the deep polar seas, from where these waters outflow into all other oceans.

Cross-References

- ▶ Alkali and Alkaline Earth Metals
- ▶ Carbonate Minerals and the CO2-Carbonic Acid System
- ▶ Chlorine
- ▶ Evaporites
- ▶ Geochemistry
- ▶ Hydrothermal vents
- ▶ Magnesium
- ▶ Ocean Biochemical Cycling and Trace Elements
- ▶ Sodium

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Oceanic Island Basalts

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Definitions

Ocean island basalts (generally referred to as OIBs) are a type of basalt erupted within the oceans, mainly in intraplate settings. Thus, OIB volcanism contrasts with the other principal types of volcanism in the ocean basins that occur along plate boundaries: mid-ocean ridge basalt (MORB) volcanism, where basalt is erupted at divergent plate boundaries, and subduction zone (or arc) volcanism, where lavas are formed in association with subduction at convergent plate boundaries. OIBs are erupted at volcanic hotspots, which correspond to the surface location of upwelling mantle plumes. Mantle plumes are buoyantly upwelling regions of the mantle that are thought to have unusually high mantle temperatures.

OIB, Hotspots, and Mantle Plumes

Many hotspots are located in intraplate settings in the oceans. However, some hotspots are colocated with mid-ocean ridges (e.g., Iceland hotspot), and at least one hotspot is located near a subduction zone, and complicated plume-trench interactions are suggested (e.g., Samoa hotspot). In the latter case, the subducting Pacific plate may interact with the upwelling Samoan plume, drawing the plume toward the downgoing slab (Druken et al. 2014).

While the term "ocean island basalt" corresponds to rock formed by intraplate volcanism that occurs in the ocean basins, OIBs are not always basaltic. OIBs encompass a broad range of compositions and span both tholeiite and alkali basalt compositions. While primitive OIBs are basaltic, highly evolved equivalents also exist, and intraplate hotspot lavas with phonolitic, trachytic, or dacitic compositions also occur. In fact, rhyolitic eruptions are common at the large central volcanoes of Iceland, and these provide an important example of the extreme variation in lava compositions identified at oceanic hotspot localities. Carbonatites, which are mantle melts composed of primary mantle carbonates, offer an additional example of the extreme compositional variability present in oceanic hotspot lavas.

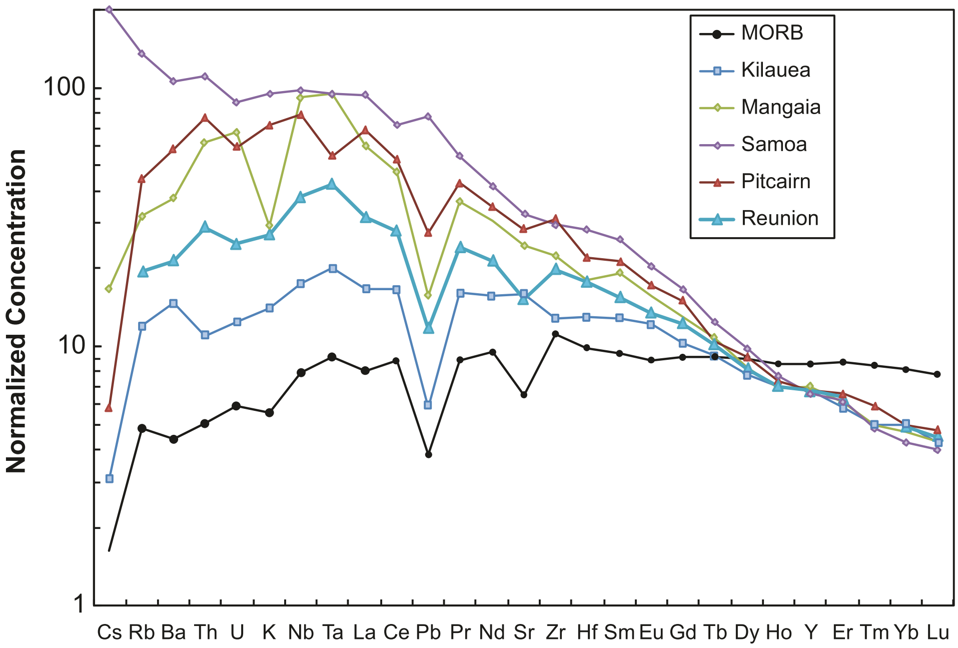
Ocean island basalts do not erupt strictly on islands. In fact, most of the volume of intraplate hotspot volcanism is erupted underwater. Many intraplate hotspot volcanoes never breach the water surface to erupt lavas subaerially, and these hotspot volcanoes exist as submarine seamounts for their entire lifespan. Oceanic hotspot volcanoes that do breach the water surface to become islands ultimately subside thermally after volcanism ceases. Thus, the processes of thermal subsidence and subaerial erosion, which effectively reduce the mass of the volcano above water, act to turn ocean islands into seamounts. Indeed, most OIBs are actually found as seamounts (Staudigel and Koppers 2015).

OIBs erupted at the Hawaiian (Weis et al. 2011) and Louisville (Koppers et al. 2012) hotspots can be explained by upwelling of a deep-seated, thermally buoyant mantle plume that partially melts beneath the oceanic plate, and the resulting melts upwell to feed an active hotspot volcano that resides above the hotspot. Because mantle plumes generally drift slowly with respect to plate velocities at the surface, a chain of age-progressive hotspot volcanoes forms over the upwelling mantle plume as the plate moves laterally over the hotspot: younger, active volcanoes are found near the hotspot, and volcanoes further downstream (in the direction of plate motion) are older and volcanically inactive. Most major hotspot-related island chains appear to be plume related (French and Romanowicz 2015), and some hotspot chains are long lived: the Hawaii and Louisville chains have produced volcanism for just over 80 million years, and it is proposed that hotspots currently active in the Cook Islands have been active for over 100 million years (Koppers et al. 2003). In the Indian Ocean, the volcanism associated with the Kerguelen mantle plume spans an age range of ~120 million years (Frey et al. 2000).

However, there does not appear to be a single mechanism responsible for generating hotspot volcanism in the ocean basins. Not all OIB localities are associated with age-progressive chains of volcanoes. Instead, some OIBs are erupted as isolated seamounts that are not part of a chain (e.g., Bermuda), and these isolated seamounts do not clearly relate to a deep-seated or long-lived plume. OIBs are also erupted along chains that do not exhibit age progressions (e.g., the Pukapuka ridge; Janney et al. 2000) and are thus not easily explained by volcanism that results from an upwelling mantle plume. The mechanisms responsible for hotspot volcanism and OIB generation at these localities are not well understood, but could relate to melting of fertile blobs in the upper mantle or shallow melting that results from tectonic stresses in the lithosphere (e.g., Sandwell et al. 1995). These alternative mechanisms for generating hotspot volcanism are not unimportant: there are >45,000 seamounts that extend >1 km above the ocean floor (Staudigel and Koppers 2015), and most of these seamounts are not clearly related to plume-fed hotspot chains.

Geochemistry and Crustal Recycling

The trace element characteristics of OIB vary considerably. Tholeiitic OIB erupted at localities like Hawaii is less enriched in incompatible elements (e.g., Rb, Ba, Th, U) – which prefer to be in the melt relative to the solid mantle that partially melted to generate the melt – than alkalic OIB (Fig. 1). While this may reflect enrichment of incompatible elements in the mantle source of alkalic OIB compared to the mantle source of tholeiitic lavas, a more likely explanation is that alkalic OIBs are the result of lower degree melting of the mantle than tholeiitic OIBs. Indeed, low degrees of mantle melting concentrate the incompatible elements in the melt relative to high degree melting (Schilling and Winchester 1967; Hofmann 2003). The degree of melting depends on both the mantle temperature and the depth to which upwelling mantle can rise. Evidence suggests that mantle plumes are hotter than the ambient depleted upper mantle that sources MORB melts (Putirka et al. 2007; Herzberg et al. 2007), yet hotspot lavas at many localities appear to be the result of low degrees of melting. The paradox of low degree melting at many hotspot localities might be explained by the role of oceanic lithosphere, which is thick in regions where the oceanic plate is old. A thick oceanic lithosphere serves to stop plume upwelling and effectively halts further adiabatic melting, thereby reducing the degree of melting (Dasgupta et al. 2010).

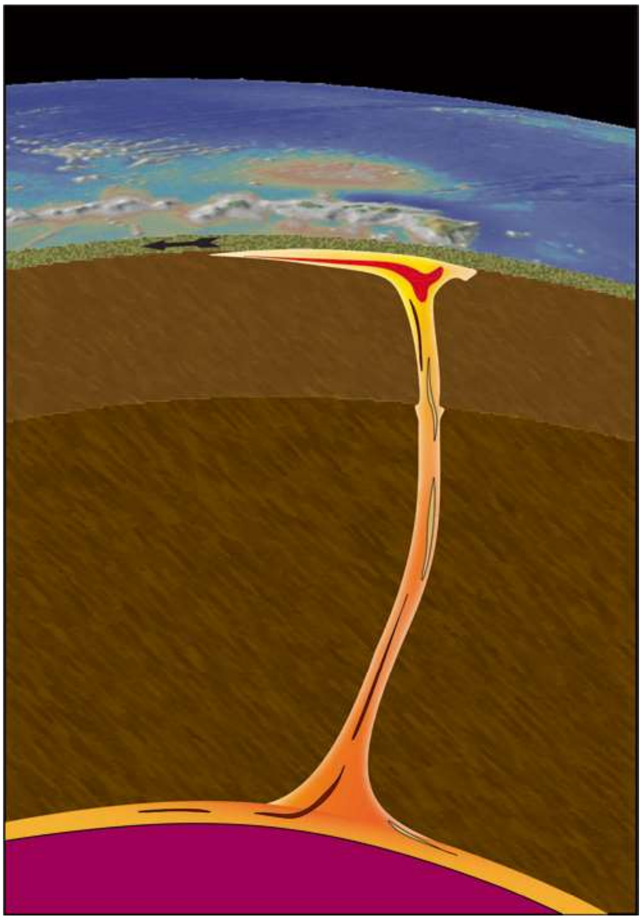


Oceanic Island Basalts, Fig. 1 Primitive mantle normalized trace element patterns for OIB from different localities. Alkalic OIB from Pitcairn, Samoa, and Mangaia is more enriched in incompatible elements than tholeiitic lavas from Hawaii and MORB tholeiites. (Figure modified after White (2013), except for Mangaia (Woodhead 1996) and MORB (Gale et al. 2013).)

The composition of the mantle that melts to generate OIBs provides important insights into the evolution and dynamics of the mantle over geologic time. Unlike major and trace elements, radiogenic isotopic ratios, like $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, and $^{206}Pb/^{204}Pb$, are not fractionated between the mantle and melts that are extracted from the mantle and as such are "fingerprints" of the mantle source of the melts. These isotopic systems provide a window into the composition of the inaccessibly deep Earth that is sampled by OIB. For over five decades, it has been known that basalts from different oceanic islands exhibit heterogeneous radiogenic isotopic compositions (Gast et al. 1964), and the global radiogenic isotopic variability observed in OIBs is described by at least four different isotopic end-members that are often referred to as HIMU (high μ, = $^{238}U/^{204}Pb$), EM1 (enriched mantle I), EM2 (enriched mantle II), and DM (depleted mantle). However, the origin of this isotopic variability is still the source of debate. A long-standing hypothesis is that subducted oceanic crust (Hofmann and White 1982) and continental crust (White and Hofmann 1982) that are isotopically heterogeneous can explain much of the radiogenic isotopic diversity observed in OIB globally. Large amounts of oceanic crust (20 km^3/year) and sediment derived primarily from the continents (0.5–0.7 km^3/year) are subducted into the mantle. If subduction has been operating for three billion years, and if subduction of oceanic crust has been constant over that time period, then ~4% of the mantle's mass is comprised of subduction oceanic crust. Similarly, ~0.1% of the mass of the mantle is subducted sediment. This subducted material enters the convecting mantle where it can reside for billion-year time scales, before being recycled into the mantle source of OIB. OIB from different localities has distinct radiogenic isotopic compositions that have been linked to a diversity of crustal protoliths of different ages that were subducted into the mantle. Stable isotopic measurements of OIB, including oxygen isotopes and mass independently fractionated sulfur isotopes (Eiler et al. 1997; Cabral et al. 2013), support the hypothesis that OIB sample melts of crustal protoliths that were once at the Earth's surface. Additionally, OIB exhibits incompatible element-enriched radiogenic isotopic signatures (higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and lower $^{143}Nd/^{144}Nd$) that provide powerful evidence that the mantle sources of these hotspots have been enriched by recycling of ancient subducted crustal material into the shallow upper mantle. In comparison, MORB derived from the upper mantle by higher degrees of partial melting tend to exhibit more incompatible element-depleted (lower $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and higher $^{143}Nd/^{144}Nd$) radiogenic isotopic compositions. Thus, plate-tectonic processes operating at the surface, including subduction, ultimately control the composition of the mantle sources that melt to generate OIB (Fig. 2).

Primordial Signature from the Deep Mantle

While OIB samples material that was subducted into the mantle, some OIB thought to be sourced by deep-seated mantle plumes exhibits primitive noble gas characteristics (Courtillot et al. 2003). For example, compared to MORB sampling the upper mantle, OIB can have elevated $^{3}He/^{4}He$ ratios that are associated with the primitive materials that constitute the building blocks of the terrestrial planets. The preservation of high $^{3}He/^{4}He$ in the mantle sources of these lavas suggests that



Oceanic Island Basalts, Fig. 2 The Hawaiian hotspots are thought to be fed by a buoyantly upwelling mantle plume that rises from the core-mantle boundary. (From White, 2014.)

ancient, primitive domains have survived in the mantle in spite of convective mixing processes that have operated in the mantle since Earth's accretion at >4.5 Ga. Supporting the hypothesis that high $^{3}He/^{4}He$ domains sample ancient domains preserved in the mantle, Mukhopadhyay (2012) found that high $^{3}He/^{4}He$ OIB exhibits different $^{129}Xe/^{130}Xe$ than MORB and the Earth's atmosphere. Because all $^{129}Xe/^{130}Xe$ isotopic heterogeneity in the Earth was generated during the lifetime of ^{129}I (half-life of 15.7 million years), the discovery of low $^{129}Xe/^{130}Xe$ in hotspot lavas indicates that the high $^{3}He/^{4}He$ reservoir formed within ~100 million years of Earth's accretion.

Some OIBs are melts of mantle domains that host ancient, primordial signatures and other OIB sample mantle domains that have a component of subducted crust that has been incorporated (recycled) into the mantle that melts to form OIB. In fact, many OIBs exhibit a mixture of primitive and recycled signatures. Regions of anomalously slow seismic velocity in the deepest mantle, referred to as large low shear wave velocity provinces (LLSVPs), are suggested to host both primitive and subducted crustal material that may be intimately associated within the LLSVPs (Li et al. 2014). The bases of deep-seated mantle plumes may extend to the LLSVPs. If mantle plumes are sourced by the LLSVPs, these plumes may convey primitive and subducted material to the shallow mantle where they are melted to generate OIB melts.

Summary

Ocean island basalts result from melting hot, buoyantly upwelling mantle beneath the world's ocean basins. Ocean island basalts sample ancient subducted crust that has been recycled through the mantle. These basalts also provide evidence that ancient, primordial reservoirs have survived in the deep Earth since accretion.

Cross-References

▶ Formation and Evolution of the Earth
▶ Geochronology and Radiogenic Isotopes
▶ Incompatible Elements
▶ Mantle Geochemistry
▶ Mid-Ocean Ridge Basalts (MORB)
▶ Partial Melting

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Oil Seeps and Coastal Bitumen

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Definitions

An **oil seep** is a place where liquid or semi-solid petroleum, commonly in association with gaseous hydrocarbons, escapes at a low rate to the Earth's surface. Those located on the sea floor produce tar or asphalt that may eventually be transported to the shore where it strands as **coastal bitumen**.

Introduction

Each year an estimated 600,000 metric tons of oil enters the global marine environment from natural seepage (NRC 2003), accounting for 47% of the total annual input and making it the single most important contributor of oil to the world's oceans (Kvenvolden and Cooper 2003). In the wake of major accidental releases of crude oil, such as the *Exxon Valdez* tanker spill in Prince William Sound, Alaska (Kvenvolden et al. 1995), and the *Deepwater Horizon* blowout in the Gulf of Mexico (Boufadel et al. 2014), it becomes necessary to distinguish the resulting marine tar residues from coastal bitumen (natural or anthropogenic) already present on the adjacent shorelines. This is achieved using various isotopic and molecular fingerprinting techniques (Peters et al. 2005).

Seep Locations

One of the first studies of global marine oil seepage, dating from a time when reports of marine seeps were scarce, concluded that there is a strong correlation between areas of high seepage potential and tectonic activity, best exemplified by the tectonically unstable circum-Pacific region (Wilson et al. 1974). Hydrocarbon seeps are now known to be widespread along both active and passive continental margins, and the mechanisms of their formation are varied. Numerous examples are described by Abrams (1996) and Judd and Hovland (2007). Typically, petroleum fluids are released to the seabed from over-pressured subsurface reservoirs where the cap rock has been breached by diapir intrusion, faulting, or other fractures. The resulting seeps are manifest on the seabed as