The Statistics of Helium Isotopes Along the Global Spreading Ridge System and the Central Limit Theorem

Don L. Anderson
Seismological Laboratory, California Institute of Technology, Pasadena

Abstract. An unbiased estimate of the arithmetic mean of the $^3He/^4He$ ratio (R) of basalts from the global spreading ridge system is 9.14 ± 3.59 Ra (n=503), where Ra is the atmospheric ratio and n is the number of data points. The ± two standard deviation (2σ) range covers much of the oceanic island and continental flood basalt data that have been attributed to 'plume' or 'lower mantle' components. The highest R values along the ridge system are associated with new ridges, backarc basins and near-ridge seamounts. Low values are associated with long-lived or abandoned ridges. The median, a more robust measure of the average, is 8.51 Ra.

1. Introduction

In their pioneering work, Craig and Lupton (1976) reported a 'strikingly uniform' $^3He/^4He$ ratio (R) for oceanic basalt glasses. Kurz and Jenkins (1981) obtained a 'remarkably constant' value of 7 to 9 Ra. A value of R = 8 ± 1 Ra has been widely quoted as the $^3He/^4He$ ratio along mid-ocean ridges (e.g., Niedermann, et al., 1997).

There has been an enormous recent increase in the number and coverage of helium measurements, and it is time to redetermine the statistics of helium along the global spreading ridge system. Previous summaries have applied 'filters' to the data to screen out samples thought to be influenced by plumes. These 'filters' involve discarding data with $^3He/^4He$ ratios higher than 9, 9.5 or 11 Ra, or from ocean depths less than 2.5 km or latitudes greater than 52°N. In recent work, values of 11 Ra are regarded as unambiguous evidence for a 'plume' or 'lower mantle' component (e.g., Poreda et al., 1993; Marty et al., 1996; 1998; Graham et al., 1998). This is circular reasoning.

The perceived near constancy of the mid-ocean ridge $^3He/^4He$ ratio has been used to argue that the upper mantle is thoroughly homogenized by convection (Richard et al., 1996). Many authors assert that "ratios higher than the mean isotopic ratio of the upper mantle (8 ± 1 Ra) indicate…a lower mantle component" or "hotspots with values higher than 7 to 9 Ra support the existence of mantle plumes from deep in Earth" (e.g., Marty et al., 1996; Graham et al., 1998). The lower mantle hypothesis is based on the assumption that high R implies "excess-^3He" and 'therefore' a deep, undegassed reservoir. The alternative hypotheses are a.) Depleted peridotite can have low $^{238}U/^{3}He$ ratios (LONU). New cracks or new volcanoes can tap this high R, low [He] shallow source for gas (Anderson, 1998a, b, 2000). b.) Ridge basalts sample and average larger volumes of mantle than islands and must therefore be more uniform.

In testing and comparing hypotheses, it is necessary to have an unbiased dataset. The current estimates of upper mantle composition are based on arbitrary cutoffs and hypotheses about the source of ‘high’ $^{3}He/^{4}He$ ratios. For example, Hilton et al. (1993) eliminate all samples from < 2.5 km depth “or having other non-MORB…characteristics.”

2. Procedure

Data is from published sources. References are given in Graham et al. (1992), Anderson (2000) and Farley and Neroda (1998), plus the references cited in the tables (GRL Online). No hypothesis was used in selecting which data to include.

I analyzed published data on samples from or near the global spreading ridge systems including the north Atlantic, central Atlantic, Azores region, south Atlantic, Shona segment, Bouvet triple junction, the Indian Ocean ridges including the Amsterdam-St. Paul segment, Red Sea, Gulf of Aden, East Pacific Rise, Easter microplate, Galápagos segment, and Chile Ridge. In an attempt to compile an unbiased dataset for the composition of the shallow mantle, I have included data from; ridge axes, near-ridge seamounts, backarc basins, microplates, near-ridge fracture zones, propagating ridges, triple junctions and the extension of ridges into continents. The true heterogeneity of the mantle can only be determined by using small volume integrators in various tectonic environments. The data is combined in order to obtain an unbiased Grand Average for the upper mantle. Subsets of the data are compiled so that various hypotheses can be tested. In previous studies, many spreading regions were regarded as 'hotspots' and were deleted from the database prior to performing statistics. A new ridge, or the tip of a propagating ridge, or early small volume melts, or off-axis seamounts may sample the shallow mantle in different ways than a mature ridge involving large degree melts. The central limit theorem (GRL Online) tells us that averages from large volumes (ridges) are more Gaussian and show less dispersion than averages from small volumes (seamounts, islands). The data supports this interpretation.

3. Results

The most important result is simply the statistic for the mean and standard deviation of the entire dataset, the Grand Average; 9.13 $\pm$ 3.57 Ra (n = 509) [median = 8.51 Ra][1].

The mean is significantly higher, the data are more normally distributed, and σ is more than three times the usually quoted estimates (based on filtered and truncated data). To check the robustness of this result, I eliminated data from Ethiopia (a new spreading center) obtaining 9.22 $\pm$ 3.32 (n = 463)[median = 8.51 Ra], and then eliminated the entire region of the North Atlantic supposedly affected by the Icelandic plume, obtaining 8.93 $\pm$ 2.85 Ra [median = 8.4 Ra]. The main result survives; the mean, median and standard deviation are much higher than estimates based on the hypothesis-dependent ‘filtered’, or biased, datasets. This has an immediate and dramatic implication. Many recent papers use R values as low as 11 Ra as “unambiguous evidence” for a lower mantle component. A large fraction of the so-called ‘hotspot’ volcanics fall within the spreading system range, which presumably reflects the composition of the shallow mantle. The main exceptions are the more extreme values (R > 20 Ra) found in Iceland, Loihi and Samoa. These also do not demand a lower mantle component since extremes in isotopic ratios are eliminated in large volume averages. A shallow U-poor, He-poor region (LONU) sampled by early dikes, cannot be ruled out (Anderson, 1998a, b, 2000). This high-R component appears to be missing at steady-state ridges, at ‘hotspots’ that have been abandoned by ridges, and at HIMU islands. Alternatively the component is overwhelmed by the higher [He] later eruptives, presumably from greater depths, or is averaged out by large volume sampling. The Pacific spreading ridge data gives 9.21 ± 3.40 Ra (n=210). When BAB are excluded, the Pacific data yields 9.00 ± 3.17 Ra (n=147). So-called ‘hotspot influenced’ sections of the ridges are summarized in Table 1. These are mainly regions of ridge reorganization, ridge propagation, incipient ridges, and fracture zones. Basalts in these areas sample the mantle in a different way than steady-state ridges. More diversity is expected. These regions have been deemed to be affected by ‘plumes’ on the basis of 1, 2 or 3 samples (out of 6 to 46 samples) with R in the 10 to 15 Ra range. This is not a statistically valid test (comparing maxima with means). In our dataset about 10 out of 200 samples, or 5%, fall in this range.

A recent paper provides data for the Midatlantic Ridge (MAR) north of Iceland (Schilling et al., 1999). The highest $^{3}He/^{4}He$ ratio (13.6 Ra) is from the Tjörnes Leaky Transform Zone, in northern Iceland. The total Arctic (north of Iceland) MAR dataset yields 8.62 $\pm$ 2.36 Ra (n=38) with a median of 7.50 Ra. This 1700 km stretch of slow-spreading ridge is supposedly affected by at least two plumes (Schilling et al., 1999), yet it falls well within the ridge averages and is similar to the Shona and Azores segments. Previous data from the Iceland region (Poreda et al., 1986; Condomines et al., 1983) yields an average of 10.6 $\pm$ 6.6 Ra (n=32) (including some altered and degassed rhyolites), so the combination yields a value close to the Grand Average of the spreading ridge system. In previous compilations, data north of 52°N along the Reykjanes Ridge, having R of 9.5 to 10.0 Ra, were eliminated as being "influenced by the Iceland plume", centered at 65°N. Values as low as 9.44 Ra, however, are obtained at 67.5°N along the Kolbeinsey Ridge, just north of Iceland. Northern Iceland itself has low values of $^3He/^4He$. This is inconsistent with the plume hypothesis. MORB-like R values are also found in Hawaii, Galápagos, Yellowstone geothermal areas, Easter microplate, Juan Fernandez chain and backarc basins, suggesting a shallow heterogeneous source.

Subsets of the data[1] show that new ridges and rifts, and propagating tears have high R. The lowest R values are along deep ocean mature ridge systems, abandoned ridges, and islands abandoned by ridges. New ridges in backarc basins have a wide distribution of R. Apparent temporal sequences may reflect a zonation of the shallow mantle, or early removal of high R (but low [He]) plums, fluid inclusions or other shallow components.

Backarc basins are ideal places to study the time evolution of new ridges since they are cut off from the deep mantle by slabs. The Manus Basin has reorganizing ridges and extensional transforms. Macpherson et al. (1998) state that the MORB-like basalts have “typical plume $^3He/^4He$ ratios…around 12.2 Ra, a value significantly higher than…most MORB 8 $\pm$ 1 Ra.” The high-R material is spatially restricted and is independent of the geochemical affinity of the lavas and has low [He], lower than MORB and many mantle xenoliths. The Manus BAB dataset yields R = 10.67 $\pm$ 3.36 Ra (n=29). In the original paper, the authors eliminated MORB-like helium ratios before calculating the statistics. The above value is similar to values at other new spreading centers and propagating fractures, and may therefore represent the shallowest mantle.

4. Reconciliation

How does one reconcile the present result with the widely quoted 8 $\pm$ 1 Ra for the $^3He/^4He$ ratio of MORB, often equated with 'upper mantle' or 'depleted, degassed mantle'? Previous compilers assumed that the distribution in MORB should be narrow, based on the very earliest work. Various attempts have been made to ‘filter’ the data to eliminate the ‘plume influence’ (Fisher, 1986; Hilton et al., 1993). I tried several schemes to ‘filter’ a preliminary version of the present dataset (n=457), which includes portions of the ridge system not available before, to simulate these previous compilations. The first experiment is a rather mild filter; all data with R > 11 Ra were discarded. The result is 7.97 $\pm$ 1.93 Ra (Table 4). The mean is similar to previous hypothesis-dependent compilations, but the σ is twice as large. This means that $^3He/^4He$ ratios of 10 and 12 Ra are within 1σ and 2σ, respectively, of the truncated mean, values usually assigned to the lower mantle. If, in addition, we arbitrarily exclude samples from depths shallower than 2.5 km, as in Hilton et al., (1993), we obtain 8.11 $\pm$ 1.41 Ra (n=238).

The final truncation is to arbitrarily eliminate all samples having R > 9.5 Ra. This draconian step finally decreases the upper bound (+1σ) to about 9 Ra, the conventional upper bound of the MORB range. This step is similar to the arbitrary truncations in recent papers (Sarda et al., 1999; Kurz et al., 1998; Botz et al., 1999). Botz et al. (1999) define 'plume-type' $^3He/^4He$ ratios as R > 8 Ra. Many of the samples eliminated are normal MORB in all respects or are from normal sections of the ridge. A ‘plume’ or ‘lower mantle’ effect has been proposed strictly on the basis that the $^3He/^4He$ ratio is higher than some preconceived notion of what is normal for ridges. From the above compilations we can make a conservative estimate that 68% of samples near spreading ridges fall between 6 and 12 Ra. Values as high as 16 Ra can still be considered to be drawn from the ridge population (2σ).

Many recent papers on helium isotopes invoke a lower mantle origin if a few samples in the study area exceed about 10 Ra. About 20% of the samples in the more recent of such papers (Niedermann et al., 1997; Moreira et al., 1995, 1996, 1999; Marty et al., 1996; Mahoney et al., 1994; Kurz et al., 1998; Basu et al., 1993, Poreda et al., 1993) exceed 10 Ra. Whether this “significantly exceeds the MORB average” depends as much on the variance of MORB as on the mean.

The means and the maximum values of the so-called lower mantle materials in the Siberian and Deccan Traps (Basu et al., 1993, 1995) fall within the range found along spreading centers and do not require a special explanation. The means of the 380 Ma carbonatites (Marty et al., 1998) and Archean komatiites (Richard et al., 1996) also fall in the range of today’s MORB, although the R of the ancient source regions would have been much higher. The maximum values of R of these ancient rocks are about the same as in modern basalts and may represent values typical at the onset of rifting. Much higher values would be expected if these are ancient analogues of modern high-R basalts rather than trapped gases held in a LONU environment (lithospheric helium). There is no statistical or experimental support for the conjecture that any of these ancient rocks are from ^{3}He-rich plumes or undegassed lower mantle. The effects of radiogenic ^{4}He and cosmogenic ^{3}He on these samples must be better understood.

5. Graham's MORB Database

David Graham (personal communications, 1999, 2000) has compiled a large dataset for MORB. He restricted the data to submarine samples and did not include backarc basin or seamount data. Altered samples and samples with low $^{3}He/^{4}He$ ratios or low [He] were excluded. An attempt was made to have a uniform spatial sampling. The results are 8.58 ± 1.81 Ra [576 samples] with a median of 8.16 Ra. The mean and stdev are somewhat lower than obtained above, as expected for the more restrictive sampling, i.e., steady-state or mature mid-ocean spreading centers, far from arcs, continents, and transform faults. However, the range is much greater than commonly quoted. The ± 2 stdev range is from 5.0 to 12.2 Ra, which encompasses much of the oceanic island range. Graham's global MORB statistic is similar to the Shona, Azores, and Galapagos datasets, and datasets filtered by depth or high-R cut-offs. Graham's estimate is probably the best large scale average of upper mantle R, depleted by prior magmatism, while the results obtained in this paper better reflect the isotopic heterogeneity of the mantle (in general, the variability of a sample depends inversely on the square root of volume sampled). [See complete text on GRL Online.]

6. Summary

An unbiased estimate of the $^{3}He/^{4}He$ ratio of basalts associated with the global spreading ridge system yields a much higher mean and variance than the commonly quoted 8 ± 1 Ra. Most of the 'high-^{3}He' hotspots, and rocks attributed to a 'lower mantle influence', are actually low-^{3}He and are well within the range of R inferred for oceanic ridges and, by implication, the shallow mantle (Anderson, 2000). The attribution of $^{3}He/^{4}He$ ratios of > 11 Ra to a plume or lower mantle source is based on invalid statistics and circular reasoning. The extreme R values found at the onset of magmatism, and in lithospheric xenoliths in Hawaii, Iceland and Samoa, may represent lithospheric helium. Based on information in xenoliths, well gases and diamonds, the lithosphere may have noble gas characteristics which are commonly attributed to plumes (Poreda and Farley, 1992; Ballentine, 1997). The Central Limit Theorem (Appendix; GRL Online) and current ideas on how ridges sample the mantle give a simple answer to the question of why $^3He/^4He$ ratios higher than about 16 Ra are so rare along the global spreading ridge system. They are simply averaged out in large volume, large melt fraction samples. The idea that high R samples must come from the lower mantle is simply an assumption, with no direct, supporting, or statistical evidence (Anderson, 2000). We do not know the $^3He/^4He$ ratio of the lower mantle. The extreme values found in Iceland and Hawaii may also exist in the mantle sampled by ridges, or at the onset of spreading.

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D. L. Anderson, California Institute of Technology, Seismological Laboratory 252-21, Pasadena, CA 91125. (e-mail: dla@gps.caltech.edu)

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[1]The complete text, with tables, figures and appendix is on GRL Online.

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Figure 1. Demonstration of the Central Limit Theorem. Particles labeled from 0 to 26 are placed in a box and then sampled one, two, and three at a time, and averaged. The initial distribution (solid line) is irregular. Sampling by two's (dashed line) gives a smoother distribution with few outliers. Sampling by three's (heavy solid line) approaches a Gaussian distribution with no extreme values. It can be shown that the variance decreases as $N^{-1/2}$ or $V^{-1/2}$. Mid-ocean ridges are large volume, V, samples compared to islands and seamounts (experiment done during one game of Scrabble©).

Table 1. Regions Possibly Affected by Ridge Propagation, Fracture Zones, Microplates, Opening Ridges, Ridge Reorganization or Other Lithospheric or Shallow Effects.

		n
Easter (1)	9.53 ± 2.95	30
Bouvet (2)	8.44 ± 2.88	24
Galápagos (3)	8.12 ± 1.17	16
Red Sea (4)	10.03 ± 1.62	12
Shona (5)	8.89 ± 2.02	8
Azores (6)	8.39 ± 1.85	11
Iceland (7)	10.60 ± 6.63	32
Ethiopia (8)	8.24 ± 5.41	46
Rodrigues Triple Junction (9)	8.32 ± 0.23	6
Amsterdam–St. Paul Plateau (10)	7.97 ± 1.56	22
Amsterdam–St. Paul Plateau (11)	9.12 ± 2.52	54

The data are from references in Farley and Neroda, 1998 (FN); and Graham et al. (1992). Later references are cited below and in the text.

(1) Poreda et al. (1993). The highest point is 11.7 Ra;
(2) Kurz et al. (1998). The highest point is 14.9 Ra;
(3) Graham et al (1993). Three points are higher than 14.5 Ra;
(4) Moreira et al. (1996). Out of 30 measurements, there is only one that is higher than 10 Ra (14.5 Ra).
(5) Moreira et al. (1995).

(6) Moreira et al. (1999). The highest point is 11.0 Ra.
(7) Poreda et al. (1986); Condomines et al. (1983); Schilling et al. (1986).
(8) Marty et al. (1996). Two points are higher than 15 Ra.
(9) Nishio et al. (1999)
(10) Graham et al. (1999). Depths greater than 2500 m.
(11) Graham et al. (1999). All points.

Table 2. Subsets of the Global Helium Dataset

		n
Propagating Lithospheric Tears	11.75 ± 5.13 Ra	57
(Samoa*, Juan Fernandez*, Galápagos)		
Manus Basin	10.67 ± 3.36 Ra	29
New Rifts	10.01 ± 4.67 Ra	239
(Red Sea, Ethiopia, Kolbeinsey R., Mohn R., Reykjanes R., Iceland, Manus, Lau, Easter, Galápagos)		
New Rifts (above minus Iceland)	9.93 ± 4.30 Ra	207
Continental Rifts or Narrow Oceans	9.93 ± 5.18 Ra	120
(Red Sea, Ethiopia, Iceland, Mohn R., Kolbeinsey R., Reykjanes R.)		
South Atlantic Seamounts	9.77 ± 1.40 Ra	5
* "EM" Islands	7.89 ± 3.63 Ra	17
(Societies, Cook-Austral) (possible old tears)		
North Chile Rise	7.78 ± 0.24 Ra	7
*Ridge Abandoned Islands	7.10 ± 2.44 Ra	_
(Gough, Azores, Tristan, Heard, Kerguelen, Reunion)		
South Chile Rise	6.88 ± 1.72 Ra	14
* Central Atlantic Islands	6.65 ± 1.28 Ra	8
(Gough, Tristan, St. Helena, Canary, Madeira, Azores; 1 or 2 points/island)		
* HIMU Islands	6.38 ± 0.94 Ra	16
* Abandoned Ridges	6.08 ± 1.80 Ra	9
(Socorro, Shimada, Guadalupe)		
Eliminate R > 11 Ra	7.97 ± 1.93	358
Eliminate d < 2500 m	8.11 ± 1.41	238
Eliminate R > 9.5 Ra	7.59 ± 1.53	198
"Pure MORB" (1)	8.58 ± 1.81	576

* Not part of global spreading ridge dataset (except for Azores region)

(1) David Graham (personal communication, 2000). Subaqueous steady-state mid-ocean ridges (no BAB, no near ridge seamounts or extensional regions, no low [He], low R (altered) samples, no on-shore ridges.

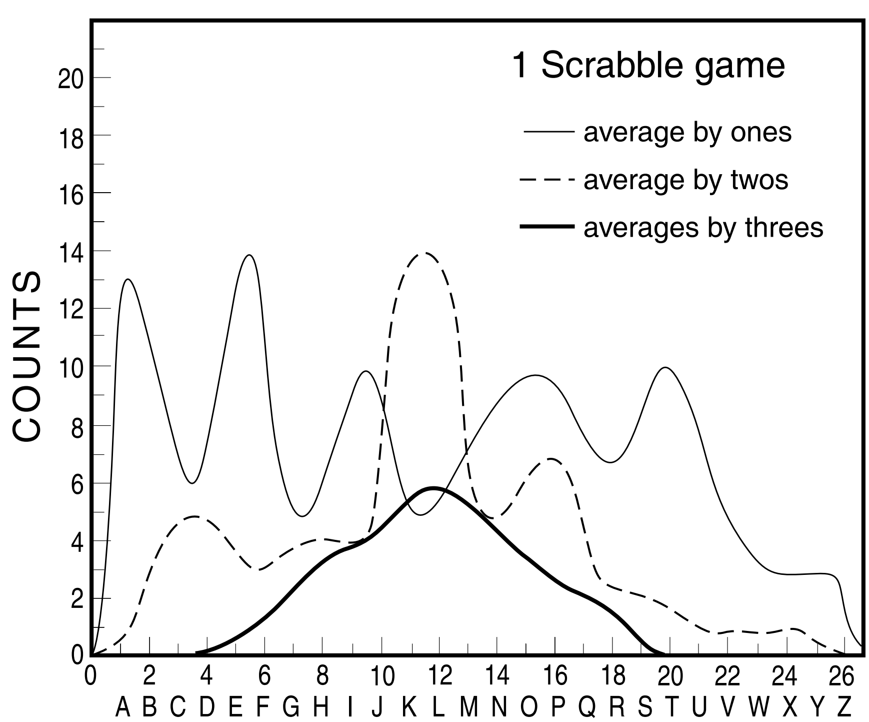
(to appear in GRL Online only, after Refs.)

Appendix: The Central Limit Theorem

Consider a population of object labeled from 0 to 26. This parameter may correspond to $^3He/^4He$ ratios. The distribution of these ratios, among the samples in the population, may be very irregular (Figure 1, solid line). Now, sample this population by taking larger numbers of samples and averaging them. Although the original population may contain samples having values as high as 25 or 26, simply by taking twice as many samples, there is very low probability of obtaining large average values (dashed lines). By averaging the population by three's, one essentially eliminates the possibility of obtaining the extreme values (0 to 4, 20 to 26). Most sample means are between 8 and 14, and the averaged population is very close to a normal distribution. Mid-ocean ridges sample large volumes of the mantle, and involve large degrees of melting. Seamounts, ocean island basalts, xenoliths, and small volume flows on continents sample far less of the mantle and involve less averaging. These samples contain a larger range of $^3He/^4He$ ratios, and exhibit a more irregular distribution, but this does not mean they came from a different population or the lower mantle.

The heavy solid line in Figure 1 was generated by sampling Scrabble blocks three at a time, and then averaging the results. The lack of high ratios (20-26) does not mean that these ratios do not exist in the population. Various standard statistical tests may indicate that the three curves in Figure 1 must come from different populations. He isotope ratios in ocean island basalts (OIB's) vary from ~4 to ~32 (e.g., Farley and Neroda, 1998), although there is a strong peak near 8.5 Ra. A secondary peak near 13 Ra is due to the large number of samples from Hawaii, Iceland, and Réunion. In contrast, the MORB He isotope ratios are strongly peaked near 8 Ra. The range is about 7 to 16 Ra. Values below 7 Ra and above 10 Ra are rare. This is usually interpreted in terms of a strikingly homogeneous or well-mixed upper mantle. However, steady-state ridges must process large volumes (V) of the mantle and, because of the absence of lithosphere at ridges, large degrees of melting are involved. MORBs represent large V averages of a mantle which may be intrinsically heterogeneous. Sampling statistics tells us that the variance of samples drawn from an inhomogeneous population decreases as $N^{-1/2}$ or $V^{-1/2}$ and therefore MORB at ridges should be more homogeneous than basalts on oceanic islands or seamounts, or the small volume melts at the onset and termination of rifting. If the variance of ocean island basalts is about twice the variance of MORB, then ridges process about four times more mantle than OIB's. This seems about right. Large V averaging eliminates outliers in the population and makes it unlikely that extreme values will be sampled, and survive the averaging process. This is a direct result of the Central Limit Theorem.

As another example I drew samples, labeled 1 to 24, randomly from a population of 100 and then averaged them by 1's, 2's, 3's, 4's, 6's and 8's. Although values as high as 21 were common in the "small volume" samples (1 and 2 samples), the highest values found for the larger sample sizes were only 14 to 15. The trends are the same as seen from ocean island basalts, the global spreading ridge system, to MORB (the largest volume integrator). The strikingly uniform value of MORB may simply reflect the Law of Large Numbers.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