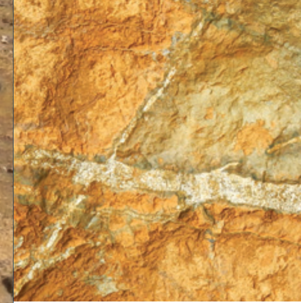
Ophiolites and Their Origins



↑ Gabbroic dikes and veins in dunite, Zambales ophiolite, Philippines (width of view 1 m).

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Ophiolites are suites of temporally and spatially associated ultramafic, mafic, and felsic rocks that are interpreted to be remnants of ancient oceanic crust and upper mantle. Ophiolites show significant variations in their internal structure, geochemical fingerprints, and emplacement mechanisms. These differences are controlled by (1) the proximity, when formed at the magmatic stage, to a plume or trench; (2) the rate, geometry, and nature of ocean-ridge spreading; (3) mantle composition, temperature, and fertility; and (4) the availability of fluids. The oceanic crust preserved in ophiolites may form in any tectonic setting during the evolution of ocean basins, from the rift–drift and seafloor spreading stages to subduction initiation and terminal closure. An ophiolite is emplaced either from down-going oceanic lithosphere via subduction-accretion or from the upper plate in a subduction zone through trench–continent collision. Subduction zone tectonics is thus the most important factor in the igneous evolution of ophiolites and their emplacement into continental margins.

Keywords: suprasubduction zone ophiolite, boninite, mid-ocean ridge ophiolite, plume-type ophiolite, continental margin ophiolite, ophiolite pulse

INTRODUCTION

Ophiolites are the remnants of ancient oceanic crust and upper mantle that were tectonically emplaced into continental margins. They display the only evidence for magmatic, tectonic, and hydrothermal processes associated with seafloor spreading prior to 170 Ma because no oceanic lithosphere older than this age is preserved in the modern oceans. The occurrence of sheeted dikes, side-by-side tabular intrusions of magma, is the primary evidence for the seafloor spreading origin of ophiolites. Ophiolites are therefore the best archives of the evolutionary history of ocean basins from their rift–drift and seafloor spreading stages to subduction initiation and final closure. Their recognition as structural analogues for oceanic crust played a significant role in the advancement of the plate tectonic theory in the 1960s, and geoscientists have used ophiolites in investigating the nature of mid-ocean ridge processes, mantle chemistry, the paleogeography of ancient ocean basins, and the tectonic evolution of orogenic belts.

Brongniart's (1821) early definition of an ophiolite was based on a suite of ultramafic, gabbroic, diabasic, and volcanic rocks in the Italian Apennines. Subsequently, Steinmann (1927) noted the common occurrence of serpentinite, basalt, and chert ("Steinmann's Trinity") in the Mediterranean mountains, and interpreted their origin as differentiated, ocean-floor magmatic units. The Dutch geologist de Roever (1957) and then the Swiss geologist Vuagnat (1964) argued that the association of these rocks was a result of mantle melting, which produced basaltic rocks on top and residual peridotites at the bottom.

By the mid-1960s, the recognition of sheeted dike complexes, fossil magma chambers in plutonic sequences, and refractory harzburgites in mantle units was instrumental in formulating a model for the formation of ophiolite within the framework of the plate tectonic theory. The ophiolite–oceanic crust analogy was confirmed at the first Penrose Conference on ophiolites (Anonymous 1972). However, Miyashiro (1973) questioned the ruling model of a mid-ocean ridge setting for the genesis of ophiolite and proposed, based on geochemical interpretations, that the Troodos oceanic crust on Cyprus was a product of island arc magmatism. This was a revolutionary but controversial development in the ophiolite concept and led to the definition of suprasubduction zone ophiolites in the early 1980s. Observations of in situ oceanic crust in spreading environments within the upper plates of subduction zones in the western Pacific during the 1980s and 1990s were particularly important for demonstrating the influence of subduction on the magmatic evolution of ophiolites. Thus, this remarkable transformation in the scientific understanding of ophiolites since 1821 has contributed significantly to major advances in various Earth science disciplines.

Ophiolites have also been indispensable for human cultures and civilizations because of the wealth of mineral and ore deposits they host. The precious metals gold, silver, and platinum-group elements (PGEs), the ferrous metals chromium, manganese, and titanium, and the base metals cobalt, copper, and nickel occur widely in the ultramafic–mafic rocks of ophiolites. The discovery of copper in the Troodos ophiolite contributed to the development of the Bronze Age (~2400 BC) and triggered a critical era in human history during which the use of bronze brought about drastic changes in farming, hunting, and warfare. Nonmetallic chrysotile asbestos and jade are mainly found in serpentinized peridotites. Asbestos, in the form of various serpentine minerals, was widely used as an effective insulator because of its resistance to fire, heat, and electrical damage; this changed when asbestos was recognized as a human carcinogen. Jade is an important

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gemstone and occupies a special place in Asian cultures, where it is valued as a precious ornamental stone and is used in the finest art objects.

This issue of *Elements* provides a broad overview of the present state of knowledge of ophiolites. In this introductory article, we discuss the internal structure and magmatic evolution of different ophiolite types, the emplacement mechanisms of ophiolites, and the ophiolite pulses during the Phanerozoic. Pearce (2014) summarizes the principles of immobile element fingerprinting of extrusive and dike rocks in ophiolites. Ishizuka et al. (2014) present the Izu-Bonin-Mariana forearc lithosphere as a modern analogue for a subduction-related ophiolite. Goodenough et al. (2014) discuss the multiphase magmatic and tectonic evolution of the Oman–UAE (United Arab Emirates) ophiolite. Staudigel et al. (2014) explore the records of microbial life preserved in modern oceanic crust and ophiolites. Yang et al. (2014) report on the occurrence and possible origin of diamonds and unusual crustal minerals in ophiolitic peridotites and chromitites.

OPHIOLITE ARCHITECTURE

According to the definition proposed during the 1972 Penrose Conference, an ophiolite sequence consists, from bottom to top, of upper mantle peridotites, layered ultramafic–mafic rocks, layered to isotropic gabbros, sheeted dikes, extrusive rocks, and a sedimentary cover (Fig. 1; Anonymous 1972). The upper mantle peridotites commonly include layers of lherzolite and harzburgite and lenses of dunite with chromitite (Fig. 1, units a, b). Harzburgitic rocks (Fig. 1, photos a, b) are characterized by the near absence of primary clinopyroxene; they are interpreted to be restites that experienced high degrees of partial melting beyond the stability of clinopyroxene, and therefore represent refractory mantle. They commonly display high-temperature deformation fabrics.

Layered ultramafic and mafic rocks form a transitional mantle–crust section (Fig. 1, unit and photo c), which corresponds to the petrological Moho (after Andrija Mohorovičić, 1857–1936) in the fast-spreading, modern oceanic lithosphere (Dilek and Furnes 2011). The overlying layered gabbro (Fig. 1, unit and photo d) consists mainly of olivine gabbro and gabbro, with subordinate troctolite, anorthosite, and wehrlite layers. Modal variations of olivine, plagioclase, and clinopyroxene define the layering in these rocks. Isotropic gabbros above the layered gabbro have heterogeneous textures and grain sizes (hence the term *varitextured* gabbro; Fig. 1, unit and photo e) and include pegmatitic gabbro veins and plagiogranite dikes near the top.

Mutually intrusive relationships (Fig. 1, photo f) may define the boundary between the isotropic gabbros–plagiogranites of the plutonic sequence and the overlying sheeted dike complex. However, this boundary is not always magmatic in nature; in some ophiolites (i.e. Troodos, Cyprus; Kizildag, Turkey) it is locally defined by low-angle normal faults (detachment surfaces) with mylonitic to cataclastic deformation bands in the gabbros (Dilek and Eddy 1992). Sheeted dikes, up to 1.5 km in total thickness, are vertical, subvertical (Fig. 1, photo g), or variously inclined, and are commonly cut by dike-parallel extensional faults, some of which acquire low-angle dips with depth (listric geometry). Rotation of sheeted dikes in the hanging wall of these listric normal faults during amagmatic extension causes the dikes to tilt.

The extrusive rocks in ophiolites consist of pillow lavas, pillow breccias, and massive lava flows (Fig. 1, units and photos h–j), which range in composition from basalt and basaltic andesite at the bottom to andesite, dacite, and rhyolite at the top. In some ophiolites, boninitic (high-Mg, high-SiO_2 andesite) dikes and lavas represent the latest stages of magmatism, as they crosscut and overlie other ophiolitic subunits (Fig. 1). Extrusive rocks are typically overlain by pelagic (Fig. 1, photo k), hemipelagic, and clastic sedimentary rocks; these rocks represent the ocean plate stratigraphy, recording the travel history of the oceanic lithosphere from ridge to trench.

MANTLE HETEROGENEITIES IN OPHIOLITES

Both ophiolites and in situ oceanic lithosphere show compositional and geochemical heterogeneities at various scales that are not consistent with steady-state magmatic accretion at a spreading center. Ophiolitic peridotites are depleted mantle residues resulting from various degrees and episodes of melt extraction from the primitive mantle. It is widely thought that systematic covariations of major and trace element distributions in ophiolitic peridotites are a result of partial melting processes. Yet, the bulk composition and the mineral chemistry of some ophiolitic peridotites are incompatible, and hence the assumption of a simple liquid line of descent for a parental melt that evolved via fractional crystallization does not work.

This discrepancy may have resulted from postcumulus infiltration by melts, which reacted and reequilibrated with the depleted host peridotites, causing their refertilization by crystallization of interstitial mineral phases (plagioclase and clinopyroxene) (e.g. Dijkstra et al. 2001). Hence the observed mineralogy, textures, and compositions of upper mantle peridotites in some ophiolites are not primary. Likewise, the removal of a melt fraction after melt–peridotite reactions and the intrusion of this melt into the lower crust may produce late ultramafic–mafic intrusions in the layered gabbros (Fig. 1). Residual peridotites may react with slab-derived fluids in a mantle wedge and may interact with asthenospheric melts at shallow depths. These processes result in the modification or total obliteration of the primary structures, whole-rock chemistry, and mineralogical compositions of oceanic peridotites (O'Driscoll et al. 2012). Therefore, the mineralogy and geochemical compositions of crustal and mantle sequences in most ophiolites do not represent a simple melt–residua relationship.

OPHIOLITE TYPES AND THEIR MELT EVOLUTION

The magmatic construction mechanisms of ophiolites depend on the geodynamic settings of their formation. Their emplacement mechanisms are also different (see below). Therefore, the occurrence and the types of ophiolites are the result of two important factors: (1) the tectonic, magmatic, and geochemical processes of ophiolite formation, and (2) the preservation of ophiolites as a result of different emplacement mechanisms.

The magmatic–structural architecture and geochemical signature of ophiolites are affected by several factors: the spreading rate and geometry in their igneous environment of formation; the proximity of this environment to mantle plumes or trenches (hence to subducting slabs); the composition, fertility, and temperature of the mantle beneath their spreading centers; the availability of fluids and recycled crustal material to the melt column(s) beneath these spreading centers; and the magnitude and nature of mantle melting and magmatic differentiation patterns (Dilek and Furnes 2011). An ophiolite is, therefore, a suite of temporally and spatially associated ultramafic, mafic, and felsic rocks that formed as the products of multiple mantle melting events and magmatic differentiation processes in a particular tectonic environment.

Ophiolites can be classified to the first order as subduction-related and subduction-unrelated types. Ophiolites whose magmatic construction was not affected by subduction processes include continental margin (CM), mid-ocean ridge (MOR), and plume-type (P) ophiolites (Table 1). These types correspond to the ophiolites developed at "normal" mid-ocean, plume-related mid-ocean, continental margin, and subducted ridges, as defined by Pearce (2014 this issue). Subduction-related ophiolites include suprasubduction zone (SSZ) and volcanic arc (VA) ophiolites (Table 1). The SSZ type encompasses ophiolites formed in subduction-initiation (forearc) and backarc basin settings.

Subduction-Unrelated Ophiolites

Tectonic extension and rifting may lead to continental breakup and development of an incipient ocean. Magmatic activity associated with this breakup and embryonic oceanic crust formation produces an ocean–continent transition (OCT) zone, where the subcontinental lithospheric mantle lherzolite is directly overlain by basaltic lavas and intruded by small gabbroic plutons and mafic dikes (Fig. 2a1; Manatschal and Müntener 2009). Formation of these crustal rocks, all with mid-ocean ridge basalt (MORB) compositions, involves small degrees of partial melting of little-depleted lithospheric mantle and slowly upwelling asthenosphere. This OCT lithosphere may be preserved in orogenic belts as CM ophiolites.

Continued lithospheric extension and magmatism in the aftermath of continental breakup lead to seafloor spreading, and new oceanic crust forms by decompression melting of uprising asthenosphere. Variations in magma supply rates and the thermal structure beneath the spreading axes control the mode of magmatic accretion and the architecture of oceanic crust produced (Fig. 2a2). In fast-spreading ridges (e.g. East Pacific Rise), where magma supply is robust, continuous magmatism keeps pace with plate separation, and synchronous extension and diking produce a Penrose-type oceanic crust with a transitional Moho (Fig. 2a2). In intermediate-spreading ridges (e.g. Costa Rica Rift), oceanic crust has a thinner volcanic sequence but a thicker sheeted dike complex in comparison to fast-spreading crust (Fig. 2a2). In slow-spreading ridges (e.g. Mid-Atlantic Ridge, SW Indian Ridge), extensional faulting and crustal attenuation may outpace magmatism episodically, resulting in the exhumation of serpentinized upper mantle peridotites and gabbros on the seafloor (Dilek and Furnes 2011). Slow-spreading oceanic crust may, therefore,

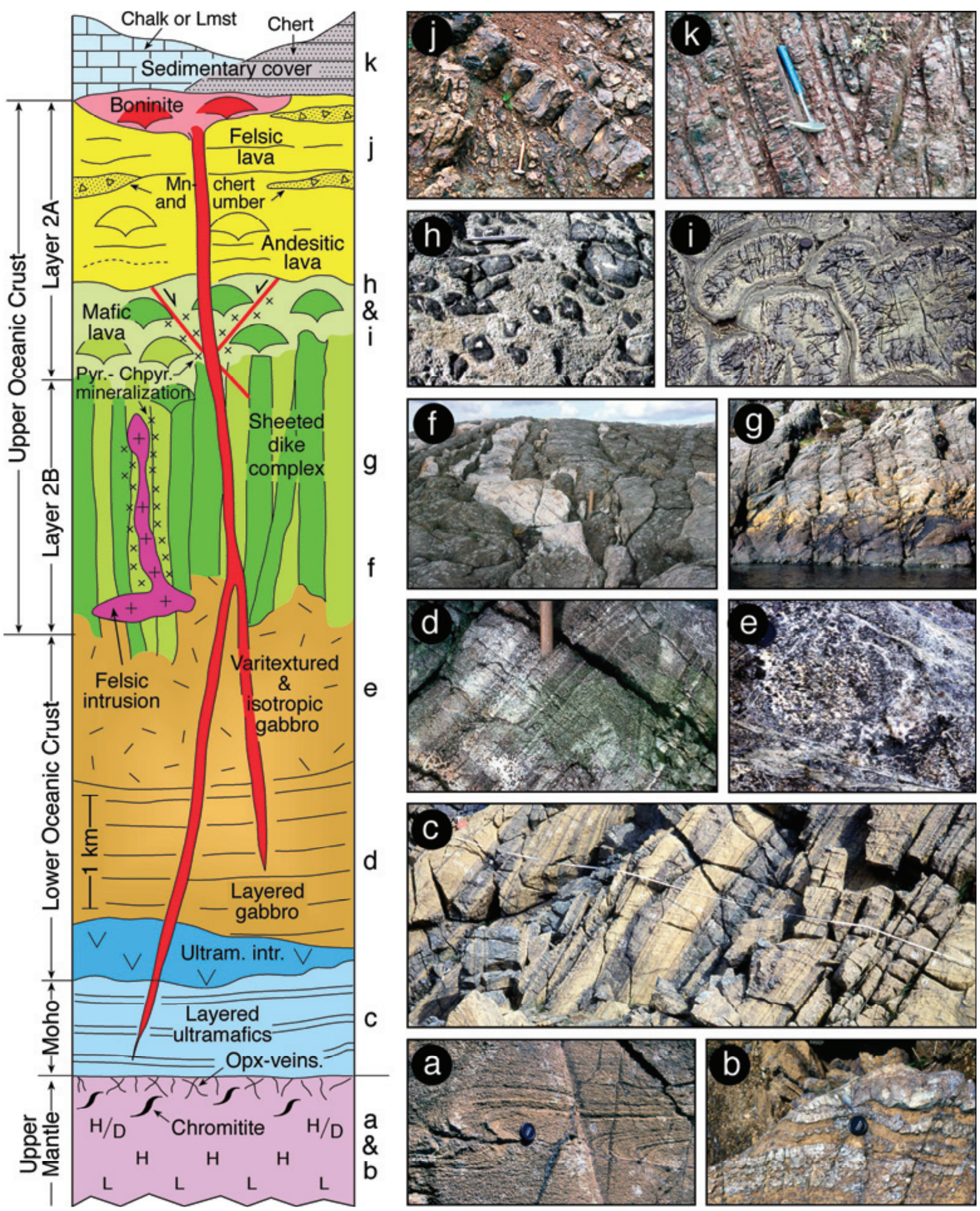


Figure 1 (**Left**) Columnar section showing the upper mantle and crustal components of a generalized suprasubduction zone ophiolite. (**Right**) Field photographs; a photo illustrating a component of a given unit has the same letter as the unit in the section. Photos (**a**) and (**b**) banded and folded harzburgite (olivine + orthopyroxene); (**c**) layered cumulates of dunite (yellow) and wehrlite (olivine + clinopyroxene; dark); (**d**) layered and folded gabbro; (**e**) varitextured gabbro; (**f**) gabbro cut by basaltic and felsic intrusions; (**g**) sheeted dike complex; (**h**) volcanic breccia with a hyaloclastic matrix; (**i**) pillow lava; (**j**) massive andesitic lava flow; (**k**) folded chert layers. Locations of photos: (a–c, i): Leka ophiolite, Norway; (d): Karmøy ophiolite, Norway; (e–h): Solund-Stavfjord ophiolite, Norway; (j, k): Mirdita ophiolite, Albania. Chpyr = chalcopyrite, H/D = harzburgite/dunite, H = harzburgite, L = lherzolite, Lmst = limestone, Opx veins = orthopyroxenite veins, Pyr = pyrite.

be thin and deformed, and the Moho may be represented by an alteration front or a detachment fault. Pillow lavas locally rest directly on exhumed, serpentinized peridotites and gabbros. Thus, MOR ophiolites may show major variations in their structural architecture and crustal thickness, depending on the spreading rate of the lithosphere (Fig. 2a2).

All MOR ophiolites plot along the mantle array in a Ta/Yb versus Th/Yb diagram and may display N-MORB (e.g. Masirah ophiolite) or E-MORB (e.g. Macquarie ophiolite) geochemistry (Fig. 2b2). The trench-proximal Taitao ophiolite in southern Chile (Le Moigne et al. 1996) is geochemically transitional between N-MORB and E-MORB (Fig. 2b2) and also shows slight crustal contamination, representing a C-MORB affinity (Pearce 2014).

P-type ophiolites form at plume-proximal oceanic ridges or as part of oceanic plateaus, and they contain massive lava flows with minor pillowed lavas, mostly picritic basalt in composition. Gabbroic to ultramafic plutons and sills are intrusive into a thick volcanic sequence (Fig. 2a3). Pillow breccias, hyaloclastites, and chert–shale layers are intercalated with basaltic lava flows at higher stratigraphic levels. P-type ophiolites display geochemical variations between N-MORB and ocean island basalt (OIB; Fig. 2b3).

The subduction-unrelated ophiolites display large variations in the Th/Yb versus Ta/Yb discrimination diagram (Fig. 2b). Their multielement patterns (Lu through Cs) vary from nearly flat, as shown by the CM Ligurian and the MOR Masirah ophiolites, to steep, as defined by the Macquarie ophiolite (Fig. 2b). These variations in incompatible element behavior are related to the degree of partial melting and the mantle temperature and fertility.

Subduction-Related Ophiolites

Suprasubduction zone (SSZ) ophiolites represent oceanic lithosphere formed in the extended upper plates of subduction zones, analogous to the modern Izu-Bonin-Mariana and Tonga-Kermadec arc–trench rollback systems (Stern and Bloomer 1992; Ishizuka et al. 2014 this issue; Pearce 2014). Specific tectonic settings of SSZ oceanic crust formation include the forearc, the backarc, and the incipient arc. Backarc tectonic environments may evolve as trench-proximal or trench-distal spreading centers showing variable subduction influence (Dilek and Furnes 2011). Extrusive and dike rocks of forearc ophiolites show time-progressive compositional and geochemical variations, from the oldest mid-ocean ridge–like (MORB-like) to the island arc tholeiite (IAT), and to the youngest boninitic affinities (Fig. 2c1; Dilek et al. 2008; Dilek and Thy 2009; Ishizuka et al. 2014).

The earlier, MORB-like rocks are the products of decompressional melting of deep and fertile lherzolitic mantle and show no subduction influence. IAT magmas are strongly influenced by slab-dehydration-driven mantle metasomatism, repeated episodes of partial melting of peridotites in the mantle wedge, melting of subducted sediments, and mixing of highly enriched liquids from the lower fertile source with refractory melts in the melt column. Shallow partial melting of ultrarefractory harzburgites produces hydrous, Si- and Mg-rich boninitic magmas in the latest stages. In a multielement diagram (Lu through Cs), the first-produced basalts display a relatively flat pattern, and the younger IAT and boninitic rocks show a progressive depletion (relative to the first-produced basalts) in Lu–Nd and Ce–Ta, and a strong enrichment in Pb, Th, and Cs (Fig. 2d1).

A volcanic arc (VA) ophiolite contains a middle crust with dioritic, tonalitic, and granodioritic intrusions (Nakajima and Arima 1998) and an uppermost crust with abundant andesitic to rhyolitic lavas and pyroclastic rocks (Fig. 2c2). The dioritic–tonalitic middle crust is produced by partial melting of the hydrated, earlier-formed mafic crust as a result of the infiltration of arc magmas. In the Th/Yb–Ta/Yb diagram, these ophiolites straddle the boundary between the IAT and calc-alkaline (CA) fields, and in the multielement diagram, the element concentrations are higher than those in SSZ ophiolites (Fig. 2d2).

The magmatic and geochemical evolution of SSZ and VA ophiolites is controlled, therefore, by the mode and nature of (1) partial melting of the mantle above the subduction zone, and (2) the dehydration of and element flux from the subducted slab into the overlying mantle. Repeated episodes of partial melting cause a progressive change in the composition of the mantle, from fertile lherzolite to ultrarefractory harzburgite, and consequently the mantle source and the magmas derived from it become depleted in incompatible elements. In the meantime, dehydration of the subducting oceanic slab and partial melting of subducted sediments lead to the incorporation of the light rare earth elements (LREEs) and the mobile elements Cs, Pb, Ba, Th, and U into the mantle wedge (Hawkesworth et al. 1997; Pearce 2014). The conservative elements Nb, Ti, Y, and the heavy REEs (HREEs) are largely unaffected by this process and hence become progressively depleted in

Table 1 OPHIOLITE TYPES AND REPRESENTATIVE EXAMPLES, WITH THEIR GEOCHEMICAL AFFINITIES AND MAJOR MINERAL PHASES

Ophiolite Types & Their Tectonic Settings			Ophiolite/Modern Examples	Geochemical Affinities	Crystallization Order of Minerals
Subduction –unrelated	Continental margin type		Ligurian and Western Alpine ophiolites; Jormua (Finland)	N-MORB, E-MORB, P-MORB & C-MORB lavas	Olivine + plag + cpx
	Mid-ocean ridge types	Plume-distal MOR	Macquarie Ridge; Masirah (Oman)	N-MORB (DMM) to E-MORB lavas	Olivine + plag
		Plume-proximal MOR	Iceland	N-MORB and P-MORB lavas	Olivine + plag ± cpx
		Trench-proximal MOR	Taitao (Chile)	N-MORB, E-MORB ± C-MORB lavas	Olivine + plag + cpx
	Plume-type		Nicoya (Costa Rica); Bolivar (Colombia)	P-MORB lavas	Olivine + plag + cpx ± opx
Subduction–related	Suprasubduction zone types	Forearc	Troodos (Cyprus); Kizildag (Turkey); Semail (Oman); Betts Cove (Canada)	FAB (MORB-like), IAT to boninite lavas	Olivine + plag + cpx + opx and Olivine + cpx + plag
		Backarc (continental & oceanic)	Rocas Verdes (Chile); Solund-Stavfjord (Norway)	BABB lavas	Olivine + plag + cpx and Olivine + cpx + plag
	Volcanic arc type		Smartville (California); Itogon (Philippines)	IAT to CA lavas; middle crust with tonalite, diorite	Olivine + plag + cpx and Olivine + cpx + plag

BABB = back-arc basin basalt; CA = calc-alkaline; C-MORB = contaminated MORB; DMM = depleted MORB mantle; E-MORB = enriched MORB; FAB = forearc basalt; IAT = island-arc tholeiite; MORB = mid-ocean ridge basalt; N-MORB = normal MORB; P-MORB = plume-influenced MORB the mantle source during the repeated episodes of melting. However, the solidus of the wedge peridotites is lowered considerably due to the input of slab-derived fluids, facilitating further partial melting, and the depleted mantle becomes progressively enriched in highly mobile incompatible elements. The sharp increase in the incompatible element concentration, the marked positive Pb anomaly, and the negative Nb anomaly displayed by VA ophiolites in comparison to SSZ ophiolites (Fig. 2d2) are mostly time-dependent phenomena because of the prolonged subduction history (~20–30 My) of VA ophiolites as opposed to the relatively shorter subduction history (<10 My) of SSZ ophiolites (Dilek and Furnes 2011).

OPHIOLITE EMPLACEMENT MECHANISMS

Among the most important factors controlling the mechanisms of ophiolite emplacement are (1) the age, thickness, and thermal state of oceanic lithosphere to be emplaced, (2) the nature and geometry of plate boundaries involved, and (3) the size and character (e.g. oceanic versus continental) of the interacting plates (Wakabayashi and Dilek 2003). Subduction zone tectonics is an essential driver for incorporating preexisting oceanic lithosphere into continental margins. The oceanic lithosphere of MOR- and P-type ophiolites is tectonically transferred from a downgoing plate to the upper plate via subduction-accretion. The oceanic lithosphere in SSZ and VA ophiolites is always part of the upper plate of a subduction system, but it gets emplaced into a continental margin in a downgoing plate via collisional processes. We examine here the emplacement mechanisms of some subduction-unrelated and subduction-related ophiolites through subduction-accretion and collisional processes (Fig. 3).

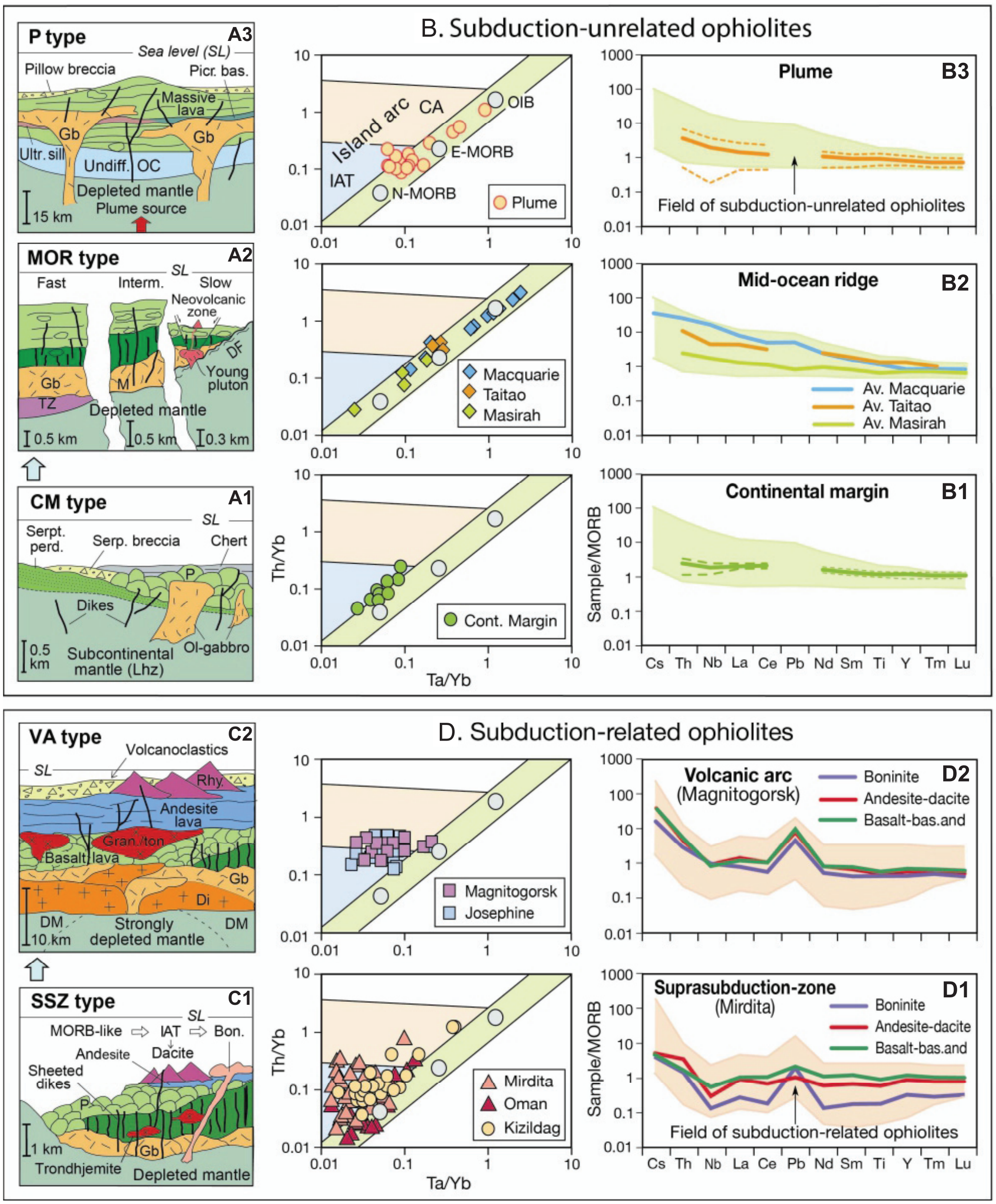


Figure 2 (Left column) Cross-sections depicting the internal structure and lithological units of different ophiolite types. (Center and right columns) Th/Yb–Ta/Yb and multielement diagrams (modified from Dilek and Furnes 2011, and data sources therein) displaying the characteristic features of a selection of ophiolite types. Key to lettering: (**A1**) CM type = continental margin type; Lhz = lherzolite; Ol = olivine; P = pillow lava. (**A2**) DF = detachment fault; Gb = gabbro; M = Moho; MOR type = mid-ocean ridge type; TZ = transition zone. (**A3**) Gb = gabbro; P type = plume type; Picr. Bas = picritic basalt; Ultr. sill = ultramafic sill; Undiff. OC = undifferentiated oceanic crust. (**C1**) Bon. = boninite; Gb = gabbro; IAT = island arc tholeiite; P = pillow lava; SSZ type = suprasubduction zone type. (**C2**) Di = diorite; DM = depleted mantle; Gb = gabbro; Gran/ton = granodiorite/tonalite; Rhy = rhyolite; VA type = volcanic arc type. (**D1**) and (**D2**) Bas. and = basaltic andesite.

Continental Margin Ophiolites: Ligurian Ophiolites

The Middle Jurassic ophiolites in the northern Apennines and the western Alps formed during and following the rifting of Adria (or Apulia) and Africa from Europe that led to the opening of the Piemont-Liguria ocean (Manatschal and Müntener 2009). These CM ophiolites were subsequently imbricated with trench deposits ("schistes lustrés" in the Alps/Apennines) and telescoped along west-vergent thrust faults in the late Cretaceous as a result of regional shortening associated with a newly developed subduction zone near the Adria continental margin (Fig. 3a). In the western Alps, a ribbon continent (the Sesia-Margna extensional allochthon) and the OCT zone crust were partly subducted beneath the Adria margin, metamorphosed to eclogite facies, and exhumed later following the continent–continent collision (Alpine orogeny).

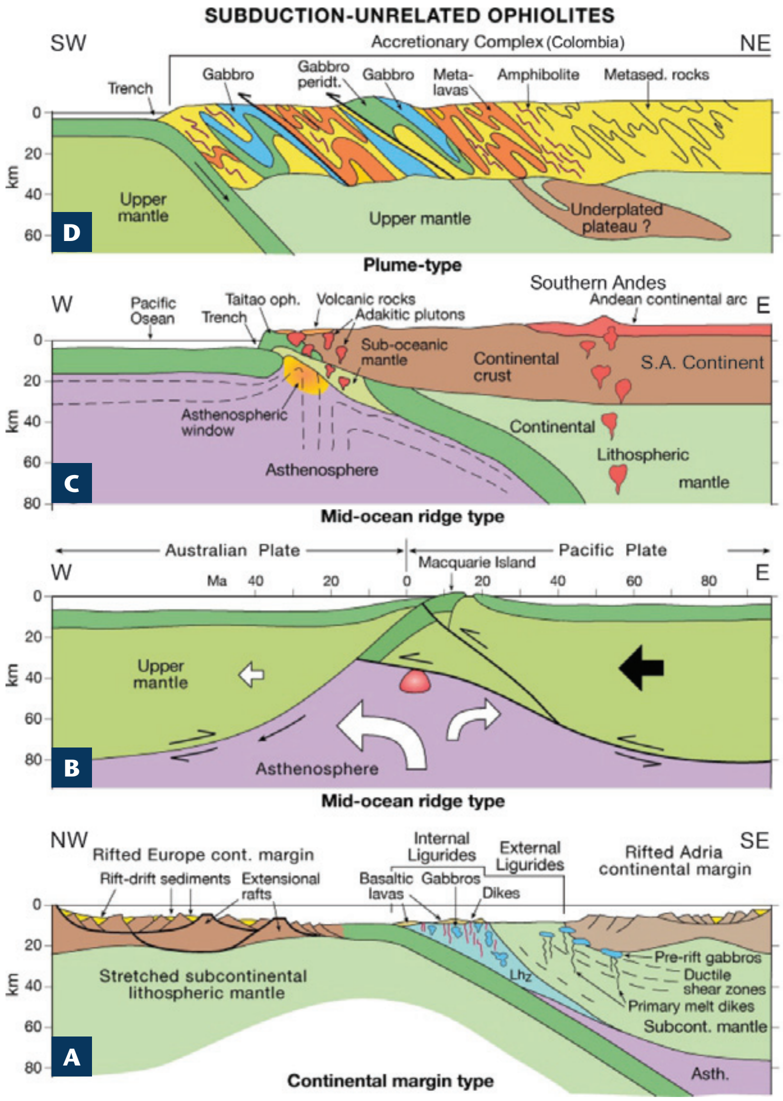
Mid-Ocean Ridge Ophiolites: Macquarie and Taitao Ophiolites

The Macquarie ophiolite in the Southern Ocean (Fig. 3b) and the Taitao ophiolite in southern Chile (Fig. 3c) are two young MOR ophiolites that experienced different processes of tectonic displacement and emplacement. The Macquarie ophiolite (11.5–9.7 Ma) is exposed along the transform fault boundary between the Australian and Pacific plates (Meckel et al. 2003). Transpression across this boundary during the last 6 million years has resulted in the tectonic displacement and uplift of the MOR crust (Fig. 3b). The transpressional, transform plate boundary here connects along-strike, to the north and south, with two active trenches and is thus in the process of being converted into an intraoceanic subduction zone (Meckel et al. 2003).

The late Miocene Taitao ophiolite in southern Chile was emplaced into the active margin of South America as a result of ridge–trench interaction (Fig. 3c; Le Moigne et al. 1996). Subduction of an oceanic ridge may result in the emplacement of a piece of young and buoyant oceanic lithosphere as an ophiolite in the upper plate (Van den Beukel and Wortel 1992). As the Chile Rise collided with the Peru-Chile Trench around 5.6 Ma, a slice of hot oceanic lithosphere was decoupled from the downgoing oceanic slab and was incorporated into the South American continental margin as a MOR ophiolite.

Plume-Type Ophiolites: Western Colombia

The Cretaceous peri-Caribbean ophiolites, exposed in Venezuela, western Colombia, Costa Rica, Hispaniola, and Puerto Rico, represent fragments of the Caribbean oceanic plateau (Kerr et al. 1998). The thick (~20 km) oceanic crust of this plateau was formed on the Farallon plate above the Galapagos mantle plume during 100–89 Ma (Hastie and Kerr 2010). This thick and buoyant oceanic crust resisted subduction and was decoupled from its lithospheric mantle,



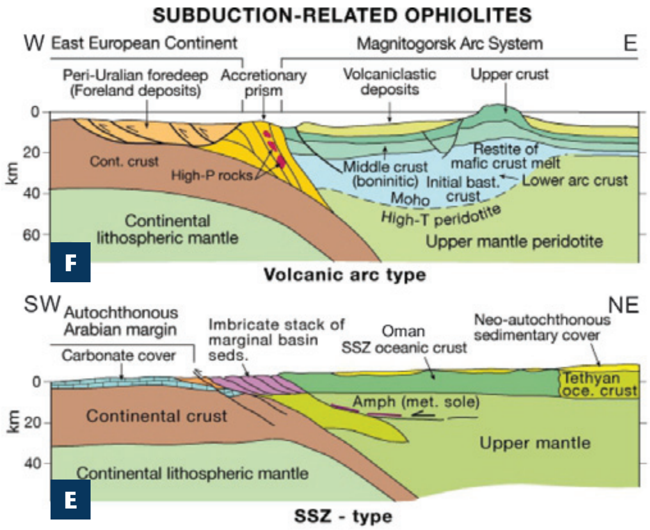


Figure 3 Select ophiolite types and their emplacement mechanisms. (**Left**) Subduction-unrelated ophiolites: (**A**) Continental margin–type Ligurian ophiolites between Europe and Adria. (**B**) Ridge-proximal Macquarie ophiolite, Southern Ocean, and subduction initiation along a transpressional, transform plate boundary. (**C**) Taitao ophiolite, southern Chile, and its emplacement via ridge–trench interaction. The ophiolite and the continental margin rocks are intruded by granitic plutons, whose melt evolution started as a result of ridge subduction. (**D**) Plume-type Caribbean ophiolite slices in a metamorphosed accretionary prism in western Colombia. (**Right**) Subduction-related ophiolites: (**E**) Suprasubduction zone (SSZ)–forearc Oman ophiolite and its metamorphic sole thrust onto the rifted margin of the Arabian plate. (**F**) Magnitogorsk volcanic arc ophiolite resting tectonically on a blueschist-bearing accretionary prism and the East European continental margin. See text for discussion.

which continued to subduct, and tectonic slices of basaltic lavas, gabbros, and ultramafic rocks were accreted into the upper-plate continental margin (Hastie and Kerr 2010). In western Colombia, basaltic, doleritic, and gabbroic rocks are tectonically intercalated with metasedimentary rocks of the accretionary prism of the northern margin of South America (Fig. 3d).

Suprasubduction Zone Forearc Ophiolites: Oman Ophiolite

The ~15 km thick Oman ophiolite is a remnant of the Tethyan oceanic lithosphere (Goodenough et al. 2014 this issue); it forms the uppermost tectonic nappe in an imbricated stack of oceanic rocks in the southeastern part of the Arabian Peninsula (Figs. 3e, 4). The Oman ophiolite rests tectonically on a discontinuously exposed metamorphic sole or a subophiolitic mélange. The metamorphic sole beneath the ophiolite shows inverted temperature and pressure gradients, indicating that it is a composite of rock slices formed at different depths and juxtaposed later by thrust faulting (Hacker et al. 1996). Pressure–temperature data suggest high-temperature metamorphism at the inception of oceanic subduction beneath the hot subophiolitic mantle in the upper plate. The forearc oceanic lithosphere of the Tethyan Ocean was displaced from its tectonic setting above this new subduction zone and was emplaced onto the Arabian margin during the continent–trench collision.

Volcanic Arc Ophiolites: Magnitogorsk Arc

The Magnitogorsk island arc system in the Urals consists of an early Devonian subduction-initiation-related volcanic complex, which is composed of high-Mg basalt, basaltic andesite, picrite, boninitic lavas and dikes, and volcaniclastic rocks. These units are overlain by early to middle Devonian calc-alkaline volcanic rocks. This volcanic complex is tectonically underlain by an accretionary prism (Fig. 3f), which includes west-vergent thrust sheets composed of metapelitic rocks, serpentinite-matrix mélange, and blueschist to eclogitic rocks (Brown et al. 2006). The protoliths of these high-pressure rocks were the passive margin units of the partially subducted East European continental margin. The emplacement of the Magnitogorsk arc system onto the East European continent was facilitated by the partial subduction of the continental margin rocks beneath the forearc (Fig. 3f).

GLOBAL DISTRIBUTION OF OPHIOLITES AND OPHIOLITE PULSES

Figure 4 shows the global distribution of Phanerozoic orogenic belts, along with representative examples of various ophiolite types (marked in different colors) and their ages. The evolution of orogenic belts of accretionary origin involved the tectonic amalgamation of oceanic terranes, such as seamounts, oceanic plateaus, and volcanic arcs, into long-lived, active continental margins facing large oceans. Important examples include the Central Asian Orogenic Belt, the North American Cordillera (including the Aleutians), the Andes, the peri-Caribbean belt, and the Japanese islands (Fig. 4). The Cordilleran, western Pacific, and peri-Caribbean orogenic belts mainly include scraped-off fragments of MOR- and P-type ophiolites that are commonly associated with accretionary prism and high-pressure metamorphic rocks (Kerr et al. 1998). The tectonic history of collisional orogenic belts involved multiple collisions between microcontinents, intraoceanic arc–trench systems, and continents following the closures of ocean basins. Examples are the Mesozoic Alpine–Himalayan and the Paleozoic Appalachian–Caledonian–Uralian orogenic belts. Collisional orogenic belts commonly display a record of rift–drift, seafloor spreading, and subduction typical of the Wilson cycle. Therefore, it is not uncommon to see CM, MOR, and SSZ ophiolites nested along and across the suture zones in these belts.

The distribution of certain ophiolite types during particular time periods coincides with major tectonic and magmatic events in Earth history. For example, the formation of the late Paleozoic and Jurassic CM ophiolites was coeval with the dismantling and rifting of the northern edge of western Gondwana. The development of the Jurassic–Cretaceous P-type ophiolites overlapped in time with the emplacement of giant dike swarms and the formation of large igneous provinces (LIPs) (Kerr et al. 1998; Vaughan and Scarrow 2003) and with the breakup of Pangea through discrete episodes of continental rifting (Dalziel et al. 2000).

The main ophiolite pulses—that is, peak times of ophiolite genesis and emplacement— in the early Paleozoic, the late Jurassic, and the Cretaceous reflect the timing of SSZ ophiolite formation, which was contemporaneous with the

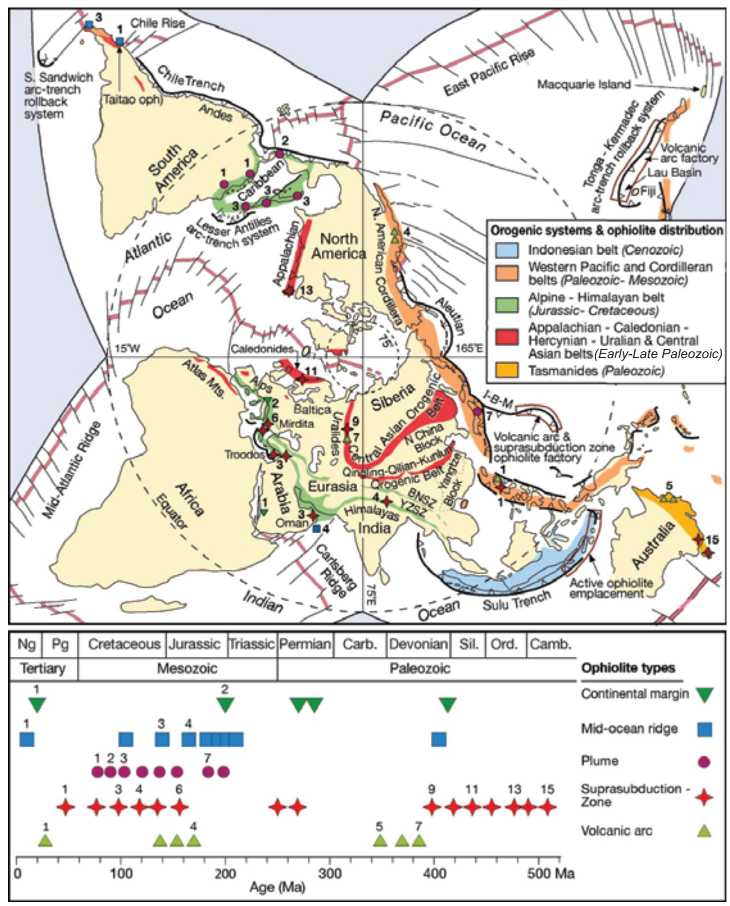


Figure 4 (**Top**) North polar projection showing the global distribution of Phanerozoic orogenic belts and examples of different ophiolite types. The two main arc–trench rollback systems, the Izu-Bonin-Mariana (IBM) and Tonga-Kermadec, are sites of modern ophiolite factories. Subduction of the northwestern Australia passive margin beneath the Sunda arc–trench system marks a modern example of ophiolite emplacement via collision. (**Bottom**) Examples of different ophiolite types and their distribution through time (identified by a number and color): continental margin type (dark green, upside-down triangle): 1–Tihama (Red Sea, Saudi Arabia), 2–Ligurian (Italy); mid-ocean ridge type (blue square): 1–Taitao (Chile), 3–Rocas Verdes (Chile), 4–Masirah (western Indian Ocean); plume type (purple circle): 1–Loma de Hiero (Venezuela) and Bolivar (southwestern Colombia), 2–Nicoya (Costa Rica), 3–peri-Caribbean (Cuba, Puerto Rica, Hispaniola); suprasubduction zone type (red star): 1–Zambales (Philippines), 3–Troodos (Cyprus), Kizildag (Turkey), and Semail (Oman), 4–Xigaze (Tibet, China), 6–Mirdita (Albania) and Pindos (Greece), 9–Magnitogorsk (southern Urals, Russia), 11–Solund-Stavfjord (southwestern Norway), 13–Bay of Islands (Canada), 15–Lachlan (southeastern Australia and Tasmania); volcanic arc type (light green triangle): 1–Itogon (Philippines), 4–Smartville and Josephine (California), 5–D'Aguilar (eastern Australia), 7–Magnitogorsk (Russia). Ng, Neogene, Pg, Paleogene.
Modified from Dilek and Furnes (2011)

closure of some ocean basins and major orogenic events (Dilek and Furnes 2011). The early Paleozoic SSZ ophiolites in the Appalachian and Caledonian orogenic belts evolved in the Iapetus Ocean and its seaways between North America, Greenland, and Baltica-Avalonia as they were closing. The Paleozoic SSZ ophiolites in Iberia, central Europe, northwestern Africa, and northern Anatolia developed in the Rheic Ocean between the Baltica-Avalonia, Laurasia, and Gondwana continental masses. The Paleozoic SSZ ophiolites in the Uralides developed in the Uralian Ocean, which separated the Baltica-Eastern Europe and Kazakhstan-Siberian continental masses (Windley et al. 2007). The late Jurassic to late Cretaceous SSZ ophiolites in the Alpine–Himalayan orogenic belt (Fig. 4) formed in various seaways of the Tethyan oceanic realm, preceding the collisions of Apulia, Arabia, India, and other Gondwana-derived microcontinents with Eurasia.

Although there appear to be spatial–temporal relationships between the formation and distribution of ophiolite types and major tectonic and magmatic events, the relative abundances of these various ophiolite types do not reflect the proportions of the different types of oceanic lithosphere that were generated. Rather, these abundances are a result of ophiolite formation, emplacement, and preservation, as discussed earlier. For example, the vast majority of MOR-generated oceanic lithosphere has been subducted. Hence, MOR ophiolites are scarce (in comparison to other ophiolite types) in the rock record, even though MOR crust is the most common type in the modern ocean system.

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