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From plate tectonics to plumes, and back again

Je n'avais pas besoin de cette hypothèse-là.[1]

–Pierre-Simon Laplace (1749–1827)[1]

1.1 Volcanoes, and exceptional volcanoes

Volcanoes are among the most extraordinary natural phenomena on Earth. They are powerful shapers of the surface, they affect the make-up of the oceans, the atmosphere and the land on which we stand, and they ultimately incubate life itself. They have inspired fascination and speculation for centuries, and intense scientific study for decades, and it is thus astonishing that the ultimate origin of some of the greatest and most powerful of them is still not fully understood.

The reasons why spectacular volcanic provinces such as Hawaii, Iceland and Yellowstone exist are currently a major controversy. The fundamental question is the link between volcanism and dynamic processes in the mantle, the processes that make Earth unique in the solar system, and keep us alive. The hunt for the truth is extraordinarily cross-disciplinary and virtually every subject within Earth science bears on the problem. There is something for everyone in this remarkable subject and something that everyone can contribute.

[1] I have no need of that hypothesis.

The discovery of plate tectonics, hugely cross-disciplinary in itself, threw light on the causes and effects of many kinds of volcano, but it also threw into sharp focus that many of the largest and most remarkable ones seem to be exceptions to the general rule. It is the controversy over the origin of these volcanoes – the ones that seem to be exceptional – that is the focus of this book.

1.2 Early beginnings: Continental drift and its rejection

Speculations regarding the cause of volcanoes began early in the history of science. Prior to the emergence of the scientific method during the Renaissance, explanations for volcanic eruptions were based largely on religion. Mt Hekla, Iceland, was considered to be the gate of Hell. Eruptions occurred when the gate opened and the Devil dragged condemned souls out of Hell, cooling them on the snowfields of Iceland to prevent them from becoming used to the heat of Hell. Athanasius Kircher (1602–1680) provided an early pictorial representation of then-contemporary thought (Fig. 1.1) that has much in common with some theories still popular today (Fig. 1.2). The *agent provocateur* might be forgiven for wondering how much progress in fundamental understanding we have actually made over the last few centuries.

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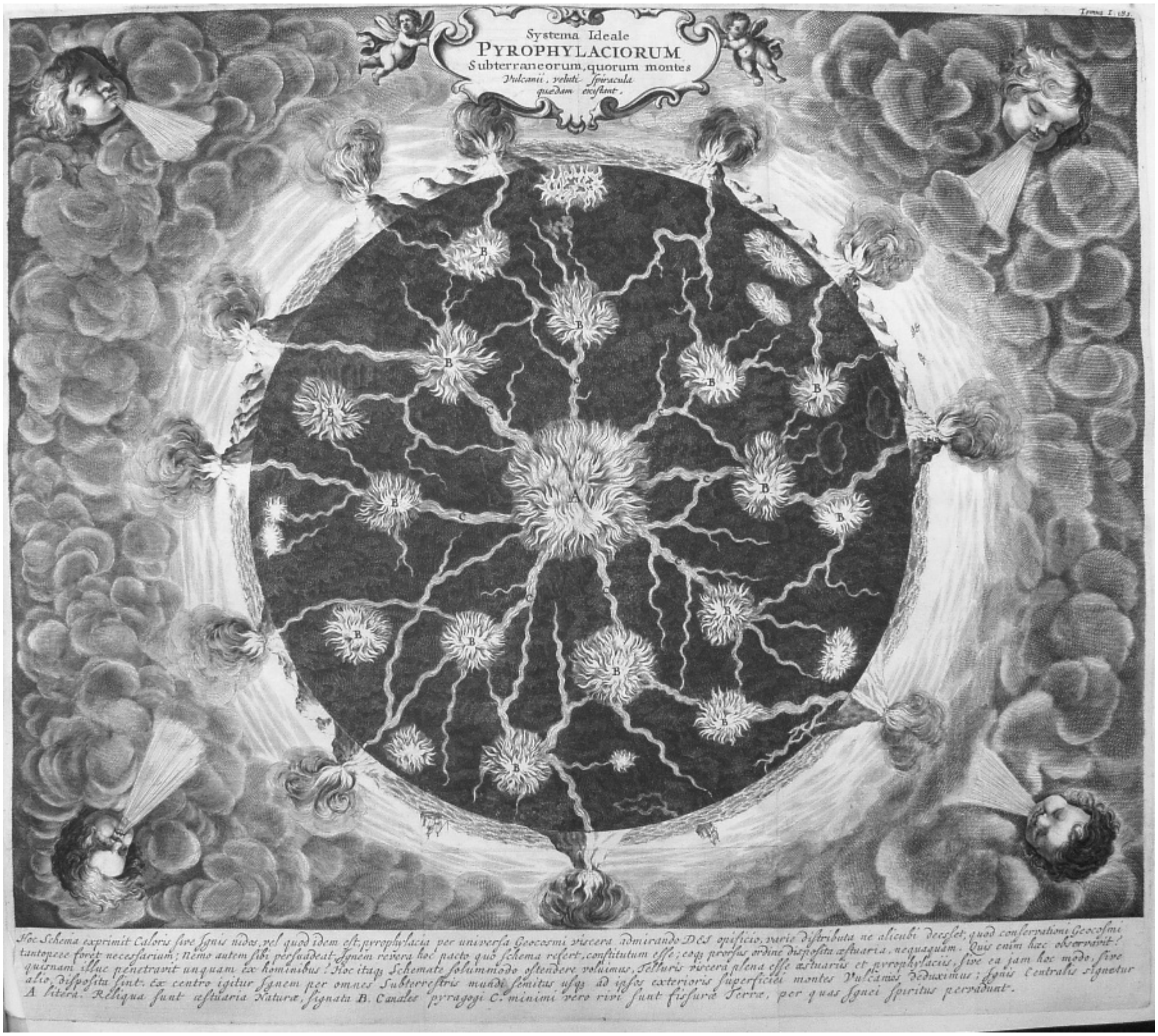

Figure 1.1 Kircher's model of the fires of the interior of Earth, from his *Mundus Subterraneus*, published in 1664 (Kircher, 1664–1678).

The foundations of modern opinion about the origin of volcanoes were really laid by the work of Alfred Wegener (1880–1930). His pivotal book *Die Entstehung der Kontinente und Ozeane* (The Origin of Continents and Oceans; Wegener, 1924), first published in 1915, proposed that continents now widely separated had once been joined together in a single supercontinent. According to Wegener, this supercontinent broke up and the pieces separated and drifted apart by thousands of kilometers (Fig. 1.3). The idea was not new, but Wegener's treatment of it was, and his work ultimately led to one of the greatest paradigm shifts Earth science has ever seen. He assembled a powerful multidisciplinary suite of scientific observations to support continental break-up, and developed ideas for the mechanism of drift and the forces

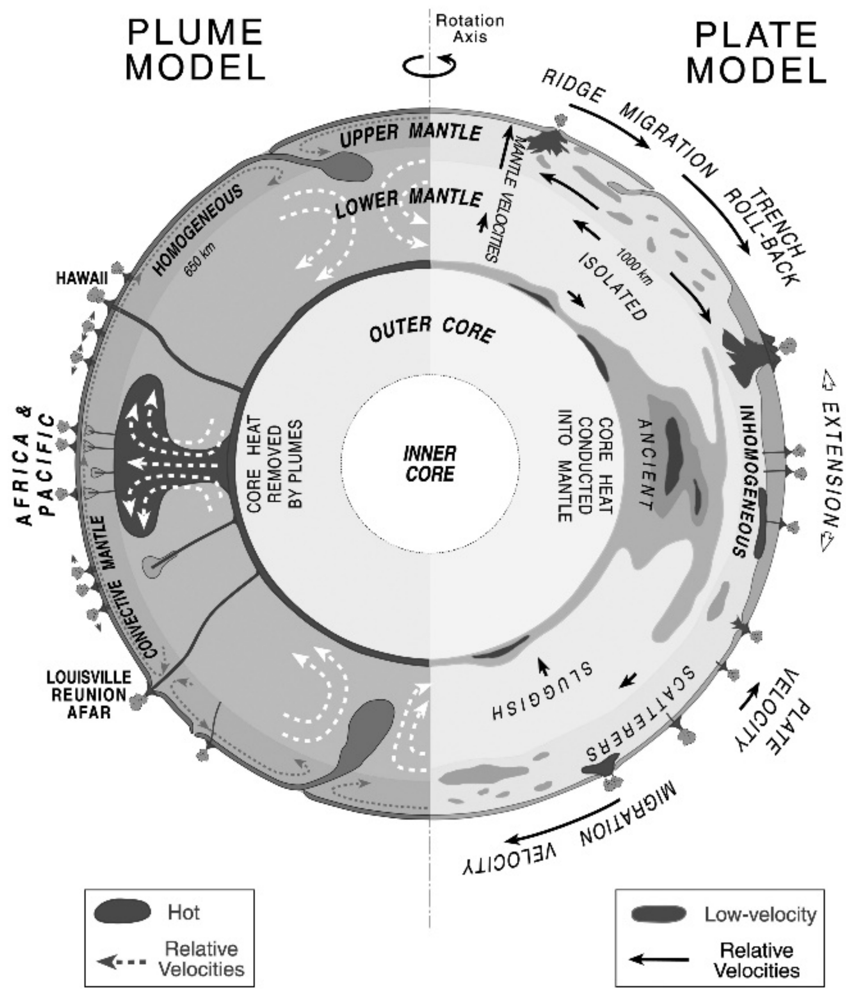

Figure 1.2 Schematic cross-section of the Earth showing the Plume model (left, modified from Courtillot et al., 2003) and the Plate model (right). The left side illustrates two proposed kinds of plumes – narrow tubes and giant upwellings. The deep mantle or core provides the material and the heat and large, isolated but accessible chemical reservoirs. Slabs penetrate deep. In the Plate model, depths of recycling are variable and volcanism is concentrated in extensional regions. The upper mantle is inhomogeneous and active and the lower mantle is isolated, sluggish, and inaccessible to surface volcanism. The locations of melting anomalies are governed by stress conditions and mantle fertility. The mantle down to ~1000 km contains recycled materials of various ages and on various scales (from Anderson, 2005). See Plate 1

that power it. He detailed correlations of fossils, mountain ranges, palaeoclimates and geological formations between continents and across wide oceans. He called the great mother supercontinent Pangaea (“all land”). He was fired with enthusiasm and energized by an inspired personal conviction of the rightness of his hypothesis.

Tragically, during his lifetime, Wegener’s ideas received little support from mainstream geology

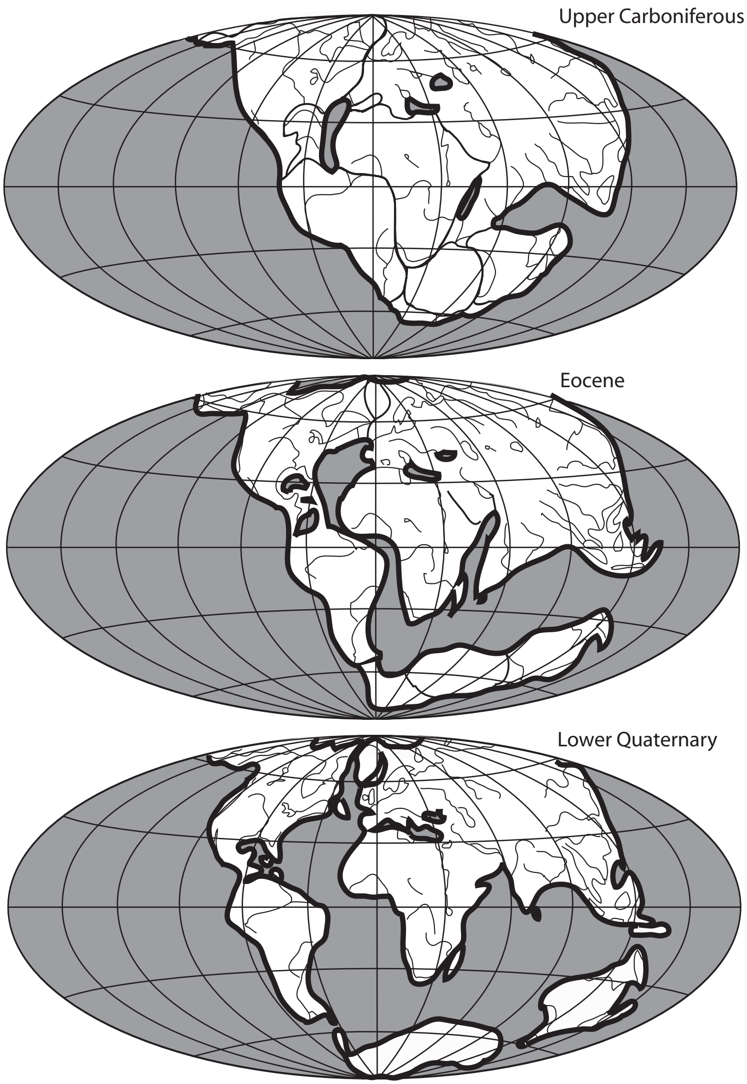

Figure 1.3 Wegener's original model for the break-up of the Pangaea supercontinent (from Wegener, 1924).

and physics. On the contrary, they attracted dismissal, ridicule, hostility and even contempt from influential contemporaries. Wegener's proposed driving mechanism for the continents was criticized. He suggested that the Earth's centrifugal and tidal forces drove them, an effect that geologists felt was implausibly small. Furthermore, although he emphasized that the sub-crustal region was viscous and could flow, a concept well established and already accepted as a result of knowledge of isostasy, the fate of the oceanic crust was still a difficult problem. A critical missing piece of the jigsaw was that the continental and oceanic crusts were moving as one. Wegener envisaged the continents as somehow to be moving through the oceanic crust, but critics pointed out that evidence for the inevitable crustal deformations was lacking.

Wegener was not without influential supporters, however – scientists who were swayed by his evidence. The problem of mechanism was rapidly solved by Arthur Holmes (1890–1965).

Holmes was perhaps the greatest geologist of the 20th century, and one of the pioneers of the use of radioactivity to date rocks. Among his great achievements was establishing a geological timescale and calculating the age of the Earth (Lewis, 2000). He had a remarkably broad knowledge of both physics and geology and was a genius at combining them to find new ways of advancing geology.

In 1929, Holmes proposed that the continents were transported by subcrustal convection currents. He further suggested that crust was recycled back into the interior of the Earth at the edges of continents by transformation to the dense mineral eclogite, and gravitational sinking (Fig. 1.4) (Holmes, 1929). His model bears an uncanny resemblance to the modern, plate-tectonic concept of subduction. Considering the vast suites of data that had to be assembled before most geologists accepted the subduction process, data that were unavailable to Holmes at the time, his intuition and empathy for the Earth were astounding.

It was not until half a century after publication of Wegener's first book that the hypothesis of continental drift finally became accepted by mainstream geology. The delay cannot be explained away as being due to incomplete details, or tenuously supported aspects of the drift mechanism (Oreskes, 1999). The case presented by Wegener was enormously strong and brilliantly cross-disciplinary. It included evidence from physics, geophysics, geology, geography, meteorology, climatology and biology. The power of drift theory to explain self-consistently a huge assemblage of otherwise baffling primary observational evidence is undeniable. After its final acceptance, its rejection must have caused many a conscientious Earth scientist pangs of guilt.

Wegener brilliantly and energetically defended his hypothesis throughout his lifetime, but this was prematurely cut short. He died in 1930 leading an heroic relief expedition across the Greenland icecap, and thus did not live to see his work finally accepted (McCoy, 2006). One can only speculate about how things might have turned out had he survived to press on indefatigably with his work.

Despite his premature demise, Wegener's ideas were not allowed to die. They were kept alive not least by Holmes who resolutely included a chapter on continental drift in every edition of his seminal textbook *Principles of Physical Geology* (Holmes, 1944). Notwithstanding this, the hypothesis continued to be regarded as eccentric, or even ludicrous, right up to the brink of its sudden and final acceptance in the

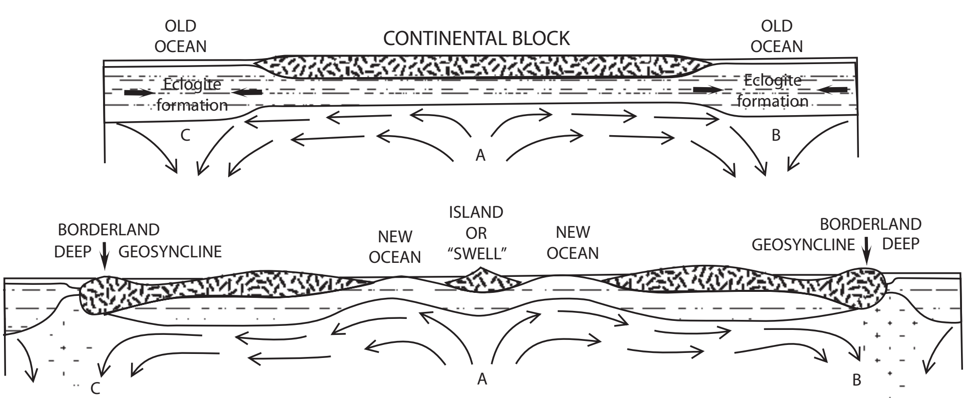

Figure 1.4 Holmes's original model for the convective system that enabled the continents to drift (from Holmes, 1944).

mid-1960s. Until then, innovative contributions and developments were often met with ridicule, rejection and hostility that suppressed progress and hurt careers. In 1954 Edward Irving submitted a Ph.D. thesis at Cambridge on palaeomagnetic measurements. His work showed that India had moved north by 6000 km and rotated by more than 30° counterclockwise, close to Wegener's prediction. His thesis was failed.[2] In 1963 a Canadian geologist, Lawrence W. Morley, submitted a paper proposing sea-floor spreading, first to the journal *Nature* and subsequently to the *Journal of Geophysical Research*. It was rejected by both. As late as 1965 Warren Hamilton lectured at the California Institute of Technology on evidence for Permian continental drift. He was criticized on the grounds that continental drift was impossible, and later that year, at the annual student Christmas party, "Hamilton's moving continents" were ridiculed by students who masqueraded as continents and danced around the room.

Continental drift was finally accepted when new, independent corroborative observations emerged from fields entirely different to those from which Wegener had drawn. Palaeomagnetism showed a symmetrical pattern of normal and reversed magnetization in the rocks that make up the sea floor on either side of mid-ocean ridges. The widths of the bands were consistent with the known time-scale of magnetic reversals, if the rate of sea-floor production was constant at a particular ridge. Earthquake epicenters delineated narrow zones of activity along ocean ridges and trenches, with intervening areas being largely quiescent. Detailed bathymetry revealed transform faults and earthquake fault-plane solutions showed their sense of slip. A "paving stone hypothesis" was proposed, which suggested the Earth was covered with rigid plates that moved relative to one another, bearing the continents along with them (McKenzie and Parker, 1967). Senior geophysicists threw their weight behind the hypothesis and the majority of Earth scientists fell quickly into line.

There has been much speculation over why it took the Earth science establishment a full half-century to accept that continental drift occurs (Oreskes, 1999). The reader is urged to read Wegener's work in its original form – to read what he actually wrote. Wegener had assembled diverse and overwhelming evidence, and a mechanism very similar to that envisaged today by plate tectonics that had been proposed by Holmes. The observations that finally swayed the majority of Earth scientists in the 1960s did not amount to explaining the cause of drift, the most harshly criticized and strongly emphasized weak spot in Wegener's hypothesis. They merely added an increment to the weight of observations that already supported drift.

It seems, therefore, that popular acceptance of a scientific hypothesis may sometimes be only weakly coupled to its merit. The popularity of an hypothesis may be more strongly influenced by faith in experts perceived as magisters than by direct personal assessment of the evidence by individuals (Glen, 2005). In highly cross-disciplinary fields where it is almost impossible for one person to be fully conversant with every related subject, this may seem to many to be the only practical way forward. However, the magisters, as the greatest will readily admit themselves, are not always right.

1.3 Emergence of the Plume hypothesis

Once continental drift and plate tectonics had become accepted, they proved spectacularly successful. A huge body of geological and geophysical data was reinterpreted, and numerous tests were made of the hypothesis. The basic predictions have been confirmed again and again, right up to the present day when satellite technology is used to measure annual plate movements by direct observation. Plate tectonics explains naturally much basic geology, the

[2] http://www.pnas.org/content/102/6/1819.full

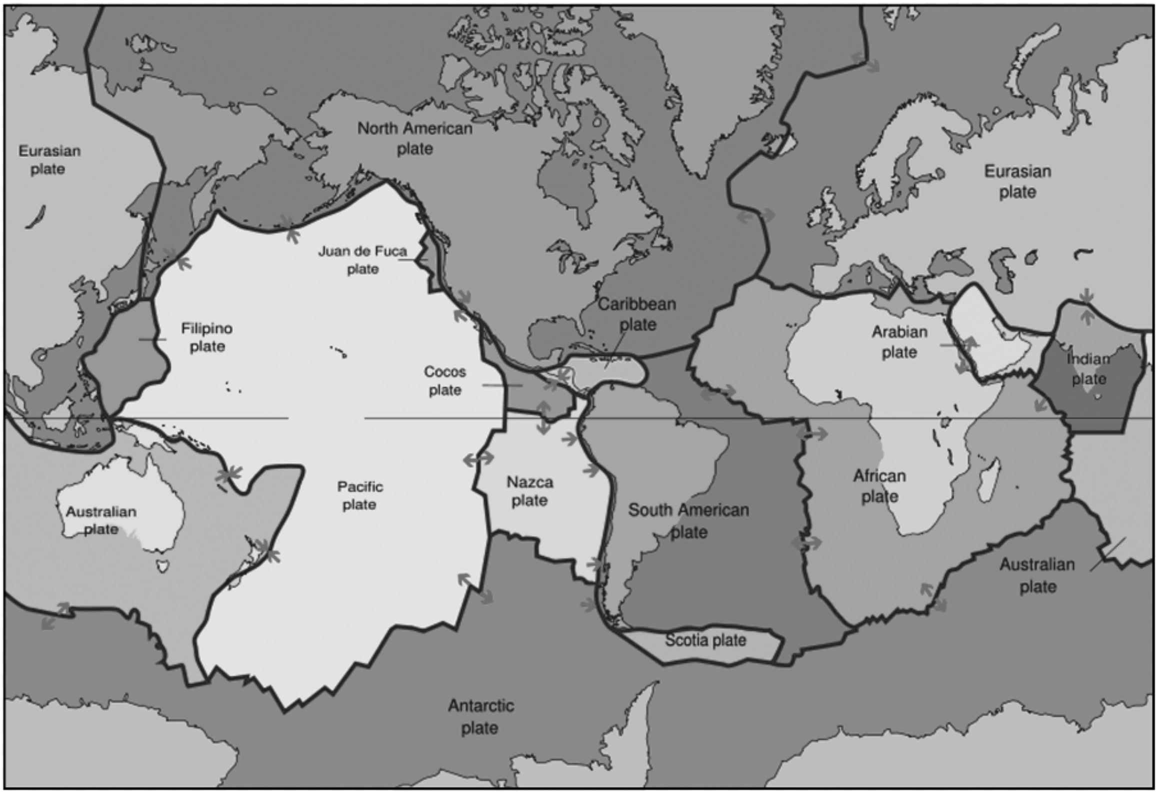

Figure 1.5 The main tectonic plates on the Earth's surface.[3]

origins of mountains and deep-sea trenches, topography, earthquake activity, and the vast majority of volcanism.

Plate tectonics views the Earth's surface as being divided up, like a jigsaw, into seven major, and many minor pieces ("plates"). Like the pieces of a jigsaw, the plates behave more or less like coherent units, that is, each moves as though it were a single entity (Fig. 1.5). Oceanic crust is created at mid-ocean ridges by a volcanic belt 60,000 km long – almost twice the circumference of the planet. It is destroyed in equal measure at subduction zones, where one plate dives beneath its neighbor and returns lithosphere back into the Earth's interior. As subducting plates sink, they heat up and dehydrate, fluxing the overlying material with volatiles and causing it to melt. This causes belts of volcanoes to form at the surface ahead of the subduction trench. In this way, processes near spreading ridges and subduction zones, where crust is formed or destroyed, account for 90% of the Earth's volcanism.

When a new hypothesis sweeps the board, and has been convincingly confirmed by testing, the things that immediately become the most interesting are the exceptions to the general rules because therein lie the next great discoveries. Following the widespread acceptance and development of plate tectonics, it rapidly became clear that several remarkable volcanic regions did not fit into the general picture. Most

[3] http://en.wikipedia.org/wiki/Plate_tectonics

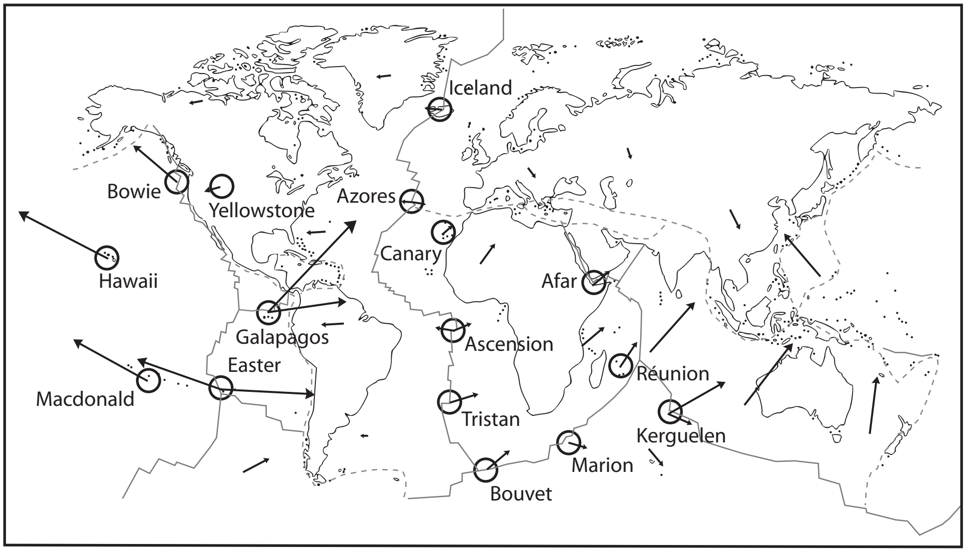

Figure 1.6 Morgan's original 16 plume localities (Morgan, 1971).

spectacular was the Big Island of Hawaii and its associated island chain, known to be time-progressive since the pioneering work of James Dwight Dana (1813–1895). The Hawaiian archipelago lies deep in the interior of the vast Pacific plate, thousands of kilometers from the nearest plate boundary of any kind (Fig. 1.5). J. Tuzo Wilson suggested that it arose from the motion of the Pacific sea floor over a hot region in the mantle (Wilson, 1963). Out of these beginnings the expression "hot spot" emerged, and the seed was sown for the modern hypothesis that any volcanism unusual in the context of plate tectonics results from local, exceptionally high temperatures in the mantle beneath.

The Plume hypothesis arrived eight years later in 1971 with the publication of a letter in *Nature* by W. Jason Morgan (Morgan, 1971).[4] Morgan suggested that there was not merely one but "about 20" hot spots on Earth. He further proposed that the "hot spots" were fixed relative to one another, and to explain this he suggested that they were sourced below the asthenosphere, which was thought to be vigorously convecting. He postulated that they were in fact fueled from great depths within the Earth, through "pipes to the deep mantle", and he termed these systems "plumes". In this hypothesis, the motions of the surface plates overhead resulted in volcanic products being constantly carried away from their parent plumes, as though on a conveyor belt, resulting in time-progressive volcanic chains.

The sites that Morgan proposed to be underlain by plumes are Hawaii, the Macdonald seamount, Easter island, the Galapagos islands, Bowie, Yellowstone, Iceland, the Azores, the Canary islands, Ascension island, Tristan da Cuhna, the Bouvet triple junction, Marion-Prince Edward island, Réunion, Kerguelen and Afar (Fig. 1.6). He suggested additionally that plumes are the driving force of plate tectonics and that the material that they transport up from deep within the Earth's mantle is relatively primordial and compositionally different from that extracted from shallower depths, for example, at mid-ocean ridges.

The prediction that lavas at "hot spots" are compositionally different from mid-ocean ridge

[4] http://www.mantleplumes.org/Morgan1971.html

basalts was confirmed almost immediately. Jean-Guy Schilling found that rare-earth- and minor-element concentrations along the mid-ocean ridge in the north Atlantic vary in a way that is consistent with Iceland being fed by a compositionally distinct source (Schilling, 1973). He went on to suggest that melts from a plume beneath Iceland, and the shallow source of mid-ocean-ridge basalts (MORB), mix along the Reykjanes ridge south of Iceland.

The new Plume hypothesis met with both advocacy and skepticism early on. It offered an elegant explanation for volcanism away from plate boundaries, time-progressive volcanic chains, relative fixity between “hot spots”, and their distinct geochemistry. However, scientists familiar with individual volcanic regions, or related aspects of Earth structure and dynamics, puzzled over how it accorded with the observations in detail. The suggestion that plumes are compositionally fertile was challenged on the grounds of density (“In other words, if fertile mantle plumes exist at all, they should be sinking, not rising”; O’Hara, 1975). The impossibility that two independent modes of convection can occur in the continuum of the Earth’s mantle, that associated with plate movements, and an entirely separate plume mode, was pointed out (“It would be most helpful if someone would explain in terms that are meaningful to geophysicists in what respects the conventional geological pictures of rising magma differ from ‘a thermal plume’.”; Tozer, 1973). It was also pointed out that in fact “hot spots” are not fixed relative to one another, and would not be expected to be so in a mantle heated internally by radioactivity (McKenzie and Weiss, 1975), immediately removing one of the primary reasons for proposing the hypothesis in the first place.

During the first two decades following the initial proposal, alternative explanations for mid-plate volcanism were suggested and explored in detail (Anderson and Natland, 2005). Proposals included propagating cracks, internal plate deformation, membrane tectonics, self-perpetuating volcanic chains, recycled subducted slabs and continental breakup (Hieronymus and Bercovici, 1999; Jackson and Shaw, 1975; Jackson et al., 1975; Shaw, 1973; Turcotte, 1974). In the early 1990s, however, the Plume hypothesis received two major boosts that greatly increased its popularity, and interest in alternatives and debate temporarily waned.

The first boost came from laboratory tank experiments that continued earlier work by Ramberg (1967; 1981) and Belousov (1954; 1962) (Campbell and Griffiths, 1990; Griffiths and Campbell, 1990). Low-density fluid injected into the bottom of tanks full of higher-density fluid showed the development of rising compositional plumes (Fig. 1.7). Mushroom-like structures formed, comprising bulbous heads followed by narrow, stem-like conduits. Geologists were presented with powerful and compelling pictorial representations of a phenomenon that fitted well with the hypothesis that flood basalts such as the Deccan Traps in India represent “plume heads”. Time-progressive volcanic trails were thus predicted to emanate from such flood basalts, representing a later ”plume tail” stage. Although the experiments were conducted using fluids with compositional density differences, it was assumed that in nature the buoyancy of plumes would be thermal in origin, and that they would rise from a thermal boundary layer – a region where a large increase in temperature occurs across a relatively small depth interval. This is generally assumed to be at the core-mantle boundary, one of only two major thermal discontinuities known to exist in the Earth. Across the core-mantle boundary, the temperature increases abruptly by roughly 1000 °C. The other thermal discontinuity is, of course, the Earth’s surface.

The second boost to the Plume hypothesis came from work on the noble gas helium (He) (Kellogg and Wasserburg, 1990). Earlier work by Craig and Lupton (1976; 1981) was developed to explain the unusually high $^{3}He/^{4}He$ ratios that had been observed in basalts from volcanic regions such as Hawaii and Iceland. In this

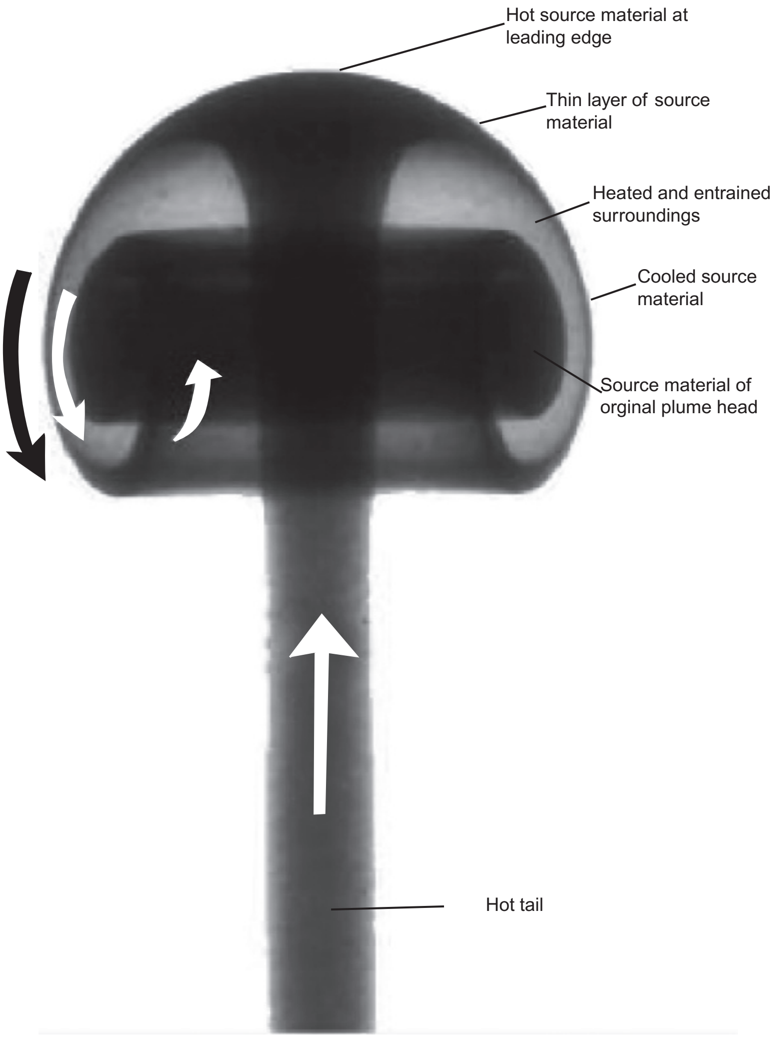

Figure 1.7 Photograph of a thermal plume formed in a laboratory experiment by injecting warm syrup into the bottom of a tank full of cooler syrup (from Campbell et al., 1989).

model, the high ratios result from an excess of ^{3}He stored in the lower mantle, and thus high ^{3}He/^{4}He ratios observed in surface rocks were postulated to indicate a lower mantle provenance (Section 7.5.1).

This model contributed to the concept that plumes can be detected using geochemistry. ^{3}He is mostly a primordial isotope. That is, almost all the ^{3}He currently in the Earth was acquired when the planet formed, at ~4.5 Ga. In contrast, the Earth's ^{4}He inventory is continually increased by the decay of uranium (U) and thorium (Th). Rising magma transports both ^{3}He and ^{4}He to the surface, where it degasses to the atmosphere and rapidly escapes to space. Volcanism thus constantly reduces the Earth's ^{3}He inventory and it is not significantly replenished. In contrast, ongoing radioactive decay maintains the Earth's stock of ^{4}He. The model that assigns a deep origin to high ^{3}He/^{4}He ratios views the lower mantle as having been much less depleted in ^{3}He than the upper mantle. This might be so if the upper mantle has repeatedly been tapped to feed the majority of the Earth's volcanism that occurs at mid-ocean ridges and subduction zones, while the lower mantle has been more isolated throughout Earth history. In this model, high ^{3}He/^{4}He ratios are a tracer for material from

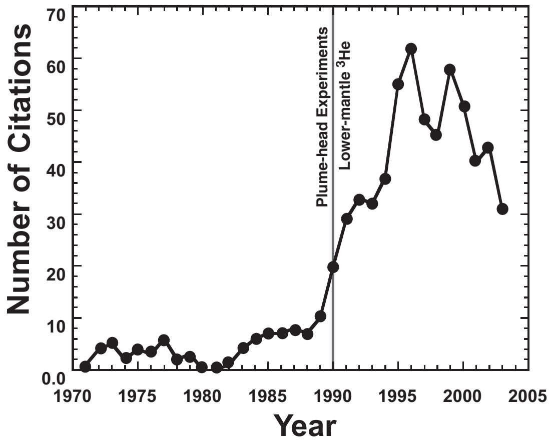

Figure 1.8 Number of published papers with "plume" in the title, in reference to mantle plumes vs. time, in the GeoRef data base[5] (from Anderson and Natland, 2005).

the deep lower mantle, and their detection supports the Plume hypothesis.

The popularity of the Plume hypothesis exploded in the early 1990s. Prior to about 1990, fewer than 10 published papers per year that refer to mantle plumes in their titles are listed by the data base GeoRef,[5] but this subsequently jumped by a factor of five or more (Fig. 1.8). During much of the last decade of the 20th century, the existence of mantle plumes was widely assumed, with little questioning by mainstream Earth science.

If the nineties was the decade of popularity of the Plume hypothesis, then the subsequent decade (the naughties) has been the decade of skepticism. The Plume hypothesis and its specific predictions have been re-examined on a fundamental basis. The most basic characteristic that makes an hypothesis scientific is its predictions, by which it can be tested. Without testable predictions, it is logically invulnerable to falsification, it ceases to be scientific, and it degenerates to a faith-based belief (Popper, 1959).

1.4 Predictions of the Plume hypothesis

The specific predictions of the Plume hypothesis is a vexed question because of the wide variation in opinion that currently exists among scientists. The original hypothesis (Morgan, 1971) predicted that:

- Plumes are fixed relative to one-another,
- Time-progressive volcanic chains emanate from them,
- They are rooted in the deep mantle, whence they transport relatively primordial mantle upward.
- They break up continents.
- They drive plate tectonics, and
- They are hot.

In the three decades that followed the original proposal, the views of scientists evolved and diversified so that today many different visions exist of what the Plume hypothesis predicts.[6] So where, then, do we now stand? Recently, a clear, basic starting position has helpfully been stated (Campbell, 2006; 2007; Campbell and Davies, 2005; Campbell and Kerr, 2007; DePaolo and Manga, 2003).[7] According to this position, a plume is a thermal instability that rises from a layer at the bottom of the mantle, which is heated from below by the Earth's core. The instability comprises a large, bulbous head, followed by a relatively narrow tail, or feeder conduit. The tail is narrow because hot, low-viscosity plume material flows up the center of a pre-existing pathway of little resistance created by passage of the initial plume head. This modern version of the Plume hypothesis

[5] the online database of the American Geological Institute: http://csaweb113v.csa.com/factsheets/georef-set-c.php

[6] http://www.mantleplumes.org/DefinitionOfAPlume.html; http://www.mantleplumes.org/PlumeDLA.html
[7] http://www.mantleplumes.org/Plumes.html

Table 1.1 The predictions of the Plume and Plate hypotheses. Italics indicate the expectations of the respective model regarding the predictions of the other.

Plume	Plate
Current standard predictions (Campbell, 2006)	
precursory domal uplift	*not expected*
flood basalt eruption	*permitted but not required*
narrow conduit to the core-mantle boundary	*not expected*
time-progressive volcanic chain	*permitted but not required*
hot source	*no, or only modest mantle temperature variations expected*
Additional predictions made by the original model (Morgan,1971)	
melting anomalies fixed relative to one another	*permitted but not required*
compositionally distinct magmas	*expected*
break continents up	magmatism *may result from, but not cause, continental breakup*
drive plate tectonics	*not expected*
	The standard predictions (Foulger and Natland,2003)
radial extension expected to accompany precursory domal uplift	lithospheric extension
permitted but not required	fertile source

may be considered the current, standard model (Table 1.1). It makes the following five basic predictions:

1 *Precursory domal uplift:* Arrival of the plume head at the base of the lithosphere results in domal uplift of 500–1000 m, a few million years before flood basalt volcanism starts (Crough, 1983). The amplitude of the uplift depends on the temperature of the plume, and the area over which uplift is significant has a diameter of ~1000 km.

2 *Flood basalt eruption (the plume head):* The arriving plume head flattens to a disk at the base of the lithosphere, causes extension, and flood basalt eruptions occur rapidly over an area 2000–2500 km in diameter. The diameter of the volcanic region is dependent on the temperature difference between the plume and the surrounding mantle. If the plume head rises beneath continental lithosphere it may cause continental break-up and formation of volcanic margins.

3 *A narrow conduit to the core-mantle boundary (the plume tail):* Following flood basalt eruption, plume material continues to flow upward from the core-mantle boundary through a conduit 100–200 km in diameter.

4 *A time-progressive volcanic chain:* As the surface lithospheric plate above moves, continuous volcanism from the relatively fixed plume tail results in a trail of volcanism. The youngest volcanism occurs above the present-day location of the plume and older volcanism occurs progressively further along the trail.

5 *High temperatures:* The lavas associated with both the plume head and the plume tail formed at unusually high temperatures. Excess temperatures of 300 ± 100 °C occur at the center of the plume head, above the tail, reducing to ~100°C further away, where cooler mantle material was entrained. Significant thermal anomalies persist below flood basalts for at least 100 Ma. Because of the high temperatures, picritic (high-MgO) basalts dominate early volcanism and the center of the plume head. Anomalously thick oceanic crust (volcanic margin) forms where continental break-up occurs.

1.5 Lists of plumes

The term "hot spot" carries with it the presumptions that the volcanism in question is fed by an unusually hot, highly localized source. Such features should be questioned, not assumed, and thus the term "hot spot" is not used in this book. Instead, the term "melting anomaly" is used, though it is itself not entirely satisfactory because what is an "anomaly" and what is merely a normal variation in a continuum is not easily decided.

Which melting anomalies are currently thought to be underlain by deep mantle plumes? In this basic question lies the first vexed problem. Over the years, many lists have been proposed for a global constellation of plumes.[8] The difficulty is that these lists vary radically both in length and content. This problem was ironically foreshadowed in the very first paper on the subject, where Morgan (1971) proposes that there are "about twenty deep mantle plumes" in the Earth, but plots only 16 in the accompanying figure (Fig. 1.6).

The numbers rose rapidly early on and within five years Burke and Wilson (1976) had proposed that there are 122 plumes. Lists were largely based on the observation of surface volcanism, but since the sizes of volcanic regions form a continuum ranging from the very large to the exceedingly small, where the cut-off line should be drawn is a subjective decision. Sleep (1990) listed 37 proposed plumes based on surface topographic anomalies ("swells") (Table 1.2), which he interpreted as the manifestations of hot plume material fluxing upward. Morgan's most recent list contains 69 proposed plumes, each assigned a degree of uncertainty (Morgan and Phipps Morgan, 2007) (Table 1.3). The world record for the plume population explosion is 5200, proposed on the basis of fractal arguments (Malamud and Turcotte, 1999).

Table 1.4 presents a recent summary of observations from 49 localities proposed to be underlain by plumes (Courtillot et al., 2003). For each locality the existence of the following observables is reviewed:

- A linear chain of dated volcanoes extending from the site of present volcanic activity;
- A flood basalt or oceanic plateau of the appropriate age at the older end of a volcanic chain;
- A high estimated buoyancy flux (in kg s^{-1}) and its reliability;
- High $^3He/^4He$ ratios in basalts; and
- Low seismic shear-wave speeds at 500 km depth beneath the present volcanically active site.

It can immediately be seen that these criteria correspond neither to the original criteria of Morgan (1971) nor to the modern standard criteria (Anderson, 2005a). This in itself illustrates the second problem – the diversity of diagnostic criteria which are, in practice, used.

Courtillot et al. (2003) categorized these 49 melting anomalies according to how many of the features listed above they display. A core-mantle-boundary origin was attributed to melting anomalies with high scores (9 localities), an origin at the base of the upper mantle at 650 km depth was assigned to anomalies with moderate scores (12 localities), and a lithospheric origin to those with low scores (28 localities) (Fig. 1.9). This approach is clearly subjective, as other criteria could have been used (Anderson, 2005a). Furthermore, it is curiously unscientific. An observation, for example of high $^3He/^4He$, could

[8] http://www.mantleplumes.org/CompleateHotspot.html

Table 1.2 Estimates of plume buoyancy fluxes.

Hotspot	Flux, Mg s^{-1} (from Sleep, 1990)	Reliability (from Sleep, 1990)	Flux, Mg s^{-1} (from Davies, 1988)
Afar	1.2	good	
Australia, East	0.9	fair	
Azores	1.1	fair	
Baja	0.3	poor	
Bermuda	1.1	good	1.5
Bouvet	0.4	fair	
Bowie	0.3	poor	0.8
Canary	1.0	fair	
Cape Verde	1.6	good	0.5
Caroline	1.6	poor	
Crozet	0.5	good	
Discovery	0.5	poor	0.4
Easter	3.3	fair	
Fernando	0.5	poor	0.9
Galapagos	1.0	poor	
Great Meteor	0.5	fair	0.4
Hawaii	8.7	poor	6.2
Hoggar	0.9	good	0.4
Iceland	1.4	good	
Juan de Fuca	0.3	fair	
Juan Fernandez	1.6	poor	1.7
Kerguelen	0.5	poor	0.7
Louisville	0.9	poor	3.0
Macdonald	3.3	fair	3.9
Marquesas	3.3	fair	4.6
Martin	0.5	poor	0.8
Meteor	0.5	poor	0.4
Pitcairn	3.3	fair	1.7
Réunion	1.9	good	0.9
St. Helena	0.5	poor	0.3
Samoa	1.6	poor	
San Felix	1.6	poor	2.3
Tahiti	3.3	fair	5.8
Tasman, Central	0.9	poor	
Tasman, East	0.9	poor	
Tristan	1.7	fair	0.5
Yellowstone	1.5	fair	
Total	54.9		

Table 1.3 Melting anomaly locations, empirical confidence estimates, and azimuths and rates of postulated plume tracks (from Morgan and Phipps Morgan, 2007). ND: not defined.

Plume	Tectonic plate	Lat (°N)	Long (°E)	Weight	Azimuth	±(°)	Rate (mm/yr)	±mm/yr
Afar	African	7.0	39.5	0.2	30	±15	16	±8
Anyuy	N American	67.0	166.0	B-	ND	ND	ND	ND
Arago	Pacific	–23.4	–150.7	1.0	296	±4	120	±20
Ascension	S American	–7.9	–14.3	B	ND	ND	ND	ND
Azores	European	37.9	–26.0	0.5	110	±12	ND	ND
Azores	N American	37.9	–26.0	0.3	280	±15	ND	ND
Baikal	European	51.0	101.0	0.2	80	±15	ND	ND
Balleny	Antarctic	–67.6	164.8	0.2	325	±7	ND	ND
Bermuda	N American	32.6	–64.3	0.3	260	±15	ND	ND
Bowie	Pacific	53.0	–134.8	0.8	306	±4	40	±20
Cameroon	African	–2.0	5.1	0.3	32	±3	15	±5
Canary	African	28.2	–18.0	1.0	94	±8	20	±4
Cape Verde	African	16.0	–24.0	0.2	60	±30	ND	ND
Caroline	Pacific	4.8	164.4	1.0	289	±4	135	±20
Cobb	Pacific	46.0	–130.1	1.0	321	±5	43	±3
Cocos-Keeling	Australian	–17.0	94.5	0.2	28	±6	ND	ND
Comores	African	–11.5	43.3	0.5	118	±10	35	±10
Crough	Pacific	–26.9	–114.6	0.8	284	±2	ND	ND
Crozet	Antarctic	–46.1	50.2	0.8	109	±10	25	±13
Discovery	African	–43.0	–2.7	1.0	68	±3	ND	ND
Easter	Nazca	–26.4	–106.5	1.0	87	±3	95	±5
Eastern Aust.	Australian	–40.8	146.0	0.3	0	±15	65	±3
Eifel	European	50.2	6.7	1.0	82	±8	12	±2
Erebus	Antarctic	–77.5	167.2	A	ND	ND	ND	ND
Etna	European	37.8	15.0	A	ND	ND	ND	ND
Fernando Do Noron	S American	–3.8	–32.4	1.0	266	±7	ND	ND
Foundation	Pacific	–37.7	–111.1	1.0	292	±3	80	±6
Galapagos	Nazca	–0.4	–91.6	1.0	96	±5	55	±8
Galapagos	Cocos	–0.4	–91.6	0.5	45	±6	ND	ND
Gough	African	–40.3	–10.0	0.8	79	±5	18	±3
Great Meteor	African	29.4	–29.2	0.8	40	±10	ND	ND
Guadalupe	Pacific	27.7	–114.5	0.8	292	±5	80	±10
Guyana	S American	5.0	–61.0	B	ND	ND	ND	ND
Hainan	China	20.0	110.0	A	0	±15	ND	ND
Hawaii	Pacific	19.0	–155.2	1.0	304	±3	92	±3

Table 1.3 *Continued*

Plume	Tectonic plate	Lat (°N)	Long (°E)	Weight	Azimuth	±(°)	Rate (mm/yr)	±mm/yr
Heard	Antarctic	–53.1	73.5	0.2	30	±20	ND	ND
Hoggar	African	23.3	5.6	0.3	46	±12	ND	ND
Iceland	European	64.4	–17.3	0.8	75	±10	5	±3
Iceland	N American	64.4	–17.3	0.8	287	±10	15	±5
Jebel Marra	African	13.0	24.2	0.5	45	±8	ND	ND
Juan Fernandez	Nazca	–33.9	–81.8	1.0	84	±3	80	±20
Karisimbi	African	–1.5	29.4	B	ND	ND	ND	ND
Kerguelen	Antarctic	–49.6	69.0	0.2	50	±30	3	±1
Kilimanjaro	African	–3.0	37.5	B	ND	ND	ND	ND
Lord Howe	Australian	–34.7	159.8	0.8	351	±10	ND	ND
Louisville	Pacific	–53.6	–140.6	1.0	316	±5	67	±5
Macdonald	Pacific	–29.0	–140.3	1.0	289	±6	105	±10
Madeira	African	32.6	–17.3	0.3	55	±15	8	±3
Maria/S.Cook	Pacific	–22.2	–154.0	0.8	300	±4	ND	ND
Marion	Antarctic	–46.9	37.6	0.5	80	±12	ND	ND
Marquesas	Pacific	–10.5	–139.0	0.5	319	±8	93	±7
Martin Vaz	S American	–20.5	–28.8	1.0	264	±5	ND	ND
Massif Central	European	45.1	2.7	B	ND	ND	ND	ND
Mt Rungwe	African	–8.3	33.9	B+	ND	ND	ND	ND
N. Austral	Pacific	–25.6	–143.3	B	293	±3	75	±15
Ob-Lena	Antarctic	–52.2	40.0	1.0	108	±6	ND	ND
Peter Island	Antarctic	–68.8	–90.6	B	ND	ND	ND	ND
Pitcairn	Pacific	–25.4	–129.3	1.0	293	±3	90	±15
Raton	N American	36.8	–104.1	1.0	240	±4	30	±20
Reunion	African	–21.2	55.7	0.8	47	±10	40	±10
Samoa	Pacific	–14.5	–169.1	0.8	285	±5	95	±20
San Felix	Nazca	–26.4	–80.1	0.3	83	±8	ND	ND
Scott	Antarctic	–68.8	–178.8	0.2	346	±5	ND	ND
Shona	African	–51.4	1.0	0.3	74	±6	ND	ND
Society	Pacific	–18.2	–148.4	0.8	295	±5	109	±10
St Helena	African	–16.5	–9.5	1.0	78	±5	20	±3
Tasmantid	Australian	–40.4	155.5	0.8	7	±5	63	±5
Tibesti	African	20.8	17.5	0.2	30	±15	ND	ND
Tristan Da Cunha	African	–37.2	–12.3	A	ND	ND	ND	ND
Vema	African	–32.1	6.3	B	ND	ND	ND	ND
Yellowstone	N American	44.5	–110.4	0.8	235	±5	26	±5

Table 1.4 Melting anomalies and their features, from Courtillot et al. (2003). Columns give name, latitude and longitude, the existence or not of a chain of dated volcanoes, the existence and age of a flood basalt or oceanic plateau at the old end, buoyancy flux and its reliability, the existence or not of high $^3He/^4He$ ratios, the existence of low seismic shear-wave speeds at 500 km depth, and the total number of these five features observed at each locality.

Hotspot	Lat	Lon (°E)	Track	Flood/ plateau	Age (Ma)	Buoy. ($10^3 kg s^{-1}$)	Reliab.	$^3He/^4He$	Tomo (500 km)	Count
Afar	10N	43	no	Ethiopia	30	1	good	high	slow	4
Ascension	8S	346	no	no	/	na	na	na	0	0+?
Australia E	38S	143	yes	no	/	0.9	fair	na	0	1+?
Azores	39N	332	no?	no	/	1.1	fair	high?	0	1+?
Baja/ Guadalupe	27N	247	yes?	no	/	0.3	poor	low	0	0+?
Balleny	67S	163	no	no	/	na	na	na	0	0+?
Bermuda	33N	293	no	no?	/	1.1	good	na	0	0+?
Bouvet	54S	2	no	no	/	0.4	fair	high	0	1+?
Bowie	53N	225	yes	no	/	0.3	poor	na	slow	2+?
Cameroon	4N	9	yes?	no	/	na	na	na	0	0+?
Canary	28N	340	no	no	/	1	fair	low	slow	2
Cape Verde	14N	340	no	no	/	1.6	poor	high	0	2
Caroline	5N	164	yes	no	/	2	poor	high	0	3
Comores	12S	43	no	no	/	na	na	na	0	0+?
Crozet/Pr. Edward	45S	50	yes?	Karoo?	183	0.5	good	na	0	0+?
Darfur	13N	24	yes?	no	/	na	poor	na	0	0+?
Discovery	42S	0	no?	no	/	0.5	poor	high	0	1+?
Easter	27S	250	yes	mid-Pac mnt?	100?	3	fair	high	slow	4+?
Eifel	50N	7	yes?	no	/	na	na	na	0	0+?
Fernando	4S	328	yes?	CAMP?	201?	0.5	poor	na	0	0+?
Galapagos	0	268	yes?	Caribbean?	90	1	fair	high	0	2+?
Great Meteor/ New England	28N	328	yes?	no?	/	0.5	poor	na	0	0+?
Hawaii	20N	204	yes	subducted?	>80?	8.7	good	high	slow	4+?
Hoggar	23N	6	no	no	/	0.9	poor	na	slow	1
Iceland	65N	340	yes?	Greenland	61	1.4	good	high	slow	4+?
Jan Mayen	71N	352	no?	yes?	/	na	poor	na	slow	1+?
Juan de Fuca/ Cobb	46N	230	yes	no	/	0.3	fair	na	slow	2+?

Table 1.4 *Continued*

Hotspot	Lat	Lon (°E)	Track	Flood/ plateau	Age (Ma)	Buoy. ($10^3\,kg\,s^{-1}$)	Reliab.	$^3He/^4He$	Tomo (500 km)	Count
Juan Fernandez	34S	277	yes?	no	/	1.6	poor	high	0	2+?
Kerguelen (Heard)	49S	69	yes	Rajmahal?	118	0.5	poor	high	0	2+?
Louisville	51S	219	yes	Ontong Java	122	0.9	poor	na	slow	3+?
Lord Howe (Tasman East)	33S	159	yes?	no	/	0.9	poor	na	slow	1+?
Macdonald (Cook-Austral)	30S	220	yes?	yes?	/	3.3	fair	high?	slow	2+?
Marion	47S	38	yes	Madagascar?	88	na	na	na	0	1+?
Marqueses	10S	222	yes	Shatski?	???	3.3	na	low	0	2+?
Martin/ Trindade	20S	331	yes?	no	/	0.5	poor	na	fast	0+?
Meteor	52S	1	yes?	no	/	0.5	poor	na	0	0+?
Pitcairn	26S	230	yes	no	/	3.3	fair	high?	0	2+?
Raton	37N	256	yes?	no	/	na	na	na	slow	1+?
Reunion	21S	56	yes	Deccan	65	1.9	poor	high	0	4
St. Helena	17S	340	yes	No	/	0.5	poor	low	0	1
Samoa	14S	190	yes	no?	14?	1.6	poor	high	slow	4
San Felix	26S	280	yes?	No	/	1.6	poor	na	0	1+?
Socorro	19N	249	no	No	/	na	poor	na	slow	1+?
Tahiti/Society	18S	210	yes	No	/	3.3	fair	high?	0	2+?
Tasmanid (Tasman central)	39S	156	yes	No	/	0.9	poor	na	slow	2
Tibesti	21N	17	yes?	No	/	na	poor	na	0	0+?
Tristan	37S	348	yes	Parana	133	1.7	poor	low	0	3
Vema	33S	4	yes?	yes? (Orange R.)	/	na	poor	na	0	0+?
Yellowstone	44N	249	yes?	Columbia?	16	1.5	fair	high	0	2+?

characterize one melting anomaly assigned a lithospheric origin (e.g., the Azores), but swell the score at another such that it is assigned a source at 650 km (e.g., Cape Verde). Since the rationale by which high $^3He/^4He$ is considered relevant to detecting plumes is based on the assumption that such ratios arise from the deep mantle, a scheme by which it could characterize a lithospheric anomaly, or decide on whether a melting anomaly is sourced in the lithosphere

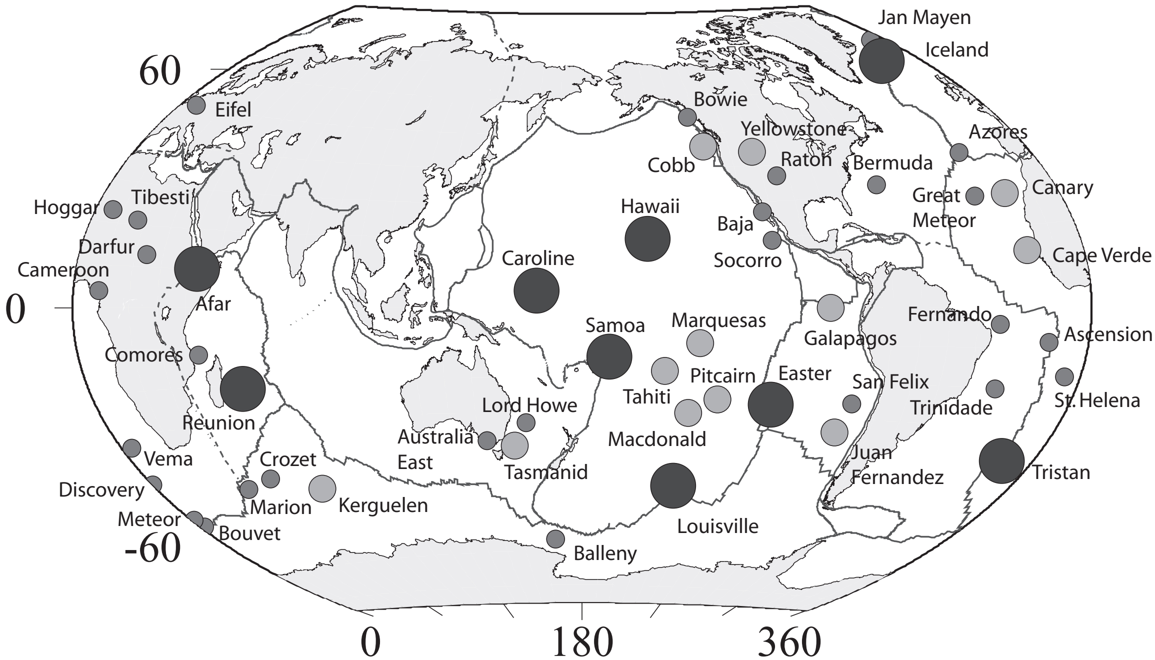

Figure 1.9 "Hotspots in the most cited catalogs" (from Courtillot et al., 2003).

or at 650 km depth, is clearly not rational. Nevertheless, Table 1.4 provides a handy summary of one group's current assessment of the basic global observations.

Several recent seismic experiments have been used to draw up lists of melting anomalies underlain by regions of low seismic wave speed, proposed to show images of plumes (Table 1.5). The list of Ritsema and Allen (2003) is based on the whole-mantle tomography model of Ritsema et al. (1999), which has a resolution of ~1000 km and is particularly reliable in the mantle transition zone, in the depth range 410–650 km. In this model, individual regions of low wave speed tend to be confined to either the upper or the lower mantle and do not traverse both. The list of possible plume localities drawn from this work comprises melting anomalies beneath which low wave speeds extend from the surface down to the base of the upper mantle at 650 km depth.

A relatively new method known as finite frequency ("banana-doughnut") tomography recently provided rather different seismic images of the mantle (Montelli et al., 2004a, b; 2006). This method involves dropping the simplifying assumption that seismic rays are infinitely narrow, and thus correcting for the finite wavelength of seismic waves. The resulting images contain smaller-scale structure and include features that traverse much of the mantle. These results have been challenged (van der Hilst and de Hoop, 2005),[9] but it is instructive, nonetheless, to compare the lists of proposed plumes from that work with other lists.

In the final column of Table 1.5, melting anomalies that erupt large volumes of tholeiitic basalt are indicated. Tholeiitic basalt is thought to result from large-degree partial melting –

[9] http://www.mantleplumes.org/BananaDoughnuts.html

Table 1.5 Melting anomalies defined as arising from the core-mantle boundary by Courtillot et al. (2003), underlain by seismic anomalies traversing the upper mantle (Ritsema and Allen, 2003), traversing the whole mantle (Montelli et al., 2004a, b; 2006) and currently erupting large volumes of tholeiitic lava.

	Courtillot et al. (2003) CMB	Ritsema & Allen (2003) TZ	Montelli et al. (2004a, b) (P waves) CMB	Montelli et al. (2006) (S waves) CMB	Tholeiitic melting anomalies
Afar	X	X			X
Ascension			X	X	
Azores			X	X	
Bowie		X			
Canaries			X	X	
Cape Verde				X	
Cook Island				X	
Crozet				X	
Easter	X	X	X	X	
Galapagos					X
Hawaii	X	X		X	X
Iceland	X	X			X
Kerguelen				X	
Louisville	X	X			
Macdonald		X			
Réunion	X				
Samoa		X	X	X	
Tahiti			X	X	
Tristan	X				
Yellowstone					X

perhaps 10–20% of peridotitic mantle or near-complete melting of eclogite. In this it contrasts with alkali basalt which is traditionally thought to arise ultimately from small degrees of partial melting – perhaps 1–2%. A current school of thought suggests that high degrees of partial melt require high temperatures and that plumes underlie only regions where large-volume tholeiitic lavas are currently being erupted.

The most striking feature of Table 1.5 is the lack of agreement between the different lists of melting anomalies proposed to be underlain by deep mantle plumes. Of the 20 melting anomalies listed, 15 appear on two or fewer of the proposed lists and none appears on every list. There is thus a fundamental difficulty in agreeing where plumes occur, even if just one criterion is used (seismology) and the list is restricted to the strongest candidates only. Afar, Iceland and Samoa, common favorites, appear on only three out of the five lists. Only Easter and Hawaii appear on four, but neither of these fulfill all the non-seismological predictions (Table 1.4).

1.6 Testing plume predictions

How may the predictions of the Plume hypothesis be tested? One of the great beauties of studying melting anomalies is the enormous variety of approaches within Earth science that can potentially contribute. On land, evidence for precursory domal uplift can be sought using stratigraphic mapping and fission track analysis. In the oceans, sedimentary layers sampled in marine drill cores testify to the water depth when they were deposited. Where a large volcanic province formed in the ocean, and was later transported away from its presumed mantle source by plate motion, initial uplift is expected to be matched by subsequent subsidence as the province drifted over cooler mantle.

The existence of plume-head-related flood volcanism can be investigated by geological mapping on land, though the total volume may be hard to assess if the thickness of the lavas cannot be estimated accurately or if much has been eroded away. Flood basalts are often referred to as "large igneous provinces" or "LIPs", a term that has been defined on the basis of the surface area covered by eruptives. Minimum areas of 100,000 km^2 and 50,000 km^2 have both been proposed (Bryan and Ernst, 2008; Coffin and Eldholm, 1992; 1993; Sheth, 2007b),[10] In the present book, the more general term "flood basalt" will be used, to avoid using leading, assumption-driven terminology. In the ocean, broad areas of unusually shallow sea floor ("plateaus") can be seen in bathymetric maps. They are usually assumed to indicate expanses of thickened crust, but this is not always true (Vogt and Jung, 2007).[11] Plateaus also show up in gravity maps as regions of anomalously high gravity because of their excess mass. The thickness of the igneous layers can be probed using seismic methods both on land and at sea, using techniques designed to study crustal structure.

The regularity of time-progression in volcanic chains can be investigated using radiometric dating. Unfortunately, many of the most remarkable chains are on the ocean floor and formidable problems have to be overcome before they can be studied (Clouard and Bonneville, 2005). First, fresh samples can only be retrieved by drilling from ocean-going research ships, an expensive enterprise. Second, although many whole-rock potassium-argon (K-Ar) dates have been derived, this method is inaccurate (Section 4.2.1). It has been superceded by the potentially much more accurate Ar-Ar method, but this has not yet been widely applied. As a result, how time-progressive volcanic chains really are, and how fixed melting anomalies are relative to one another, is still surprisingly poorly known. Many studies deal with this by simply assuming that chains trending in the expected direction are regularly time-progressive. Obviously this is unsafe, and there have been some notable surprises when detailed investigations have been made (McNutt et al., 1997; Tarduno and Cottrell, 1997).

The question of how fixed melting anomalies are relative to one another is generally studied using dates, sample locations and knowledge of the relative motions between the plates on which the melting anomalies lie. Ideally, some fixed frame of reference would be used. The position of the Earth's magnetic pole is a candidate, since it is thought to have been roughly aligned with the rotation axis throughout geological time. Palaeomagnetism can then be used to measure the latitudes of lavas when they were erupted. A problem with this approach, however, is that it cannot yield longitude.

[10] http://www.mantleplumes.org/TopPages/LIPClassTop.html

[11] http://www.mantleplumes.org/Superswell.html; http://www.mantleplumes.org/Bermuda.html

Seismology is essentially the only method currently available that can test for conduits extending from the surface to the core-mantle boundary beneath melting anomalies. For this, techniques are needed that are powerful enough to image Earth structure much deeper than the crust, and extending throughout the mantle. Seismic tomography, using either local or global instrument arrays, is a commonly used technique. Unfortunately, it typically suffers from inadequate spatial resolution or inability to image sufficiently large depths. Tomography has thus been supplemented by methods designed to target localized regions of interest deep in the mantle. For example, the waveforms of carefully selected seismic waves that passed through the target region have been modeled in detail. The deep mantle and the core-mantle boundary beneath currently active volcanic regions are of particular interest because this is where the roots of plumes are hypothesized to lie.

High temperature is perhaps the most basic and fundamental of all the characteristics attributed to plumes. It can potentially be investigated using many different approaches, including seismology, petrology, vertical motions and heat flow (Foulger et al., 2005a). A significant initial challenge is, however, deciding on the norm against which the mantle temperatures beneath melting anomalies should be compared. Typically, the mantle temperature beneath mid-ocean ridges is chosen because they are assumed to have sampled "normal-temperature" mantle. Ridges have been widely studied using seismological and other geophysical methods, and the lavas erupted there have been sampled by dredging, so many data are available to study them. However, it is not clear that these can be compared with melt extracted from very different depths because they probably derive from within the surface conductive layer, and not from below it (Section 6.1; Presnall et al., 2010).

The plethora of methods available to estimate temperature vary hugely in precision, ambiguity, and how closely they approach a true measure of the temperature of the melt source. Seismic wave speeds are notoriously ambiguous. They vary not just with temperature but also with composition and the presence of partial melt. For example, even a trace of partial melt can radically lower seismic wave speed. The problem is that it is usually impossible, in practice, to separate out the contributions from individual effects. Seismology can tell us little about temperature, even though it is widely assumed to be the most powerful indicator of temperature for the deep mantle. Petrological methods suffer from the difficulty of acquiring a fresh sample confidently known to represent the original melt. Specimens are almost always modified by material lost during crystallization or gained during transport to the surface. Only glass samples devoid of crystals can confidently be assumed to correspond directly to an original liquid. Petrological thermometry has to make simplifying assumptions that are often unlikely to be realistic (Section 6.2.2).

Petrological and geochemical methods have also been widely applied in efforts to obtain the compositions of melt sources, their locations in the mantle, and their histories of formation. Deducing source composition from lava composition is inherently ambiguous, however, and geochemistry has almost no power to constrain depth of origin below ~100 km. Only if melting anomalies are shallow-sourced is geochemistry likely to be important in constraining their origins.

These are practical problems that present great challenges, but the picture heretofore painted is nevertheless straightforward. A precisely defined Plume hypothesis has been developed, clear, specific predictions have been made, and techniques exist, albeit inaccurate and in need of improvement, to test those predictions. If things were thus simple, and required only rigorous application of the scientific method, our problems would be only scientific ones. Unfortunately, there is another dimension to how plume science is, in reality, practiced. That is, every one of the five basic features predicted, and also the predictions of many variants of the hypothesis, is commonly either considered optional or its absence, even in the face of extensive searching, is considered to be inconclusive. This problem besets both theoretical and observational work, and renders the hypothesis essentially unfalsifiable.

From the theoretical point of view, the expectation of simple, domal precursory uplift has been brought into question by numerical modeling. For rheologicaly realistic lithospheres that include the viscoelastic layers that are known to exist, the pattern of vertical motion is predicted to be a complex mix of uplift and subsidence (Burov and Guillou-Frottier, 2005a).[12] A bulbous plume head and an initial flood basalt is not predicted if a plume has a higher viscosity than the mantle through which it rises. In that case, a distinct head does not develop (Davies, 1999, p. 303). The necessity of observing a narrow conduit extending to the core-mantle boundary is relaxed if the plume is postulated to pulse, be discontinuous, or arise from the base of the upper mantle at a depth of 650 km. The lack of time progression of volcanism can be explained away by postulating irregular lateral flow of plume material. How high a temperature anomaly is required at the surface is, in practice, vague. Hot, rising material is expected to entrain cooler mantle and to reduce the temperature anomaly in the shallow part of the plume where melting is thought to occur. Some estimates of plume temperature anomalies proposed are <100 °C, and these fall within the normal variation in mantle temperature expected from place to place as a result of plate-tectonic-related processes such as subduction and continental insulation.

Technical, scientific problems can be addressed scientifically. However, immunity of an hypothesis to testing is something that science cannot deal with. Is the Plume hypothesis immune, and no longer scientific? This is not merely detached philosophical speculation but touches on the very issue of whether a fundamental scientific problem actually exists or not.

[12] http://www.mantleplumes.org/Burov2005.html

1.7 A quick tour of Hawaii and Iceland

Hawaii and Iceland exemplify the difficulties that a flexible hypothesis presents. In agreement with the predictions, the Hawaiian-Emperor volcanic chain is unidirectionally time-progressive, and picrite glass samples have been found and interpreted as indicating a high source temperature (Section 6.5.3). Nevertheless, the system is lacking a flood basalt at its old end, there is no evidence for precursory uplift there, and a conduit to the core-mantle boundary beneath the "Big Island" of Hawaii has not been observed (Fig. 1.10). On the other hand, a flood basalt is currently forming at the young end of the chain. Suggested solutions to these problems with the Plume hypothesis include the subduction and disappearance of an original plume-head-related volcanic plateau that preceded formation of the Emperor chain, and insufficient resolution in seismic tomography of the mantle beneath Hawaii. The recent surge in volcanic output has been explained by a pulsing plume.

In the Iceland region, the story is close to the reverse. Uplift accompanied flood basalt eruption early in the volcanic sequence. However, there is no time-progressive volcanic chain – volcanism has always been centered on the mid-ocean ridge, currently at Iceland (Foulger and Anderson, 2005; Foulger et al., 2005a; Lundin and Doré, 2005, 2004).[13] Also, a large suite of independent methods indicate strongly that the temperature of the mantle beneath the north Atlantic is possibly 50–100 °C higher than is typical beneath mid-ocean ridges, but certainly not approaching the 200–300 °C predicted for plumes. Iceland is more easily studied seismically than Hawaii, and multiple, independent, high-quality seismic studies leave little doubt that there is no low-wave-speed conduit extending down to the core-mantle boundary.

[13] http://www.mantleplumes.org/Iceland1.html
http://www.mantleplumes.org/Iceland2.html;

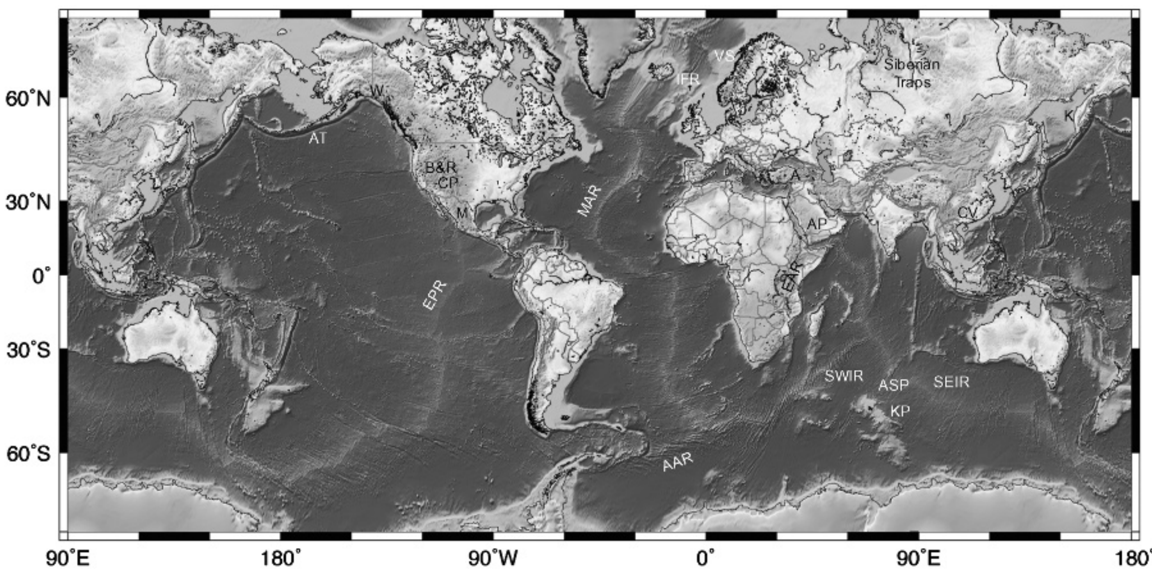

Figure 1.10 Global topography and bathymetry, from gravity measurements:[14] IFR – Iceland-Faeroe Ridge; VS – Vøring Spur; CV – Changbai Volcano; AP – Arabian Peninsula; W – Wrangellian terrain; AT – Aleutian Trench; EPR – East Pacific Rise; CP – Colorado Plateau; K – Kamchatka; A – Anatolia; M – Mexico; B&R – Basin and Range Province; EAR – East African Rift; AAR – American-Antarctic Ridge; MAR – Mid-Atlantic Ridge; ASP – Amsterdam-St Paul Plateau; SWIR – Southwest Indian Ridge; SEIR – Southeast Indian Ridge; KP – Kerguelen Plateau. See Plate 2

As is the case for Hawaii, present-day volcanism is also forming a second flood basalt at Iceland (Fig. 1.10).

Variants of the basic Plume hypothesis can again account for all the unpredicted features. These include lateral flow of material to the mid-Atlantic ridge from a relatively fixed plume that did not pierce the surface at its true location, and pulsing, discontinuous and tilting plumes. The lack of picrite glass samples, which might provide evidence for high temperatures, has been attributed to the inability of dense melts to rise through the thick pile of basaltic lavas. A cool plume under Iceland has also been suggested. Most of these variants, if also applied to Hawaii, would predict observations there at odds with what is found.

[14] http://topex.ucsd.edu/WWW_html/mar_topo.html

Let us back track and consider the additional predictions of the original hypothesis (Morgan, 1971), that have been discarded in the more modern version. These are that plumes are fixed relative to one another, that they transport compositionally distinct, primordial material to the surface from the deep mantle, and that they break continents up and drive plate tectonics.

Relative fixity is difficult to test for the Emperor seamount chain, because there is no other clear, simple, time-progressive chain of the same age (76–50 Ma) on a different plate. The fixity of the Emperor volcanic locus relative to the Earth's geomagnetic pole has been investigated and it has been discovered that Emperor volcanism migrated south by at least 800 km and possibly by as much as 2000 km, across a slow-moving or even stationary Pacific plate during formation of the chain (Sager, 2007; Tarduno and Cottrell, 1997). This is the exact opposite scenario to that of a fixed plume with a plate moving overhead transporting volcanoes away. At ~50 Ma, the time of the "bend" in the Emperor-Hawaiian chain, the behavior appears to have abruptly reversed. The Pacific plate started to move rapidly northward with respect to the geomagnetic pole and the volcanic locus suddenly stopped. In the case of Iceland, volcanism has always been centered on the mid-Atlantic ridge, a location that is not fixed relative to any other melting anomaly.

Again, these features, unpredicted by any version of the Plume hypothesis, have been explained away by *ad hoc* variants. The apparent wandering of the postulated Hawaiian plume has been explained by "mantle wind", i.e., distortion of the plume conduit, and consequential displacement of the surface volcanic locus, by large-scale mantle convection unrelated to plumes (Steinberger et al., 2004). The exact opposite argument has been used to explain the persistence of high-volume volcanism on the mid-Atlantic ridge at Iceland. There, it has been suggested that material flowed laterally from a relatively fixed plume to the northwest, one that was not "blowing in the mantle wind", and which did not penetrate the surface vertically above (Vink, 1984). The volcanism that formed the Emperor-Hawaiian chain is thought to have started on a spreading ridge (Norton, 2007) but it subsequently migrated away and into the deep interior of the thick Pacific plate, penetrating the surface without difficulty, even in the past when its production was much lower than at the present day. This plume material evidently had no tendency to flow laterally and erupt at the nearest ridge.

Let us turn to composition. The prediction that lavas at proposed plume localities are compositionally different from mid-ocean-ridge basalts (MORB) fits the observations well. The enriched basalts found, for example, at oceanic islands, typically contrast geochemically with MORBs in rare-earth- and incompatible-element contents, radiogenic isotopic signatures and sometimes in their noble gas isotope ratios. The difficulties that arise from this are two-fold. First, the geochemical signatures have been found to arise from the inclusion in the source of near-surface materials such as sediments and subducted oceanic crust. Second, virtually identical geochemical signatures are widespread in basalts scattered throughout the continents and oceans where plumes have not been proposed and are not expected (Fitton, 2007). Such basalts are found on isolated seamounts, in small-volume eruptions in rift valleys, and even in long-lived, low-output volcanic provinces that have erupted similar material for tens of millions of years as the region drifted thousands of kilometers from its original position. Examples of such regions are the Scottish Midland Valley and the rift zones of Europe. A recent plume-compliant explanation for this enigma suggests that the entire asthenosphere is made up of material transported up from the deep mantle in plumes. All surface volcanism, regardless of its cause, then arises from various melt fractions extracted from a global layer of plume material (Yamamoto et al., 2007a; b).

The final prediction, that plumes break continents up and drive plate tectonics is at best only partially consistent with the observations. The North Atlantic Igneous Province is linked to break-up of the Eurasian supercontinent, starting at ~54 Ma, at which time voluminous volcanic margins formed. In contrast, no evidence is available concerning an hypothetical plume head stage for the Emperor-Hawaiian system because the oldest part of the Emperor chain abuts the Aleutian trench. Earlier features may have been subducted, though there is no evidence for this (Shapiro, 2005). The remarkable contrasts between these two huge volcanic provinces, both of which are proposed to be caused by the same geodynamical phenomenon, could hardly be more striking.

Modern plume science, outlined above, thus leaves us in a quandary, both regarding its predictions and the flexibility with which it is applied. On the one hand, clear, specific predictions have been proposed, both early in the history of the hypothesis, and more recently, following decades of research and testing. Some data are consistent with the hypothesis, but in most cases the predictions have not been confirmed. In this respect the Plume hypothesis contrasts starkly with plate tectonics. The predictions of that theory have been spectacularly confirmed over many years, often using methods unconceived when the hypothesis was first proposed. This is not to say that the original plate tectonic concept has survived testing unmodified. Indeed, plates are now known to be not rigid and many details of early suggested plate boundaries have been revised. Nevertheless, observation has tended to strengthen and confirm the basic concept, and discrepancies have been second-order in nature and compliant with the overall, basic model.

In the case of the Plume hypothesis, testing has instead tended to turn up first-order problems requiring major revisions, often different for different proposed plumes. This should scarcely come as a surprise because a striking feature of the volcanic regions proposed to be underlain by plumes is their extreme diversity. They comprise a group much less homogenous than either mid-ocean-ridge spreading segments or subduction-zone volcanoes. No one volcanic system on Earth fulfills all the predictions, and most fulfill very few or even none. A composite of observations drawn from more than one melting anomaly is needed in order to assemble a full set of postulated plume attributes. Notwithstanding this, failure of the predictions is rarely considered to be a threat to the hypothesis. How then, can the Plume hypothesis be tested? Can it ever be rejected, and what is the way forward?

1.8 Moving on: Holism and alternatives

Two possible fresh avenues of approach spring to mind. The first is to take a holistic investigative approach, both to individual melting anomalies and to the global constellation as a whole. A variant of the Plume hypothesis may indeed be designed to account for an individual discrepancy in a particular data set at a volcanic locality, but is this variant consistent with other, cross-disciplinary observations? Mutually inconsistent variants proposed, for example, to satisfy separate seismic, geochemical and geochronological observations, cannot all be correct. Furthermore, a variant that explains the observations at just one, or very few, proposed plume localities is unconvincing if it is not generally applicable in similar situations elsewhere, that is to say, if it is not predictive.

If the Plume hypothesis does not fulfill minimum reasonable scientific expectations, then what does? The second approach is to develop and test alternatives, and it is therein that the real excitement and potential for progress lies. Interest in alternative models waned during the 1990s. However, the present century has seen a resurgence of interest in response to the growing weight of evidence that the difficulties with the Plume hypothesis are insurmountable. Today, the alternative "Plate" hypothesis encompasses diverse, shallow-based models for melting anomalies that are linked by their common association with the effects of plate tectonics. Describing this hypothesis, and weighing the evidence against both it and the Plume hypothesis, is the subject of the present book.

1.9 The Plate hypothesis

The Plate hypothesis postulates that melting anomalies on the surface of the Earth arise from shallow-based processes related in various ways to plate tectonics (Anderson, 2001a; 2007; Foulger, 2007; Foulger and Natland, 2003).[15] Simply put, it suggests that melting

[15] http://www.mantleplumes.org/PTProcesses.html; http://www.mantleplumes.org/PLATE.html

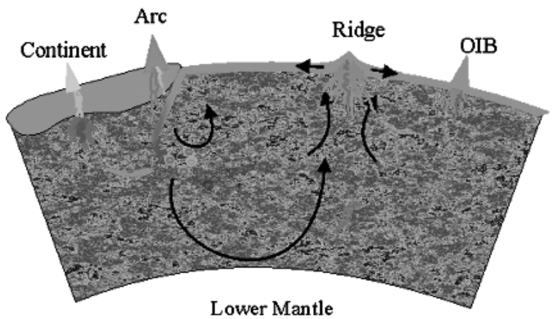

Figure 1.11 The upper mantle is kept inhomogeneous by continuous melt extraction and lithosphere recycling at subduction zones and beneath continents, which makes plate tectonics work (from Meibom and Anderson, 2004). See Plate 3

anomalies arise from permissive volcanism that occurs where the lithosphere is in extension (Favela and Anderson, 1999; Natland and Winterer, 2005). The volume of magma produced is variable, and related to the fusibility of the source beneath and the availability of pre-existing melt (Fig. 1.11). Where extension occurs above a fertile source or regions containing partial melt, enormous volumes of magma may form and be intruded and erupted. Where it occurs above refractory, infertile, sub-solidus mantle, little melt may be produced. For a given temperature, larger volumes of melt will be produced from a source with a low solidus temperature, than from one with a higher solidus temperature (Table 1.1). The eruption rate is controlled by factors such as lithospheric stress and thickness, the quantity of pre-existing melt, and the amount of volatiles.

Plate tectonics constantly maintains a state of variable stress in the lithosphere, with extension in some places and compression in others. This extension may be localized, for example, at continental rifts, mid-ocean ridges, and triple junctions, or it may be distributed in broad regions such as the Basin and Range province in western North America, and in diffuse oceanic plate boundaries. It is in these regions where melting anomalies are most expected and, indeed, where they are most commonly present. The plates are not considered to be absolutely rigid, but they are recognized as being capable of internal deformation, both in continental and oceanic regions. Extension in intraplate oceanic regions is more difficult to study than on land, because most of the sea floor is known only through sensing from space using satellites or from the surface of the ocean. This is comparable to mapping an area on land from several kilometers away, using binoculars. The Plate hypothesis suggests that volcanism itself is an intrinsic indication of where the lithosphere is in extension.

The fertility of source material, often but not necessarily always in the mantle, also varies as a result of processes ultimately related to plate tectonics. New crust is created at spreading ridges by the extraction of melt from the mantle. New mantle lithosphere accumulates beneath the crust as the plates drift away, cool and thicken. The components of the mantle that melt first and form the crust are necessarily the most fusible ones, and the remaining refractory residuum is left behind.

The recycling of slabs comprising crust and mantle lithosphere back into the mantle at subduction zones reintroduces fusible material from the near-surface into the mantle as concentrated packages made up of diverse rock types. Delamination and gravitational instability perform a similar role in recycling continental lithosphere. These are processes by which over-thickened lithosphere, which has densified by mineralogical phase changes, detaches and sinks into the asthenosphere. They are ultimately related to plate tectonics, since it is processes such as continental collision that thicken the lithosphere.

In addition to dehomogenizing the crust and upper mantle compositionally, such processes also dehomogenize it thermally. Melt migrating from one region to another, and the subduction or sinking of cold, dense material, transport heat

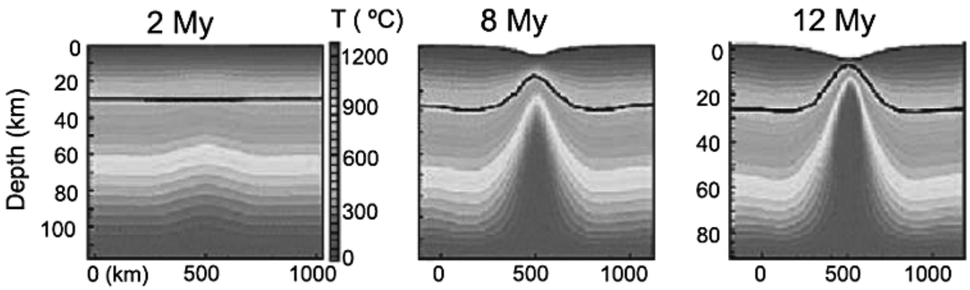

Figure 1.12 Thermal evolution of lithosphere overlying normal-temperature asthensophere during extension leading to continental break-up. Massive volcanism results, building volcanic margins. Black line indicates the Moho (from van Wijk et al., 2001).

as well as compositionally distinct material. In this way, plate-related processes result in variations in temperature from place to place, though these are on the whole expected to be more subdued and less localized than the temperature anomalies predicted by the Plume hypothesis.

These are broad generalizations. Is it possible to be more specific about exactly what is envisaged and predicted? Within the scope of the Plate hypothesis many different phenomena are expected to lead to volcanism. While this may seem untidy and at odds with Occam's Razor – the desirability of maximum simplicity – it is in keeping with the enormous diversity of melting anomalies that is immediately obvious from a mere glance at any list (Tables 1.1–1.5).

Specifically, the main processes that fall under the umbrella of the Plate hypothesis are:

- *Continental break-up:* In the Plate hypothesis, continental break-up, for example, such as formed the Atlantic ocean, is viewed as part of a continual self-reorganization of the plates (Anderson, 2002). Self-reorganization may be brought about by changing plate boundary conditions, for example, the collision of continents, subduction of entire plates, or by local changes in the temperature of the upper mantle brought about by continental insulation. The process of continental break-up is expected to start with extension and to continue through rifting to fragment separation and formation of a new ocean basin. It is expected to be complicated, shedding fragments of continental lithosphere into the new ocean, sometimes large enough to form microcontinents, to cycle continental lithospheric material into the mantle beneath the new ocean, and to be accompanied by massive magmatism that builds volcanic margins (Fig. 1.12).

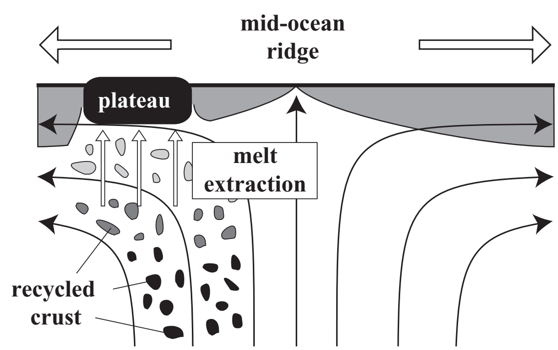

Figure 1.13 Mechanism for the production of excess melt at or near a spreading ridge, as a result of upwelling of fusible material (from Korenaga, 2005).

- *Fertility at mid-ocean ridges:* The most obvious sites of surface extension are mid-ocean ridges. Where these encounter an unusually fertile source region, enhanced magmatism may occur (Fig. 1.13). Many melting anomalies do indeed lie either directly on ridges or close to them, for example, Iceland and Tristan (Figs 1.6 and 1.9). Of the 16 plume localities originally proposed by Morgan (1971), 12 lie on or close to spreading ridges.

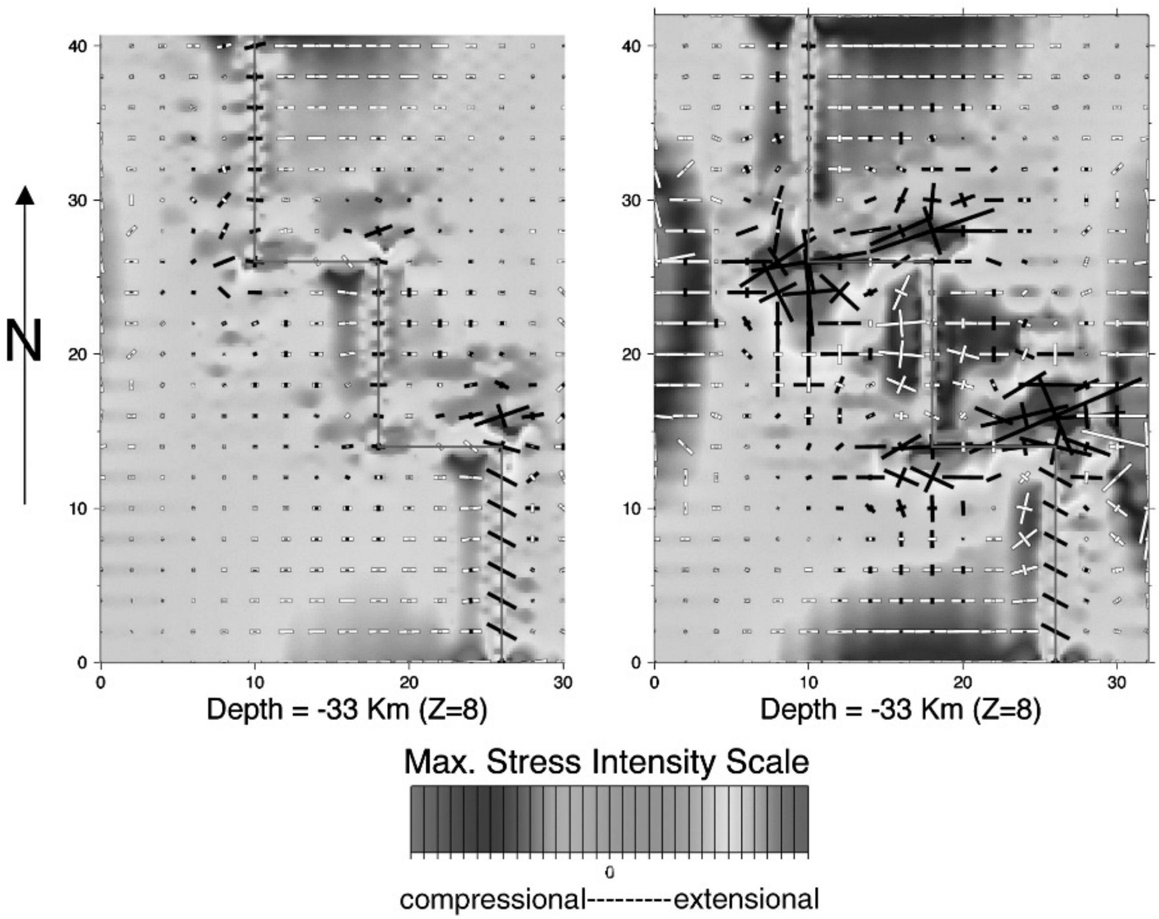

Figure 1.14 Predicted variations in stress at ridge-transform intersections: left: a weak transform, right: a strong transform. Lines indicate the type and intensity of maximum stress, black: compressional, white: extensional. Regions of strong lithospheric extension, encouraging magmatism, are predicted on the outer corners of the ridge-transform intersections (from Beutel, 2005).[16] See Plate 4

- *Enhanced volcanism at plate boundary junctions:* The sites of excess volcanism at or near spreading plate boundaries are often also the sites of complexity in the plate boundary configuration. Excess volcanism commonly develops on the outside of ridge-transform intersection corners. There, extensional stress is predicted to develop when slip on the transform lags behind spreading. The stronger the transform, the larger the extensional stress that builds up (Fig. 1.14) (Beutel, 2005). Examples include Ascension Island and the Amsterdam-St Paul plateau on the South East Indian ridge. Excess volcanism may also occur along oblique or "leaky" transforms. The Terceira "rift" in the Azores Plateau, the Voring Spur along the trend of the Jan Mayen Fracture zone, and the Iceland-Faeroe Ridge have been proposed as features of this kind (Gernigon et al., 2009).[17]

  Excess volcanism also commonly occurs at ridge-ridge–ridge-triple junctions for example, the Azores. There, the flow of upwelling material is expected to

[16] http://www.mantleplumes.org/RTIntersections.html

[17] http://www.mantleplumes.org/JanMayen.html

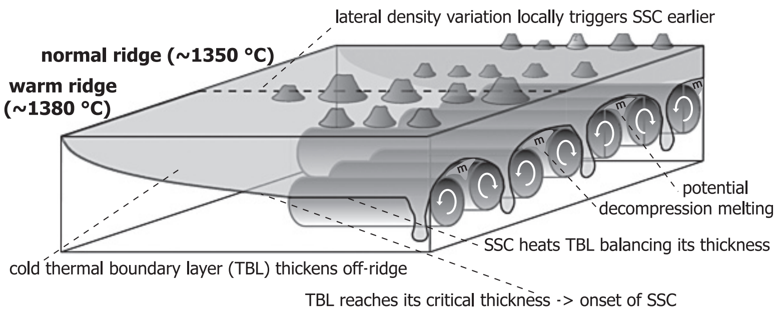

Figure 1.15 Small-scale sublithospheric convection (SSC) spontaneously evolves at the bottom of mature oceanic lithosphere. SSC organizes as rolls aligned by plate motion, and decompression melting occurs above the upwellings (from Ballmer et al., 2009).

be modified by the change in architecture of the base of the lithosphere. As a result, both passive upwelling and temperature are predicted to increase (Georgen and Lin, 2002).

Even more complex is the tectonics of diffuse or rapidly evolving plate boundary regions. Such regions may feature one or more of overlapping parallel ridge segments, microplates, propagating ridges and ridge jumps. At such localities distributed enhanced volcanism is expected to reflect the distributed and rapidly evolving spatial pattern of extensional stress. Examples include Easter, Iceland and the Bouvet triple junction.

- *Small-scale sublithospheric convection:* Small-scale convection is predicted to onset spontaneously beneath oceanic lithosphere as it is transported away from the ridge where it formed, and cools and thickens (Fig. 1.15). Such convection takes the form of rolls orientated parallel to plate motion (Richter and Parsons, 1975). It successfully explains the corrugated sea-floor fabric on either side of the East Pacific Rise, for example, the Hotu Matua and Sojourn ridges (Fig. 1.16). Individual rolls are predicted to be of the order of 1000 km long and spaced at intervals of 200–300 kilometers. Volcanism may last for a few million years, dwindling as the convection process cools the asthenosphere and shuts itself down. The Marshall and Line islands, the Gilbert ridges and the Cook-Austral and Pukapuka volcanic chains are well explained by this process (Ballmer et al., 2007; 2009; Weeraratne et al., 2007).[18]
- *Oceanic intraplate extension:* It is a misconception to think of the plates as strong, rigid entities that break only under the influence of some external and extraordinary *force majeure*. They are in truth weak, and their interiors are maintained in a constant state of stress disequilibrium by plate-tectonic-related processes. The stress fields in the interiors of oceanic plates vary from place to place because of factors such as the variation in plate boundary type around the plate perimeters, thermal effects such as rapid cooling of the plates near ridges (Forsyth et al., 2006; Sandwell and Fialko, 2004), local volcanism and plate bending, for example, near to subduction zones and massive volcanic loads (Fig. 1.17). The widespread diffuse volcanism in the Pacific plate, volcanic ridges, and chains with irregular time progressions have been modeled by plate-related processes (Hieronymus and Bercovici, 1999; 2000).
- *Slab tearing or break-off:* Disruption of subducting slabs and mantle flow at relatively shallow depths may occur in trenches near to the ends of slabs or when continents collide, subduction stops, and slabs break off. Examples of places where processes of this kind are occurring today are Kamchatka, Anatolia and Mexico (Fig. 1.18).
- *Shallow mantle convection:* Abrupt lateral changes in the architecture of the base of the lithosphere may induce local convection cells in the asthenosphere. For example, at continental edges, 200-km-thick, cold, cratonic lithosphere may abut oceanic lithosphere only a few tens of kilometers thick. Where warm asthensophere beneath the oceanic lithosphere is juxtaposed against the sub-continental lithosphere, it may cool and sink. This mode of convection has been called EDGE convection (Edge Driven Gyres and Eddies). It can erode the sub-continental lithosphere and enhance upwelling in the interior of ocean basins (Fig. 1.19) (King, 2005; King and Anderson, 1998).

It has also been suggested that convection limited to the upper mantle can result from dense material,

[18] http://www.mantleplumes.org/VolcRidges.html; http://www.mantleplumes.org/Pukapuka.html

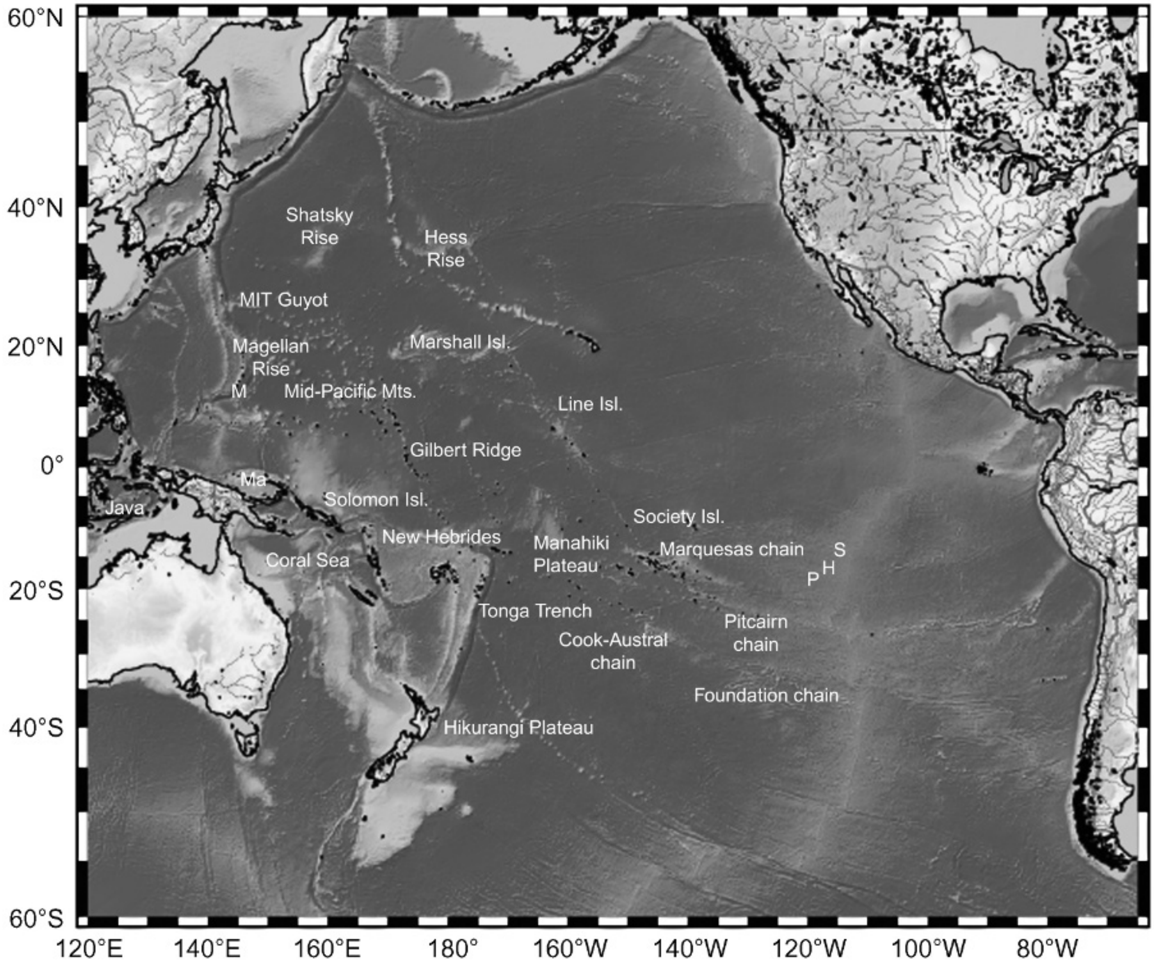

Figure 1.16 Map of the Pacific showing place names: P – Pukapuka Ridge; S – Sojourn Ridge; H – Hotu Matua Ridge; M – Mariana Trench; Ma – Manus Basin. See Plate 5

for example, eclogite blocks, possibly from delaminated continental mantle lithosphere or lower crust, sinking to their level of neutral buoyancy, heating to ambient mantle temperature and then rising again as a result of their newly acquired thermal buoyancy. This process is analogous to the rising and sinking of suspended objects in a Galileo thermometer.[19] It has been termed the "eclogite engine", and proposed as an explanation for mid-ocean swells and plateaus such as Cape Verde and the Rio Grand Rise (Anderson, 2007a).

- *Abrupt lateral changes in stress at structural discontinuities:* The lithospheric stress field may change abruptly where the shapes or structures of continents or plate boundaries change radically, for example, the northern termination of the Tonga trench in the southwest Pacific and the Cameroon region, West Africa (Fig. 1.10).
- *Continental intraplate extension:* The continental crust can extend both in a localized, focused manner

[19] http://en.wikipedia.org/wiki/Galileo_thermometer; http://www.mantleplumes.org/TopPages/HotSlabsTop.html

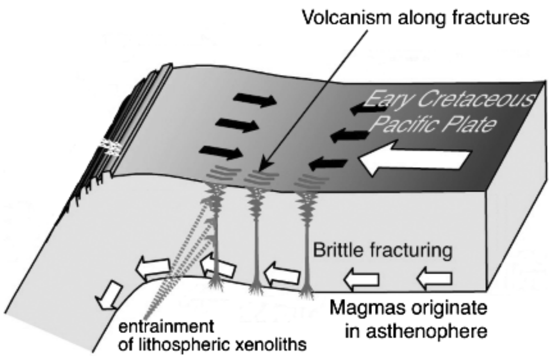

Figure 1.17 Schematic diagram illustrating volcanism resulting from oceanic intraplate extension. Magmas escape from the asthenosphere to the surface as a result of extension of the lower lithosphere and migration through the upper lithosphere via fractures created by flexure of the plate as it approaches a subduction zone (adapted from Hirano et al., 2006). "*Volcanism in Response to Plate Flexure*", Hirano, N. et al. **313**: 1426–1428, 2006. Reprinted with permission from Science.

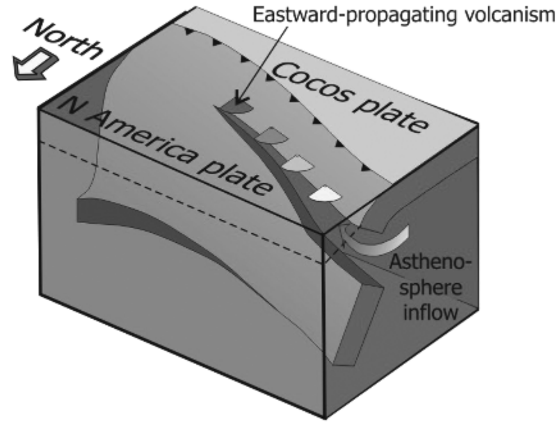

Figure 1.18 Schematic diagram illustrating progressive slab tearing and break-off, resulting in migrating volcanism as sub-slab asthenosphere upwells through the gap. This model was proposed to explain migrating Miocene volcanism in Mexico (modified from Ferrari, 2004).[20] "*Slab detachment control on mafic volcanic pulse and mantle heterogeneity in central Mexico*", Ferrari, L **32**: *77–*80, 2004. Reprinted with permission from *GSA*.

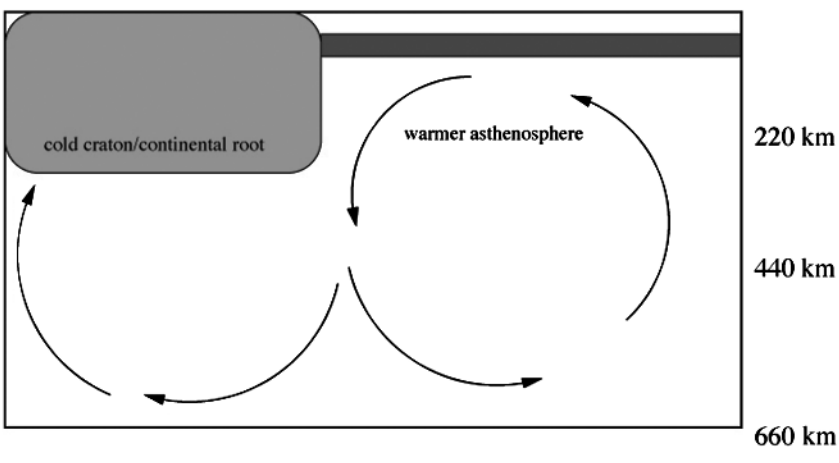

Figure 1.19 Small-scale "EDGE" convection cell at a craton boundary (from King and Anderson, 1998).

and also in a diffuse style throughout broad regions. The Basin and Range province in the western USA (Wernicke, 1981), the continent of Africa, including the East African rift valley (Bailey and Woolley, 2005), and Europe, including the Rhine graben (Chalot-Prat and Girbacea, 2000; Wilson and Downes, 1991; Ziegler, 1992), are examples of regions that are both in extension and volcanically active. Evidence for extension accompanying the outpouring of continental flood basalts is provided by the widths of feeder dikes, for example, those from which the Columbia River Basalts flowed. The

[20] http://www.mantleplumes.org/Mexico2.html

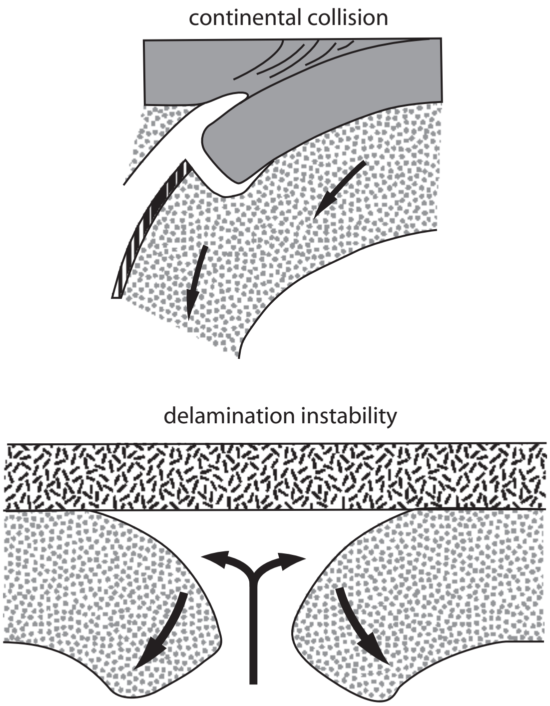

Figure 1.20 Recycling of lithosphere in continental collisions and by delamination[21] (Bird, 1979).

surface extension then amounts to the sum of all the dike widths (Christiansen et al., 2002).

- *Catastrophic lithospheric thinning:* Where the lithosphere becomes over-thickened, for example in continental collision zones or by deep intrusions, its lowermost parts may become negatively buoyant. This may be aided by sinking to depths and pressures where transformation to eclogite occurs. Eclogite is the dense equivalent of basalt and transformation begins at ~50 km. The high-density lithosphere keel may peel off ("delaminate") (Fig. 1.20) (Bird, 1979) and sink into the asthenosphere, or simply form a bulbous gravitational instability and drop off – a down-going, or inverse plume (Fig. 1.21) (Daly, 1933; Elkins-Tanton, 2005; Kay and Kay, 1993). Part of the lower crust may also be removed in the process. This process can potentially explain flood basalts in intra-continental areas where the lithosphere was initially very thick, and where it was preceded by subsidence and not uplift. It may have played an important role in the Basin and Range province, the Columbia River Basalts, the Colorado Plateau and the Siberian Traps.

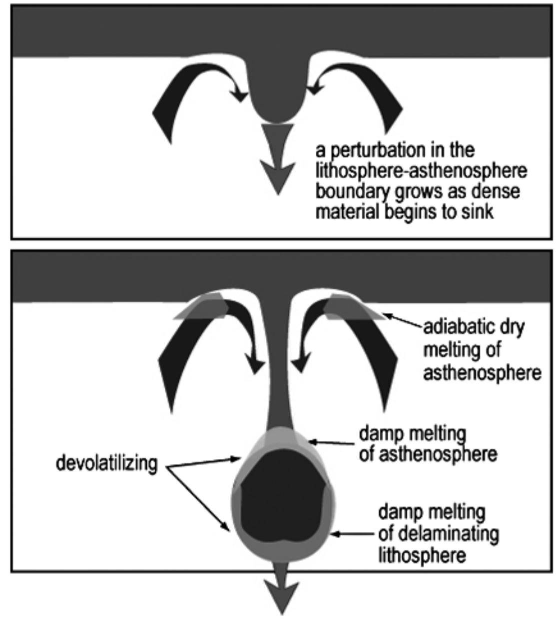

Figure 1.21 Loss of lithosphere by a gravitational instability.[22]

- *Sublithospheric melt ponding and draining:* If the asthenosphere is locally above its solidus, melt may form over a long period of time and large volumes may pond at the base of the sub-continental mantle lithosphere (Fig. 1.22). Later rifting and fracturing of the lithosphere may permit this melt to escape to the surface in a much shorter time than it took to accumulate (Silver et al., 2006). Only relatively narrow feeder dikes are required (Rubin, 1995). This mechanism may explain the rapid formation of flood basalts in the absence of rifting of the magnitude needed for decompression upwelling to account for the melt volumes emplaced. In these cases, flood basalt eruption does not correspond to the melt-production time-scale, but to the reservoir-drainage time-scale.

[21] http://peterbird.name/publications/1979_delamination/1979_delamination.htm

[22] http://www.mantleplumes.org/LithGravInstab.html

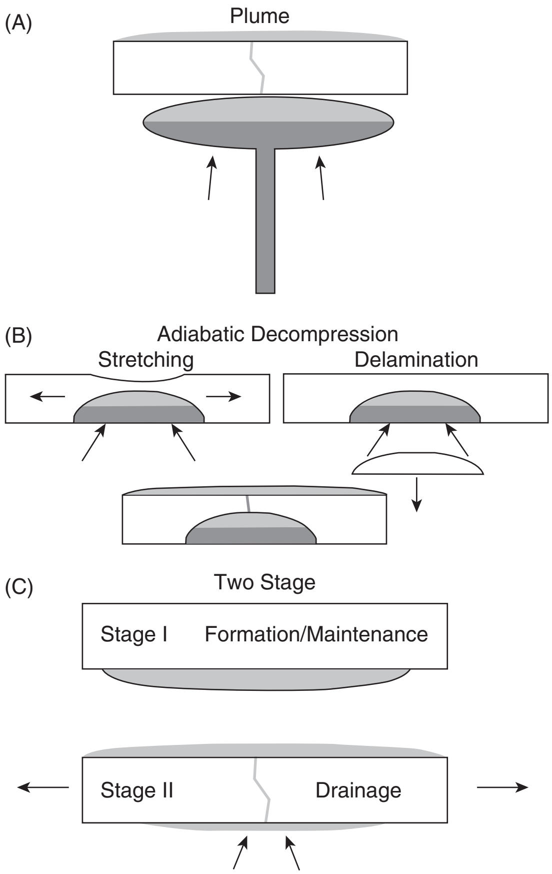

Figure 1.22 Competing models for the formation of continental flood basalts: dark gray indicates regions of elevated temperature or volatile content, light gray indicates zones of partial melt. (A) Plume model; (B) Adiabatic-decompression melting models; (C) Two-stage melt ponding and draining model (from Silver et al., 2006).

In addition to these terrestrial processes, melting anomalies might also be triggered by the impact of bolides arriving from space (Hamilton, 1970; Ingle and Coffin, 2004; Jones et al., 2002; 2003; 2005; Price, 2001).[23] Such impacts can theoretically induce an amount of melting equivalent to a large flood basalt. Melting anomalies postulated to exist on other planets, and on moons, are also the subject of considerable work. Venus is of particular interest because it features many circular structures variously postulated to be caused by external means – meteorite impacts – or internal plumes (Hamilton, 2005; 2007a; Jurdy and Stoddard, 2007; Matias and Jurdy, 2005; Stofan and Smrekar, 2005; Vita-Finzi et al., 2005). Olympus Mons on Mars is the largest volcanic feature known in the solar system and has been attributed to a giant bolide impact (Reese et al., 2007).[24] Studying features on other planets is more difficult than studying terrestrial examples because the available data are fewer and of poorer quality. Thus, if the origins of melting anomalies on Earth, which can be examined closely and sampled extensively, are disputed, then clearly determining the origins of candidates on remote planets presents an even greater challenge.

The picture painted above is complex. The Plate hypothesis views plate tectonics as a system that is richer and more varied than the simple picture commonly presented in textbooks, of rigid plates floating on a uniform, viscous mantle, with no complications or second-order effects.

A simplifying statement may nevertheless be made. The Plate hypothesis attributes the causative processes of melting anomalies to the Earth's top thermal boundary layer – the surface, in contrast to the Plume hypothesis which attributes them to its bottom one – the core-mantle boundary. The plate view is intrinsically appealing in a number of respects. Some 90% of the heat lost from the Earth's surface is generated internally in the mantle by radioactive decay. Only ~10% is thought to be input into the mantle from the core (Anderson, 2007b). The Earth's top thermal boundary layer has an area four times that of the bottom thermal boundary layer and it is thus a heat transmitter over twice as powerful per unit area. The Plate hypothesis furthermore views mantle convection, plate tectonics and surface

[23] http://www.mantleplumes.org/Impacts.html

[24] http://www.mantleplumes.org/TopPages/PlanetaryTop.html

volcanism of all kinds as interrelated and interdependent elements of a single planetary dynamic system. It does not suffer from the philosophical awkwardness of the Plume hypothesis, which proposes a convective mode that is separate and independent of normal mantle convection.

1.10 Predictions of the Plate hypothesis

What are the specific predictions of the Plate hypothesis? They are, in general, simply that:

- Melt extraction will occur where the lithosphere is locally in extension. Evidence for extension may include dikes, normal faulting, and continental separation or be found using geodetic surveying, for example, using GPS.
- The volume of magma extracted will be related to the fertility of the source. The primary evidence will be compositional and will comprise mainly petrological and geochemical observations.

The Plate hypothesis is ambivalent regarding several specific predictions of the Plume hypothesis. Vertical motions preceding and accompanying melt extraction are expected to vary according to the dominant process at work. For example, volcanism accompanying the detachment of thickened lithosphere via a gravitational instability is predicted to be preceded by subsidence as the crust is dragged down by initial sinking of the thickened root. The eruption of a flood basalt may or may not be followed by subsequent small-volume volcanism, depending on the ensuing stress state of the lithosphere. Narrow conduits transporting hot material from the core-mantle boundary to the surface beneath currently active melting anomalies such as Hawaii and Iceland are not expected. Volcanic chains may or may not be time-progressive, depending on whether the extending region is localized at one end, or extends along the entire chain. The temperature of the mantle is expected to vary laterally, but the high, localized anomalies of 200 °C or more that are predicted by the Plume hypothesis to occur beneath active volcanic regions are not expected.

In the Plate hypothesis, long-lived intraplate melting anomalies that lie on the same plate may remain broadly fixed relative to one another or to migrate slowly. This is because they occur in response to large-scale, plate-wide stress fields that are governed by the distant, plate boundary configuration. As long as the boundary configuration remains the same, extending regions and melting anomalies will retain stable relative locations. If the boundary configuration evolves, for example when a ridge is subducted, then the intraplate stress field and relative locations of melting anomalies will change in response. In this way, time-progressive volcanism may develop on a plate that moves rapidly compared with the time-scale of evolution of its boundary. Melting anomalies are not thought to cause continental breakup, but they are thought to form in response to it. They are not thought to drive plate tectonics.

1.11 Testing the Plate hypothesis

How may the Plate hypothesis be tested? As for the Plume hypothesis, almost every discipline in Earth science may be brought to bear. In many cases the same methods and experimental approaches suitable for testing the Plume hypothesis also provide data relevant for testing the Plate hypothesis. These include study of the history of vertical motion and eruption, especially the initial stages, and source temperature and underlying mantle structure.

Additional approaches that may be important target horizontal motions, and the sources of the lavas. The Plate hypothesis predicts that volcanism occurs in extensional regions. Geological techniques can assess past lithospheric extension, and geodetic surveying, for example, using GPS, can measure present-day movements. Geochemistry and petrology may be more important techniques than hitherto appreciated for shedding light on the origin of melting anomalies. They have very little power to determine the depth of origin of magmas, but if the sources and volumes of magma produced are indeed related only to shallow recycling of near-surface materials, then depth is less of an issue. In this case, the nature and origin of the recycled component – issues that can be addressed by petrology and geochemistry – become more important and supercede the search for core-mantle-boundary and deep-mantle tracers, for example, noble gas isotope ratios.

Most importantly, a change to a more open-minded and scientific philosophy is needed. The Plate hypothesis cannot be tested unless there is acceptance that the Plume hypothesis is not proven, and may be falsified at a specific locality. In addition, the concept must be shed that a model may be assumed correct despite serious problems, simply because an alternative perceived to be better has not yet been developed.

How has the Plate hypothesis fared in recent years, and what is its potential for the future? This is for the reader to decide. The purpose of this book is to summarize critically the main facts and arguments that relate to these questions, for consideration alongside contrasting arguments presented elsewhere. To whet the appetite, let us tour Hawaii and Iceland again, and review the observations there from a fresh viewpoint.

1.12 Revisiting Hawaii and Iceland

In the context of the Plate hypothesis, the absence of evidence for a flood basalt and associated uplift at the old end of the Emperor chain is permitted, as is the huge upsurge in volcanic rate over the last 5 Ma that has built the Hawaiian archipelago. Recent conclusions that up to 60% of Hawaiian basalts are derived from mantle peridotite fluxed with melt from recycled crust (Sobolev et al., 2007), are predicted. A seismic anomaly beneath Hawaii that is continuous from the surface to the core-mantle boundary, currently the target of an ongoing ocean-bottom-seismometer experiment (Laske et al., 2007), is not expected.

A fertile source for Hawaiian lavas is well-documented, but what about the extension predicted by the Plate hypothesis? A major remaining challenge is testing whether Hawaiian chain-normal extension occurs. Numerical modeling suggests that the region is generally in a chain-normal extensional stress field (Stuart et al., 2007), but can extension be measured locally? There are great obstacles in the way. Apart from the few relatively small islands that make up the Hawaiian archipelago, the whole region lies in the deep ocean, presenting huge challenges regarding both technology and cost. Where land is exposed, for example on the Big Island of Hawaii, the vast lava pile blankets all features except those associated with the most superficial layers of the five massive volcanoes that make up the island. How, in such an environment, can we detect lithospheric extensions that might be small, and last only for a few million years at any one locality?

Compared with Hawaii, Iceland is much easier to study. It is surrounded closely by continents and the island itself is relatively large. A much more complete set of observations is thus available than exists for Hawaii. Several observations in the north Atlantic, surprising in the context of the Plume hypothesis, are permitted by the Plate hypothesis. These include the time-scale of the main phase of uplift, which was contemporaneous with continental break-up rather than preceding it (Maclennan and Jones, 2006). The late formation of a second flood basalt, the still-developing Iceland plateau, is also permitted, as is the absence of a time-progressive volcanic chain. The presence of no more than a moderate temperature anomaly in the mantle is expected. The absence of a seismically imaged conduit extending to the core-mantle boundary and the focusing of volcanic production at the extending mid-ocean ridge, are predicted. Geochemical evidence is essentially unequivocal that recycled fusible near-surface material exists in the source of Icelandic lavas (Fitton et al., 1997; Sobolev et al., 2007). The existence of the vast and complex North Atlantic Igneous Province, within which Iceland sits, is considered to be a consequence of Eurasian supercontinent break-up, not a cause of it.

1.13 Questions and problems

The recent explosion of skepticism about the Plume hypothesis has brought with it the realization that many issues that had previously been assumed settled are, in fact, still open questions. The subject has become enriched with new questions. Why do huge volcanic regions erupt without precursory uplift, and perhaps even following subsidence? What process can cause many millions of cubic kilometers of basalt to be erupted in just a few million years or less, even through thick continental lithosphere? Can any process form melt at the huge and sustained rates at which it is sometimes erupted, or must the melt be formed and stored over longer periods? What is the source of the melt, and the ubiquitous enriched geochemical signatures? What is the involvement of recycled near-surface materials such as crust and mantle lithosphere, and how deeply are they circulated? What is the role of the mantle transition zone between 410 and 650 km depth? Why are some volcanic chains time-progressive, whereas others erupted irregularly along much of their lengths for long periods of time? How does the temperature of the mantle vary throughout the Earth, and are elevated temperatures required to produce large volumes of melt, even if fusible source materials are available?

The Plume hypothesis has served scientists well over the last three decades. It has provided a framework within which huge bodies of data have been gathered, and predictions against which the results have been matched. However, a candid appraisal of the hypothesis in the light of the very data whose collection it inspired renders inescapable the conclusion that it is, in many respects, wanting. It must thus lie in facing up to the problems, and posing radical new questions, that the real and important future progress will be made. We must stop sweeping the problems under the rug and deal with them instead.

1.14 Exercises for the student

1. What is a plume?
2. Design an experiment that could conclusively test for the existence of a plume.
3. Which melting anomalies are the most likely to be underlain by plumes?
4. How well do postulated plume localities score, according to the criteria defined in Section 1.4?
5. Develop Plate models for the melting anomalies listed in Table 1.4.
6. How may the Plate hypothesis be tested?