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HOTSPOTS AND MANTLE PLUMES: CONSTRAINTS FROM STATISTICAL ANALYSIS

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A b s t r a c t

Statistical analysis of the global hotspot distribution is made and current state-of-the-art of the theory of mantle plumes is discussed. Both the fractal dimension analysis and the spherical harmonic correlation are performed to infer some constraints on possible hotspots and mantle plumes sources. Such a joint analysis suggests a compound model, in which the upper mantle exerts strong influence on the hotspot distribution.

Key words: hotspots, mantle plumes, fractal dimension, spherical harmonics correlation.

1. INTRODUCTION

Hotspots and mantle plumes are recently among the most lively issues in geodynamics. This is mostly due to the fact that they offer universal explanation for various plate-related phenomena, such as volcanic island chains, continental splitting, continental flood basalt, large igneous provinces, etc.

Classical mantle plumes proposed by Wilson (1963) and Morgan (1971; 1972), i.e., narrow, cylindrical upwellings, conveying heat from the deep mantle to the litho-

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sphere, confirmed by laboratory experiments (e.g., Whitehead and Luther, 1975) as well as theoretical studies on a nature of the D″ layer (Stacey and Loper, 1983), met general acceptance as a source of hotspot volcanism. Over the next 35 years the theory has been developing, and many types of mantle plumes have been proposed (for a short review see Loper, 1991), e.g., plumes originating from possible second boundary layer, the 660-km discontinuity, or even the so-called mid-mantle plumes (Cserepes and Yuen, 2000) below 660 km.

Since the beginning of 1990s, another view on the relationship between mantle plumes and hotspots has emerged. Reinterpretation of geochemical data (Anderson, 1998b) as well as analysis of the tectonic environment of hotspots (Anderson, 1999) called into question the mantle plume paradigm. However, recent tomographic evidences (e.g., Bijwaard and Spakman, 1999) support the idea of narrow whole-mantle plume. More detailed review of the hotspot and mantle plume theory may be found, e.g., in Malinowski (2002).

The main aim of this paper is to answer the question whether statistical methods could put some constraints on hotspot volcanism sources.

2. HOTSPOTS ON THE EARTH SURFACE

Since the early work of Morgan (1971) who proposed 19 hotspots, the number of volcanic features believed to be hotspots has exceeded 100 (Burke and Wilson, 1976; Vogt, 1981). Certainly only some of them may be associated with D″ plumes: Richards et al. (1988) give a list of 47 such hotspots, Crough and Jurdy (1980) included 42 and more recently Steinberger (2000) enlisted 44 hotspots. The present author's compilation of 7 published hotspot sets represents a list of 130 hotspots. It can be obtained in digital form upon request.

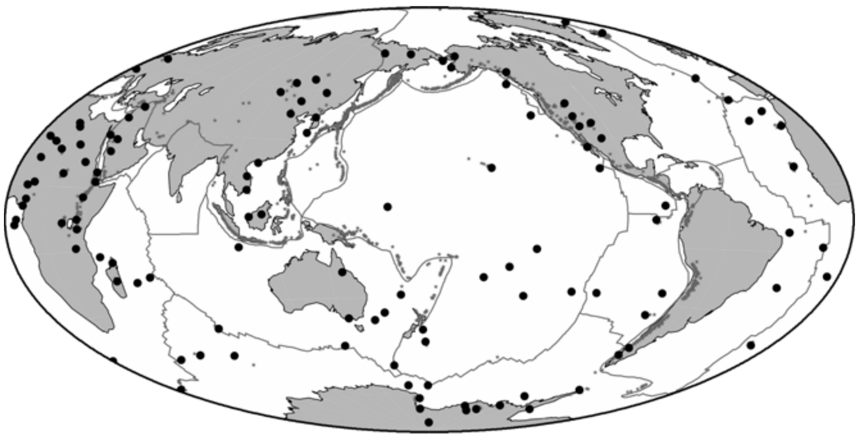

Fig. 1. The global hotspot distribution according to Vogt (1981). Black dots – hotspots.

In reference to surface features, hotspots seem to be distributed non-randomly (Fig. 1). In fact, most of the midplate volcanism lies near plate or craton edges (Vogt, 1981; Wen and Anderson, 1997). Thus, it seems that statistical survey could shed some light on the origin of hotspots, although a compound model is generally prefered (Kedar *et al.*, 1993; Yamaji, 1992), in which the upper mantle exerts strong influence on hotspot distribution. Both experimental (Davaille, 1999) and seismic tomography results (Ritsema *et al.*, 1999; Megnin and Romanowicz, 2000) are in accordance with the model of lower mantle doming and small scale upper mantle plumes in the area of South Pacific and African superswells resulting in the observed bipolar hostpot distribution, e.g., Stefanick and Jurdy (1984), (Fig. 1).

3. HOTSPOTS AS A FRACTAL SET

Since "thermal convection in the mantle clearly exhibits thermal turbulence, and turbulent flows often satisfy self-similarity and power law statistics" (Malamud and Turcotte, 1999), it seems quite justifiable to describe hotspot distribution by means of fractal dimension analysis, a tool commonly used to study chaotic processes and their evolution. By means of the fractal dimension analysis we intend to prove that hotspots are not randomly distributed over the Earth surface.

Sets that exhibit scale invariance and whose dimensions are not integers may be treated as statistical fractals and one of its measures is correlation exponent dimension D_2. This comes easily from the generalised dimension definition for $q = 2$ (Grassberger and Procaccia, 1983):

$$\hat{D}_q = \lim_{r\to 0} \frac{\log C_q(r)}{\log r} , \tag{1}$$

where $C_q(r)$ is the correlation sum defined as

$$C_q(r) = \lim_{N\to\infty} \left\{ \frac{1}{N} \sum_{i=1}^{N} \left[\frac{1}{N} \sum_{j=1}^{N} H\left(r - \left\| \mathrm{X}_i - \mathrm{X}_j \right\| \right) \right]^{q-1} \right\}^{\frac{1}{q-1}} , \tag{2}$$

where N is the number of set points X_i, and $\|X_i - X_j\|$ are distances between them. $H(s)$ is the Heaviside's step function.

The dimension is obtained as the slope of the function in double logarithmic plot of $C_q(r)$ *vs* r. It implies that the estimate of D_2 is biased by the determination of scaling region. To check also the underestimating influence of the amount of data points on the correlation exponent, Nerenberg and Essex's (1990) expression for approximate estimate error has been used:

$$\left| \Delta D_2 \right| = \frac{1}{\ln(k)} \left[\frac{2+D}{\sqrt{2}N} \right]^{2/(2+D)} \left[\frac{(k-1)\,\Gamma(D/2+2)}{\Gamma(1/2)\,\Gamma(D/2+3/2)} \right]^{D/(D+2)} . \tag{3}$$

The dimensions listed in Table 1 have been computed for various hotspot sets using eqs. (1) and (2).

Table 1

Correlation dimensions for various hotspot sets

Hotspot set	Number of data points N	Correlation dimension D_2	Estimate error ΔD_2
Chase (1979)	24	0.95	0.50
Occurrence in sets ≥ 3	38	1.08	0.35
Crough and Jurdy (1980)	42	1.18	0.35
African Plate	45	1.34	0.35
Richards *et al*. (1988)	47	1.21	0.35
Wilson (1973)	66	1.25	0.29
Occurence in sets ≥ 2	69	1.19	0.29
All without Richards *et al*. (1988)	83	1.14	0.25
All without African Plate	85	1.13	0.25
Burke and Wilson (1976)	117	1.23	0.20
Vogt (1981)	117	1.26	0.20
Author's list (all)	130	1.25	0.19

Since the described method is well-known in analysing the epicentre distribution (e.g., Mortimer and De Luca, 1999), a specific code written for mining induced seismicity by A. Cichy (Department of Geophysics, UMM) has been used. For this reason, original spherical coordinates of hotspots locations have been expressed in 3D Cartesian.

The optimum scaling region has been found for r from 1000 to 3400 km, which is consistent with some regional features like hotspot provinces according to Vogt (1981). Observed dimension values are generally close to 1, which could be interpreted as the tendency of hotspots to create some linear patterns. The values of the fractal dimension for hotspot sets obtained by Jurdy and Stefanick (1990) by "box count" method are fairly similar to ours (see Fig. 2), with the exception for Wilson (1973) set. We have to stress that for small data sets those values are highly underestimated. To illustrate this phenomenon, we calculated D_2 for sets of points uniformly distributed over a sphere. For 47 such points, the $D_2 = 1.3$ for $N = 117$, $D_2 = 1.42$ and for $N = 1000$, $D_2 = 1.83$. The D_2 estimates for real hotspot sets (Richards *et al*., 1988 and Vogt, 1981) are lower than those expected for randomly distributed points. Thus,

Table 2

Statistics for perturbed Richards *et al.* (1988)
and Vogt (1981) sets

Number of data points N	Mean correlation dimension $\bar{D}_2$	Standard deviation	Confidence interval 95%
47	1.14	0.11	0.03
117	1.29	0.10	0.03

we may assume that hotspots are more "organised" than the random field. We computed also the D_2 for 50 perturbed (by adding random rotation from -10^{o} to 10^{o}) Richards and Vogt sets; the results are shown in Table 2.

The value $D_2 = 1.21$ for the original Richards *et al.* (1988) set is higher than the mean for perturbed sets ($\bar{D}_2 = 1.14$). In the case of Vogt (1981) set, the original $D_2 = 1.26$ is lower than the mean for perturbed sets ($\bar{D}_2 = 1.29$). Those differences are however, not statistically significant.

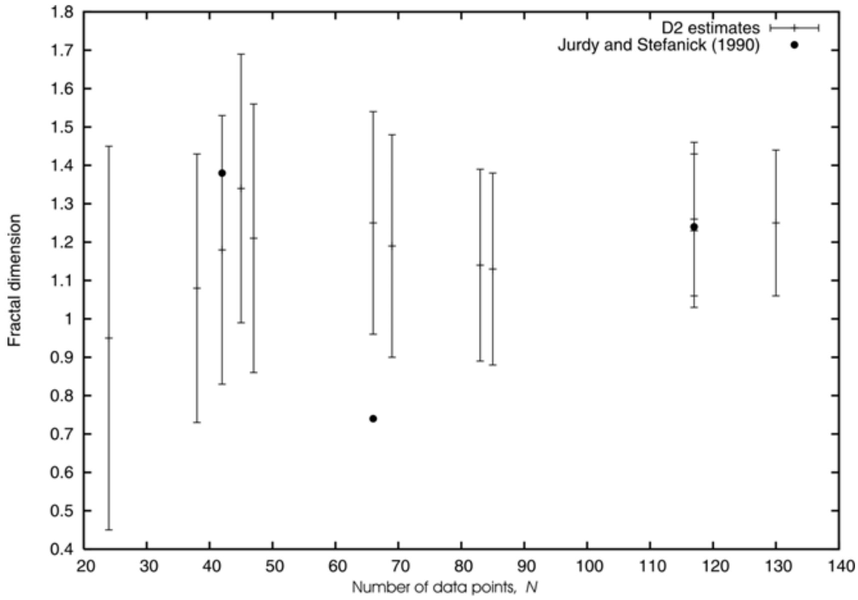

Fig. 2. The fractal dimension D_2 estimates for various hotspot sets (from Table 1), plotted as a function of the number of data points N with respective error bars $\pm\Delta D_2$. Results of Jurdy and Stefanick (1990) are indicated by dots.

Additionally, for the largest hotspot set the spectra of generalised dimension have been computed. It has the typical form for the statistical multifractal set, i.e., set that is characterised by several fractal dimensions. Because of the small number of data, this result could not be interpreted quantitatively, but it certainly confirms the complexity in hotspot distribution.

The fractal analysis seems to favour a compound model of hotspot origin. Specifically, the self-similarity in the distribution observed for hotspots lying on superswells could be interpreted in terms of lower mantle doming and small-scale plumes or upwellings in the upper mantle. As noted in previous works (Malinowski, 2000a, b) fractal analysis is insufficient to distinguish between plume and non-plume hotspots: there is a need to combine those results with other methods, e.g., spherical harmonics correlation. Following the conclusions of Jurdy and Stefanick (1990) we may say that “the current locus of hotspots activity is more chain-like than two-dimensional in plane form”.

4. FURTHER CONSTRAINTS FROM SPHERICAL HARMONICS ANALYSIS

Following some previous studies (Richards *et al.*, 1988; Kedar *et al.*, 1993) hotspots may be represented as Dirac deltas on the sphere. For such a rough approximation, the spherical harmonic expansion coefficients are:

$$\left.\begin{matrix} C_{nm} \\ S_{nm} \end{matrix}\right\} = \frac{1}{4\pi}\frac{1}{N}\sum_{i=1}^{N}\left[P_{nm}(\cos\theta_i)\begin{Bmatrix}\cos(m\lambda_i)\\ \sin(m\lambda_i)\end{Bmatrix}\right], \tag{4}$$

where θ_i, λ_i denote the geographical coordinates of the hotspot i, N is the total number of hotspots in the set and P_{nm} is the fully-normalised associated Legendre polynomial.

Subsequently, we may define the root-mean-square amplitude spectrum (Kaula, 1967):

$$A_n = \sqrt{\sum_{m=0}^{n}\left(C_{nm}^2 + S_{nm}^2\right)}\sqrt{\frac{1}{2n+1}} \tag{5}$$

to see which part of the field is represented by certain harmonic degree.

Taking another global geophysical field decomposed into a set of coefficients (A_{nm}, B_{nm}), we may define a correlation coefficient of the n-harmonic component of that field with the hotspot distribution as a function of harmonic degree n (Eckhardt, 1984):

$$r_n = \frac{\sum_{m=0}^{n}(C_{nm}A_{nm} + S_{nm}B_{nm})}{\sqrt{\sum_{m=0}^{n}\left(C_{nm}^2 + S_{nm}^2\right)}\sqrt{\sum_{m=0}^{n}\left(A_{nm}^2 + B_{nm}^2\right)}} . \tag{6}$$

The expansion of the field at each harmonic degree n acts as a low-pass filter, representing wavelengths λ up to

$$\lambda = \frac{2\pi R}{\sqrt{n(n+1)}} , \tag{7}$$

where R is a sphere radius.

For the spherical harmonics expansions of Richards *et al.* (1988), Wilson (1973) and Vogt (1981) hotspots lists (see Fig. 3), the correlation coefficients with the following fields have been calculated:

– tomographic S-wave velocity model MDLSH (Tanimoto, 1990). Coefficients refer to slowness perturbation. Correlations for layers 2 (220-400 km), 3 (400-670 km) and 11 (2630-2891 km);

– residual geoid heights – after subtracting the effects of crustal density structure and cooling of the oceanic mantle (Kaban *et al.*, 1999);

– residual isostatically compensated geoid heights (Kaban *et al.*, 1999).

(Note: Geoid models are referred to the best-fit ellipsoid, not to the hydrostatic-equilibrium figure of the Earth.)

The correlation coefficients are shown in Table 3. The significance of correlation has been tested using t-Student test with $2n$ degrees of freedom (n is a harmonic degree). Spherical harmonics degrees 2 and 6 correlation is especially significant, because there are peaks in the amplitude spectrum of the hotspot sets (Fig. 3).

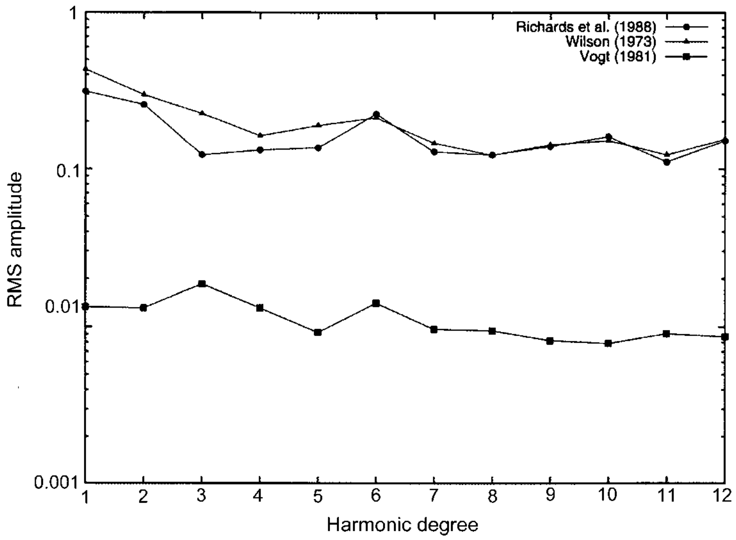

Fig. 3. RMS amplitude spectrum of the spherical harmonic representation of hotspot sets.

Table 3

Results of the spherical harmonic correlations

n	Seismic model MDLSH (Tanimoto, 1990)									Geoid heights					
	2630-2891 km layer 11			400-670 km layer 3			220-400 km layer 2			residual			isostatic		
	R	W	V	R	W	V	R	W	V	R	W	V	R	W	V
1	-0.12	0.36	0.27	0.72	1.00	0.95	0.82	0.99	0.89						
2	**-0.96**	**-0.91**	-0.52	-0.15	-0.32	-0.53	-0.10	-0.25	-0.31	-0.18	-0.04	-0.12	0.33	-0.17	**-0.96**
3	-0.17	0.76	0.76	0.55	-0.29	-0.42	0.41	-0.42	-0.47	-0.58	-0.54	-0.40	-0.75	0.55	0.66
4	-0.16	0.18	0.37	0.00	0.33	0.16	-0.24	0.00	-0.25	-0.06	0.04	-0.05	-0.37	0.00	-0.01
5	0.35	-0.50	0.06	0.00	-0.32	-0.49	0.06	-0.06	-0.39	-0.22	-0.33	-0.22	0.30	-0.04	0.29
6	0.19	0.24	0.29	-0.62	-0.47	-0.61	-0.71	-0.65	**-0.80**	-0.49	**-0.78**	-0.58	-0.11	-0.08	-0.14

Explanations: bold values – coefficients significant at 95% level of *t*-Student test, underlined values – coefficients significant at 80% level of *t*-Student test. Abbreviations: R – Richards *et al.* (1988) set, V – Vogt (1981) set, W – Wilson (1973) set.

In the lower mantle (layer 11 of MDLSH), the n = 2 correlation for Richards *et al.* (1988) and Wilson (1973) sets exceeds 95% confidence level. Such a good correlation between hotspots and seismic velocities near D″ layer led several authors (e.g., Richards *et al.*, 1988) to the conclusion that those hotspots may be associated with deep mantle plumes. The minus sign confirms relationship between hotspots and areas of slower than average *S*-wave propagation. In the upper mantle, the essential correlations are also present, e.g., the n = 6 correlation for Vogt (1981) set in layer 2 exceeds 95% confidence level. This may suggest that the upper mantle may be a source region of those hotspots or exerts a strong influence on their distribution.

All correlation coefficients for residual geoid have the minus sign: this could be explained by the fact that nearly all hotspots are in the areas of high topography and the image of residual geoid reproduces an approximately residual topography taken with the minus sign (Kaban *et al.*, 1999). Since various tomographic models, after velocity to density conversion, reflect the amplitude spectrum of the isostatic geoid (Kaban *et al.*, 1999), we may try to interpret the calculated correlations jointly. For Vogt (1981) set, n = 2 correlation (95%) with the geoid suggests connection with sources in the lower mantle, whereas the n = 2 correlation with layer 11 of MDLSH is not significant. However, the n = 3 correlation for geoid (80%) has a support both in the n = 3 correlation for layer 11 (near 95%) and a peak in the amplitude spectrum of Vogt (1981) hotspots (Fig. 3). This may be the evidence for a relationship between those hotspots and the mid-mantle density heterogeneity. The likely sources of the anomalous mass distribution in the mantle are subducted slabs (if only they are able to penetrate deeper than the 660-km discontinuity), so this suggests a strong influence of the past subduction over the occurrence of hotspot volcanism.

Looking at changes in the correlation sign or the lack of correlation, we may get some more insight, as noted, e.g., by Kaban *et al.* (1999), who give two examples of interpreting geoid signals:

– To achieve isostatic compensation when the residual geoid heights are minus and there are no isostatic geoid undulation, there should be a density inhomogeneity in the upper mantle.

– To achieve isostatic compensation when the residual geoid heights are minus and the isostatic geoid undulation are plus, the mantle density inhomogeneity should be accompanied by some additional forces.

We may find that the first case is typical for the $n = 6$ correlation for all sets. The change of the $n = 3$ correlation sign from minus in the residual geoid to plus in the isostatic geoid implies the second case (Wilson and Vogt sets). The last result suggests that hotspots from Wilson and Vogt's sets (the numerous ones) may be connected with convective flows in the upper mantle, which act as additional forces.

5. CONCLUSIONS

The interpretative potential of the fractal dimension analysis is constrained by the small number of data, which is the cause of the estimate bias. For this reason, we may describe only some qualitative features of hotspot distribution. The results obtained for original and simulated sets suggest that hotspots form some small-scale patterns (clusters) which might be described as "linear". This seems to be consistent with both geological observations and former studies (Jurdy and Stefanick, 1990). However, the most informative result is that the distribution of hotspots is self-similar in the range of 1000-3400 km. This accounts for groups of hotspots in the Pacific and Africa.

The constraints for the spherical harmonic correlation come from the assumed representation of hotspots (Dirac delta), as well as the structure of the tomographic models itself and also from uncertainties in the relationship between density anomalies, viscosity pattern and the geoid. To the first order, good correlation observed between Richards's *et al*. and Wilson's hotspot sets and MDLSH layer 11 seems to support the idea of deep mantle plumes. However, for shallower depths, 220-400 km, all the analysed sets reveal also significant correlation, what may favour an upper mantle origin. In addition, results coming from correlation with isostatic geoid for Wilson and Vogt sets give support to the idea of Anderson (1998a) who considers hotspots as a result of the so-called edge driven convection (see, King and Anderson, 1998).

Concluding all the results: we cannot exclude any of the presumed hotspot sources, but a compound model of the origin of hotspots seems the most appropriate.

Whether the classical mantle plumes from D″ really exist or not, the upper mantle plays important role in forming the midplate volcanism.

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