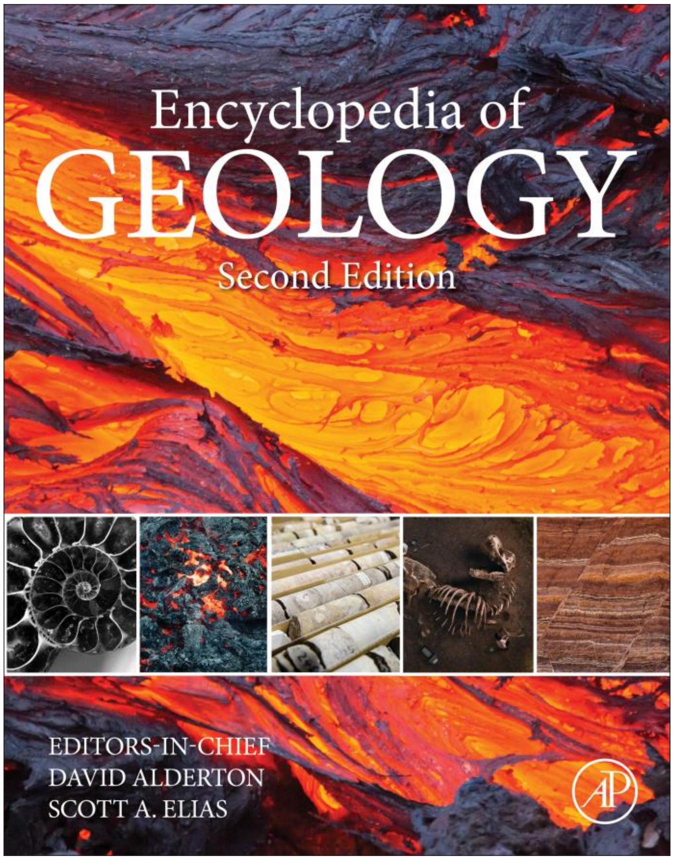

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The Plate Theory for Volcanism

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Statement of Plate Theory

The Plate Theory for volcanism proposes that all terrestrially driven volcanism on Earth's surface, including at unusual areas such as Iceland, Yellowstone and Hawaii, is a consequence of plate tectonics. Specifically, the Theory proposes that volcanism occurs in response to lithospheric extension which permits melt to escape to the surface. This melt may pre-exist in the crust and/or mantle and, if the extension is sufficient to thin the lithosphere and permit the asthenosphere to rise, magma volumes may be supplemented by additional melt formed by decompression upwelling (Fig. 1).

The spatial distribution of volcanism at any one time reflects the instantaneous lithospheric stress field. Changes in spatial distribution of volcanism with time reflect evolution of the stress field. Regular time-progressive volcanism that forms linear volcanic chains, or other spatial patterns, indicate evolution of the stress field. This in turn results from evolution of the factors that govern the plate stress field. Those include cooling and contraction of the lithosphere, vertical motions driven by isostasy, and changes in the global plate-boundary configuration, e.g., the subduction of a spreading ridge.

In Plate Theory the active element driving volcanism is the lithosphere and not the asthenosphere or deeper regions of the mantle. Lithospheric extension is required for magmatism to occur. The mere presence of melt in the crust or mantle is not a sufficient condition to explain volcanism. The processes that cause lithospheric extension are the driving factors and melt escape to the surface is passive.

Background, History, Development and Discussion

The theory of plate tectonics, developed in the late 1960s and 1970s, explained spectacularly well a large majority of volcanism on Earth's surface. This includes volcanism at spreading plate boundaries, where plates move apart and asthenosphere upwells, decompresses and produces the melt that is erupted and intruded at the near surface to form new oceanic crust. At subduction zones, dehydration of downgoing slabs fluxes the mantle wedge above with volatiles, lowering the solidus and producing partial melt. That partial melt is erupted at sites of back-arc extension including back-arc basins such as the Sea of Japan, and volcanic arcs such as the Aleutian arc.

Several apparently anomalous volcanic regions were, however, not obviously explained by rigid plate tectonics. These include the 450-km-wide island of Iceland, which lies astride the mid-Atlantic ridge in the northeast Atlantic Ocean, the Yellowstone-Eastern Snake River Plain system, and the Hawaiian archipelago and associated linear seamount chain. Explanations were particularly needed for the Hawaiian system. Its apparently regularly time-progressive volcanic chain seemed to offer a strong clue, once it was realized that the Pacific plate on which it lies moves northwest relative to the geomagnetic pole.

Early hypotheses proposed include the propagating crack theory (Jackson and Shaw, 1975), and the theory that a hot region existed in the asthenosphere over which the Pacific plate moved (Wilson, 1963). This raised the question of how the heat could have been constantly resupplied over the 80-Myr lifetime of the Hawaiian and Emperor volcano chains. It was suggested that this occurred via a narrow convection current rising from the core-mantle thermal boundary layer at ~3000 km depth in the Earth (Morgan, 1971).

The latter hypothesis—that of mantle plumes—was extended to other volcanic regions considered to be sufficiently far from the rigid-plate-tectonic norm that a different causative mechanism seemed necessary. It attributed excess melt to high source temperatures and considered the melt-formation process to drive the volcanism with the lithosphere essentially passive. The study of volcanic anomalies then became an exercise in mapping melt in the mantle.

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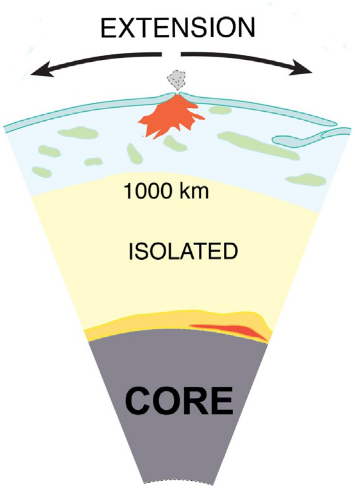

Fig. 1 Schematic illustration of the Plate Theory for volcanism. Mid-blue: lithosphere, light-blue/green: the inhomogeneous upper mantle, yellow: lower mantle, orange: core-mantle boundary region. Extension of the lithosphere permits pre-existing melt (red) to rise passively from shallow depth and supply surface volcanism.

Mantle plumes became the preferred working hypothesis for ~20 years. However, the most direct test of it that can be made—measurement of the mantle source temperature—is a notoriously difficult problem. Lavas erupted at Earth's surface derive from polycrystalline materials of poorly known composition and depth (pressure) and have complex histories of partial melting, partial crystallization and magma mixing on their journey to the surface. Any inferences from their petrology regarding source temperature, composition or location suffer badly from the inverse problem, i.e., interpretations of data are highly ambiguous. Supporting methods applied to constrain some unknowns, e.g., using seismology to constrain source depth, measure physical parameters that are at best only weakly correlated with petrology and also suffer from their own interpretive ambiguities. Meanwhile, the assumption, in the absence of compelling evidence, that the sources of unusual volcanism are exceptionally hot, became intrenched in geological thinking by popularization of the catchphrase "hot spot."

Other predictions of the mantle-plume hypothesis, e.g., the formation of a steadily dwindling, time-progressive volcanic chain, tended to defy confirmation. This and other difficulties resulted, early in the 21st century, in other hypotheses being explored in particular those that widened the scope of volcanism attributable to plate tectonics (Foulger et al., 2005). Relaxing the assumption that Earth's tectonic plates are rigid offered the possibility that the extension at spreading plate boundaries essentially comprises an extreme end-member and that extension also occurs in plate interiors. This is clearly true for regions such as the Basin Range province, United States, and areas where dikes and plutons intrude the crust and take up intraplate crustal extension.

Lithospheric Extension

Generalized intraplate extension is shown by non-closure of plate-motion circuits, which is up to a few mm a^{-1}, the equivalent of an additional slow-spreading plate boundary. Such extension results primarily from three processes:

1. Evolution of the plate-boundary configuration, including slab roll-back, the annihilation of plates or plate boundaries, and the creation of new ones. Because plate tectonics on the surface of Earth is a closed system, a change in one plate boundary will affect the entire global system.
2. Vertical motions consequential to such processes as delamination of the lower crust and mantle lithosphere and isostatic motions in response to erosion, mountain building or changes in the mass of icecaps.
3. Thermal contraction of the lithosphere (e.g., Kreemer and Gordon, 2014). This may be particularly strong in large plates, e.g., the Pacific plate.

Extension resulting from these processes manifests itself in structures and regions such as:

- Continental rift zones, e.g., the Rhine Graben, the East African Rift and the mid-American Rift;
- Diffuse oceanic plate boundaries, e.g., Iceland and the India-Australia plate boundary (Foulger et al., 2019b; Zatman et al., 2005);
- Continental back-arc extensional areas, e.g., the Basin Range province, United States, and the Tyrrhenian Sea;
- Oceanic back-arc basins, e.g., the Manus Basin;
- Fore-arc regions, e.g., the western Pacific (Hirano et al., 2006); and
- Continental regions undergoing lithosphere delamination, e.g., New Zealand (Stern et al., 2013).

The breakup of supercontinents and development of new oceans begins with continental rifting. This may nucleate in zones of pre-existing structure and begin in shear, which pre-weakens the lithosphere. Disintegration of continents progresses to ocean crust formation where strong, localized, persistent, extensional zones develop that are accommodated 100% magmatically. These are classified as spreading plate boundaries and, in first-order plate tectonics, form boundaries of rigid plates. Where extension is isolated and ephemeral it is considered to be intraplate. It occurs in both oceanic and continental crust and its characteristics range from close to those of spreading plate boundaries, e.g., at the East African Rift, to small-scale, diffuse, and intermittent. Magmatism may occur at any of these sites.

A region that exhibits a wide spectrum of extension styles is the northeast Atlantic Realm (Foulger et al., 2019a). Intracontinental rifting, testifying to an unstable lithosphere, occurred in the region from the Late Paleozoic. Final, catastrophic destabilization occurred in the late Cretaceous/Early Paleocene, possibly as a result of rollback of the Alpine slab which induced distributed extension throughout the European hinterland. Extreme rifting nucleated along the older Caledonian suture. Final localization of extension and onset of oceanic crust formation occurred at 54 Ma in the northeast Atlantic. At the latitude of Iceland, diffuse continental extension persisted.

Some major continental rift zones may be thought of as failed continental breakup axes. Several comprise an arm of a triple junction. For example, the East African Rift connects with the Red Sea and the Gulf of Aden, which proceeded to sea floor spreading. The two arms of the Mid-American Rift comprise a triple junction with a third which rifted the Amazonia craton from Laurentia at ~1.1 Ga (Stein et al., 2018).

The western United States also hosts diverse volcanism related to lithospheric extension. The ~1500-km Cascade volcanic arc extends from British Columbia to California forming a classic back-arc volcano chain. Diffuse extension persists throughout a region now ~1000 km broad via normal faulting—the Basin Range Province. Small-volume volcanism is scattered throughout this region.

The vast Pacific plate, which covers about 1/3 of the globe, experiences significant internal extension as a result of thermal contraction of the lithosphere. This process amounts to a few mm a^{-1} of both extensional and shear deformation. The region with the greatest shear deformation gradient is an east-west swathe extending from Samoa to the Easter microplate on the East Pacific Rise (e.g., Kreemer and Gordon, 2014). This zone contains an abundance of young volcanic features and island/seamount chains, including the Cook-Austral chain, the Marquesas and Society Islands, the Tuamotu Archipelago, the Fuca and Pukapuka ridges and Pitcairn Island.

Melt in the Mantle

The total volume of magma, both intruded and erupted, at a region of extension is dependent on two factors:

- the availability of pre-existing melt, and
- the amount added to this by upwelling decompression melting. This is governed by the thickness of the lithosphere, the amount of extension, and the fusibility and temperature of the source.

Pre-existing melt is widespread in the crust and mantle. It is prima facie stored in the crust beneath active volcanoes where relatively shallow reservoirs are fed by deeper ones. A small percentage of partial melt, perhaps up to 1%, is retained in the asthenospheric seismic low-velocity zone between ~50 and 150 km depth (Sifré et al., 2014). Geophysical data, including field seismological observations and laboratory measurements of parameters such as seismic attenuation and electrical conductivity, show that such melt exists. Petrological modeling suggests that it likely results from lowering of the mantle solidus by CO_2. This partially molten layer is thought to provide the weak layer that lubricates plate motions. As a result of this pre-existing melt, magmatism can occur where lithosphere extension is modest and induces little or no decompression upwelling. Such magmatism is expected to be relatively minor in volume, e.g., at the Cameroon and Pitcairn-Gambier volcanic lines.

When asthenosphere rises and decompresses, the rate at which melt is formed is strongly dependent on the height to which the asthenosphere can rise, i.e., the depth to the base of the lithosphere. The lithosphere is thinnest at mid-ocean ridges and thickest beneath cratons. Numerical modeling shows that the largest flood basalts erupted in both these environments cannot have been supplied by melt produced by upwelling decompression on the same timescale as emplacement (Cordery et al., 1997). It thus follows that the melt must have formed over a longer time period than eruption, accumulated in a reservoir, and erupted when released by stress conditions in the lithosphere. The feature most capable of functioning as a retaining cap for such melt reservoirs is the lithosphere/asthenosphere boundary.

The development of major magma reservoirs at the base of the lithosphere is surprising because large percentages of partial melt are not expected to be retained in the mantle. Nevertheless, it appears to be required by observations at some large-volume magmatic provinces, e.g., the Great Dyke (Zimbabwe) and the Bushveld complex (South Africa) (Silver et al., 2006). In those cases, xenolith evidence shows that the lithosphere was thick and remained intact before, during, and after large-volume magmatism. As a result, melt production at a sufficient rate from massive decompression upwelling can be ruled out and the only alternative is that large volumes of melt must have pre-existed. It is possible, though not required, that smaller flood basalts may also have been produced by this process.

Where lithospheric extension and thinning is severe, permitting asthenosphere to upwell to shallow depth, sufficient melt may be formed by decompression melting to explain the magma volumes observed. This process can account for the magma volume rates necessary to feed oceanic crust formation at mid-ocean ridges, which are up to ~1 km^3 a^{-1} per kilometer of ridge. There, the lithosphere is thin and the ongoing magmatic rate modest. This process could also explain minor magmatism in or near continental rifts that extend slowly.

Where extremely thick lithosphere is ruptured and extension is strong and persistent, e.g., during continental breakup, vast volumes may be produced and form volcanic margins. Continents may have lithosphere up to ~200 km thick and on rupture asthenosphere upwells by this amount. Millions, or even tens of millions, of cubic kilometers of melt can be produced along axes hundreds of kilometers long. This occurred, for example, when the North Atlantic Ocean opened and large volumes of melt formed as the asthenosphere rose from the base of the Pangaean lithosphere to the surface. Catastrophic rupturing of the lithosphere likely induced massive delamination of its deeper parts and sinking of Rayleigh-Taylor instabilities, destabilizing the entire upper mantle and inducing local convection beneath. Numerical modeling has shown that this process can explain the volumes of melt observed along the Atlantic seaboards (Simon et al., 2009).

Studying Intraplate Volcanism

When volcanic activity occurs, it affects every aspect of the natural environment in its vicinity. As a consequence almost every sub-discipline of Earth science can contribute to understanding its source. This includes tectonophysics, structural geology, geochronology, sedimentology, geothermometry, geodesy, numerical modeling, mineralogy, petrology, geochemistry and geophysics. The history and philosophy of science can also play a role because methodological problems can hinder the development of new hypotheses. Methods aimed at studying the deep mantle are of little relevance.

Tectonophysics, the study of the physical processes that give rise to surface tectonic deformation, includes measurement or calculation of the stress- and strain fields on Earth's surface and the rheologies of the crust, mantle, lithosphere and asthenosphere. These govern processes on local and regional scales and at structural boundaries such as the destruction of continental crust via gravitational instability and oceanic crust via subduction, convection in the mantle which influences the amount of melt available, the history and origin of continental rifting and its continuation to supercontinent disintegration, and second-order effects of plate tectonics such as thermal contraction of the lithosphere.

Structural geology involves applying three-dimensional geological observations on local and regional scales to deduce the tectonic history that preceded volcanic activity. This method can unravel the evolution of the stress field that resulted in the final geology including vertical and horizontal motions, e.g., mountain building, basin formation, lithospheric shortening and, importantly, extension. Structural geology can organize key observational evidence concerning the deformation that culminated in volcanism. Structural geology is an important but under-used method in the study of intraplate volcanism.

Geochronology can provide key information regarding the time-progression of magmatism. It has shown, for example, that many flood basalts erupted relatively quickly. For example, the ~4×10^6 km^3 Siberian Traps were emplaced over about 40 Myr, but the majority was produced in just in 2–3 Ma. These findings were key in showing that some volcanism occurs on a timescale much shorter than any process can generate the melt (Section "Melt in the Mantle") leading to the conclusion that large accumulations of melt must be retainable in the mantle under some circumstances. Geochronology has also revealed the spatial development of volcanism. At some localities, e.g., the Cameroon volcanic line, basaltic volcanism has been ongoing along the entire line simultaneously, suggesting a linear zone of extension or persistent cross-lithospheric pathway for melt. In other cases, e.g., the Galapagos region, volcanism is scattered in time and space throughout a broad two-dimensional region (O'Connor et al., 2007). At the other end of the behavioral spectrum clear, linear time-progressions of volcanism have been documented, e.g., the Emperor-, Hawaii-, and Louisville volcano chains.

Sedimentology can be applied to study vertical motions—a key component of tectonics. Sedimentology can reveal the environment in which a rock formed, e.g., if a region was uplifting or subsiding before and after volcanism. Sedimentary stratigraphy of the rocks underlying the Siberian Traps was key to showing that the region was subsiding immediately prior to flood basalt eruption (Czamanske et al., 1998). This led to investigation of whether major delamination of the lower lithosphere could have triggered the volcanism (Elkins-Tanton and Hager, 2000). Likewise, sedimentary observations showed that evidence was lacking for regional, kilometer-scale uplift immediately prior to emplacement of the Emeishan basalts (Ukstins Peate and Bryan, 2008).

Geothermometry can help to distinguish between high-temperature or low-melting-point sources. Many methods and techniques have been tried, although not all are based on valid initial assumptions. Seismological methods include mapping the maximum depth of earthquakes, i.e., the depth at which brittle failure gives way to ductile flow, and the thickness of the igneous crust (Korenaga et al., 2002). Seismic wave speeds have been used to estimate temperature but this rests on the unverifiable assumption that other factors do not vary, e.g., composition, mineralogy or percentage of partial melt (Foulger et al., 2013).

Petrological and geochemical methods for estimating source temperature include mapping the variation of sodium and iron in lavas (Langmuir et al., 1992), determining mineralogical phase relations in laboratory experiments (Presnall and Gudfinnsson, 2008), olivine control-line modeling and rare-earth-element modeling. Other methods include using ocean-floor bathymetry under the assumption that oceanic crust subsides as it cools and is thus a proxy for temperature, and direct measurement of heat flow through the crust.

Geodesy can test the hypothesis that volcanism occurs in response to extension, the ultimate and most direct test of Plate Theory. Geodetic data are becoming increasingly available from dense, continuously recording Global Positioning System (GPS) networks. Intraplate deformation is an order of magnitude less than plate-boundary deformation, or even smaller, and secular deformation may be difficult to separate from episodic large-magnitude motions in seismically and volcanically active areas. In serendipitous situations deformation fields can give information about crustal rheological structure, as was accomplished in Iceland following a major dike injection event (Foulger et al., 1992; Heki et al., 1993).

Numerical modeling can test whether certain scenarios can be ruled out or whether they remain viable working hypotheses. A positive numerical modeling outcome, i.e., one that reproduces a given set of observations, is not "proof" that a model is correct but it can be a useful check on whether a model is worth pursuing. Successful models explain diverse geological observations, e.g., seismic, gravity, bathymetry and petrological data, and not just one kind.

Mineralogy, petrology and *geochemistry* can provide information about the composition of the source rock and the melting, melt-extraction, mixing and assimilation processes that melt underwent on its journey from source to surface. For example, geochemistry constrains the source of the Paraná flood basalt to be the continental lithosphere (Comin-Chiaramonti et al., 1997) and strongly suggests a such a component in Icelandic lavas also (Natland, 2007). It can, to a lesser degree, constrain the location of the melt source. For example, it can determine whether a melt formed in the plagioclase, spinel or garnet facies, which vary in depth from 0 to >60 km. Diamonds form in the deep lithosphere and their presence in volcanics suggests that the lithosphere was at least ~100 km thick when the volcanism occurred. Geochemistry can also provide comparative information, and isotope geochemistry can indicate the age of a component in the source.

Geophysics includes magnetic surveying, which is powerful to unravel the history of tectonism and magmatism in oceanic settings. Crustal seismology can measure layer thicknesses and, along with gravity data, provide subsurface information to inform structural geology. Electrical surveying, e.g., magnetotelluric sounding, can map layers with characteristic electrical conductivities that may comprise influential rheological features, e.g., ductile layers.

History and philosophy of science is particularly relevant to Plate Theory. At the time of writing Plate Theory is relatively young, largely developing in the first two decades of the 21st century in response to failures to confirm the predictions of mantle plume theory. The history of science contains many examples of the disproportionate difficulties in progressing new theories that challenge entrenched ones, the failure for 50 years to accept the reality of continental drift being the most notable geological example. The need to understand these difficulties makes the history and philosophy of science particularly applicable (Rossetter, 2020).

Methods that probe great depths in the mantle, including the deepest upper mantle and the lower mantle, are of little relevance to Plate Theory which predicts that volcanism is induced by lithospheric processes and fed by the shallowest melt available. Such methods are, in any case, challenged to provide deep geological information. Whole-mantle seismic tomography is used to map seismic wave-speed structure on a global scale but interpretation of seismic wave speeds in terms of petrology is ambiguous. Geochemical theories which purport to map melt sources in the deep lower mantle typically rely on untestable a priori assumptions that certain chemical tracers characterize those depths. Nevertheless, no geochemistry requires a source in the deep mantle. Although the results of mantle tomography and geochemistry are often combined, neither type of data has much power to reduce ambiguity in interpretations of the other.

In Plate Theory, the active element that induces melt to escape from the surface is the lithosphere. The occurrence of volcanism on Earth's surface is not explained by mapping the distribution of melt in the subsurface.

Examples

In this section Plate Theory will be illustrated by application to three type-examples of volcanic regions popularly considered to be exceptional in the context of plate tectonics. The most extreme volcanic anomaly on any plate boundary is Iceland, an extensive volcanic island that straddles the mid-Atlantic ridge in the northeast Atlantic.

The type example of a persistent intraplate continental volcanic anomaly is Yellowstone, United States, together with the Eastern Snake River Plain to its west. Hawaii, along with its associated linear chain of older islands and seamounts and their continuation to the NNW as the Emperor seamount chain, is arguably the most important currently active intraplate oceanic volcanic anomaly.

Iceland

Iceland is a 450 × 300 km, ~1-km high basaltic shield that straddles the mid-ocean ridge in the northeast Atlantic Ocean (Fig. 2). The accretionary plate boundary is exposed there as ~20 *en echelon* spreading segments, some in left-stepping- and others in right-stepping arrays. Iceland also exposes over 100 active or extinct central volcanoes, some with spectacular calderas and others without. The island has been studied extensively onshore and offshore for many decades, applying all the subdisciplines of Earth science listed in section "Studying Intraplate Volcanism" and more.

Iceland cannot be understood in isolation from the structure and tectonic history of the wider region. The northeast Atlantic formed when, after an extended period rifting, Pangaea broke up in the early Cenozoic with separation of Greenland from Eurasia. North of the future location of Iceland the new breakup axis, the Aegir Ridge, propagated south along the 400-Ma Caledonian suture, formed when an earlier ocean closed. South of the future location of Iceland the proto-Reykjanes Ridge breakup axis propagated north, splitting the North American Craton (Fig. 2). Intense magmatism emplaced several million cubic kilometers of magma, building volcanic margins along the coasts of Greenland and Scandinavia.

The new axis to the south formed ~100 km west of the axis to the north. The oppositely propagating tips of the two new axes stalled at the boundary of the Caledonian Suture, where the tectonic fabric was transverse to the direction of propagation. At this time they were still separated by ~300 km in the along-strike direction. The new rifts never ultimately joined up.

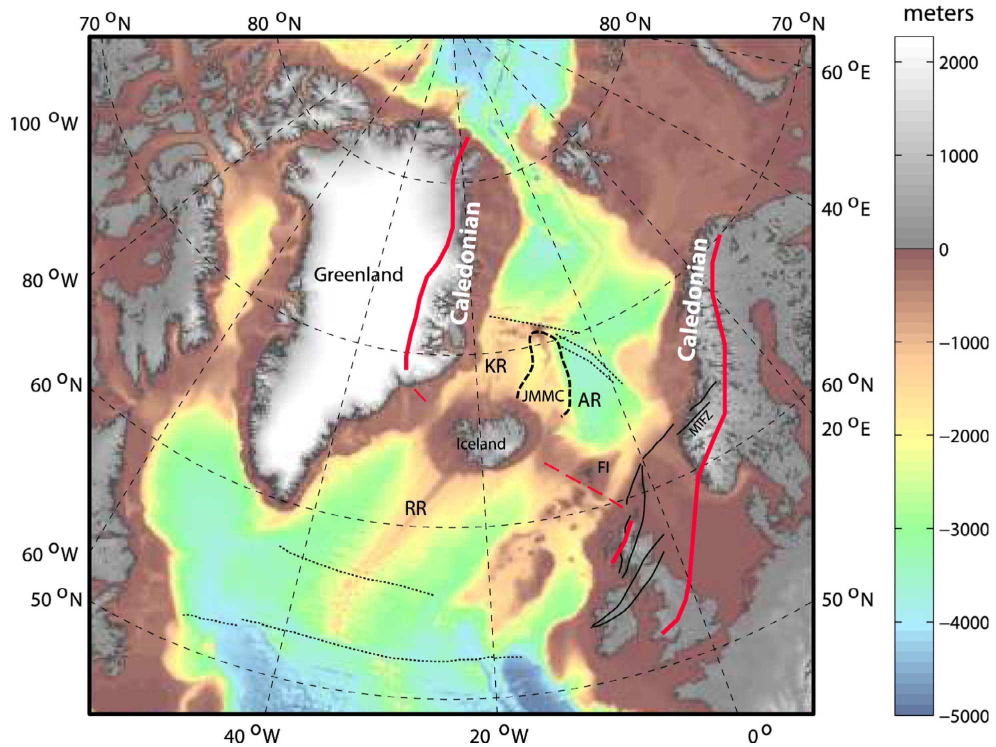

Fig. 2 Regional map of the North East Atlantic Realm. Bathymetry is shown in color and topography in land areas in gray. *RR*, Reykjanes Ridge; *KR*, Kolbeinsey Ridge; *JMMC*, Jan Mayen Microcontinent; *AR*, Aegir Ridge; *FI*, Faroe Islands. Red lines: boundaries of the Caledonian orogen and associated thrusts, dashed where extrapolated into the younger Atlantic Ocean. Adapted from Foulger GR, Doré T, Emeleus CH et al. (2019b) The Iceland Microcontinent and a continental Greenland-Iceland-Faroe Ridge. *Earth-Science Reviews* 206: 102926, https://doi.org/10.1016/j.earscirev.2019.102926.

While the new breakup axes developed to full seafloor spreading, the ~100 × 300-km continental region that separated the new rift tips, the Iceland Microcontinent (Foulger et al., 2019b), extended diffusely along multiple northerly orientated, parallel rift axes with diffuse shear between them. The continental crust stretched by ductile flow and was capped by intrusions and basalt lavas. This style of extension persists to the present day. In Iceland extension occurs across multiple parallel rift zones that have limited lifetimes and frequently become extinct to be replaced by new zones to the sides. Old, extinct rift zones have been mapped both in Iceland and offshore on the submarine ridges connecting Iceland to Greenland and the Faroe Islands.

Numerical modeling suggests that when Pangaea broke up at this latitude the thick crust and mantle lithosphere of the frontal Caledonian suture delaminated and was replaced by upwelling asthenosphere. This heated the lower crust, enhancing ductile flow in and around the Iceland Microcontinent.

This model provides an explanation for many unusual features in the Iceland area (Foulger et al., 2019b), the most striking of which are:

- The persistence of a subaerial land bridge between Greenland and the Faroe Islands which was not broken until the northeast Atlantic Ocean had attained a width of ~1000 km. Older parts then subsided below sea level and now form a shallow bathymetric ridge spanning the ocean (Fig. 2);
- Instability and tectonic decoupling of the spreading ridges immediately north and south of Iceland. To the north the early Aegir Ridge spread in a fan-shaped manner with extension grading from full sea-floor spreading at its northern end to distributed continental extension at its southern end. The Aegir Ridge became extinct at ~31–28 Ma and extension was transferred to a new ridge—the Kolbeinsey Ridge—which developed ~400 km to the west in the continental crust of Greenland. Sea floor spreading about the Kolbeinsey Ridge transported a block of continental crust—the Jan Mayen Microcontinent—into the ocean.

  South of Iceland the Reykjanes Ridge is also unstable but with an entirely different style. After ~16 Myr of spreading normal to the ridge strike, the direction of extension changed and the linear Reykjanes Ridge became a ridge-transform "stair step" array. Persistent instability subsequently migrated the ridge eastward via a series of southerly migrating ridge propagators that transferred ~30 km of the Eurasian plate to the North American plate. The onset of propagators correlates with ridge migrations in Iceland.
- The crust beneath the Greenland-Iceland-Faroe Ridge is generally 30–40 km thick. Its physical properties—low seismic wave speed coupled with high density—cannot be explained as thick oceanic crust. Instead, it has similar properties to high-velocity lower crust detected beneath the passive margins of Greenland and Scandinavia that is almost certainly magma-inflated continental crust.

In the light of these observations, it appears that the broad subaerial domal exposure of basalt on the mid-Atlantic ridge that is Iceland results from persistent distributed extension in a local continental area whose structure is unfavorable to extension in the dominant regional direction. This has led to an exceptionally prolonged rift-to-drift history. The melt production rate is similar to the adjacent oceanic ridges which produce basaltic crust ~10 km thick. At Iceland, instead of building oceanic crust this melt is emplaced in and on a lower-crustal layer that is largely stretched continental crust.

In addition to explaining the unusual tectonic features, this model can also explain the exotic petrology and geochemistry of Iceland. The volcanics there include ~10% of silicic and intermediate rocks and geochemistry similar to flood basalts emplaced on continental crust, e.g., the Karoo and Paraná flood basalts.

Yellowstone

Yellowstone and the Eastern Snake River Plain (Y-ESRP) together comprise an east-west oriented belt of large, silicic caldera volcanoes that young to the east, terminating in the presently active Yellowstone volcano (Fig. 3). This belt is blanketed by basaltic lava flows that, in contrast, show no time progression. Its favorable location in a continental interior has facilitated extensive research for decades. However, this has largely comprised seismology and geochemistry applied to map melt in the deep subsurface, methods not best suited to developing a Plate Theory for Yellowstone (Section "Studying Intraplate Volcanism").

As is the case for Iceland, Y-ESRP volcanism can only be understood in the wider historic and regional geological context. The tectonics of the western United States, including the neighboring Basin Range Province to the south, is strongly influenced by subduction of the East Pacific Rise beneath the western margin of the North American plate, starting at ~17 Ma. The resulting change of the plate boundary from subduction to a shear (dominated by the San Andreas Fault system) placed the entire western United States in extension ("Western North American Plate Tectonic History" https://www.youtube.com/watch?v=XBt-C-hgR5I). This was accompanied by widespread volcanism that commenced with outpouring of the 234,000-km^3 Columbia River flood basalts through a ~250-km-long northerly trending zone of feeder dikes that widened the crust by several kilometers.

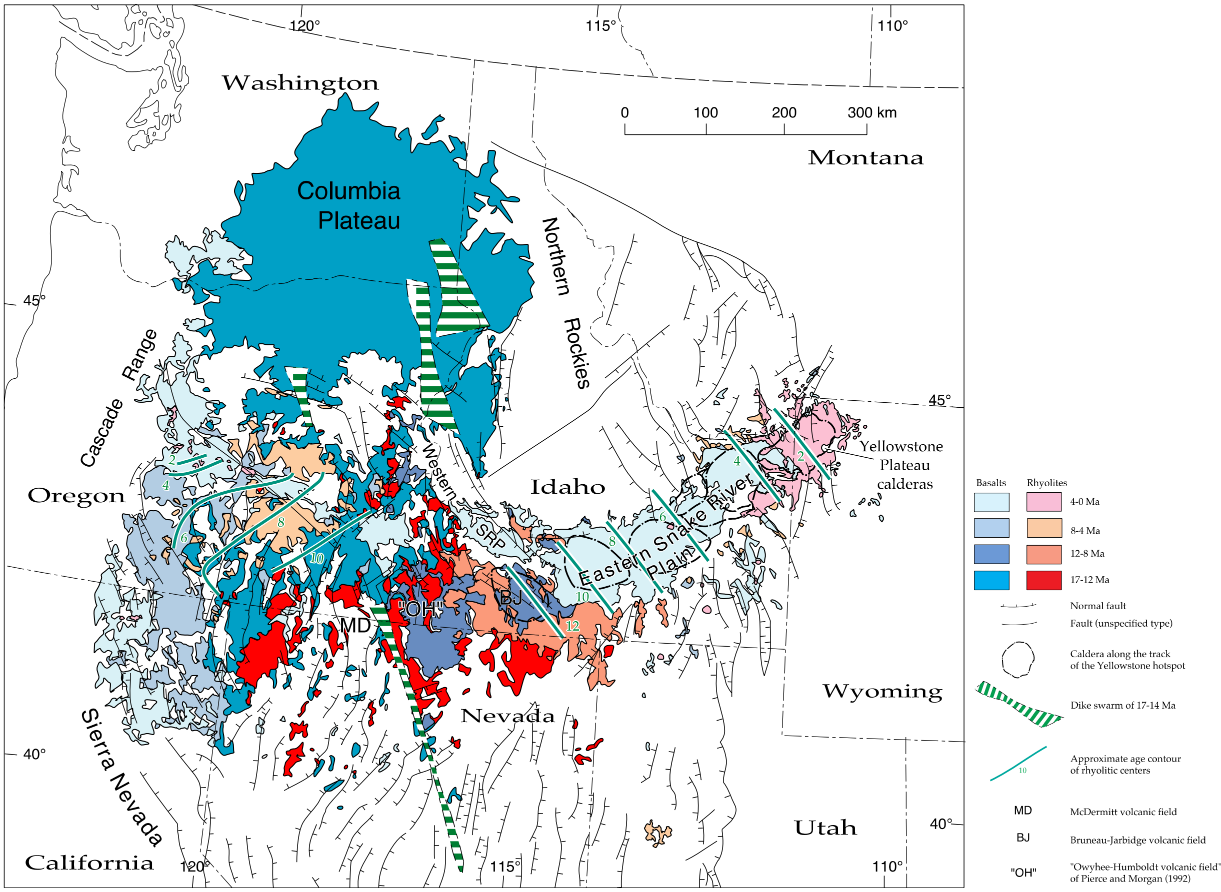

Fig. 3 Map of the northwestern United States showing Basin Range faults, and basalts and rhyolites of 17 Ma and younger. Approximate age contours of rhyolitic volcanic centers (~12, 10, 8, 6, 4, and 2 Ma) across the Eastern Snake River Plain are shown. A contemporaneous trend of oppositely propagating rhyolitic volcanism that trends northwest across central Oregon is indicated by similar contours. From Christiansen RL, Foulger GR and Evans JR (2002) Upper mantle origin of the Yellowstone hotspot. *Bulletin of the Geological Society of America* 114: 1245–1256.

Widespread extension via distributed normal faulting accompanied by scattered volcanism subsequently formed the Basin Range province. Eruptions were particularly abundant in three east-west zones comprising the Y-ESRP volcanic zone, the Valles volcanic zone, and the subsidiary St. George volcanic zone. Of these the Y-ESRP zone is unusual because of the time-progression of a line of silicic caldera-forming volcanoes and because of the geothermal features of Yellowstone which are amongst the most spectacular in the world.

Plate Theory attributes volcanism to lithospheric extension, and the silicic compositions of the volcanoes indicate a source in the lower crust. It thus follows that along the Y-ESRP zone the lithospheric extension that led to melting of the lower crust is predicted to have migrated regularly from west to east in the period ~17 Ma to present (Foulger et al., 2015). There is geological evidence for this. Lateral migration of silicic volcanism has gone hand-in-hand with a similar migration of accelerated normal-fault motion on nearby, large, range-bounding faults (e.g., Rodgers et al., 1990). These findings are supported by measurements of recent deformation made using GPS surveying. The most intense zones of current extension in the Basin Range province as a whole lie in the far west and east, with little extension in the central 500 km (Thatcher et al., 1999).

The evidence is thus strong that the rhyolitic volcanism in the Y-ESRP zone followed easterly migration of a northerly orientated, regional-scale axis of strong Basin Range extension. The style of extension in the Basin Range region is "dry" (normal faulting) whereas it is "wet" (magmatic) in the Y-ESRP zone.

Analogs for extension-driven silicic magmatism are found elsewhere in the western United States. The Coso Hot Springs, California, is a nascent core complex forming at a right-stepping *en echelon* offset in a dextral strike-slip system (Monastero et al., 2005). Long Valley caldera, at the northern end of Owens Valley, also erupts lavas ranging in composition from rhyolite to basalt and lies in an area of lithospheric dilation induced by regional fault and block movements (Riley et al., 2012).

The persistent basaltic volcanism must result from ongoing extension along the entire length of the Y-ESRP zone. Evidence for this is found in recent GPS measurements. Data collected 1987–2003 show significantly slower extension north of the ESRP (~2.0 mm/year) than to the south (~3.4 mm/year) (e.g., Puskas and Smith, 2009). Little deformation is detected in the ESRP itself. Extension must occur there, however, because it occurs both to the north and south. Geological evidence for historic extension is found in northwesterly orientated, dike-fed volcanic rift zones which produce basalt flows (Kuntz et al., 1992). Analogy with similar volcanic systems in Iceland and on mid-ocean ridges suggests that such diking episodes are brief, lasting just days or weeks. Surface extension along the ESRP is thus probably episodic with brief active periods alternating with long periods of quiescence.

The Hawaii and Emperor Volcano Chains

Of all oceanic volcanic systems on Earth, the Hawaii-Emperor system has been the most influential regarding theories for the origin of intraplate volcanism. Despite this, it presents a perfect storm of obstacles to study. It is remote, lying thousands of kilometers from the nearest substantial continental landmass, it is surrounded by deep ocean, and the area exposed above sea level is limited. Much of the system is blanketed by thick basalt flows which obscure deeper structure. Both the Hawaii- and its continuation in the Emperor chain lie within the ~90–120 Ma Cretaceous magnetic quiet zone where variations in age of the lithosphere are not easily determined. The Emperor chain started at a spreading ridge, but this has now been subducted. Considerable work has been done to reconstruct the plate tectonic history of the Pacific ocean, but this task is hindered because earlier plates and plate boundaries have been subducted (Norton, 2007). Perhaps because of these factors no mature model of any kind whose predictions have consistently yielded positive tests is yet available for the Hawaii volcanic system.

Any theory must account for several first-order observations which include the following:

- Hawaii lies at almost the exact geometric center of the Pacific plate. It is situated at the mid-point of a line dividing the western Pacific plate, which is surrounded on three sides by subduction zones, from the eastern Pacific plate which is mostly bounded by spreading ridges;
- The rate of melt production has varied by a factor of ~250, from as little as 0.001 $km^3\ a^{-1}$ at ~50 Ma to as much as 0.25 $km^3\ a^{-1}$ at the present time. The rate of melt production that has built the ~10,500-km^2 Big Island, an amalgamation of five major volcanoes, has been entirely exceptional for the last ~2 Ma;
- The locus of the most productive Hawaiian volcanism has remained essentially stationary respect to the geomagnetic pole and the geometry of the Pacific plate, at ~19°N, for ~50 Myr. To the NW lies a ~3500-km-long linear chain of islands and seamounts that progressively age, subside and generally reduce in volume such that the most northwesterly comprise only small seamounts. Volcanism is not confined to the southeasternmost island, however—historic eruptions have occurred along the southeastern ~1000 km of the chain (U.S. Geological Survey, 2007). This extent of current volcanic activity may be compared with the Y-ESRP zone which is ~600 km long;
- The oldest end of the Hawaiian seamount chain is continuous with the youngest end of the north-northwest-trending Emperor chain via the 60-degree "bend". The Emperor chain formed over ~30 Myr with a magma production rate of 0.01–0.02 $km^3\ a^{-1}$. The locus of Emperor volcanism was not geostationary but migrated south-southeast over a distance of ~1000 ± 500 km as the chain was built (Fig. 4). The 60-degree "bend" cannot be explained as a change in direction of motion of the Pacific plate because no such change occurred;
- No regional heatflow anomaly is detected around extinct islands and seamounts, suggesting the volcanoes are local thermal features only.

Plate Theory predicts that the volcanoes of the Hawaii and Emperor chains erupted at a region of extension in the Pacific plate. The interior of the plate is in extension as a result of tectonic activity at the surrounding plate boundaries, thermal contraction and isostatic vertical motions. Of particular note is that volcanism at the Hawaiian locus onsets on new parts of the Pacific plate as they are transported into the region subject to radial drag by subducting slabs to the north, west and south.

The extensional region that permitted the volcanism that built the Emperor chain originated at a spreading ridge. Over the following ~30 Myr the stress field evolved, migrating the locus of extension and accompanying volcanism south-southeast into the interior of the plate at rates of ~5–17 cm a^{-1} (Sharp and Clague, 2006). At ~50 Ma the stress regime stabilized with respect to the plate boundary configuration, the extensional region became geostationary, the rate of motion of the Pacific plate to the northwest greatly increased, and the Hawaii chain developed. To a first approximation it may be said that during Emperor times the Pacific plate was near-stationary and the volcanic locus migrated across it, but during Hawaiian times the plate moved rapidly and the volcanic locus was stationary. There is currently no explanation for this curious behavior that is, as a practical matter, testable.

The great variability in volcanic rate along the Emperor and Hawaii chains is expected to reflect melt availability. The oldest Emperor volcanoes erupted on oceanic lithosphere which was, at the time, young and thus thin. In general, the sizes of seamounts increase with age of the sea floor, approximately doubling between seafloor aged 10 and 100 Ma at the time of seamount eruption (Wessel, 1997). This suggests that the amount of melt available increases with depth in the mantle from which it is obtained. This may indicate that decompression melting contributes since that would increase with the lithospheric thickness through which asthenosphere rises on its way to the surface. The Emperor and Hawaii chains show a similar tendency in general, with the volume rate of the Hawaii chain roughly double that of the Emperor chain.

The extraordinary and exceptional magma rate over the last ~2 Myr suggests a radical change in magma accessibility compared with earlier times. A pre-existing melt reservoir or a source with exceptional fusibility may have suddenly become available. Green and Falloon (2005) have suggested, on the basis of petrology and geochemistry, that this source may be old metamorphosed oceanic crust adrift in the asthenosphere. Such a source is fusible and would yield greater melt volumes at a given temperature than mantle peridotite.

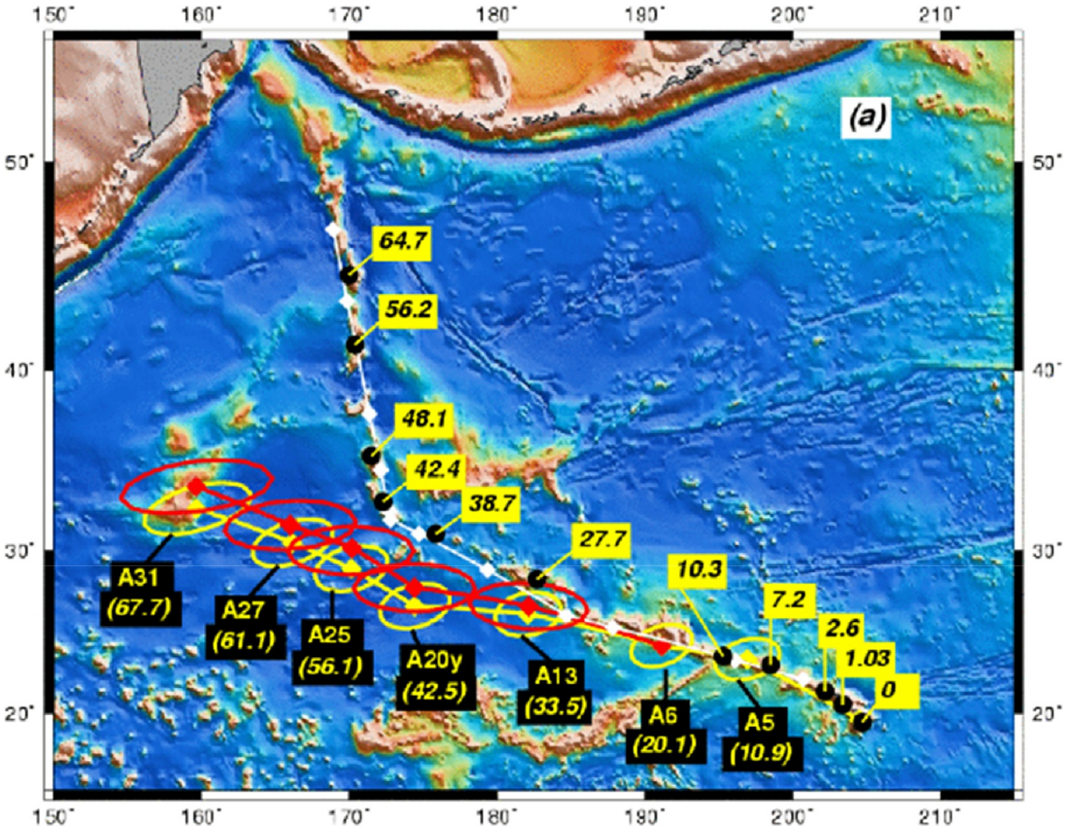

Fig. 4 Seamounts and volcanoes of the Hawaii and Emperor chains, labeled with ages in yellow boxes. Red and yellow lines with 95% confidence error ellipses: predicted positions for seamounts and volcanoes assuming relative fixity with Indo-Atlantic melting anomalies. Labels A# denote magnetic anomalies with ages in millions of years given in parentheses. From Raymond CA, Stock JM and Cande SC (2000) Fast Paleogene motion of the Pacific hotspots from revised global plate circuit constraints. In: Richards MA, Gordon RG and van der Hilst RD (eds.), *History and Dynamics of Plate Motions*, pp. 359–375, AGU Geophysical Monograph.

The most promising ways forward to develop a testable Plate Theory for the Hawaii-Emperor volcanic system are:

(a) To refine theories for the history of Pacific Ocean plate tectonics, including evolution of the plate collage that created it and the configuration of its boundaries and lithosphere age. This requires study of the history of both intra-Pacific and circum-Pacific plate boundaries. The results could be modeled numerically to determine the time-varying stress field in the relevant region;
(b) To interpret the petrology and geochemistry of Emperor and Hawaiian lavas in terms of source composition and lithosphere or asthenosphere affinities; and
(c) In future sea-bottom geodesy may be possible which will enable current deformation to be measured directly.

Discussion

Plate Theory for volcanism implies that intraplate- and exceptional plate-boundary volcanism can be explained by second-order processes associated with plate tectonics that are a consequence of non-rigidity of the plates. In this view, extensional features of the lithosphere form a spectrum with spreading plate boundaries at one extreme and rigid, essentially undeforming cratons at the other. Extensional areas considered to be intraplate are those not connected to the spreading plate boundary system. Most have not developed to the degree that full fracture of the lithosphere is perpetuated and at any site extension may be localized and ephemeral. Plate Theory offers the possibility that essentially all volcanism may be explained by a single, universal theory—plate tectonics.

Plate Theory is relatively young and remains to be applied to many volcanic systems. As such it offers many exciting research opportunities to those seeking new challenges. Particular mention might be made of the Samoa, Louisville, Easter, Galapagos, Réunion, Afar, Azores and Tristan volcanic systems. These present prime targets for Plate Theory since each is clearly associated with nearby unusual tectonic features. These include the junction of the transform and subducting parts of the Tonga Trench (Samoa), the Eltanin Fracture Zone (Louisville), the Easter Microplate and Sala y Gomez Fracture Zone (Easter) and the 90.5 oblique Transform Fault (Galapagos).

Summary

Plate Theory considers intraplate volcanism and unusual volcanism at plate boundaries to result from extension of the lithosphere that permits existing melt to escape to the surface. Melt volumes may be enhanced by decompression melting where asthenosphere rises to the surface from great depth. Regular time-progressions of volcanism result from migration of regions of extension across plates. These migrations may correlate with motion of the host plate because intraplate stress fields are relatively stable with respect to the plate boundary configuration. Radical changes in the spatial distribution of volcanism are expected to accompany major reorganizations of the plate boundary. The mere presence of underlying melt is not a sufficient condition for volcanism to occur—lithospheric extension is required. Thus, mapping the distribution of melt in the subsurface is not sufficient to explain volcanism.

Lithospheric extension results primarily from evolution of the plate-boundary configuration, vertical motions resulting from processes such as lithosphere delamination, and thermal contraction of the lithosphere. The amount of melt available, which determines the volcanic rate, is governed by the amount of melt pre-existing in the crust and mantle, and the extent to which this can be supplemented by decompression melting in upwelling material.

The methods most relevant to Plate Theory are tectonophysics, structural geology, geochronology, sedimentology, geothermometry, geodesy, numerical modeling, mineralogy, petrology, geochemistry and geophysics. Methods that target deeper parts of the mantle, e.g., whole-mantle tomography and the geochemistry of the core-mantle boundary region, are of little relevance to Plate Theory because those regions have little or no influence on volcanism at Earth's surface.

The Iceland-, Yellowstone- and Hawaii volcanic systems may be considered type examples of spreading-ridge-, continental intraplate- and oceanic intraplate volcanic anomalies. Iceland, a uniquely large subaerial exposure on a spreading plate boundary, owes its anomalous elevation to a substrate of stretched, magma-inflated continental crust. The Y-ESRP volcanic system is a component of the volcanically active, extending Basin Range region of the western United States. Volcanic migration there follows migration of an axis of strong Basin Range extension. Plate Theory for the Hawaii-Emperor volcanic system predicts persistent extension in a linear zone in the center of the Pacific plate. It, along with other working hypotheses, remain to be adequately tested in the uniquely challenging environment of the remote central Pacific Ocean.

Plate Theory explains all terrestrially sourced volcanism with a single, universal theory—plate tectonics. This is achieved simply by accepting that the plates are not rigid, a proposal that is self-evidently true. Plate Theory negates the need for multiple, ad hoc theories for features that clearly form part of the same spectra as those associated with plate tectonics.

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