Challenges in Geodynamics
Weeks 2 - 7

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1 Overview

1. Throughout the year you are expected to spend a total of 200 Student Learning and Activity Time (SLAT) hours on this module. During the Michaelmas and Epiphany Terms there are 3 staff contact hours timetabled per week, taught in single, 3-hr blocks.

   As a rule of thumb you should devote at least one hour to private study or reading for each timetabled hour.

2. You are expected to spend some of your self-study SLAT hours reading additional material, *e.g.*, books, scientific papers, popular articles and web pages, to broaden your knowledge. In tests and examinations, evidence for reading outside of lecture and practical handouts is required in order to earn 1st class marks. You will find suggestions for suitable books and web pages in the course notes.

3. You will get the most out of classroom hours if you have done the relevant recommended reading in advance.

4. If you miss classroom sessions through illness or for any other reason, it is your responsibility to make up the work missed. Lecturers will assume that you have done this.

5. The function of the staff contact hours is to stimulate you to think, and to underpin, support, and broadly guide your self-study work. It is your responsibility to acquire a good knowledge and understanding of the subject with the help of the staff contact hours. This will require that you do not limit your learning activities solely to attending lectures and practicals.

2 Background reading

The textbook for teaching weeks 2 - 7 is:

Foulger, G.R. (2010), *Plates vs. Plumes: A Geological Controversy*, pp. 328+xii, Wiley-Blackwell, ISBN 978-1-4051-6148-0.

Additional books you may find helpful include:

Davies, G. F. (1999), *Dynamic Earth: Plates, Plumes and Mantle Convection*, pp. 458+xi, Cambridge University Press, Cambridge.

Schubert, G., D.L. Turcotte, and P. Olson (2001), *Mantle convection in the Earth and planets*, 1st edition, 940+xvi pp., Cambridge University Press, Cambridge.

3 Lectures 2-7

Lecture 2: The Plates vs. Plumes controversy, surface dynamics

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Lecture 4: Chemistry, heat & temperature

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4 Assessment

Summative assessment of the material studied in teaching weeks 2-7 will take place during the summer examination.

5 Introduction

In weeks 2-7, students will explore the “Plates vs. Plumes” debate for themselves via lectures and group work where each student group focuses on a single, different melting anomaly “hot spot”. The supporting lectures will cover the many aspects of the structure and dynamics of the interior of Earth that have consequences for magmatism on Earth’s surface. Material will touch on the core-mantle boundary, the D” layer, the lower mantle, the upper mantle, the near-surface and the surface itself. Almost every Earth science subdiscipline, from palaeontology to mantle tomography, is relevant. In order to fully understand this great debate, it is necessary to be enormously cross-disciplinary–a great challenge in itself. Throughout the treatment of the material emphasis will be placed on how sure we are of our models, what is observed on Earth's surface, and how observations can be used to narrow down different models for the deep interior.

Since about the year 2000, what was largely assumed to be a settled subject–the question of the depth of origin of intraplate magmas–developed into an intense debate as scientists began to question the strength of evidence for an ultra-deep origin (plumes). This debate is now widely considered to be one of the most challenging in Earth science today. Settling it is difficult, not only because of scientific problems, but also for human and philosophical reasons.

The classes in Weeks 2-7 will explore this challenge as follows. Each week will commence with a ~ 45-minute lecture, followed by a 10-minute break. We will then reconvene in workgroups, each comprising ~ 6 - 7 students, for a 2-hr session.

The 2-hr group work sessions will focus on exploring the Plates vs. Plumes challenge for individual melting anomalies (“hot spots”). This will require group research, independent thinking, fact-checking, data-gathering, and data-analysis. For this you will use skills you have acquired during your degree courses so far, including computer- and literature-based skills, collegiality and teamwork. You will be expected to reason, apply logic, and re-assess any initial thoughts, assumptions and judgments. You will be expected to acquire the ability to change your mind with dignity, if you think that a change is justified by the new information you have learned. You will also acquire the ability to be proven right with humility. You will learn to open your mind and to be able to question starting assumptions, and abandon them if required by observations.

The reason we do science is because we hope and want to grow in wisdom and knowledge and change our views. We do not do science in order to confirm our original assumptions and opinions. This would mean we had learned nothing new by our work. If everyone had done this through history we would still think that the Earth is flat and the Sun revolves around it. A research project that does nothing more than confirm our original hypothesis is a disappointingly unproductive one.

In each session, the workgroups will gather data from various sources on the internet, synthesize them, analyze and evaluate them. In order to facilitate this work, bring your laptops or other mobile devices so you can perform internet searches and efficiently compile notes. Each group will bring to bear its organizational and teamwork skills by structuring itself, allocating tasks as appropriate (e.g., fact checking, result collation, debate chairing/moderating, documenting results, designing and preparing Powerpoint slides). Groups should swap duties around from week to week so everyone practices different team-member skills.

I recommend the textbook Foulger, G.R. (2010), *Plates vs. Plumes: A Geological Controversy*, 328+xii pp., Wiley-Blackwell, ISBN 978-1-4051-6148-0. There are several copies in the library, including e-books. I can provide price-discounted (author signed!) copies to students who wish to buy their own. There are many books that assume the mantle plume model is correct, typically without question, but this is the only book that fully documents the case for a Plate-related origin for surface magmatism. It is supported by the website http://www.mantleplumes.org/ which is a discussion forum containing short articles written by ~ 700 scientists on the subject.

To read the views of your peers from earlier years, you can check out the subpage http://www.mantleplumes.org/Student%27sCorner.html. Good Powerpoint presentations produced by workgroups on this course may be posted there also. For additional starter-level material that is aimed at the technical level of the general public, take a look at http://www.mantleplumes.org/TopPages/MagazineTop.html .

The book Davies, G.F. (1999), *Dynamic Earth: Plates, Plumes and Mantle Convection*, 458+xi pp., Cambridge University Press presents a good summary of the deep-origin (plume) world view. However, it is structured to assume unquestioningly that plumes exist rather than to argue for them on the basis of critical evaluation of observational evidence.

6 Lecture 2: The Plates vs. Plumes controversy, surface dynamics

The Plates vs. Plumes controversy: Two radically different views exist of the origin of large-volume magmatism (as exemplified by flood basalts), and persistent, low-volume magmatism (as exemplified by volcano chains). These are the Plate- and the Plume hypotheses. The

Plume hypothesis envisages a large, thermal diapir that rises from the core-mantle boundary, actively penetrates the lithosphere, and causes surface volcanism. It is envisaged to be independent of shallow structures and processes, and to be driven by thermal energy from Earth's core.

The Plate hypothesis is the conceptual inverse. It envisages magmatism to be driven by shallow processes that ultimately draw their driving forces from plate tectonics. Magmatism is envisaged to be a passive reaction to lithospheric extension, and its quantity and chemistry to reflect source fusibility and composition. Thus, "anomalous" magmatism, is expected to occur preferentially near extensional plate boundaries, e.g., the mid-Atlantic ridge, and continental rift zones. The mere formation or existence of melt in the mantle is not considered sufficient to explain surface eruptions–lithospheric extension is required to release it. Where volumes are large, the chemical fingerprints of high source fusibility are expected.

Hypothesis-testing normally comprises testing predictions against observations. The conventional Plume hypothesis predicts a) surface uplift tens of millions of years before flood volcanism, b) flood volcanism lasting a few tens of millions of years, c) a "plume tail" extending from the surface to the core-mantle boundary, d) a time-progressive volcanic chain, and e) high source temperatures. These predictions are rarely confirmed with confidence, and have never all been confirmed at a single volcanic province. The Plume hypothesis has undergone extensive ad hoc elaboration over the years to accommodate this quandary, including proposals that plumes can arise from almost any depth and that plume material can flow sideways for thousands of kilometres.

The Plate hypothesis predicts that a) volcanism is associated with extension, and b) large-volume magmatism is related to source fusibility. Prediction a) is confirmed at some volcanic provinces, e.g., Iceland, and in the East African Rift, though observations are lacking from many, less accessible regions, e.g., in the remote interiors of oceanic plates. Prediction b) is manifest in the "ocean island basalt" chemical signature of many lavas, which indicates a component of recycled, near-surface, fusible material in the magma source. Nevertheless, there are many gaps in our knowledge that remain to be filled by innovative new experiments. Key challenges lie in testing whether volcanism on the oceanic Pacific plate accompanies extension, and whether source fusibility can quantitatively explain the volumes of magma observed at melting anomalies.

Surface dynamics: Theories regarding the dynamics of the interior of Earth cannot move beyond the speculation stage if their predictions cannot be checked. Seismology is essentially the only method by which the internal Earth structure can be probed in any detail, but it only provides a snapshot of structure–it cannot show dynamics unless assumptions are made about the interpretation of seismic anomalies. These interpretations are often ambiguous and unsafe.

In contrast, dynamic processes can be studied at the near surface. In addition to magmatic processes, movements of Earth's surface occur in response to the movement of material beneath. Near-surface processes that are intimately linked to internal dynamics include:

- Continental breakup;
- Intraplate extension;
    i. Continental;
    ii. Oceanic.

- Volcanism
- Slab tearing & breakoff;
- Catastrophic lithosphere thinning;
- The arrival of a mantle upwelling (a diapir or a mantle plume).

Continental breakup: Major surface motions accompany rifting, including shoulder uplift, subsidence of neighbouring regions, and post-rifting erosion. Where the whole of the lithosphere is breached–up to a 200-km-thick plate in some cases–these vertical motions may be up to 10 km in amplitude. New coastlines are thus often flanked by linear mountain ranges, *e.g.*, the Gulf of Aden and the North Atlantic. Scaled-down versions occur in Europe, *e.g.*, the Rhine Graben. Continental rifting is accompanied by upwelling of asthenosphere to fill the gap between the two new continental edges, resulting in the formation of volcanic margins.

Volcanism: The very process of formation, rising and eruption of melt results in vertical motions at the surface, and changes in surface elevation. Processes that contribute include:

- Partial melting of the source;
- Removal of melt from depth;
- Chemical depletion of the source (the creation of residuum);
- Heating & expansion of the lithosphere by through-going melt;
- Intrusion and eruption of the melt;
- Erosion and redistribution of sediments.

Co-magmatic uplift may amount to ~ 250 m per km of emplaced magma. For example, if a flood basalt 10 km thick (including intrusives) is emplaced, surface uplift may be as large as 2.5 km from these processes alone. The Hawaiian swell is an example of a region that stands anomalously high, and some, if not all of this, must be a result simply of the volcanism itself.

Slab tearing & breakoff: This process has been invoked to account for volcanism in many places, *e.g.*, Mexico and the Mediterranean belt. In eastern Anatolia (Turkey) detailed results from petrology, seismology, geochemistry and age dating have been integrated to argue for a model for volcanism there involving the breakoff of a subducting slab following collision of the Arabian plate with Eurasia.

Catastrophic lithosphere thinning: This includes both the detachment of Rayleigh-Taylor (gravitational) instabilities, and the delamination of thickened, densified lower lithosphere. Such processes have been modeled numerically. The sequence of events predicted is surface subsidence, followed by volcanism, and surface uplift. This process might explain the enigmatic observation that emplacement of the Siberian traps–the largest terrestrial flood basalt–was preceded by widespread, major subsidence as evidenced by the fact that they are underlain by the largest coal deposits in the world.

Mantle plume arrival: The arrival of a rising mantle plume at the base of the lithosphere is predicted to cause domal surface uplift to commence about 10 Ma before volcanism starts, depending on various modeling parameters. Some scientists consider precursory domal uplift to be the strongest, most unequivocal evidence in favour of a mantle plume. Evidence for uplift may be sought by studying the geology beneath the lowermost layers of a flood basalt (often interpreted as mantle plume head volcanism). Sediments that indicate progressive uplift prior to the first eruptions, *e.g.*, conglomerates, might provide such evidence.

Areas where there has been considerable controversy regarding the observations include the Siberian traps, the Paraná basalts (South America), the Columbia River basalts, the North Atlantic Igneous Province, the Emeishan basalts (China), Afar, and the Ontong Java plateau. In some cases, there is essentially universal agreement that either subsidence or grossly inadequate uplift occurred, most notably in the cases of the largest terrestrial flood basalt (the Siberian traps) and the largest oceanic plateau (the Ontong Java plateau). Whatever is said for other flood basalt provinces, models different from the standard mantle plume model are thus needed for these two huge volcanic provinces.

In the cases of smaller provinces, there is still vigorous debate in some cases, with scientists arguing on both sides. This debate was recently highlighted by the journal *Nature*, in papers and a comment-reply exchange between renowned scientists. They took the opposing views a) that mantle plumes are proven by observations of precursory uplift prior to flood basalt eruption, and b) that of the 77 LIPs known since the Archean, not a single one reliably shows kilometre-scale precursory uplift. Clearly this is a promising field for anyone who is interested in plunging into an open question and deciding for themselves on which side they consider the greatest weight of evidence to fall.

7 Lecture 3: Magmatism: Volumetric, spatial & temporal aspects

Volcanism on Earth's surface is a subject of interest for diverse reasons–academic curiosity, mineral resources, and the mass budget of the atmosphere. A particularly interesting piece of recent research tested the hypothesis (or, more accurately, unsubstantiated, politically motivated claim) that anthropogenic CO_2 is insignificant compared with that generated by currently active volcanoes. This was emphatically falsified by a quantitative study that showed that anthropogenic CO_2 is the equivalent of several supervolcano eruptions per year [Gerlach, 2011].

Terminology that has become common in Earth science tends to encourage the view that magmatic rates and the sizes of volcanic provinces are bi-modal–either "normal" or "large igneous provinces" (LIPs), with clear water in between. An examination of the data shows that this is not so. The sizes of magmatic provinces range across the full spectrum.

Oceanic crust varies from zero to over 40 km in thickness, if the seismic data are plotted uncritically. The distribution of sizes of Pacific seamounts is interesting, showing that the sizes of the largest seamounts in any particular region correlate with age of the sea floor. It has been suggested that older (thicker, colder, stronger) lithosphere can support larger seamounts, but this does not explain why larger volcanic events should occur over such lithosphere in the first place. In fact, it is counter-intuitive. The largest volcanic edifice on the sea floor is the Ontong-Java Plateau, at ~50-100 x 10^6 km^3. The largest flood basalt on land is the Siberian Traps, at ~10 x 10^6 km^3.

In the Iceland area, there are huge variations in igneous crustal thickness. The region is characterised by shallow bathymetry, but this is not restricted to Iceland itself. Iceland is merely the subaerial tip of a vast bathymetric swell that extends for ~ 3,000 km, between the latitudes of ~ 50˚ and ~ 80˚. (Iceland lies at latitude ~ 65˚ ± 1˚). Because a large landmass is exposed at Iceland, it has been intensively studied using virtually every Earth science method in existence. It is clearly anomalous on a global basis–there is only one Iceland on the planet (an only one Hawaii, for that matter).

Along the entire length of the 3,000-km-long bathymetric swell, the igneous crust varies from normal oceanic values to over 40 km in central Iceland. Some of this huge thickness may represent a submerged microplate of the kind known to exist on the East Pacific Rise in the vicinity of Easter Island. As yet, this theory has not been tested and nor has anyone designed a suitable test. If all of the observed ~ 40-km thickness of crust-like material were indeed basaltic, because of its low density, considerations of isostasy would *require* that Iceland stand ~ 4 km high above sea level. However, it only stands ~ 1 km high. The problem of the true petrology of the Icelandic "lower crust", which appears to have mantle-like density, is another problem that has not yet been resolved.

South of Iceland, the mid-Atlantic ridge is flanked by the so-called "chevron ridges", which are oblique zones of slightly thickened crust that form features resembling giant V's about the ridge. For many years it was assumed that they resulted from pulses of magma from Iceland migrating south along the ridge at the rate of a few cm/yr. Recently they have been interpreted as forming at the tips of ridge propagators, a process well known from work in the Galapagos region of the Pacific spreading ridge system[1].

Hawaii is another example of where the volcanic rate has varied enormously. During the lifetime of the Emperor and Hawaiian volcanic chains, the eruption rate has varied from essentially zero, a the "great bend" to ~ 0.25 km^3/year at present. The youngest part of the Hawaiian chain is large enough that it falls within the classification of a "LIP", so it is true to say that a LIP is currently forming at the present day.

Older, and more conventionally recognized flood basalts include the Deccan and the Siberian traps. These flood basalts also had eruptive rates that peaked at ~ 10^6 km^3/Ma (1 km^3/year). Numerical modeling work has attempted to show how such enormous amounts of melt could form. It has not been possible to simulate melting at the huge rates at which that the largest flood basalts are erupted. Many scientists have thus concluded that melt accumulation and ponding over a much longer time period that eruption is necessary to explain the observations [Silver *et al.*, 2006]. On the other side of the coin, many volcanic areas erupt slowly, and relatively small volumes of magmatism dribble out over several tens of Ma, *e.g.*, the Scottish Midland Valley volcanic province. It is not realistic to assume that all significant volcanic provinces are a) vast, and b) erupted extremely quickly.

No reflection on volcanism would be complete without some mention of time-progressive volcanic chains and their possible power to provide a fixed reference frame to which all other motions might be referred. Contrary to conventional wisdom, the Hawaii volcanic locus ("hot spot") has not remained fixed relative to Earth's magnetic pole during formation of the Emperor and Hawaiian volcanic chains[2]. Its migration rate across the Pacific plate has also varied from ~ 17.0 - 4.6 cm/year.

Melting loci ("hot spots") are not fixed relative to one another between different tectonic plates. Many island chains in the Pacific are not time-progressive and, curiously, many of the "bends" in Pacific island and seamount chains did not occur at the same time, nor simultaneously with the bend in the Emperor-Hawaiian chain. Nevertheless, some very long chains, notably the Emperor-Hawaiian, the Louisville, the Ninety-East ridge and possibly the

[1] http://www.mantleplumes.org/Disclosure.html

[2] http://www.mantleplumes.org/HawaiiBend.html

Laccadives-Chagos-Réunion chain do age in a uni-directional sense. Further study of these, in particular those chains that are lacking in sufficient data, is likely to be a rich subject of research in future.

8 Lecture 4: Chemistry, heat & temperature

Geochemistry & petrology: The core-mantle boundary (CMB)–the surface of the core–is extremely sharp. It only has a few kilometres of topography, and is somewhat analogous to Earth's surface (Table 1).

Table 1: Comparison between the surface of Earth and that of the core.

Parameter	Earth's surface	Core-mantle boundary
Relief	a few kilometres	a few kilometres
Density increase	~ 2,500 kg/m^3	~ 6,300 kg/m^3
Temperature increase	~ 1,300˚C	~ 1,000˚C
Change of state	fluid –> solid	solid –> fluid

The CMB is blanketed by a seismically distinct, relatively thin layer that forms the bottom-most part of the mantle. This layer is known as D" (D-double-primed). It is important because it controls the transmission of heat, and material (if that occurs) from the core to the mantle, and from there to Earth's surface.

This layer is called D" as a result of the early division of Earth by the seismologist Edward Bullen (1906–1976) into layers labeled by the letters A through G [Bullen, 1947]. As knowledge of the internal structure of the planet improved, the original divisions were subdivided using primes, thus D' and D". Today, the only division commonly used is D", which has thus become a curious piece of residual nomenclature.

Essentially all our knowledge of D" comes from seismology. It is:

- about 200 km thick;
- has topography of ~ 40 km;
- a major seismic discontinuity–an *S*-wave velocity jump of ~ 3% occurs on its upper surface;
- laterally inhomogeneous–variations of up to 10% in *Vs* occur. This almost certainly requires partial melt;
- possibly chemically distinct.

The core is virtually isothermal because it is convecting vigorously. The mantle can maintain temperature and composition differences because it convects only sluggishly, and therefore D" is a "thermal boundary layer". It has a high temperature gradient, and temperature rises across it by ~ 1,000˚C from mantle to core. Its temperature gradient is probably laterally variable. The first accurate determination of the depth to D" by Gutenberg was made in 1912, and he obtained a value of ~ 2,900 km.

There is intense speculation about the structure and dynamics of D" because it is implicated in whether or not material and heat from the core affect the surface measurably. There is certainly heat transfer from the core to the mantle, some of which ultimately reaches the surface, but it is unclear if this significantly affects the nature of surface volcanism and tectonics. There is, at present, no equivocal evidence for material transfer from the core to the surface.

Postulated core tracers are the Pt-Re-Os isotope system and the Hf-W (Hafnium-Tungsten) isotope system. Both of these involve complex chains of reasoning regarding how quickly Pt, Re, Os and W partitioned into the core, and how quickly the core formed[3]. Scientists have studied lavas, *e.g.*, at Hawaii, but have not, so far, found the predicted isotope ratios and have found that the remelting of near-surface materials can explain the geochemical observations.

The $^{3}He/^{4}He$ isotope system has been widely used to infer material from the deep mantle (not the core). $^{3}He/^{4}He$ in MORB is ~ 8 x the atmospheric value (Ra). $^{3}He/^{4}He > 8$ Ra has been observed at oceanic islands such as Hawaii and Iceland. Since the lavas at those places were, at the time high-$^{3}He/^{4}He$ was discovered, assumed to arise from thermal plumes that transport material up from the deep mantle, the observed ratios were presumed to characterize the lower mantle. This theory is controversial, and shallow lithologies that could be the sources of high-$^{3}He/^{4}He$ have been proposed[4]. It is an issue that attracts curiously strong feelings amongst practitioners specializing in this isotope system.

There is considerable heat loss from the core to the mantle. The total heat loss from Earth's surface is, again, a subject of controversy, but in general is thought to be ~ 40 TW. Of this, 5-10 TW is estimated to be conducted out of the core, but this estimate is uncertain.

Today's mantle has a composition far from that of chondritic meteorites. Elements have been removed by sinking into the core (siderophiles), volatile loss to space, and from the rising of crust-forming elements (lithophile). (When Earth scientists say "crust", they generally mean continental crust.) At least 30-95% of the mantle is depleted in the fusible elements that make up the continental crust. The exact % is poorly known, however, and critically, it is unknown whether the depleted and undepleted parts are in physically separated regions of the mantle, whether both types are intimately mixed, or whether any entirely depleted or undepleted rocks exist.

This problem has profound implications for the interpretation of geochemical data. Modern geochemical interpretations draw heavily on concepts such as "end-members" and "reservoirs", and it is easy to forget that we do not know whether these concepts represent physically separated volumes of rock or not. It is unknown whether any "primitive mantle"

[3] http://www.mantleplumes.org/Os-W.html

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

(i.e., "bulk silicate earth", or the silicate portion of Earth that remained after removal of the core, but before the separation out of the continental crust) is left unprocessed within Earth.

Geochemistry has little power to reveal unequivocally the depth of origin of lavas. A few indicators such as evidence for spinel- or garnet-facies protoliths, the existence of diamonds, and the occasional report of evidence for TZ-depth mineral phases or their ghosts, give evidence for residence at particular pressures in the mantle. Arguments for derivation of materials from deep in the lower mantle or near the core, remain model dependent and must be viewed as postulates and not facts.

Heat & temperature: In addition to looking for core- and D"-layer tracers, geochemistry also addresses the issue of the source temperature of lavas. There is debate regarding whether intraplate magmas derive from unusually hot, deep sources (plumes) or from the shallow mantle at relatively normal temperatures. An adiabatic temperature profile of Earth shows positive jumps of ~ 50˚C at the 410 and 520-km discontinuities in the transition zone (TZ), and a temperature drop of ~ 30˚C at the 650-km discontinuity at the base of the TZ.

The temperature of the mantle, its variation from place to place, and variations in the melting point of mantle materials, are key to understanding where and how melt is generated. There are many approaches to trying to measure and map the temperature of the mantle. Unfortunately, there are also many pitfalls and it is questionable if any of the methods available to us are sufficiently reliable and accurate to distinguish between competing melt-generation models, *e.g.*, Plate and Plume.

The two basic competing models for the generation of intraplate volcanism are:

1. The delivery of unusually hot material to the surface from a thermal boundary layer at depth, via plumes that rise by virtue of their thermal buoyancy. In this model, the lithosphere is considered to be essentially passive and to not impede the eruption of rising melt;
2. The melting of unusually fusible (i.e., low-melting-point) rocks, *e.g.*, recycled, subducted slabs, under essentially normal temperature conditions. In this model, the lithosphere is an active player, and it prevents or permits volcanism, depending on its stress state.

The thermal profile of the lithosphere is not well known, but Earth's surface may comprise a conduction layer within which temperature rises for the shallowest ~ 100 km. Volatiles may have a profound effect on the solidus, in particular CO_2 and H_2O.

<u>Surface heat flow:</u> Because we cannot drill very far down into Earth, to make direct measurements of temperature, studying surface heat flow is one of the few ways to gather data relevant to the temperature of the interior. Heat flow data gathered at sea are the simplest to interpret because oceanic areas are much less affected by tectonism and structural complexities than continental areas. Marine heat flow is measured using a thermistor probe, which is dropped overboard from research ships[5]. Both the general pattern of heat flow in ocean basins, and heat flow at specific sites thought to be underlain by anomalous mantle, have been studied with a view to detecting lateral variations in mantle temperature. Problems include the effect of hydrothermal circulation, which may result in very variable results from

[5] For more on measuring heat flow on the ocean floor, see: http://tigger.uic.edu/~cstein/

place to place, and in the long time that it takes for heat to conduct through the lithosphere. The latter may preclude observing the signal of re-heating events postulated to have occurred in the last few tens of Ma.

Seismology: Several seismological methods are used for estimating temperature, including measuring:

- the thickness of the igneous crust, a proxy for temperature;
- the topography on the TZ-bounding discontinuities;
- the correlation between lower-crustal wave speed and thickness of the igneous crust. This is expected to be positive for a thermal origin of excess magmatism, and negative for a postulated compositional origin (i.e., a low melting point);
- wave-speeds. These are frequently interpreted under the assumption that they are proxies for temperature, but this is invalid.

Petrology & geochemistry: Again, there is a large suite of approaches for estimating temperature and temperature variations, and as is the case with seismology, general practice and assumptions tend to lag behind the cutting edge. Widely used methods include:

- The "global systematics". This proposes that low Na and high Fe in basalts indicates high temperature. This method, proposed in the 1990s on the basis of empirical data, is widely applied. However, Prof. Yaoling Niu, amongst others has recently shown it to be invalid by testing using much larger, modern databases than were available in the 1990s [Niu & O'Hara, 2008; Presnall & Gudfinnsson, 2008];
- Olivine control-line modeling. This method seeks to estimate the temperature of an original melt using samples that are presumed to represent different stages of fractional crystallization of a melt. It has been widely applied to lavas postulated to be plume-derived and thus predicted to have high source temperatures. One problem with this method is that only volcanic glass can be unambiguously relied upon to represent an original melt, and glass of the necessary composition is only found at Hawaii. That may have originated from unusually great depth and is likely not comparable to MORB. Another problem is that there is no consensus on what olivine geothermometer should be used, and different geothermometers may give results that vary by more than the temperature variations being sought (*i.e.*, the uncertainties are > 100%);
- Rare-earth modelling assumes a uniform source composition, so it cannot be used to test for temperature differences between magmas that are postulated to arise from protoliths with different compositions.

Ocean-floor bathymetry: If ocean floor formed from a hot source, it is expected to stand shallower to begin with, and to subside faster than normal crust as it drifts away from its source. This principle has been used to test the hypothesis that oceanic plateaus formed from hot sources. Nannofossils and foraminifera in deep-sea drilling cores have been used to examine the subsidence history of many plateaus, but have not confirmed the predicted high subsidence rates.

A review of all available mantle temperature estimates for the Iceland region has failed to come up with unequivocal evidence for exceptionally high temperatures. Some scientists would dispute this finding, dismissing criticisms of particular methods. Others would argue that the required evidence simply remains to be found. Performing literature reviews for different regions postulated to result from high-temperature sources, *e.g.*, Afar, Réunion, Samoa, would make good student projects.***

9 Lecture 5: Mantle structure I

The mantle is exposed at the surface at a few places, *e.g.*, the Gakkel ridge in the North Atlantic, but this is rare. Mostly, it can only be studied by indirect means. Scientists speculate, and do theoretical modeling, but these endeavours are pointless unless used to make predictions that can be tested using observations.

By far the most effective way of studying the mantle is by using seismology. Other disciplines, such as gravity, geochemistry and heat flow, are much less focused. The main problem with using seismology is, however, in interpretation. Seismic wave speeds, for example, vary as a result of composition, physical state (solid or liquid), mineral phase, and temperature (the weakest effect) (Table 2). These effects are responsible for variations of up to several % in wave-speed, and it is not usually possible to separate the effects out. Thus, seismic tomographic images, often coloured red through blue, cannot be viewed as geological images. In particular, it is important to take on board that seismic wave speeds are not a thermometer. Red on a seismic tomography image does not equal hot, and blue does not equal cold.

Table 2: Typical reductions in V_P and V_S for plausible variations in composition, degree of partial melt and temperature in the mantle.

Phase	**Partial melt (per 1% inc. in melt content)**	**Composition (per 10% decrease in Mg/(Mg+Fe) in olivine)**	**Temperature (per 100˚C increase)**
V_P	2-3%	7%	1%
V_S	3-10%	12%	1.5%

A rare case where the effects of composition and temperature could be separated out is the case of the "Large Low-Shear-Velocity Provinces" (LLSVPs), also nicknamed the "superplumes". The analysis of seismic normal modes–extremely long wavelength seismic waves that excite the whole Earth and are sensitive to very large bodies–has shown that the LLSVPs owe their low wave speeds (red) to a high-density composition, and not to high temperature. Unfortunately, there is widespread assumption to the contrary, doubtless because they are traditionally illustrated as red, and because of the nickname that was attached to them before their true nature became known. Some seismologists now refer to them as "superpiles", as they are expected to tend to sink or at least remain in place, and not to rise.

Recently the exciting discovery was made of a very-high-pressure mineral phase called post-perovskite, in the D" layer. It is probably the origin of the seismic discontinuity at D". Since its pressure and temperature conditions can be measured in high-pressure laboratory apparatuses, it could potentially be used to map a pressure-temperature (PT) horizon at D”.

The transition zone (TZ) is an important region of the mantle. Its base at 650 km depth is generally taken to be the base of the upper mantle, although some place this at the base of Bullen’s region C, at ~ 1,000 km. A series of mineralogical phase changes occur throughout the TZ. Because of their positive (negative) Clapeyron slopes, the phase changes at 410/650-km depth encourage/discourage the transfer of material across. This means that subducting slabs are encouraged to sink through the boundary at 410 km depth, and hot risers are encouraged to pass on up through it. At the 650-km discontinuity, subducting slabs are inhibited from passing on through to greater depth, and rising convection currents are inhibited from carrying on through to shallower depths.

The depths of the 410- and 650-km discontinuities are temperature dependent, and thus in principle they might be used as thermometers. Unfortunately, again, they are also dependent on composition (typically the Mg/Fe proportions) and the presence of water. Furthermore, phase changes occur in both olivine and garnet mineralogies at 650 km depth and these changes are partially (wholly?) canceling. The topographies of the 410- and 650-km seismic discontinuities are thus weaker to map temperature in the mantle than was initially hoped.

10 Lecture 6: Mantle structure II

There is intense speculation concerning whether there is exchange of material between the upper and lower mantle. Seismically they are very different. The seismic structure of the upper mantle resembles the surface (i.e., the distribution of oceans and continents) at all depths. Immediately below 650 km depth, however, the structure changes radically, and essentially all resemblance to the surface disappears. The amplitudes of variations in wave speed also become much less. This persists downward until D” is reached, when again the seismic structure correlates with the surface. This is very puzzling, and no satisfactory explanation for it has yet been proposed.

Studies of the entire mantle generally involve the use of permanent, global seismograph stations and large earthquakes occurring along plate boundaries. Other experiments to study particular areas of interest required seismologists to stage intense, local experiments of their own. An example of such an experiment was conducted in Iceland by Durham University. It required the deployment of 30 seismic stations over the entire island. Several of these were technically and physically challenging to maintain and one even involved heroic journeys up onto Vatnajökull, the largest icecap in Europe. Another experiment, run by the Scripps Institute of Oceanography, involved the deployment of ~ 40 ocean-bottom seismographs (OBSs) for 2 years around Hawaii. Experiments of this sort may consume many years of a scientist’s career.

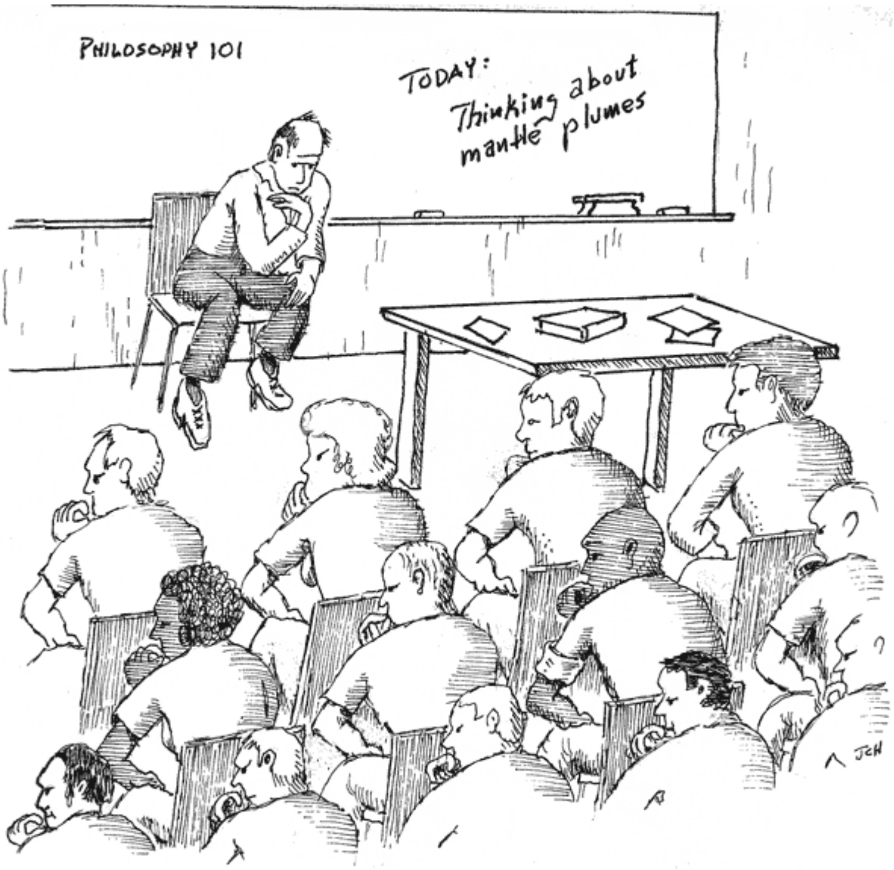
Although seismic tomography images are widely relied upon to illuminate the structure of the mantle, and many interpretations of other kinds of data, *e.g.*, geochemistry, are done with reference to them, it is not widely appreciated that there are numerous problems with mantle tomography that can give spurious or misleading results:

- The distribution of seismic stations is not uniform over Earth because they are concentrated on land and in wealthy nations;

- The distribution of earthquakes is even less uniform, being largely limited to plate boundaries;
- As a result of the above, sampling of the mantle by seismic rays is highly non uniform;
- In addition, different ways of displaying seismic results enable the scientist to obtain images that give very different impressions. Examples of these techniques include:
    i. The degree of saturation of the colour-scale used may be varied;
    ii. Different cross sections may be drawn and they may be truncated to give the impression desired;
    iii. The "average background" value may be varied. This enables the seismologist to expand and contract blue/red anomalies at will.

These problems result in wide variations in results from different groups (i.e., poor repeatability) leaving non-seismologists (and seismologists!) not knowing which result to believe if any [Foulger *et al.*, 2014]. As these problems become better understood, a healthy caution is beginning to creep into the art of interpreting seismic tomography images.

11 Practicals: The Plates vs. Plumes Controversy



From Science Askew, by Jack Holden

11.1 Overview

The class will divide into 10 groups, each of 6-7 people. Each group will choose a different "hot spot" to study during the practicals of Weeks 2-7. Some recommended ones are:

1. Hawaii
2. Iceland
3. Galapagos
4. Tristan
5. Yellowstone
6. Samoa
7. Afar
8. Réunion
9. Azores
10. Cameroon
11. Canary
12. Easter
13. Kerguelen
14. Louisville
15. SE Australia

The "hot spots" in the above list are ranked roughly according to how much published material is available about them. During Practicals Weeks 2-6, groups will gather information about their chosen "hot spot". In the practical session in Week 7, each group will deliver a PowerPoint presentation and take questions from the audience.

Over 500 webpages presenting relevant material at a level accessible to cross-disciplinary scientsts are available at http://www.mantleplumes.org . The website is structured to provide four categories of material–Mechanisms (e.g., plume, EDGE convection), Localities (e.g., Hawaii, Iceland), Generic (e.g., thermal, seismology) and Other (e.g., magazine articles, Powerpoint slides, job- and studentship advertisements).

There is also a place for best student work. If your Powerpoint presentations are good, they can be placed on this webpage and you will be able to list them on your CVs.

http://www.mantleplumes.org/StudentsCorner.html

For Weeks 2-7, follow @MantlePlumes. I try to make daily posts there of material of interest to the "Plates vs. Plumes controversy" community. During Weeks 2-7 I will try to make these relevant to the group projects. Your own comments, questions etc. will be welcomed, but keep your posts professional and focused on the science.

Below are guidelines as to how to plan and conduct your research work. This plan dovetails with the background that will be taught in each lecture. The information each group gathers need not be limited to what is suggested below.

Week 2: Precursors and the onset of activity in the region: Evidence for precursory tectonics e.g., extension, uplift, subsidence.

Week 3: Time history of volcanism: Is it continuous or intermittent? Does it onset with a flood-basalt eruption? Does it form linear, time-progressive volcanic chains, or is it distributed? Is it really anomalous in volume? What exactly do we mean by "anomalous"?

Week 4: Evidence for chemical and temperature anomalies: Is there evidence for core-mantle boundary tracers or recycled shallow material (i.e., recycled into the shallow mantle via subducting slabs or delamination)? Is there evidence for low, normal, or high mantle temperatures? To what are we comparing our temperature estimates (i.e. what is "normal")?

Weeks 5-6: Mantle structure: Evidence for seismic anomalies at the core-mantle boundary and topography on the transition zone boundaries. What is the spatial relationship of the group's "hot spot" with a) lower-mantle structure (e.g., the LLSVPs) and b) surface extensional features (e.g., mid-ocean ridges, rift valleys)? Evidence for seismic anomalies in the upper and lower mantle, largely from tomography. Consideration of their size, depth extent and continuity. Consideration of the repeatability of different studies. Different possible interpretations of these anomalies.

Week 7: Powerpoint presentations: One person from each group will give her/his group's 5-min presentation. After each presentation, the whole group will come to the front and take 5 min of questions/discussion from the audience. The audience will come prepared to pose plenty of questions. Remember that the only stupid question is the one that isn't asked.

The presentations will be of a critical nature. They will not seek to bolster up any one model, but instead will attempt to falsify a) the plume hypothesis, and b) the plate hypothesis, for the subject "hot spot". A suitable presentation structure would be:

- 1 title/author slide;
- 3 slides attempting to falsify the plume hypothesis at your "hot spot";

- 3 slides attempting to falsify the plate hypothesis at your "hot spot";
- 1 wrap-up slide, including a summary statement and suggestions for further work. Suggestions should state what postulate they would potentially be able to falsify, thereby narrowing down the plate vs. plume ambiguity at the group's chosen "hot spot".

11.2 Week 2

How do we do science? We erect hypotheses, list their predictions, and test them by making observations.

Read the original paper suggesting deep mantle plumes [Morgan, 1971]. In it, Morgan lays out a theory for how the mantle convects. List the predictions he made. There are at least seven. Have all or any of them been falsified?

Predictions of the plume hypothesis: http://www.mantleplumes.org/Plumes.html

Predictions of the plate hypothesis: http://www.mantleplumes.org/PTProcesses.html

Proceed with the Week 2 task given under "*Overview*" above.

11.3 Week 3

Are observations *consistent* with a hypothesis? Do they *require* a particular interpretation. Can they *rule out* some hypothesis? An example that illustrates what these things mean is early speculations about the origin of Earth's dipole magnetic field. Often the best we can hope for is that our results will rule out one of several candidate hypotheses.

Example: It has been claimed that the total heat loss from melting anomalies postulated to be fed by plumes ("hot spots") is approximately equal to the heat transmitted from the core to the mantle. It has further been argued that this supports the plume hypothesis.

Does the observation require the proposed interpretation?

Proceed with the Week 3 task given under "*Overview*" above.

11.4 Week 4

Are "hot spots" hot, and if so, how hot? What "normal" mantle temperature are these anomalies relative to? How well do we know that temperature?

Is it reasonable to use the same "normal temperature" for all "hot spots"? For example, some may be continental and others oceanic, melts may have formed at different depths, and Earth has cooled over geologic time.

Is the term "hot spot" a good one for the phenomenon you are studying?

Proceed with the Week 4 task given under "*Overview*" above.

11.5 Weeks 5-6

What do plumes look like? What exactly are we looking for? How wide are they and how deep do they extend? What about plate-based mechanisms? What sort of anomalies would we expect to see in the crust and mantle, if any? We need to know this information before we can design experiments to test hypotheses.

If you define the size, shape, and strength of the anomaly expected for a given process, what would happen if you performed an experiment and didn't find it? Reflect on this using a) a plume, and b) an EDGE convection cell, as examples.

11.6 Week 7

There will be no lecture. The 3-hour class will be devoted to the Powerpoint presentations and discussion with the following target schedule:

time	Group #	"hot spot"
9:10 - 9:20	1	TBA
9:20 - 9:30	2	TBA
9:30 - 9:40	3	TBA
9:40 - 9:50	4	TBA
9:50 - 10:00	5	TBA
10:00 - 10:10	6	TBA
10:10 - 10:20	7	TBA
10:20 - 10:30	8	TBA
10:30 - 10:40	9	TBA
10:00 - 10:10	10	TBA

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11.7 Reprint of Morgan (1971)

ards should contribute to our knowledge of the nature and magnitude of the systematic errors in this field.

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Convection Plumes in the Lower Mantle

The concept of crustal plate motion over mantle hotspots has been advanced[1] to explain the origin of the Hawaiian and other island chains and the origin of the Walvis, Iceland–Farroe and other aseismic ridges. More recently the pattern of the aseismic ridges has been used in formulating continental reconstructions[2]. I have shown[3] that the Hawaiian–Emperor, Tuamotu–Line and Austral–Gilbert–Marshall island chains can be generated by the motion of a rigid Pacific plate rotating over three fixed hotspots. The motion deduced for the Pacific plate agrees with the palaeomagnetic studies of seamounts[4]. It has also been found that the relative plate motions deduced from fault strikes and spreading rates agree with the concept of rigid plates moving over fixed hotspots. Fig. 1 shows the absolute motion of the plates over the mantle, a synthesis which satisfies the relative motion data and quite accurately predicts the trends of the island chains and aseismic ridges away from hotspots.

I now propose that these hotspots are manifestations of convection in the lower mantle which provides the motive force for continental drift. In my model there are about twenty deep mantle plumes bringing heat and relatively primordial material up to the asthenosphere and horizontal currents in the asthenosphere flow radially away from each of these plumes. The points of upwelling will have unique petrological and kinematic properties but I assume that there are no corresponding unique points of downwelling, the return flow being uniformly distributed throughout the mantle. Elsasser has argued privately that highly unstable fluids would yield a thunderhead pattern of flow rather than the roll or convection cell pattern calculated from linear viscous equations. The currents in the asthenosphere spreading radially away from each upwelling will produce stresses on the bottoms of the lithospheric plates which, together with the stresses generated by the plate to plate interactions at rises, faults and trenches, will determine the direction in which each plate moves.

Evidently the interactions between plates are important in determining the net force on a plate, for the existing rises, faults and trenches have a self-perpetuating tendency. The plates are apparently quite tough and resistant to major changes, because rise crests do not commonly die out and jump to new locations and points of deep upwelling do not always coincide with ridge crests. (For example, the Galapagos and Réunion upwellings are near triple junctions in the Pacific and Indian Oceans. Asthenosphere motion radially away from these hotspots would help to drive the plates from the triple junctions, but there is considerable displacement between the "pipes to the deep mantle" and the lines of weakness in the lithosphere which enable the plates to move apart.) Also, a large isolated hotspot such as Hawaii can exist without splitting a plate in two. I believe it is possible to construct a simple dynamic model of plate motion by making assumptions about the magnitude of the flow away from each hotspot and assumptions about the stress/strain rate relations at rises, faults and trenches. Such a model has many possibilities to account for past plate motions; hotspots may come and go and plate migration may radically change the plate to plate interactions. But the hotspots would leave visible markers of their past activity on the seafloor and on continents.

This model is compatible with the observation that there is a difference between oceanic island and oceanic ridge basalts[5,6]. It suggests a definite chain of events to form the island type basalt found on Hawaii and parts of Iceland. Relatively primordial material from deep in the mantle rises adiabatically up to asthenosphere depths. This partially fractionates into a liquid and solid residual, the liquid rising through vents to form the tholeiitic part of the island. The latter alkaline "cap rocks" would be generated in the lithosphere vent after plate motion had displaced the vent from the "pipe to the deep

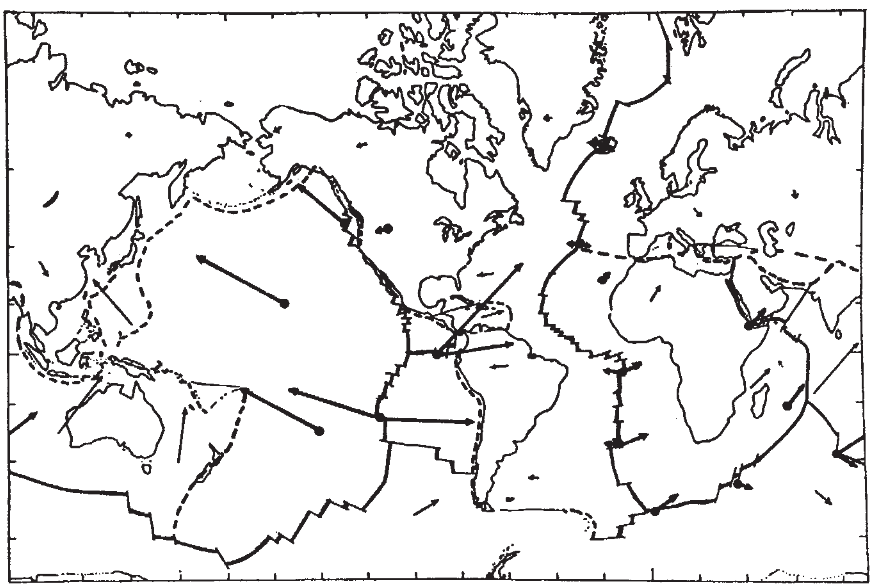

Fig. 1 The arrows show the direction and speed of the plates over the mantle; the heavier arrows show the plate motion at hotspots. This synthesis was based on relative plate motion data (fault strikes and spreading rates) and predicts the directions of the aseismic ridges/island chains emanating from the hotspots.

mantle". In contrast, the ridge basalts would come entirely from the asthenosphere, passively rising to fill the void created as plates are pulled apart by the stresses acting on them. The differences in potassium and in rare earth pattern for island type and ridge type basalts may be explained by this model. Moreover, the 2 billion year "holding age" advocated by Gast[7] to explain lead isotope data of Gough, Tristan da Cunha, St Helena and Ascension Islands may reflect how long the material was stored in the lower mantle without change prior to the hotspot activity.

My claim that the hotspots provide the driving force for plate motions is based on the following observations to be discussed below. (1) Almost all of the hotspots are near rise crests and there is a hotspot near each of the ridge triple junctions, agreeing with the notion that asthenosphere currents are pushing the plates away from the rises. (2) There is evidence that hotspots become active before continents split apart. (3) The gravity pattern and regionally high topography around each hotspot suggest that more than just surface volcanism is involved at each hotspot. (4) Neither rises nor trenches seem capable of driving the plates.

The symmetric magnetic pattern and the "mid-ocean" position of the rises indicate that the rises are passive. If two plates are pulled apart, they split along some line of weakness and in response asthenosphere rises to fill the void. With further pulling of the plates, the laws of heat conduction and the temperature dependence of strength dictate that future cracks appear down the centre of the previous "dike" injection. If the two plates are displaced equally in opposite directions or if only one plate is moved and the other held fixed, perfect symmetry of the magnetic pattern will be generated. The axis of the ridge must be free to migrate (as shown by the near closure of rises around Africa and Antarctica). If the "dikes" on the ridge axis are required to push the plates apart, it is not clear how the symmetric character of the rises could be maintained. The best argument against the sinking lithospheric plates providing the main motive force is that small trench-bounded plates such as the Cocos plate do not move faster than the large Pacific plate[8]. Also, the slow compressive systems would not appear to have the ability to pull other plates away from other units. The pull of the sinking plate is needed to explain the gravity minimum and topographic deep locally associated with the trench system[9], but I do not wish to invoke this pull as the principal tectonic stress. This leaves sub-lithospheric currents in the mantle and the question now is: are these currents great rolls (mirrors of the rise and trench systems), or are they localized upwellings (that is, hotspots)?

A recent world gravity map[10] computed for spherical harmonics up to order 16 shows isolated gravity highs over Iceland, Hawaii, and most of the other hotspots. Such gravity highs are symptomatic of rising currents in the mantle. Even if the gravity measurements are inaccurate (different authors have very different gravity maps), the fact remains that the hotspots are associated with abnormally shallow parts of the oceans. For example, note the depth of the million square kilometres surrounding the Iceland, Juan de Fua, Galapagos, and Prince Edward hotspots. The magnitude of the gravity and topographic effect should measure the size of the mantle flow at each hotspot.

There is evidence of continental expression of hotspot activity in the lands bordering the Atlantic: the Jurassic volcanics in Patagonia (formed by the present day Bouvet Island plume), the ring dike complex of South-west Africa and flood basalts in the Parana Basin (Tristan da Cunha plume), the White Mountain Magma series in New Hampshire (the same hotspot that made the New England Seamount Chain (Azores plume?)), the Skaegaard and the Scottish Tertiary Volcanic Province (Iceland plume) and perhaps others. I claim this line-up of hotspots produced currents in the asthenosphere which caused the continental break-up leading to the formation of the Atlantic. Likewise the Deccan Traps (Reunion plume) were symptomatic of the forthcoming Indian Ocean rifting. A search should be made for such continental activity, particularly in East Africa and the western United States (the Snake River basalts?) as an explanation for the rift features found there. There is a paucity of continental hotspots in Fig. 1; perhaps this is a bias due to continental complexity versus oceanic simplicity, but the model presented here predicts that most hotspots will be near a spreading rise.

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Fossil Pingos in the South of Ireland

Remains of former pingos or ice-lens mounds are known in the Low Countries, Scandinavia, East Anglia[1] and Wales[2]. They are also widely distributed in the south of Ireland.

Fine examples occur near Camaross, on the road from Wexford to New Ross, 9 km west-north-west of Wexford town. A cluster of at least twenty fossil pingos north-east of Camaross Cross Roads (S891249) have been specially photographed by Dr J. K. St Joseph, Director in Aerial Photography, University of Cambridge (obliques 23/890245 and 7; verticals K17/W25–30). Part of K17/W26 is reproduced here by kind permission (Fig. 1*a*).

Three fossil pingos are seen. Pingo A (top right) has a basin about 60 m in diameter; the enclosing rim, which is almost complete, rises in a grassy ridge 1.5 m above the surrounding badly drained rushy ground (well seen on the south-east side). The elongated basin of pingo B does not contain open water, but the rushy vegetation inside the rim and outside it on the south-east is in contrast with the grass cover of the rim. Pingo C (bottom left) has an elongated basin which contains a wet swamp. In this vicinity, ridges of rock at about 75 m OD (ordinance datum) separate small valleys whose lower slopes (falling from north-west to south-east) are covered by soliflucted till with very poor natural drainage. The pingos formed near the base of the slopes.

Fine examples also occur at 60 m OD in Carrigeenhill Townland (W945953) on the road from Fermoy to Tallow, 14 km east-south-east of Fermoy. Here there is a rock-ridge to the north of the road, and a small valley partly filled with badly drained soliflucted till to the south. A large field abutting against the south side of the road showed at least three pingo basins and several curved ridges. When seen, the field was in the course of being drained and the lay-out of the drainage ditches had been imposed by the distribution of the pingo basins and ridges, which had disturbed the solifluction slope.

About 5 km west-north-west of Castleisland, the road from Castleisland to Tralee runs through a series of groups of fossil