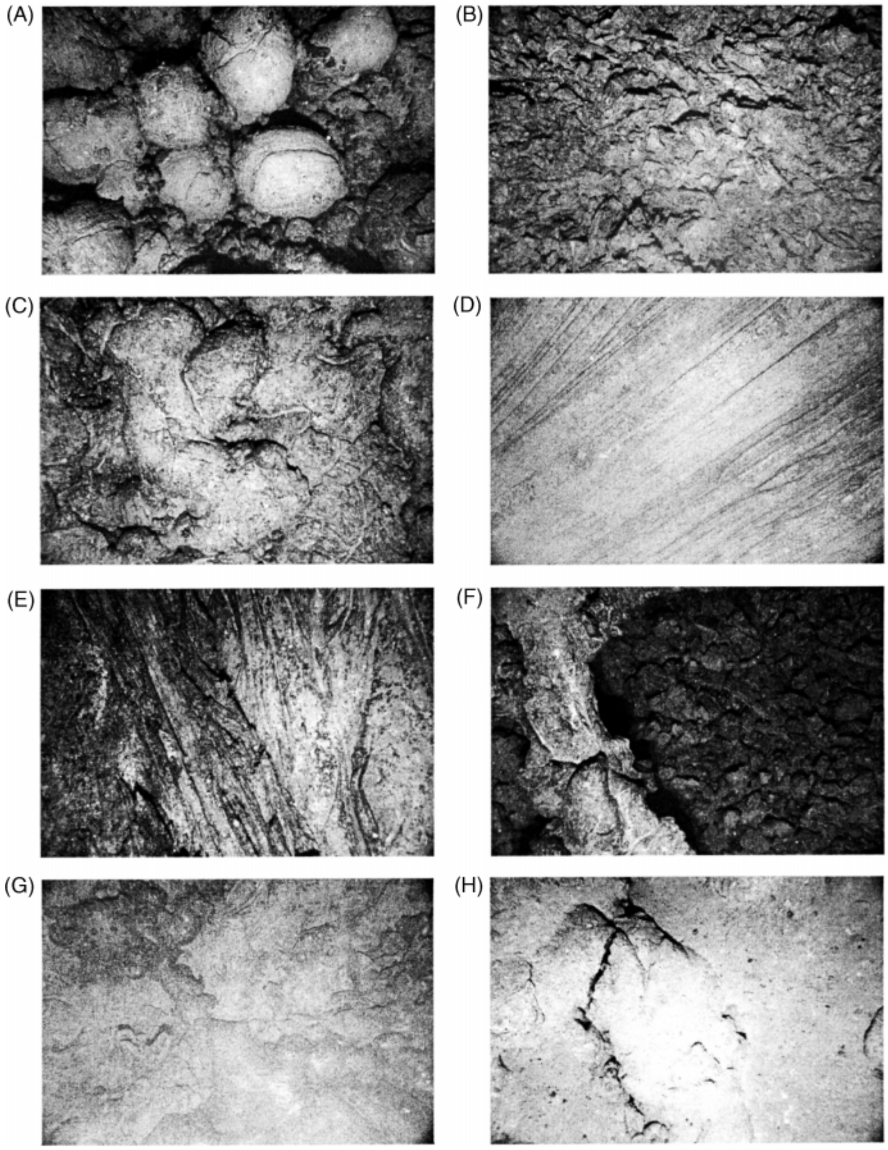

**Figure 1** Examples of different morphologies, surface textures and sediment cover on lava flows on the northern East Pacific Rise. Digital images were taken from heights of 5–10 m above the seafloor using the Woods Hole Oceanographic Instution's camera system. The dimensions of the photographs are approximately 4.5 m × 3.0 m. (A) Pillow lava. (B) Hackly or scrambled flow. (C) Lobate lava. (D) Lineated sheet flow. (E) Ropy sheet flow. (F) Collapse structure in lobate flows. (G) A young flow contact on top of older flows. (H) Heavily sediment covered lobate flow with small fissure. Images from Kurras *et al.* 2000.

## Magma Generation

Primary MORB magmas are generated by partial melting of the upper mantle; believed to be composed of a rock type termed peridotite which is primarily composed of the minerals olivine, pyroxenes (enstatite and diopside), and minor spinel or garnet. Beneath ridges, mantle moves upward, in part, due to convection in the mantle but possibly more in response to the removal of the lithospheric lid above it, which is spreading laterally. Melting is affected by the decompression of hot, buoyant peridotite that crosses the melting point (solidus curve) for mantle material as it rises to shallow depths ($<100$ km), beneath the ridges. Melting continues as the mantle rises as long as the temperature of the peridotite remains above the solidus temperature at a given depth. As the seafloor spreads, basaltic melts formed in a broad region (10s to 100s of kilometers) beneath the ridge accumulate and focus so that they feed a relatively narrow region (a few kilometers) along the axis of the ridge (**Figure 1**).

During ascent from the mantle and cooling in the crust, primary mantle melts are subjected to a variety of physical and chemical processes such as fractional crystallization, magma mixing, crustal assimilation, and thermogravitational diffusion that modify and differentiate the original melt composition. Consequently, primary melts are unlikely to erupt on the seafloor without undergoing some modification. Picritic lavas and magnesian glasses thought to represent likely primary basalts have been recovered from a few ocean floor localities; commonly in transform faults (**Table 1**). MgO contents in these basalts range from ~10 wt% to over 15 wt% and the lavas typically contain significant amounts of olivine crystals. Based on comparisons with high-pressure melting experiments of likely mantle peridotites, the observed range of compositions may reflect variations in source composition and mineralogy (in part controlled by pressure), depth and percentage melting (largely due to temperature differences), and/or types of melting (e.g., batch vs. fractional).

## Ocean Floor Volcanism and Construction of the Crust

Oceanic crust formed at spreading ridges is relatively homogeneous in thickness and composition compared to continental crust. On average, oceanic crust is 6–7 km thick and basaltic in composition as compared to the continental crust which averages 35–40 km thick and has a roughly andesitic composition. The entire thickness of the oceanic crust has not been sampled *in situ* and therefore the bulk composition has been estimated based on investigations of ophiolites (fragments of oceanic and back-arc crust that have been thrust up on to the continents), comparisons of the seismic structure of the oceanic crust with laboratory determinations of seismic velocities in known rock types, and samples recovered from the ocean floor by dredging, drilling, submersibles, and remotely operated vehicles.

Rapid cooling of MORB magmas when they come into contact with cold sea water results in the formation of glassy to finely crystalline pillows, lobate flows, or sheet flows (**Figure 1**). These lava flows typically have an ~0.5–1 cm-thick outer rind of glass and a fine-grained, crystalline interior containing only a few percent of millimeter-sized crystals of olivine, plagioclase, and more rarely clinopyroxene in a microscopic matrix of the same minerals. MORB lavas erupt, flow, and accumulate to form the uppermost volcanic layer (Seismic Layer 2A) of ocean crust (**Figure 2**). Magmas that do not reach the seafloor cool more slowly with increasing depth forming intrusive dikes at shallow levels (0.5–3 km) in the crust (layer 2B) and thick bodies of coarsely crystalline gabbros and cumulate ultramafic rocks at the lowest levels (3–7 km) of the crust (layer 3) (**Figure 2**).

Although most magma delivered to a MOR is focused within the neovolcanic zone, defined by the axial summit collapse trough or axial valley, off-axis volcanism and near-axis seamount formation appear to add significant volumes of material to the uppermost crust formed along ridge crests. In some portions of the fast spreading East Pacific Rise, off-axis eruptions appear to be related to syntectonic volcanism and the formation of abyssal hills. Near-axis seamount formation is common along both the East Pacific Rise and medium spreading rate Juan de Fuca Ridge. Even in areas where there are abundant off-axis seamounts they may add only a few percent to the volume of the extrusive crust. More detailed studies of off-axis sections of ridges are needed before accurate estimates of their contribution to the total volume of the oceanic crust can be made.

Oceanic transform faults are supposed to be plate boundaries where crust is neither created nor destroyed, but recent mapping and sampling indicate that magmatism occurs in some transform domains. Volcanism occurs in these locales either at short, intratransform spreading centers or at localized eruptive centers within shear zones or relay zones between the small spreading centers.

## Mid-Ocean Ridge Basalt Composition

Ocean floor lavas erupted along mid-ocean ridges are low-potassium tholeiites that can range in composition from picrites with high MgO contents to ferrobasalts and FeTi basalts containing lower MgO and high concentrations of FeO and $TiO_2$, and even to rare, silica-enriched lavas known as icelandites, ferroandesites and rhyodacites (**Table 1**). In most areas, the range of lava compositions, from MgO-rich basalt to FeTi basalt and ultimately to rhyodacite, is generally ascribed to the effects of shallow-level (low-pressure) fractional crystallization in a subaxial magma chamber or lens (**Figure 2**). A pronounced iron-enrichment trend with decreasing magnesium contents (related to decreasing temperature) in suites of genetically related lavas is, in part, what classifies MORB as tholeiitic or part of the tholeiitic magmatic suite (**Figure 3**).

Although MORB are petrologically similar to tholeiitic basalts erupted on oceanic islands (OIB), MORB are readily distinguished from OIB based on their comparatively low concentrations of large ion lithophile elements (including K, Rb, Ba, Cs), light rare earth elements (LREE), volatile elements and other trace elements such as Th, U, Nb, Ta, and Pb

**Table 1** Average compositions of normal and enriched types of basalts from midocean ridges and seamounts

| | *Normal* | | | | | | | *Enriched* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Oxide wt%* | *Pacific* | *Atlantic* | *Galapagos* | *Seamounts* | *Pacific Picritic* | *Pacific Ferrobasalt* | *Pacific High-silica* | *Pacific* | *Atlantic* | *Galapagos* | *Seamounts* |
| $SiO_2$ | 50.49 | 50.64 | 50.41 | 50.03 | 48.80 | 50.61 | 55.37 | 50.10 | 51.02 | 49.17 | 50.19 |
| $TiO_2$ | 1.78 | 1.43 | 1.54 | 1.28 | 0.97 | 2.36 | 2.10 | 1.86 | 1.46 | 1.94 | 1.74 |
| $Al_2O_3$ | 14.55 | 15.17 | 14.75 | 15.97 | 17.12 | 13.30 | 12.92 | 15.69 | 15.36 | 16.86 | 16.71 |
| FeO* | 10.87 | 10.45 | 11.19 | 9.26 | 8.00 | 13.61 | 13.11 | 9.78 | 9.56 | 9.21 | 8.77 |
| MnO | 0.20 | 0.19 | nd | 0.15 | 0.14 | 0.23 | 0.21 | 0.19 | 0.18 | | 0.15 |
| MgO | 7.22 | 7.53 | 7.49 | 8.06 | 10.28 | 5.92 | 3.64 | 7.00 | 7.31 | 6.93 | 6.80 |
| CaO | 11.58 | 11.62 | 11.69 | 12.21 | 11.93 | 10.43 | 8.05 | 11.17 | 11.54 | 10.90 | 10.67 |
| $Na_2O$ | 2.74 | 2.51 | 2.28 | 2.68 | 2.32 | 2.74 | 3.33 | 3.04 | 2.52 | 3.16 | 3.38 |
| $K_2O$ | 0.13 | 0.11 | 0.10 | 0.08 | 0.03 | 0.16 | 0.44 | 0.43 | 0.36 | 0.66 | 0.75 |
| $P_2O_5$ | 0.17 | 0.14 | 0.14 | 0.13 | 0.07 | 0.22 | 0.40 | 0.24 | 0.19 | 0.32 | 0.33 |
| Sum | 99.62 | 99.61 | 99.60 | 99.73 | 100 | 99.39 | 99.40 | 99.37 | 99.31 | 99.14 | 99.34 |
| K/Ti | 7.49 | 7.70 | 6.24 | 6.10 | 3.0 | 7.04 | 13.80 | 22.26 | 23.67 | 32.77 | 39.05 |
| $N =$ | 2303 | 2148 | 867 | 623 | 10 | 706 | 97 | 304 | 972 | 65 | 197 |

Analyses done by electron microprobe on natural glasses at the Smithsonian Institution in Washington, D.C. (by W. Melson and T. O'Hearn) except the picritic samples that were analyzed at the USGS in Denver, Co. Enriched MORB in this compilation are any that have K/Ti values greater than 13. High-silica lavas have $SiO_2$ values between 52 and 64. $K/Ti = (K_2O/TiO_2) \times 100$. $N =$ number of samples used in average. FeO* = total Fe as FeO.

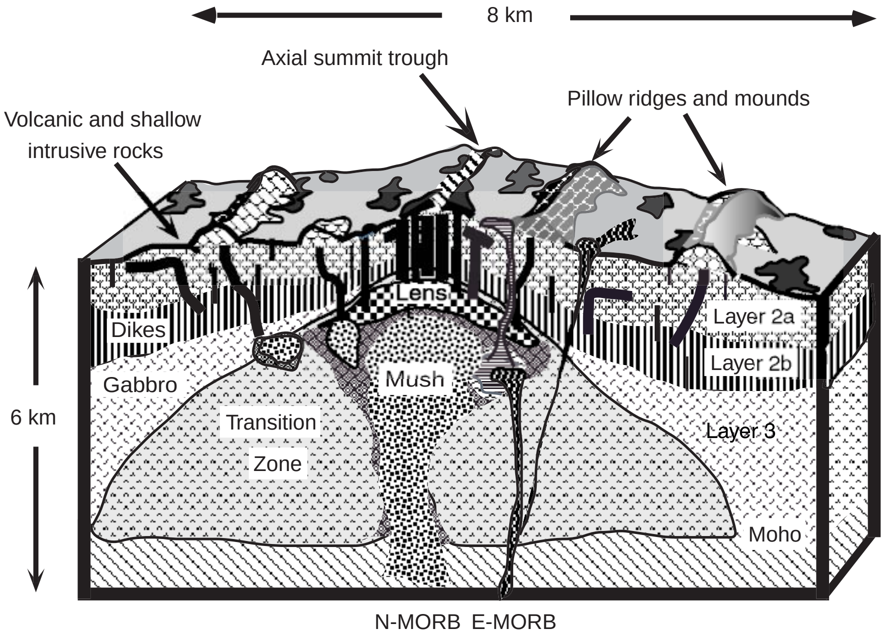

**Figure 2** Diagrammatic three-dimensional representation of oceanic crust formed along a fast-spreading ridge showing the seismically determined layers and their known or inferred petrologic composition. Note that although most of the volcanism at midocean ridges appears to be focused within the axial summit trough, a significant amount of off-axis volcanism (often forming pillow mounds or ridges) is believed to occur. Much of the geochemical variability that is observed in MORB probably occurs within the crystal–liquid mush zone and thin magma lens that underlie the ridge crest. The Moho marks the seismic boundary between plutonic rocks that are gabbroic in composition and those that are mostly ultramafic but may have formed by crystal accumulation in the crust.

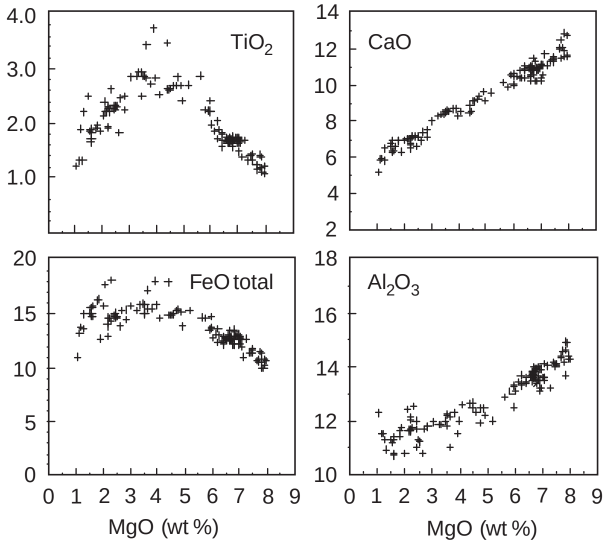

**Figure 3** Major element variations in MORB from the Eastern Galapagos Spreading Center showing the chemical trends generated by shallow-level fractional crystallization in the oceanic crust. The rocks range in composition from basalt to ferrobasalt and FeTi basalt to andesite.

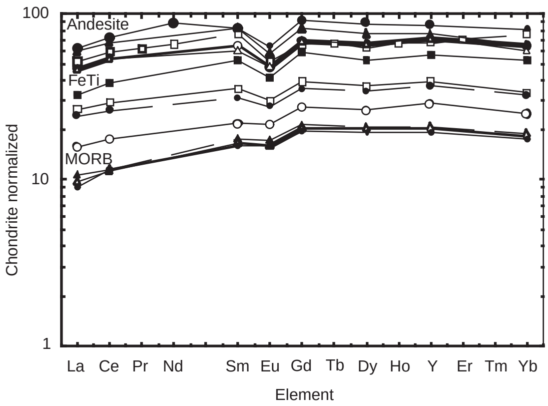

**Figure 4** Chondrite-normalized rare earth element (REE) abundances in a suite of cogenetic lavas from the Eastern Galapagos Spreading Center (also shown in **Figures 3** and **6**). Increasing abundances of REE and the size of the negative europium anomaly from MORB to andesite are consistent with evolution of the suite primarily by fractional crystallization. Concave-down patterns are an indication of their 'normal' depleted chemical character (N-MORB).

that are considered highly incompatible during melting of mantle mineral assemblages. In other words, the most incompatible elements will be the most highly concentrated in partial melts from primitive mantle peridotite. On normalized elemental abundance diagrams and rare earth element plots (**Figure 4**), normal MORB (N-type or N-MORB) exhibit characteristic smooth concave-down patterns reflecting the fact that they were derived from incompatible element-depleted mantle. Isotopic investigations have conclusively shown that values of the radiogenic isotopes of Sr, Nd, Hf and Pb in N-MORB are consistent with their depleted characteristics and indicate incompatible element depletion via one or more episodes of partial melting of upper mantle sources beginning more than 1 billion years ago. Compared to ocean island basalts and lavas erupted in arc or continental settings, MORB comprise a relatively homogeneous and easily distiguishable rock association. Even so, MORB vary from very depleted varieties (D-MORB) to those containing moderately elevated incompatible element abundances and more radiogenic isotopes. These less-depleted MORB are called E-types (E-MORB) or P-types, indicative of an 'enriched' or 'plume' component (**Table 1**) typically associated with intraplate 'hot spots'. Transitional varieties are classified as T-MORB. Enriched MORB are volumetrically minor on most normal ridge segments, but can comprise a significant proportion of the crust around regions influenced by plume magmatism such as the Galapagos Islands, the Azores, Tristan, Bouvet, and Iceland.

## Mineralogy of MORB

The minerals that crystallize from MORB magmas are not only dependent on the composition of the melt, but also the temperature and pressure during crystallization. Because the majority of MORB magmas have relatively similar major element compositions and probably begin to crystallize within the uppermost mantle and oceanic crust (pressures less than 0.3 GPa), they have similar mineralogy. Textures (including grain size) vary depending on nucleation and crystallization rates. Hence lavas, that are quenched when erupted into sea water, have few phenocrysts in a glassy to cryptocrystalline matrix. Conversely, magmas that cool slowly in subaxial reservoirs or magma chambers form gabbros that are totally crystalline (holocrystalline) and composed of well-formed minerals that can be up to a few centimeters long. Many of the gabbros recovered from the ocean floor do not represent melt compositions but rather reflect the accumulation of crystals and percolation of melt that occurs during convection, deformation and fractional crystallization in the mush zone hypothesized to exist beneath some midocean ridges (**Figure 2**). These cumulate gabbros are composed of minerals that have settled (or floated) out of cooling MORB magmas and their textures often reflect compaction, magmatic sedimentation, and deformation.

MOR lavas may contain millimeter-sized phenocrysts of the silicate minerals plagioclase (solid solution that ranges from $CaAl_2Si_2O_8$ to $NaAlSi_3O_8$) and olivine ($Mg_2SiO_4$ to $Fe_2SiO_4$) and less commonly, clinopyroxene ($Ca[Mg,Fe]Si_2O_6$). Spinel, a Cr-Al rich oxide, is a common accessory phase in more magnesian lavas where it is often enclosed in larger olivine crystals. Olivine is abundant in the most MgO-rich lavas, becomes less abundant in more evolved lavas and is ultimately replaced by pigeonite (a low-Ca pyroxene) in FeO-rich basalts and andesite. Clinopyroxene is only common as a phenocryst phase in relatively evolved lavas. Titanomagnetite, ilmenite and rare apatite are present as microphenocrysts, although not abundantly, in basaltic andesites and andesites.

Intrusive rocks, which cool slowly within the oceanic crust, have similar mineralogy but are holocrystalline and typically much coarser grained. Dikes form fine- to medium-grained diabase containing olivine, plagioclase and clinopyroxene as the major phases, with minor amounts of ilmenite and magnetite. Gabbros vary from medium-grained to very coarse-grained with crystals up to a few centimeters in length. Because of their cumulate nature and extended cooling histories, gabbros often exhibit layering of crystals and have the widest mineralogic variation. Similar to MORB, the least-evolved varieties (troctolites) consist almost entirely of plagioclase and olivine. Some gabbros can be nearly monomineralic such as anorthosites (plagioclase-rich) or contain monomineralic layers (such as olivine that forms layers or lenses of a rock called dunite). The most commonly recovered varieties of gabbro are composed of plagioclase, augite (a clinopyroxene) and hypersthene (orthopyroxene) with minor amounts of olivine, ilmenite and magnetite and, in some cases, hornblende (a hydrous Fe-Mg silicate that forms during the latest stages of crystallization). Highly evolved liquids cool to form ferrogabbros and even rarer silica-rich plutonics known as trondhjemites or plagiogranites.

The descriptions above pertain only to those portions of the oceanic crust that have not been tectonized or chemically altered. Because of the dynamic nature of oceanic ridges and the pervasive hydrothermal circulation related to magmatism, it is common for the basaltic rocks comprising the crust to be chemically altered and metamorphosed. When this occurs, the primary minerals are recrystallized or replaced by a variety of secondary minerals such as smectite, albite, chlorite, epidote, and amphibole that are more stable under lower temperature and more hydrous conditions. MOR basalts, diabases and gabbros are commonly metamorphosed to greenschists and amphibolites. Plutonic rocks and portions of the upper mantle rich in olivine and pyroxene are transformed into serpentinites. Oceanic metamorphic rocks are commonly recovered from transform faults, fracture zones and slowly spreading segments of the MOR where tectonism and faulting facilitate deep penetration of sea water into the crust and upper mantle.

## Chemical Variability

Although MORB form a relatively homogeneous population of rock types when compared to lavas erupted at other tectonic localities, there are subtle, yet significant, chemical differences in their chemistry due to variability in source composition, depth and extent of melting, magma mixing, and processes that modify primary magmas in the shallow lithosphere. Chemical differences between MORB exist on all scales, from individual flows erupted along the same ridge segment (e.g., CoAxial Segment of the Juan de Fuca Ridge) to the average composition of basalts from the global ridge system (e.g. Mid-Atlantic Ridge vs. East Pacific Rise). High-density sampling along several MOR segments has shown that quite a diversity of lava compositions can be erupted over short time (10s–100 years) and length scales (100 m to a few kilometers). Slow spreading ridges, which do not have steady-state magma bodies, generally erupt more mafic lavas compared to fast spreading ridges where magmas are more heavily influenced by fractional crystallization in shallow magma bodies. Intermediate rate-spreading centers, where magma lenses may be small and intermittent, show characteristics of both slow-and-fast spreading centers. In environments where magma supply is low or mixing is inhibited, such as proximal to transform faults, propagating rift tips and overlapping spreading centers, compositionally diverse and highly differentiated lavas are commonly found (such as the Eastern Galapagos Spreading Center, **Figures 3**, **4** and **6**). In these environments, extensive fractional crystallization is a consequence of relatively cooler thermal regimes and the magmatic processes associated with rift propagation.

Local variability in MORB can be divided into two categories: (1) those due to processes that affect an individual parental magma (e.g., fractional crystallization, assimilation) and (2) those created via partial melting and transport in a single melting regime (e.g., melting in a rising diapir). In contrast, global variations reflect regional variations in mantle source chemistry and temperature, as well as the averaging of melts derived from diverse melting regimes (e.g. accumulative polybaric fractional melting). At any given segment of MOR, variations may be due to various combinations of these processes.

### Local Variability

Chemical trends defined by suites of related MOR lavas are primarily due to progressive fractional crystallization of variable combinations and proportions of olivine, plagioclase and clinopyroxene as a magma cools. The compositional 'path' that a magma takes is known as its liquid line of descent (LLD). Slightly different trajectories of LLDs (**Figure 5**) are a consequence of the order of crystallization and the different proportions of crystallizing phases that are controlled by initial (and subsequent changing) liquid composition, temperature, and pressure. In some MORB suites, linear elemental trends may be due to mixing of primitive magmas with more evolved magmas that have evolved along an LLD.

Suites of MORB glasses often define distinctive LLDs that match those determined by experimental crystallization of MORB at low to moderate pressures that correspond to depths of ~1 to 10 km within the oceanic crust and upper mantle. Much of the major element data from fast-spreading ridges like the East Pacific Rise are best explained by low-pressure (~0.1 GPa) fractional crystallization whereas at slow-spreading ridges like the Mid-Atlantic Ridge data require higher pressure crystallization (~0.5–1.0 GPa). This is consistent with other

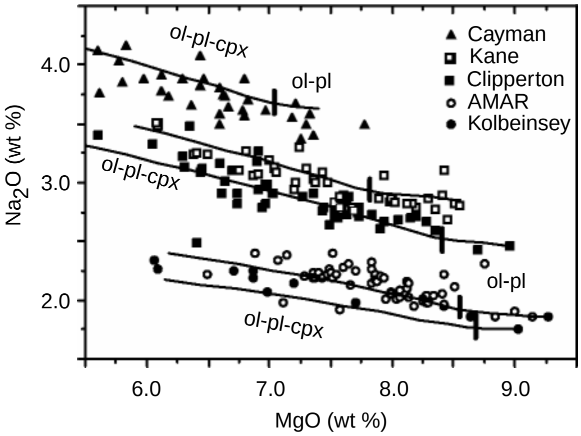

**Figure 5** MgO vs. $Na_2O$ in MORB from five different Ridge segments (Mid Cayman Rise in the Caribbean; near Kane Fracture Zone on the Mid-Atlantic Ridge, 23°N; AMAR on the Mid-Atlantic Ridge around 37°N; East Pacific Rise near the Clipperton Fracture Zone around 10°N; Kolbeinsey Ridge north of Iceland. Lines are calculated Liquid Lines of Descent (LLDs) from high MgO parents. Bar shows where clinopyroxene joins plagioclase and olivine as a fractionating phase. $Na_8$ is determined by the values of $Na_2O$ when the LLD is at MgO of 8 wt%. (Adapted with permission from Langmuir *et al.*, 1992.)

evidence suggesting that magmas at fast-spreading ridges evolve in a shallow magma lens or chambers and that magmas at slow-spreading ridges evolve at significantly greater depths; possibly in the mantle lithosphere or at the crust–mantle boundary. Estimated depths of crystallization correlate with increased depths of magma lens or fault rupture depth related to decreasing spreading rate.

Cogenetic lavas (those from the same or similar primary melts) generated by fractional crystallization exhibit up to 10-fold enrichments of incompatible trace elements (e.g., Zr, Nb, Y, Ba, Rb, REE) that covary with indices of fractionation such as decreasing MgO (**Figure 6**) and increasing $K_2O$ concentrations and relatively constant incompatible trace element ratios irrespective of rock type. In general, the rare earth elements show systematic increases in abundance through the fractionation sequence from MORB to andesite (**Figure 4**) with a slight increase in light rare earth elements relative to the heavy-rare earth elements. The overall enrichments in the trivalent rare earth elements is a consequence of their incompatibility in the crystals separating from the cooling magma. Increasing negative Eu anomalies develop in more fractionated lavas due to the continued removal of plagioclase during crystallization because Eu partially substitutes for Ca in plagioclase which is removed during fractional crystallization.

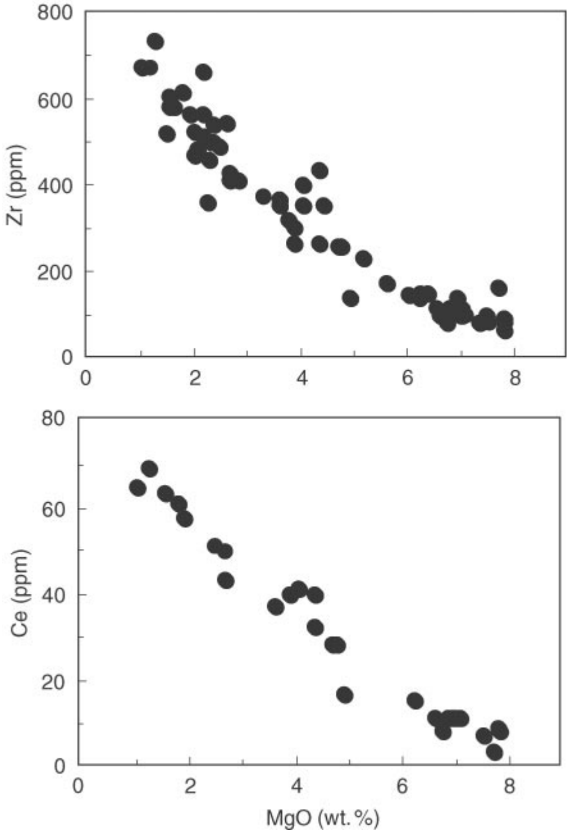

**Figure 6** Trace element (Zr and Ce) versus MgO variation diagram showing the systematic enrichments of these highly incompatible elements with increasing fractionation in a suite of cogenetic lavas from the Eastern Galapagos Spreading Center.

### Global Variability

MORB chemistry of individual ridge segments (local scale) is, in general, controlled by the relative balance between tectonic and magmatic activity, which in turn may determine whether a steady-state magma chamber exists, and for how long. Ultimately, the tectonomagmatic evolution is controlled by temporal variations in input of melt from the mantle. Global correlation of abyssal peridotite and MORB geochemical data suggest that the extent of mantle melting beneath normal ridge segments increases with increasing spreading rate and that both ridge morphology and lava composition are related to spreading rate.

The depths at which primary MORB melts form and equilibrate with surrounding mantle remain controversial (possibly 30 to 100 km), as does the mechanism(s) of flow of magma and solid mantle beneath divergent plate boundaries. The debate is critical for understanding the dynamics of plate spreading and is focused on whether flow is ‘passive’ plate driven flow or ‘active’ buoyantly driven solid convection. At present, geological and geophysical observations support passive flow which causes melts from a broad region of upwelling and melting to converge in a narrow zone at ridge crests.

It has also been hypothesized that melting beneath ridges is a dynamic, near-fractional process during which the pressure, temperature, and composition of the upper mantle change. Variations in these parameters as well as in the geometry of the melting region result in the generation of MORB with different chemical characteristics.

Differences in the major element compositions of MORB from different parts of the world’s oceans (global scale) have been recognized for some time. In general, it has been shown that N-type MORB from slow-spreading ridges such as the Mid-Atlantic Ridge are more primitive (higher MgO) and have greater $Na_2O$, $Al_2O_3$ and lower FeO and $CaO/Al_2O_3$ contents at given MgO values than lavas from medium- and fast-spreading ridges (**Figure 7**). A comparison of ocean floor glass compositions (over 9000) analyzed by electron microprobe at the Smithsonian Institution from major spreading centers and seamounts is presented in **Table 1**. The analyses have been filtered into normal (N-MORB) and enriched (E-MORB) varieties based on their

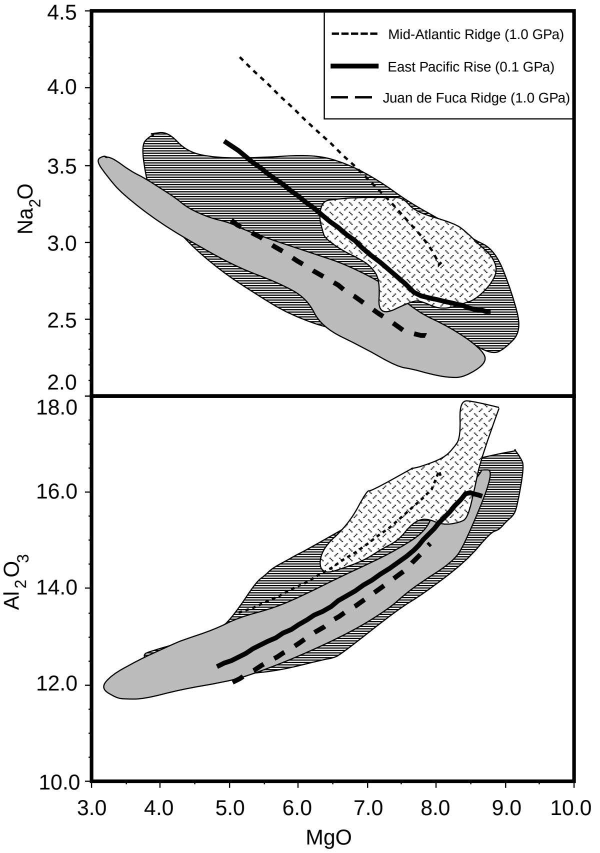

**Figure 7** Major element variation diagrams showing compositional ranges from different spreading rate ridges. Generally higher $Na_2O$ and $Al_2O_3$ concentrations in Mid-Atlantic Ridge (hatchured field) lavas in comparison to MORB from the Juan de Fuca (grey field) and East Pacific Rise (dark field) are shown. Lines show calculated liquid lines of descent at 0.1 and 1.0 GPa for parental magmas from each ridge.

K/Ti ratios (E-MORB $[K_2O/TiO_2] \times 100 > 13$) which reflect enrichment in the highly incompatible elements. These data indicate that on average, MORB are relatively differentiated compared to magmas that might be generated directly from the mantle (compare averages with picritic basalts from the Pacific in **Table 1**). Furthermore, given the variability of glass compositions in each region, N-MORB have quite similar average major element compositions (most elemental concentrations overlap at the 1-sigma level). E-MORB, are more evolved than N-MORB from comparable regions of the ocean and there are a higher proportion of E-MORB in the Atlantic (31%) compared to the Pacific (12%) and Galapagos Spreading Center region (7%). Unlike the Atlantic where E-MORB are typically associated with inflated portions of the ridge due to the effects of plume–ridge interaction, East Pacific Rise E-MORB are randomly dispersed along-axis and more commonly recovered off-axis.

As well as having higher $K_2O$ contents than N-MORB, E-MORB have higher concentrations of $P_2O_5$, $TiO_2$, $Al_2O_3$ and $Na_2O$ and lower concentrations of $SiO_2$, FeO and CaO. Positive correlations exist between these characteristics, incompatible element enrichments and more radiogenic Sr and Nd isotopes in progressively more enriched MORB.

Direct comparison of elemental abundances between individual MORB (or even groups) is difficult because of the effects of fractional crystallization. Consequently, fundamental differences in chemical characteristics are generally expressed as differences in parameters such as $Na_8$, $Fe_8$, $Al_8$, $Si_8$ etc. which are the values of these oxides calculated at an MgO content of 8.0 wt% (**Figures 5** and **8**). When using these normalized values, regionally averaged major element data show a strong correlation with ridge depth and possibly, crustal thickness. MORB with high FeO and low $Na_2O$ are sampled from shallow ridge crests with thick crust whereas low FeO– high $Na_2O$ MORB are typically recovered from deep ridges with thin crust (**Figure 8**). This chemical/tectonic correlation gives rise to the so-called 'global array'. Major element melting models indicate there is a strong correlation between the initial depth of melting and the total amount of melt formed. As a consequence, when temperatures are high enough to initiate melting at great depths, the primary MORB melts contain high FeO, low $Na_2O$ and low $SiO_2$. Conversely, if the geothermal gradient is low, melting is restricted to the uppermost part of the upper mantle, and little melt is generated (hence thinner crust) and the basaltic melts contain low FeO, high $Na_2O$ and relatively high $SiO_2$.

Although the global systematics appear robust, detailed sampling of individual ridge segments have shown MORB from limited areas commonly exhibit chemical correlations that form a 'local trend' opposite to the chemical correlations observed globally (e.g., FeO and $Na_2O$ show a positive correlation). A local trend may reflect the spectrum of melts formed at different depths beneath one ridge crest rather than the aggregate of all the melt increments.

Although the original hypothesis that global variations in MORB major element chemistry are a consequence of total extents of mantle melting and mean pressure of extraction due to variations in mantle temperature, more recent evidence suggests that heterogeneity in the mantle also plays an important role in defining both global and local chemical trends. In particular, U-series data suggest some MDRB melts equilibrate with highly depleted mantle at shallow depths whereas others equilibrate with less depleted garnet pesidatite at depths greater than ~80 km.

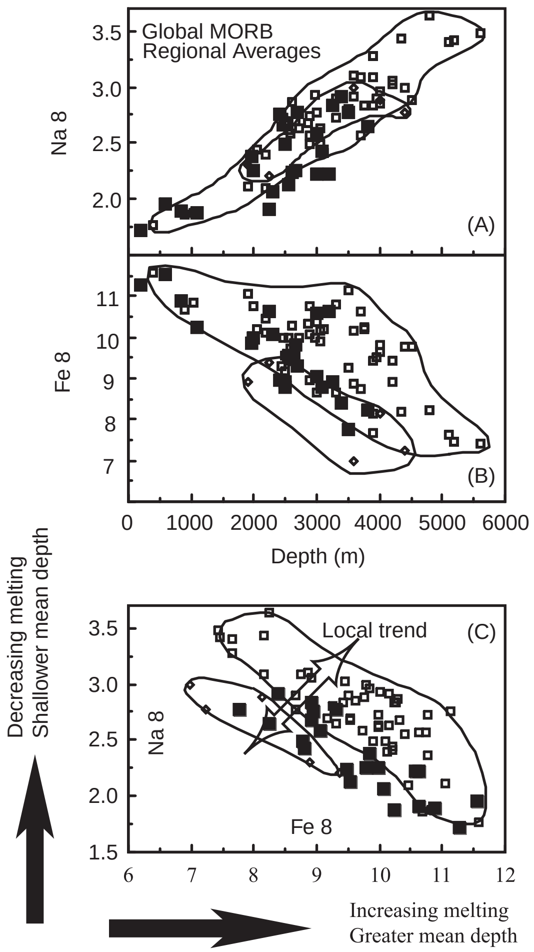

**Figure 8** (A) and (B) Global correlations between regional averages of ridge axial depth and the $Na_8$ and $Fe_8$ of MORBs. Different groups of MORB are distinguished. □, Normal ridge segments; ◇, ridges behind island arcs; ■, ridges influenced by hot spots. (C) Global trend of $Na_8$ vs. $Fe_8$ due to differences in extents and depths of melting. Representative 'Local trend' is common along individual portions of some ridges. (Adapted with permission from Langmuir *et al.*, 1992.)

## Conclusions

Passive rise of the mantle beneath oceanic spreading centers results in the decompression melting of upwelling peridotite which gives rise to a spectrum of MORB compositions varying from extremely depleted to moderately enriched varieties. The compositional variability in primary MORB result from combinations of differing source compositions, extents and styles of partial melting, and depths of melt formation. The moderately evolved composition of most MORB primarily reflects the effects of crystal fractionation that occurs as the primary melts ascend from the mantle into the cooler crust. Although MORB are relatively homogeneous compared to basalts from other tectonic environments, they exhibit a range of compositions that provide us with information about the composition of the mantle, the influence of plumes, and dynamic magmatic processes that occur to form the most voluminous part of the Earth's crust.

## See also

**Mid-Ocean Ridge Seismic Structure. Mid-Ocean Ridge Tectonics, Volcanism and Geomorphology. Propagating Rifts and Microplates. Seamounts and Off-ridge Volcanism.**

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# MID-OCEAN RIDGE SEISMIC STRUCTURE

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## Introduction

New crust is created at midocean ridges as the oceanic plates separate and mantle material upwells and melts in response through pressure-release melting. Mantle melts rise to the surface and freeze through a variety of processes to form an internally stratified basaltic crust. Seismic methods permit direct imaging of structures within the crust that result from these magmatic processes and are powerful tools for understanding crustal accretion at ridges. Studies carried out since the mid 1980s have focused on three crustal structures; the uppermost crust formed by eruption of lavas, the magma chamber from which the crust is formed, and the Moho, which marks the crust-to-mantle boundary. Each of these three structures and their main characteristics at different midocean ridges will be described here and implications of these observations for how oceanic crust is created will be summarized. The final section will focus on how crustal structure changes at ridges spreading at different rates, and the prevailing models to account for these variations.

Seismic techniques employ sound to create cross-sectional views beneath the seafloor, analogous to how X-rays and sonograms are used to image inside human bodies. These methods fall into two categories; reflection studies, which are based on the reflection of near-vertical seismic waves from interfaces where large contrasts in acoustic properties are present; and refraction studies, which exploit the characteristics of seismic energy that travels horizontally as head waves through rock layers. Reflection methods provide continuous images of crustal boundaries and permit efficient mapping of small-scale variations over large regions. Locating these boundaries at their correct depth within the crust requires knowledge of the seismic velocity of crustal rocks, which is poorly constrained from reflection data. Refraction techniques provide detailed information on crustal velocity structure but typically result in relatively sparse measurements that represent large spatial averages. Hence the types of information obtained from reflection and refraction methods are highly complementary and these data are often collected and interpreted together.

Much of what we know about the seismic structure of ridges has come from studies of the East Pacific Rise. This is a fast-spreading ridge within the eastern Pacific that extends from the Gulf of California to south of Easter Island. Along this ridge, seafloor topography is relatively smooth and seismic studies have been very successful at imaging the internal structure of the crust. Comparatively little is known from other ridges, in part because fewer experiments have been carried out and in part because, with the rougher topography, imaging is more difficult.

## Seismic Layer 2A

### Early Studies

Seismic layer 2A was first identified in the early 1970s from analysis of refraction data at the Reyk-