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# HOTSPOTS: THE FIRST 25 YEARS

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"Our extrapolations [...] show that there will be 1,000,000 hotspots by the year 2000. We hope someone proves that hotspots do not exist, before it is too late." [Holden and Vogt, 1977].

*Abstract.* The Wilson [1963] — Morgan [1971] hotspot hypothesis has been extremely successful for determining past plate motions and has served as a stimulating influence in many fields of Earth Science. In this paper, we provide a brief review of some of the important landmarks in the development of the unified geophysical-geochemical hotspot or plume model for linear island and seamount chains. We briefly review topics under the headings of kinematics, hotspot-plate interactions, and petrology and geochemistry, and then take a closer look at some problems that have developed with the simplest hotspot model in each of these categories. These second-order problems include such items as departure from linearity, prolonged volcanism at certain sites, and isotopic complexity, which are exemplified by such chains as the Cook-Australs, the Marquesas, and the Gulf of Alaska. In such cases, the hotspot model requires additional complexity in order to explain the observations. It is clear that not all oceanic or continental intraplate volcanism can be explained in terms of the classical hotspot hypothesis unless hotspots are part of a continuum which contains upwelling blobs of various size, longevity and isotopic characteristics. Within this context, we discuss some of the possible constraints provided by isotopic and convection modelling, and conclude that not all plumes are created equal.

## Introduction

It has now been close to 25 years since J. Tuzo Wilson proposed his famous interpretation of the Hawaiian and other island chains [Wilson, 1963]. The purpose of this paper is to present a brief review of the principal milestones of the hotspot theory in the past quarter-century and of its fundamental remaining problems, and to discuss how the latter may in the future affect our views on the origin and mechanisms of mid-plate volcanism.

Because of the voluminous character of the subject, our review cannot pretend to describe every achievement nor treat every aspect of hotspot theory in the past 25 years (a full book would not suffice; and indeed the literature is rich in reviews on various individual topics). Rather, our purpose is to give a kind of report card of how well the simple model of a universal, long-lasting, radiogenic hotspot, deeply and securely anchored in the mantle, fares against the rapidly growing datasets in many Earth science

disciplines. The original notion of fixed hotspots, later correlated with a chemically distinct source in the deep mantle [Schilling, 1973], has been of immense value in unraveling past plate motions and has served as a stimulus for studies of mantle convection and chemical geodynamics [Allègre, 1982]. The hotspot hypothesis has several closely interrelated aspects treated in the literature: (i) kinematic aspects of their fixity and utility for studies of past plate motion [e.g., Minster and Jordan, 1978; Morgan, 1981; Gordon and Henderson, 1987]; (ii) links with the physics of mantle convection [Davies, 1984; Olson and Christensen, 1986], and the dynamics of mantle plumes [Ribe, 1983]; and (iii) the related issue of the chemical diversity of the Earth's mantle [Allègre et al., 1980; Gurnis and Davies, 1986; Zindler and Hart, 1986].

In the first section, we attempt to describe a "simple" universal hotspot model, explaining most first-order observations regarding island and seamount chains, and we list the basic successes of this approach. We then take a closer ("second-order") look at the various characteristics of linear island chains, address a number of problems with their interpretation in the framework of the simple theory, and discuss the constraints they may put on the origin and mechanism of extrusion of ocean island basalts.

## A Brief Review of the "Simple" Hotspot Model

As early as the 19th century, Dana [1849] interpreted the degree of erosion of the various Hawaiian islands to infer that volcanic activity along the chain had progressed southeastwards with time; indeed, a correct description of this progression is found in ancient Hawaiian mythology in the form of the successive dwellings of the goddess Pele, although it is not clear that it associated her with the actual building of the islands. The systematic recognition of the linearity of islands chains, notably in the Pacific Ocean, goes back to Wegener [1915] who mentioned in his book on continental drift the existence of oceanic islands aligned perpendicular to the drifting direction of continents.

In 1963, and following systematic dating of igneous rocks from oceanic islands, J. Tuzo Wilson made the fundamental, quantitative observation that the age of an island is usually different from that of the adjoining sea floor, and further established a linear correlation between the age of volcanism and distance along the oceanic chain; he went on to propose his now famous model, in which, as the plate passes over a magma source fixed with respect to the mantle,

"the islands are in fact arranged like plumes of smoke [....]
carried downwind from their sources"
[Wilson, 1963].

The ensuing success of the model was due to its simplicity, its
universality (the same model explains observations in geographi-
cally different areas), and to the fact that it could account simply
for many observations, which fall grossly into three categories:
plate kinematics, hotspot/plate interactions, and origin and chem-
ical nature of the hotspot magmas. We will now review very
quickly the principal milestones in the model's development.

### Kinematics

The simple hotspot model is based on the assumption that the
magma sources are securely anchored in the deep mantle; as such,
they can provide a reference frame for the study of the plates'
absolute motions both at present and in the past. That this is at
all possible as demonstrated for example by Minster and Jordan
[1978] (and that the hotspots are therefore, to a precision of
1 cm/yr, fixed with respect to each other), constitutes in itself a
major success of this simple model; further successes in the field
of plate kinematics include: (i) the explanation of the linearity
and asymmetry of island chains, with the center of present
activity located at one end [Wilson, 1963]; (ii) the parallelism of
the various island chains inside a given oceanic plate [Wilson,
1963]; (iii) the reconstruction of the change of direction of the
Pacific plate's motion about 43 Ma b.p. [Christofferson, 1968] on
the basis of the sharp bends observed for example along the
Hawaii-Emperor chain; (iv) the linearity of the age-distance rela-
tionship along a given chain, and the consistency of the inferred
rates of progression amongst chains [Duncan and McDougall,
1976; Jarrard and Clague, 1977].

We must stress that the above are major observations of an
absolutely fundamental character, and that they remain the basis
for the firm, undeniable success of the hotspot hypothesis.

An implicit assumption of the hotspot model is the long-lived
character of the mantle source, in other words that hotspots can-
not be born and killed, or turned on and off, at will. It is obvious,
for example, that the model would make no sense if the lifetime
of the hotspot source were shorter than the age separation
between two islands in a chain. At the other extreme, a first-
order assumption for the "simple" hotspot model is that of their
continuous existence and activity since at least 125 Ma [Anderson,
1982; Chase and Sprowl, 1983], and possibly 200 Ma [Le Pichon
and Huchon, 1984]. Such an assumption of long-lived character
can then be tested in the oceans by retracing the tracks of
hotspots into the geological past, and effecting associations with
islands and seamounts; and on continents by looking for evidence
of hotspot tracks in the stratigraphic record of uplifts prior to
Jurassic time [e.g., Crough, 1981].

Perhaps the most ambitious and successful such study is Gor-
don and Henderson's [1987], who claim to account for all major
islands and plateaux in the Pacific plate by considering 14
hotspots, moving at most 1 cm/yr with respect to each other. In
the Southern Atlantic and Indian Oceans, Duncan [1981] and
Morgan [1981] similarly accounted for much of the seamount and
island volcanism.

### Interaction with the Plate

One of the fundamental points in the simple hotspot model is
that ideally it considers little mechanical interaction between the
plume and the oceanic lithosphere. This idea is indeed inherent
in the concept of the oceanic island being the "trace", on the
moving plate, of the relative motion of the two systems (plate and

deep mantle). Although it was realized early on that this is only
an assumption, the following observations seem to confirm it, at
least to a first approximation:

While some temporary deviation of the trace of a hotspot chain
is observed (e.g., in the Hawaiian chain) when passing over a
major fracture zone [Epp, 1978], this signature typically lasts no
longer than 300 km, and the linearity of the chain is quickly
restored, attesting to the robust character of the plate/mantle
velocity vector.

The formation of discrete islands in a chain was explained on
the basis of the experimental study of the ascending motion of
buoyant pipes under various conditions of density and viscosity
contrasts [Skilbeck and Whitehead, 1978]. It was suggested that
the characteristic separation between individual islands must
increase with plate thickness [Vogt, 1974], which readily explains
the formation of discrete islands on older lithosphere, and of con-
tinuous plateaux at the ridges. While this model requires the pipe
to bend during the formation of an island, the short duration of
this process (1—2 Ma) constitutes only a small perturbation to
the model.

An alternate model for the upwelling column is that of discon-
tinuous blobs [Schilling and Noe-Nygaard, 1974], explored experi-
mentally by Olson and Singer [1985], who found that such blobs
were favored over a continuous plume, under the conditions of
large horizontal velocities in the mean mantle flow typically
expected in mid-plate regions. Using this model, they calculate a
replication time on the order of 5 Ma, generally consistent with a
distributed melt model for Hawaii.

Since the oceanic plate has a finite elastic rigidity, it must
deform under loading by islands, and a considerable number of
studies have addressed this problem [e.g., Walcott, 1970; McNutt
and Menard, 1978; Watts et al., 1985]. While a general correlation
was established between the flexure of the plate and its age at the
time of island formation [Watts, 1978], early studies pointed to a
deficiency in the elastic response of the plate, as predicted by ade-
quate models of its rheology and thermal history, leading to the
concept of "lithospheric thinning" in the plate [Detrick and
Crough, 1978]. As discussed below, some controversy remains as
to whether the hotspot is the thinning agent, or results itself from
the delamination of the plate. Still, the concept of thinning has
been by and large successful in explaining the wealth of geophysi-
cal data made available in the past decade from satellite
altimetry [McNutt, 1984].

### Origin of Hotspots; Petrology and Chemistry

The fixity of hotspots, and the fact that they produce vol-
canoes, led quickly to the notion that they could be the surface
expression of buoyantly rising convective instabilities [Morgan,
1971; 1972a,b]. In this way, the hotspot, or plume, hypothesis
became closely linked with questions regarding the possible
geometry of mantle convection: mantle plumes could rise from the
deep mantle and melt as a result of adiabatic decompression [Tur-
cotte and Oxburgh, 1978], thus producing volcanoes.

In 1965, isotopic analysis of ocean basalts [Tatsumoto et al.,
1965] began to provide evidence that the Earth's mantle is chemi-
cally and isotopically diverse. In a series of landmark papers,
Schilling and others showed that basalts from Hawaii, Iceland, the
Azores and other regions were enriched, relative to MORB, in the
light rare Earth elements and other so-called incompatible or
magmatophile elements [Schilling and Winchester, 1967; Schilling,
1971, 1973; Schilling et al., 1983]. Further, they were able to show
that isotope ratios showed a gradual change from normal mid-
oceanic ridge basalt [MORB] values to more radiogenic values as
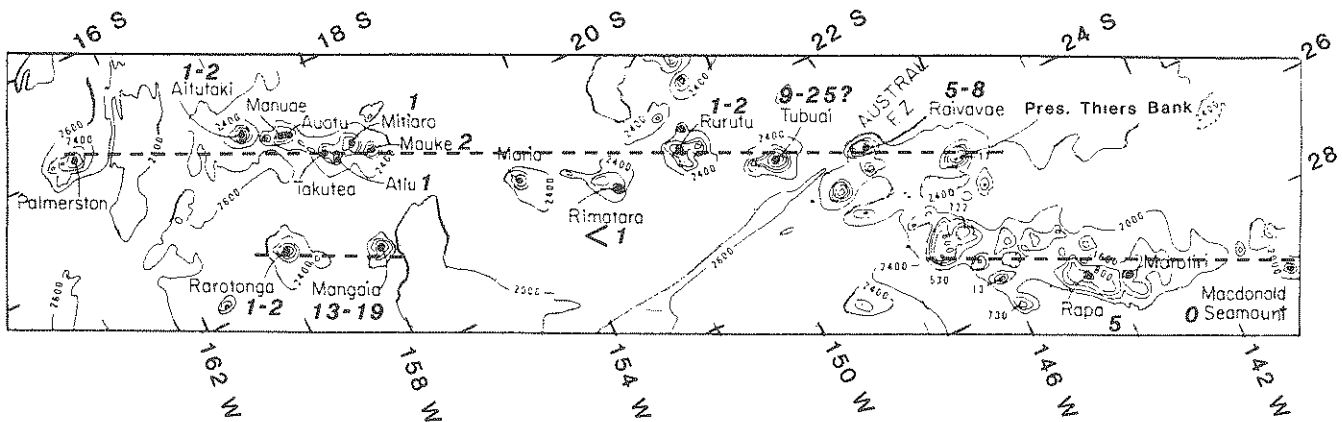hotspot islands were approached. These observations provided an

Fig. 1. Map of the Cook-Austral Island chain adapted from Turner and Jarrard [1982]. Numbers in italic indicate ages of islands along the chain (in Ma). The two dashed lines identify the two subchains parallel to each other, offset 250 km at the level of President Thiers Bank, and running concurrently in the Cook Islands. Note the gross violations of age-distance relationships.

important link between diapiric convective instabilities (geophysical plumes) and the evolving idea of mantle heterogeneity, because they provided for simple mixing of two mantle components: a depleted MORB mantle source, and a presumably deeper, enriched, plume source. So, in its simplest form, the combination of rising convective instabilities with chemical and isotopic stratification of the mantle gave rise to a "unified plume theory". This simple model of a convective upper mantle as a source for MORB with a separately convecting deeper layer as the source of the enriched plumes was found to be consistent with both Sr and Nd isotope ratios [DePaolo and Wasserburg, 1976, 1979]. The good correlation between bathymetry and chemical anomalies along mid-ocean ridges has been convincingly demonstrated, though it is best developed along the Mid-Atlantic Ridge [Schilling et al., 1983; Hamelin et al., 1984].

### A Second-Order Look; Problems with a Simple Hotspot Theory

In this section, we examine a number of problems and irregularities which surface when attempting to describe all island chains in the framework of the simple theory mentioned above. It must be emphasized that many of these problems are observed in chains other than Hawaii-Emperor, which because of its accessibility, volume of extruded material, present-day subaerial activity, and well-documented history of scientific investigation, has remained the classical model of a hotspot chain. However, as more data (in fields as different as isotope geochemistry and satellite geodesy) become available for islands in the other chains, a long string of problems arise. We address them in the order of the broad categories listed above; however, these problems are often intermixed, through alternate explanations (e.g., the introduction of several hotspots in a single chain).

*Plate Kinematics*

*Failure to remain a linear chain.* This problem is particularly acute in the Austral Islands, where lateral offsets on the order of 300 km are frequent (Figure 1). In the southern section, two major portions of the chain, each running for 600 km or more, are offset laterally about 250 km between President Thiers' Reefs and the seamounts to the west of Rapa. This is significantly longer than observed, for example in the Hawaiian chain, upon passage

over a major fracture zone; in addition, this offset in the Austral chain is not correlated with a fracture zone, but rather located as much as 300 km east of the Austral Fracture Zone. In the western portion of the Cook-Austral Islands, the two chains run concurrently, parallel to each other (the northern branch from Aituki to Mauke and the southern one from Rarotonga to Mangaia). A possible explanation would involve two hotspots, rather than one; this would require turning them on and off frequently, in order to account for the complex geography of the chain.

A similar problem, though less acute, is the observation that some linear island chains consist not of a single straight line of volcanic edifices, but instead of overlapping, and occasionally alternating, en-échelon systems. Good examples are Hawaii [Jackson et al., 1972], the Society Islands [Talandier and Okal, 1984], and the New England Seamounts. More complex variants, such as "cross-trends" that disturb the linearity of hotspot tracks are also observed, as for example, in the Line Islands [Epp, 1984; Schlanger et al., 1984] (although Gordon and Henderson [1987] interpret the disturbance as a crossover with the pre-existing track of the Marquesas hotspot). Finally, it may be noted that in the case of many large volcanoes within hotspot chains, the forms of individual non circular islands may not be parallel to the trend of the chain: very localized non-linearity of this type is usually caused by the development of long volcanic rift zones and probably reflects local tectonics and edifice effects [Fiske and Jackson, 1972; Vogt and Smoot, 1984].

*Duration of volcanism along a chain and/or fluctuation in the rate of extrusion.* Some islands chains are clearly much shorter than others: the Marquesas are an obvious example, although Gordon and Henderson [1987] have traced the activity of the Marquesas hotspot backwards in time all the way to the Shatsky Rise (about 130 Ma b.p.), claiming continuous activity evidenced by geoid highs in the absence of major seamounts between the Marquesas and the Line Islands. These authors thus alleviate the need for bringing to life, or "turning on" the Marquesas hotspot as recently as 10 Ma, as would be suggested by the lack of islands or seamounts northwest of Eiao. It must however be accepted that the level of activity of this particular hotspot fluctuated substantially in the past few million years; in particular, there is no evidence, not even seismic, of any activity younger than about 1 Ma. In the continuous upwelling pipe model of Morgan [1971], one must then assume that the burner was adjusted from "sim"

to "hot" at 10 Ma, and probably back to "sim" about 1 Ma ago. In the alternate model of the "chain of blobs" [Schilling and Noe-Nygaard, 1974], one would assume that the number or size of the blobs suddenly increased during that same period. Although Olson and Singer [1985] suggest that interaction between rising blobs and the mean flow of the mantle, plus interaction of the rising blobs with the lithosphere, could in general result in such behavior, the specific reasons for the Marquesan sequence eludes us completely. Similarly, Gordon and Henderson [1987] had to introduce the concept of "waning" for several hotspots (Brahms, Rachmaninoff, Gardner, and possibly Louisville) in their Pacific model describing most islands, major seamounts and plateaux as derived from hotspots.

A much more common case is that of more continuously variable extrusion rates along the length of an island/seamount chain [e.g., Vogt, 1981]. An excellent example is the Hawaii-Emperor chain which shows gaps and large variations in the extrusion rate along the chain [Shaw, 1973]. Epp [1978] shows that this is very common in the North Pacific, and recent data from the Louisville Ridge in the South Pacific indicate non-uniform eruption rates as well [Lonsdale, 1987]. Atlantic and Indian Ocean hotspots [Morgan, 1978, 1981, 1983; McDougall and Duncan, 1980; Duncan, 1981; Hartnady and le Roex, 1985] exhibit the same phenomena.

A variation of this problem concerns the massive extrusion of volcanics, together with sill emplacement, during the Cretaceous, in what is now the Western Pacific Basin [Schlanger et al., 1981]. This enigmatic basin-wide event has no modern parallel. We speculate that it could be linked to the dispersal of Pangea [Le Pichon and Huchon, 1984], though this requires a long-time gap between dispersal (Late Triassic - Early Jurassic), and Mid-Pacific volcanism. Alternatively, one can be tempted to explain this volcanism by multiple crossings of hotspot traces; however the presently active hotspots, when traced back in time [Gordon and Henderson, 1987], cannot explain the 3 to 4 episodes of volcanism documented on the plate in the Nauru, Marshall and Mariana basins. Furthermore, in such a model, the interpretation of the apparently simple cooling and subsidence of the region [Schlanger and Moberly, 1986] remains problematic.

A related problem is posed by the vast oceanic plateaux for which hotspot origin has been suggested [Mahoney, 1987]. Alternatively, several plateaux and related sill complexes have been interpreted as large outpourings due chiefly to very rapidly changing spreading patterns [Winterer, 1976; Castillo et al., 1986].

*Duration of volcanism on an individual island.* It is a basic aspect of the simplest hotspot theory that only one island or seamount be active at a time. At the young end of many hotspot chains, this is not the case. For example, post-erosional basalts are 1-3 Ma younger than shield-building lavas on Oahu and the Samoan Islands [Jackson, 1976; Natland and Turner, 1987]. The petrologic characteristics of these volcanics (i.e., highly alkaline and silica-undersaturated) indicate generation at great depth and their small volumes (considerably less than 1% of the edifice) suggest that they could be remnants from the main thermal event causing shield building. The example of Hawaii and Samoa suggest that post-erosional activity survives for at least 3—4 Ma after shield-building. Most thermal models would indicate that this stretches the upper limit for the continued presence of a single magma body, but such time scales may be characteristic for the waning of deep thermal events. The gravitational anchor model of Shaw and Jackson [1973] provides some rationale for continued eruption of tiny volumes of post-erosional products. On Samoa, the volumes of post-erosional products is much larger, but still only a fraction of the entire edifice.

In some cases, however, prolonged volcanism at a single volcano presents a more serious problem for the simple hotspot model.

Excellent examples are the Canary Islands, where active volcanism has occurred for $\simeq$20 Ma [Schminke, 1975], and the Caroline Islands, where volcanism has occurred for $\simeq$ 8 Ma [Mattey, 1982; Dixon et al., 1984]. Clearly, and until more is known about the average active life of oceanic volcanoes, this problem must be held in abeyance. The case of contemporaneous activity at several sites along a chain is similarly problematic: in the Line Islands, Haggerty et al. [1982] and Schlanger et al. [1984] have documented Late Cretaceous volcanism taking place simultaneously over a distance of 2500 km. Similarly, along the so-called Easter hotline, contemporaneous young volcanism has occurred over a linear distance of 2700 km [Bonatti and Harrison, 1976]. Continental examples of this phenomenon are present in Australia [Pilger, 1982].

*Violation of age-distance relationships.* Some of the linear chains have been found to exhibit strong departures from the predicted age-distance relationships. While some of these inconsistencies may be due to the poor quality of the early datasets, relying heavily on K/Ar ages, there are clear cases of outright violation: In the Southern Cook Islands, only 210 km separate Rarotonga (1.1—2.3 Ma) and Mangaia (13—19 Ma) [Turner and Jarrard, 1982]; in this case, the direction of progression of age itself is wrong. Other examples include Rurutu, located in the middle of the Cook-Austral chain, and dated no older than 1 Ma [Dalrymple et al., 1975].

In the case of Tubuai, the morphology of the island leads to considering two major episodes of volcanism dated 25($\pm$10)—17 Ma and 16—9 Ma, respectively; one Tubuai basanite has been dated as young as 1 Ma. The duration of volcanism on Tubuai is thus at least 16 Ma, and possibly 24 Ma [Mottay, 1976]; indeed, the Austral-Cook chain is clearly the least convincing example of age-distance correlation among Pacific chains [Duncan and McDougall, 1976; Jarrard and Clague, 1977]. Several avenues can be explored to account for this discrepancy: one of them is to use several hotspots (at least three, according to Turner and Jarrard [1982]) to describe the chain; however, each must be turned on and off very fast (in less than a few Ma) to explain the absence of present-day activity, except at the southeastern end of the chain at Macdonald. Another possibility is to interpret the younger, strongly alkalic, formations as comparable to the simple posterosional activity discussed above for Oahu; the extended period of retention of the magma source involved in this model, is however, difficult to explain by any simple thermal model.

Other examples of age-distance discrepancy include the Pratt-Walker-Bowie chain in the Gulf of Alaska, which has volcanoes that are both too young and too old to be part of a single hotspot chain [Dalrymple et al., 1987]; the Cocos Ridge, which has a 2—3 Ma volcano (Cocos Island) astride a portion of the ridge predicted to be 12—14 Ma [Castillo and Batiza, 1986], and the Caroline Island chain [Dixon et al., 1984; Mattey, 1982], which suffers from age discrepancy and/or prolonged volcanism (up to 8 Ma) on single island volcanoes.

Volcanoes along a chain that are too old to fit the age progression may be explained as having been present on the lithosphere prior to passing over the hotspot. These could be ridge-generated [Batiza, 1981, 1982; Batiza and Vanko, 1984], which can be tested by petrologic means since they would be mostly tholeiitic like MORB. Alternatively, they could be isolated off-ridge volcanoes like Henderson Seamount, in the Eastern Equatorial Pacific [Honda et al., 1987]. In some cases, the flexure response of the lithosphere can be used to determine the age difference between the load (volcano) and the plate [Watts et al., 1980].

Explaining the presence of volcanoes that are much younger than the proper age along a chain can be more problematic, because it is usually difficult to determine whether the young vol-

canics are a thin cap on a volcano of the correct age or whether the entire edifice is a young volcano. In the former case of volcanic reactivation, renewed volcanism can be caused by passage over a second hotspot; this possibility can be tested kinematically, as done by Gordon and Henderson [1987]. Another alternative is fortuitous volcanic reactivation as discussed by McBirney [1963] and Sykes [1978]. Thus, the presence of volcanoes whose ages violate the predicted age-distance relationship does not necessarily disprove their possible hotspot origin; however, in cases where there are many such volcanoes, as in the Gulf of Alaska [Dalrymple et al., 1987], the hotspot model loses the appeal of its simplicity.

*Relative motion between hotspots.* Gordon and Henderson [1987] have proposed to account for minor deviations from predicted hotspot tracks by allowing Pacific hotspots to move slowly with respect to each other. When referred to Hawaii, the maximum motion required is 8 mm/yr; the maximum relative motion between two hotspots is about 11 mm/yr between Easter and Tahiti. These numbers are comparable to those mentioned by Morgan [1972a] or Molnar and Francheteau [1975]; in the Pacific, Chase and Sprowl [1984] have proposed to interpret them as representative of the motion of the hotspots away from the geoid high. However, the general difference in order of magnitude between plate/hotspot and hotspot/hotspot velocities constitutes only a minor adjustment to the simple model.

## Interaction with the Plate

*Action of a hotspot on a ridge system: Trapping.* While the general concept of the robustness of the plate/mantle velocity vector with respect to encounter with a hotspot is at first order satisfactory, the conspicuous presence of a large number of hotspots on, or in the immediate vicinity of, mid-ocean ridges arouses suspicion that hotspots may be able to "trap" ridges, or vice versa. Iceland is the perfect example of a hotspot having managed to trap a mid-oceanic ridge through an episode of ridge-jumping, about 9 Ma ago [Morgan, 1981]. The experiments of Olson and Singer [1985] provide some insight into this process, because they show that hotspot fixity is enhanced by the vertical, rather than horizontal, mantle flow expected beneath ridges.

More generally, there is some evidence that the distribution of hotspots is controlled by lithospheric vulnerability [Gass et al., 1978; Pollack et al., 1981], which is a combination of plate speed and thickness. Though this interpretation has been questioned by Vogt [1981] and Stefanick and Jurdy [1984] on several grounds, it is clear that the old, cold and strong lithosphere, though cracked, may act to filter thermal and magmatic events that are transitory, weak, or of small size. The observation that off-ridge non-hotspot volcanoes are added to the lithosphere at rates consistent with plate thickening [Batiza, 1981; Smith and Jordan, 1985] could indicate progressive decrease of availability of magma. Alternatively, it could indicate progressive thermomechanical difficulty for the rising magma to puncture the lithosphere [Spera, 1980; Spence and Turcotte, 1985; Scott et al., 1986].

On the other hand, there exist a number of cases of oceanic islands which were clearly generated on-ridge by a hotspot which is presently an intraplate feature. Examples include the Kerguelen hotspot (which generated the Broken Ridge in an on-ridge geometry), the Tristan da Cunha hotspot [Humphris et al., 1985], and the Northern Tuamotus, which have little if any signal in the geoid, but are abruptly terminated at the Austral Fracture zone [Pilger and Handschumacher, 1981]. One must therefore admit that, just as a ridge can be trapped by a hotspot, it can also escape one. Using the example of the Tuamotu Islands, Okal and Cazenave [1985] speculated that a hotspot had been responsible

for rift propagation, in the sense of Hey's [1977] model, an idea already proposed by Vogt [1971] and Vogt and Johnson [1973] to explain "V"-shaped structures at the Mid-Atlantic and Galapagos spreading centers, and by Schilling et al. [1982] on the basis of petrological and geochemical arguments in the Galapagos. This idea has also recently been investigated by Phipps Morgan and Parmentier [1985], who showed that lateral magma-fracture is a plausible mechanism for rifts propagating away from a hotspot; indeed all propagating rifts move away from topographic highs. Okal and Cazenave [1985] proposed that the "circle of influence" of a hotspot for such effects could be on the order of 500 km wide, a figure comparable to estimates of its structural anomaly obtained from seismic probing [e.g., Tryggvason et al., 1983].

*Action of a ridge system on a hotspot: Leaking.* At the same time, and along the Oeno-Henderson-Ducie-Crough lineament, Okal and Cazenave [1985] noticed that, over a distance of 1000 km, the chain is misaligned by 15° from the azimuth of the plate's absolute velocity. They explained this situation by assuming that conversely, an existing fracture zone can deviate the surficial expression of a hotspot, as long as the lateral distance does not exceed the radius of influence mentioned above. These speculative models fall into the general category of deviated and/or leaking hotspots, which have now been proposed for about a decade. In particular, Schilling [1985] has recently demonstrated a related phenomenon of hotspot-ridge interaction. His evidence shows that hotspots moving off-ridge may maintain a flow channel to the ridge, resulting in predictable geochemical anomaly widths and elevations. This follows the earlier suggestion of Morgan [1978], based entirely on plate kinematics and age-distance relationships, who proposed that in the vicinity of Mid-Ocean Ridges, hotspots could "leak" along horizontal sublithospheric channels into the Mid-Oceanic Ridge, in order to explain the volcanism of such islands as Amsterdam in the Indian Ocean and Darwin in the Galapagos. Okal and Stewart [1982] speculated that interplate earthquakes located at the mouths of such channels may exhibit slow strain release, as a result of thermal decoupling of the transform faults. Epp [1984] lists several examples of these and other perturbations to the simple hotspot model that may obscure or complicate the simplest pattern discussed earlier.

*Plate thinning: Plume control vs. delamination.* McNutt [1984] reviewed general evidence for an anomalously weak elastic response of the lithosphere under the load from hotspot islands; her observations are readily interpreted in the context of the thinning of the plate. However, as more geoid data become interpreted, it is becoming clear that the response of the plate to hotspot loads, as quantified by its elastic thickness and depth of isostatic compensation, can vary greatly between hotspot chains, and even inside a chain. In a recent review, Calmant [1987] has found elastic thickness values varying from less than 6 km (and thus basically unmeasurable) under the youngest Austral Islands (Rapa, Macdonald) to $\simeq$ 20 km in the Marquesas, and $\simeq$ 30 km under the Hawaiian swell. Similarly, McNutt [1987] has found that the depth of compensation of the Marquesas is considerably smaller than for the Hawaiian chain (45 vs. 70 km).

In the Austral Islands themselves, Calmant and Cazenave [1986] have pointed out that the extreme southern (and youngest) group, Macdonald and Rapa, are practically not supported elastically, and largely compensated, while the next group to the west, Raivavae, Tubuai, and Rurutu, have elastic thicknesses on the order of 10 km. This situation cannot be explained simply, all the more so since these same authors have estimated that it may take 3—4 Ma before the plate attains its permanent flexural rigidity through initial stress relaxation, as suggested by a strong elastic response under Tahiti already documented by McNutt and Menard [1978].

While the interpretation of the weakened elastic response of the lithosphere must clearly be sought in its thermal regime, a consistent explanation of its observed variation has yet to emerge. McNutt [1987] has put constraints on the depth extent of the temperature anomaly below the Hawaiian and Marquesan swells. Detrick and Crough [1978] showed that lithospheric thinning was taking place too fast to be explained by simple conduction of heat from the plume; a number of models in which convection provides the additional heat flux could better explain the thinning of the plate [Spohn and Schubert, 1982], especially under temperature-dependent rheologies which can reduce the required excess mantle heat flux [Yuen and Fleitout, 1985].

A completely alternate view of lithospheric thinning is the delamination model, in which the location of volcanism may be the result, as opposed to the cause, of the plate's thinning. This model, developed initially for continental volcanoes [Bird, 1979] can reconcile the obviously hot state of the volcanic sites with apparently "colder" geophysical data, such as normal values of whole mantle *ScS* travel times [Best et al., 1974] and *Q* [Sipkin and Jordan, 1980], or long-wavelength positive gravity anomalies [Sleep, 1984]. In such a model, one would invoke a form of anchoring of the delaminating plate to ensure the kinematic characteristics of the island chain.

*Geochemistry and Origin of Hotspots*

*Variations in chemistry.* When compared to MORB, oceanic basalts generally have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ isotopic ratios. However, a continuum of values is featured between the less radiogenic islands, such as Iceland and Easter, which approach MORB characteristics, and the highly radiogenic ones, such as Tristan, Gough and Samoa. The situation is made more complex when other isotope couples are considered, including the various Pb isotopes and $^3He/^4He$. These recent geochemical observations require at least four and possibly six different endmember mantle components, and we refer to Zindler and Hart [1986] for a complete review of these arguments.

An important aspect of the extreme variability of the isotopic signature of hotspot volcanics is the fact that significant isotopic differences can be documented inside a given chain, or even between various magmatic stages on a single island. For example, in the Austral Islands, Pb and Sr isotope studies indicate that the southernmost group (Macdonald, Marotiri, Rapa) is much less radiogenic than the next one to the north (Tubuai, Rurutu), but that these differences cannot be simply due to a variable degree of mixing [Grall et al., 1985]. Further North, Rarotonga and Mangaia have fundamentally different isotopic signatures, despite being only 200 km apart [Palacz and Saunders, 1986]. This is in agreement with the extreme gradients featured in the Austral Islands region on the so-called "Dupal" anomaly maps [Hart, 1984].

On Ua Pou in the Marquesas Islands, Duncan et al. [1986] have documented an increase in $^{87}Sr/^{86}Sr$ from the shield-building tholeiites to the later-stage alkali basalts. This situation is the opposite of that on Hawaii [Chen and Frey, 1983], and this clearly requires different processes of interaction between the plume and the lithospheric plate in the two chains.

*Depth of hotspot sources and/or plumes.* That magma is supplied to growing island chains over long periods of time, and that these sources remain reasonably stationary with respect to each other is very well established, although it is clear that kinematic perturbation can occur and that diapirically upwelling mantle and/or mush interacts with the lithosphere in several ways. The major remaining question about the "simple" unified geochemical/geophysical plume hypothesis concerns the depth of

origin of the upwelling mantle material (e.g., core-mantle boundary [CMB], lower mantle, transition zone, upper mantle?), and in particular whether this depth is similar for all plumes. This question is important because it is now well-known that while the source of mantle plume magmas is usually different from the MORB source, different plumes may have different mantle sources, and furthermore, enriched plume-like sources exist in the upper mantle [Batiza and Vanko, 1984; Zindler et al., 1984]. These observations provide important constraints for the related questions of chemical and isotopic stratification of the mantle, and of the dominant modes of mantle convection (i.e., whole mantle vs. layered). Also, isotopic systematics and mass balance calculations can provide strong constraints on planetary accretion and differentiation. But accurate calculations of this sort require that the nature of all major reservoirs be well known; in this way, the question of the origin of hotspots magmas becomes pivotal.

Early models, such as Morgan's [1971], argued for a plume source at the core-mantle boundary [CMB]. These were based principally on seismological contentions that significant structural anomalies existed on the CMB below Hawaii [Kanasewich et al., 1973]. These were explained later as artifacts of small scale variations under the receiving seismic arrays [e.g., Capon, 1974; Okal and Kuster, 1975], and indeed the recent tomographic models of the deepest mantle have in general failed to reveal a direct geographical correlation between structure on the CMB and the surface of the planet [Dziewonski, 1984; Morelli and Dziewonski, 1985]; an exception would be Lavely and Forsyth's [1986] observation of a seismic anomaly under the Azores-Gibraltar region. The recent tomography of the CMB carried out at wavelengths of $\simeq$ 1000 km, fails to correlate topographic anomalies on the CMB with hotspot locations at the surface [Gudmundsson et al., 1986].

DePaolo [1980] presented a simple model in which plumes originate within a homogeneous lower mantle that convects separately from the upper mantle region supplying MORB. Chase [1981] and Davies [1984] present both geophysical and geochemical arguments in a favor of a "plum-pudding" model similar to that favored by Allègre et al. [1982], Zindler et al. [1984], and Zindler and Hart [1986]. In these models, the whole mantle or the upper mantle contain heterogeneous domains of variable compositions, size and convective-mixing history. Several recent studies, summarized by Gurnis and Davies [1986] have investigated the question of whether heterogeneities in the mantle can survive intact after diffusion and physical mixing due to convection. They conclude that isotopic heterogeneities, large and small, can survive for long periods, consistent with geochemical evidence.

The difficulty of assigning a depth of origin to island, seamount and MORB sources is due partly to the fact that magmas re-equilibrate during ascent thus masking evidence of a previous higher pressure history. It is for this reason that the plume source has been placed by various workers at a great range of depths: from the CMB [Anderson, 1975] to as shallow as the base of the lithosphere [Anderson, 1985], and even the crust [O'Hara and Yarwood, 1978]. In the absence of direct seismological evidence for the depth of origin of plumes, the debate about the depths and the geometry of plume sources can be expected to continue.

*Age and geographical location of hotspots.* Studies of the geographical distribution of hotspots indicate that they are preferentially located within a geoid high covering half of the Earth [Chase, 1979; Crough and Jurdy, 1980; Vogt, 1981; Stefanick and Jurdy, 1984]. This geoid high was apparently the former site of Pangea and was located along an equatorial belt [Anderson, 1982; Le Pichon and Huchon, 1984]. In contrast, the geoid low which is also hemispheric and makes a "tennis ball" pattern with equatorial significance with the geoid high marks the site of ancient (200-125 Ma) subduction [Chase, 1979; Chase and Sprowl, 1983;

Jurdy, 1983]. These observations can be interpreted to show that: (i) the location of hotspots and subduction zones control the position of the Earth's spin axis [Crough and Jurdy, 1980; Jurdy, 1983; Le Pichon and Huchon, 1984]; (ii) the present geoid pattern may reflect deep mantle convection [Chase, 1979 and others]; and (iii) the present hotspots were caused by heating from the thermal blanket effect on Pangea over the mantle [Anderson, 1982; Le Pichon and Huchon, 1984].

These suggestions provide a self-consistent scenario in which continents aggregate at the Equator, heat the mantle below by a thermal blanketing effect causing episodic production of many hotspots which then cause fragmentation and dispersal of the supercontinent. This suggestion is consistent with the lack of direct evidence for hotspots older than 200-125 Ma, and has important implications for the evolution of convective patterns within the Earth. It is possible that such a scenario could result in cycles of supercontinent formation and break-up on the order of 400 Ma long [Le Pichon and Huchon, 1984; Bond et al., 1984]. Note however that the continent concentrations necessary to explain the origin of hotspots in this model have not all been proven from a geological standpoint.

If these suggestions prove to be correct, then continental break-up by hotspots may probably indicate a lower mantle source for hotspots initially. If such a source persists over the lifetime of hotspots ($\simeq$200 Ma), the isotopic differences among hotspots, together with variation along a single chain, and even within a single volcano, permit the conclusion either that the lower mantle is heterogeneous or that the lower mantle material mixes freely with heterogeneous upper mantle material during ascent. Alternatively, after the initial paroxismal event, the convective pattern could change, rooting diapiric convective instabilities at many levels in the mantle.

Clearly, any model linking the geophysical characteristics of mantle plumes has the difficult task of explaining the very common, but inconsistent, interchain, intrachain, and interisland differences in isotopic ratios discussed earlier that document mixing of several distinct mantle sources. Without finer independent constraints on depth of generation, the simplest approach is to invoke a plum-pudding model. In some favorable cases, however, like Ua Pou, it has been possible to obtain some geometric constraints on the mantle sources, but this is unusual and not repeatable.

## Conclusions

### Not All Hotspots are Created Equal

The first observation resulting from this brief review is that, as more and more geophysical and geochemical data are obtained and analyzed, it appears that substantial differences between chains exist at nearly every stage of the genesis of the islands:

In the first place, the chemical nature of the mantle heterogeneities from which ocean island basalts are derived is clearly variable. Recent advances in isotope analyses now require at least four and possibly six separate reservoirs [Zindler and Hart, 1986], the isotopic signatures of the islands resulting from a mixing between endmembers, whose variability cannot be confined to the shallow region of interaction with the lithosphere.

The obvious differences in rates of lava extrusion between island chains are most probably accompanied by variations in the depth of melting, as witnessed by substantial differences in major element composition (e.g., the absence of tholeiites on the Society Islands). Similarly, the actual mechanism of interaction with the plate during the final stages of magma ascent is highly variable, as evidenced by the differing trends in the evolution of

isotopic signatures found in the Marquesas and Hawaiian chains [Duncan et al., 1986]. Despite their relatively low contribution to the total volumes erupted, the level of activity during the posterosional stages also vary significantly.

Finally, the mechanical relationship between plate and island is itself the subject of substantial variation, with no universal correlation with plate age. The degree of thinning and re-heating (or, alternatively, of delamination) undergone by the plate must be adjusted by variations in the thermomechanical properties of the plume/plate system which presently elude us.

### A Clear Scofflaw: the Cook-Austral Chain

In Section 2 of this paper, we have often drawn on the Cook-Austral Islands to find examples of substantial deviation from the "simple" hotspot model. This has included: failure to remain a single linear chain (Raivavae-Rapa, Rarotonga-Aituki); violation of age-distance relationships (Rarotonga; Rurutu); prolonged or renewed episodes of volcanism (Tubuai); strong isotopic gradients (Macdonald-Rapa vs. Tubuai-Rurutu; Rarotonga vs. Mangaia); and rapid lateral variations in the mechanical response of the plate to loading (Macdonald-Rapa vs. Tubuai-Rurutu).

These anomalies, and the correlation of some of the properties among smaller geographic entities, suggest that the production of islands involved processes of differing chemical, thermal and mechanical nature, for groups such as Macdonald and Rapa on the one hand, and Rurutu and Tubuai on the other. It is therefore tempting to assume physically different upwelling systems (plumes or blobs), which in turn supports a discontinuous nature for the mantle heterogeneities responsible for island chains [Schilling and Noe-Nygaard, 1974; Schilling et al., 1982].

About the only remaining characteristics of a hotspot chain upheld in this case are its general WNW-ESE orientation, and the location of the only known active volcano (Macdonald) at its eastern end. One may even challenge the latter, since the chain, when prolonged $\simeq$1200 km over poorly chartered waters, encounters in the vicinity of 35°S, 125°W a geoid high clearly apparent on worldwide maps [e.g., Francheteau, 1983], correlated with an area of anomalously shallow bathymetry, where the very few available shiptracks are densely populated with seamounts. The nature and origin of this volcanism, and its possible relationship with the Cook-Austral hotspot[s] remains an open problem.

When regrouped, all this negative evidence makes a clear maverick, if not an outright scofflaw, of the Cook-Austral chain. Actually, one starts wondering whether the hotspot theory would have emerged as it did, had more cases of Austral-type chains been documented (especially if located in more accessible regions) early in the game.

### A Final Perspective

With the above remarks in mind, we must also emphasize that not all intraplate volcanism forms linear island chains. Some may also form isolated volcanoes [Batiza, 1982], large plateaux, which may not all be convincingly explained by hotspots, and even basin-wide volcanic events [Schlanger et al., 1981]. It may then be possible to regard hotspot chains as part of a continuum starting at tiny, ephemeral, blobs, and ranging to vast hemispheric upward surges of hot material. This approach allows for variation in their rate of thermal and magmatic activity, with, for example, the Marquesas representing a single, short-lived burst of thermal activity, Hawaii, a prolonged episode of sustained extrusion, and the other chains having a presumably more complex history [McNutt, 1987]. It also accommodates readily such variations to the hotspot model as described by Epp [1984] or the "hot line" concept of Bonatti and Harrison [1976].

Further, the size and distribution of plumes or blobs may vary with time, and be partly filtered by a cracked, though strong, lithosphere. Treating this speculative notion requires both additional field evidence for the characteristics of volcanism, and laboratory theoretical tests to determine whether such a scheme is permitted by known properties and history.

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