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Discussion

The book by G.R. Foulger: from melting anomalies to hypotheses on plates or plumes?

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Abstract: The book «Plates vs. plumes: a geological controversy» (Fig. 1) is intended for the advanced student who is not satisfied by the present-day interpretation of intraplate volcanism. From systematic descriptions of the geological controversy on the plate and plume hypotheses, it follows that, unlike predictions of the former, those of the latter have not been confirmed by observations. Recent intraplate volcanism is explained adequately by models of lithospheric extension and local convection in the upper mantle.

Key words: plates, plumes, hypotheses, intraplate volcanism, models of lithospheric extension, convection.

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Книга Ж.Р. Фулджер: от расплавных аномалий к плитным или плюмовым гипотезам?

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Аннотация: Книга «Плиты против плюмов: геологическая полемика» (рис. 1) предназначена для продвинутого студента, неудовлетворенного современной интерпретацией внутриплитного вулканизма. Из систематического изложения геологической полемики по плитной и плюмовой гипотезам следует, что, в отличие от предсказаний первой, предсказания второй не подтверждены наблюдениями. Новейший внутриплитный вулканизм объясняется более правдоподобно моделями растяжения литосферы и локальной конвекции в верхней мантии.

Ключевые слова: плиты, плюмы, гипотезы, внутриплитный вулканизм, модели растяжения литосферы, конвекция.

1. Introduction

How should the student of geodynamics be taught? The question may seem rhetorical, because the correct answer obviously should be: «One must give the student the latest knowledge, taken from the geological community, in a common sense way.» Gillian R. Foulger [*2010*] argues, however, in the new textbook «Plates vs. Plumes: a geological controversy» that the predictions of the plume hypothesis, embodied in mainstream geology, are not supported by scientific evidence. To some extent, this statement sounds initially paradoxical, since modern models for plate kinematics are based on progressions of volcanic hotspots. It is believed that the shift of volcanism is consistent with plate motions, at least during the last 3 Ma [*Gripp, Gordon, 2002*]. The book describes models for both plates and plumes. Its polemical style is justified by using the same subjects, approaches, and methods for both hypotheses. The student is invited to decide for himself the extent of their validity.

The development of science often moves into a state of repeated declarations that proliferate over time without radical movements or breakthroughs. For example, the conceptual basics of geomorphology that were embodied by Walther Penck [*1924*] in the early 20th century, mainly for sites in Europe, were applied to studies of topography in different areas of the world. Numerous descriptive papers have not moved beyond the originally applied geomorphologic approaches. The situation is somewhat different in scientific areas where new data disagree with mainstream geology. Lord Kelvin's viewpoint on the physical nature of the cooling Earth lost common sense value after the discovery of radioactivity. However, hypotheses on geosynclines and a cold Early Earth are still occasionally used in current geological publications.

New ideas were often disapproved of by the geological community. Those of Wegener entered into mainstream geology only after considerable delay. In contrast, a plume hypothesis of Morgan [*1971*] was adopted for common use amazingly quickly (Fig. 2). Morgan postulated the ascent of material to the surface of the Earth from a deep mantle reservoir (i.e. from its lower thermal boundary layer). The suggested plume mechanism was considered afterwards, in many papers, to be a universal explanation for intraplate volcanism.

In the preface, the reader becomes acquainted with the professional credo of the author – Gillian R. Foulger, Professor of Geophysics at the University of Durham, UK. Her doubts about the plume hypothesis were generated by personal experience in seismological work in Iceland. To support a systematic study on plume problems, she created the website www.mantleplumes.org that collectes publications both that support and violate the plume hypothesis. Besides, Foulger has published two Geological Society of America special volumes: Plates, plumes, and paradigms [*2005*] and Plates, plumes, and planetary processes [*2007*]. In 2007 and 2008, she organized a section

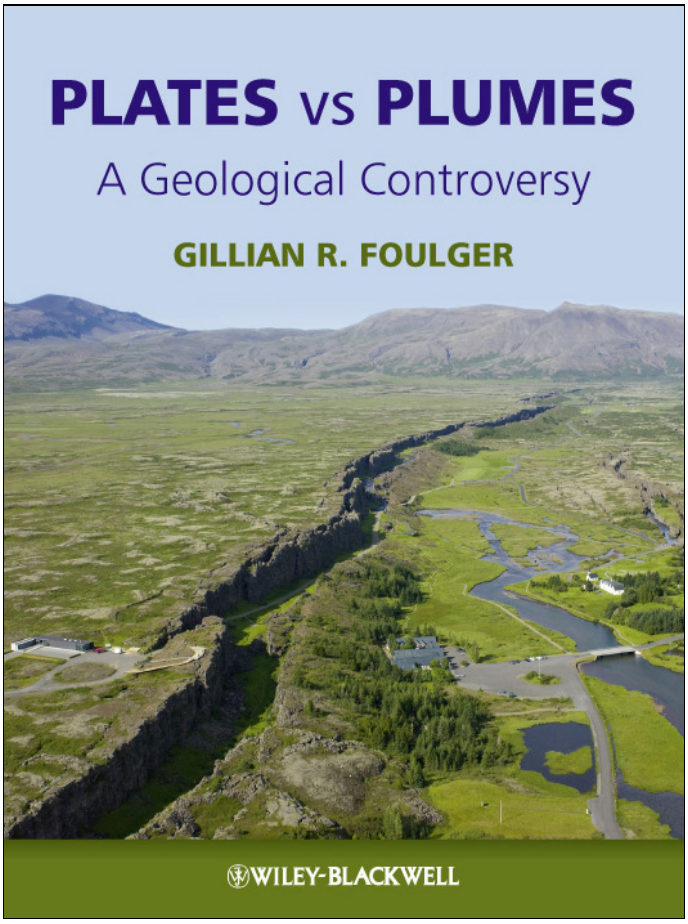

Fig. 1. Title page.

Рис. 1. Титульная страница книги Ж.Р. Фулджер.

«Melting anomalies» for the General Assembly of the European Geoscience Union in Vienna. In 2005, she was awarded the prestigious Price Medal by the Royal Astronomical Society.

Her textbook presents the viewpoint of a geophysicist on plates and plumes in terms of geophysical, geological, geochronological, geochemical, and petrologic data. The extensive bibliography of the book has some national limitations. For instance, among the 699 references, there are only 10 by Russian authors. Another limitation of the book is the choice of subjects. The main focus is certainly Iceland and Hawaii, generally considered as classic expressions of plume dynamics in the oceanic environment. Personally, I would be interested to assess the hypotheses for Asia, East Africa, and North America. In this review, I follow the main ideas presented in the book through my continental geological experience, that is combined with teaching at Irkutsk State University.

The book is well illustrated and gives clear statements of the author's viewpoints. The eight chapters contain introductions, the predictions of the plume and plate hypotheses, observations, and discussions. Before reading

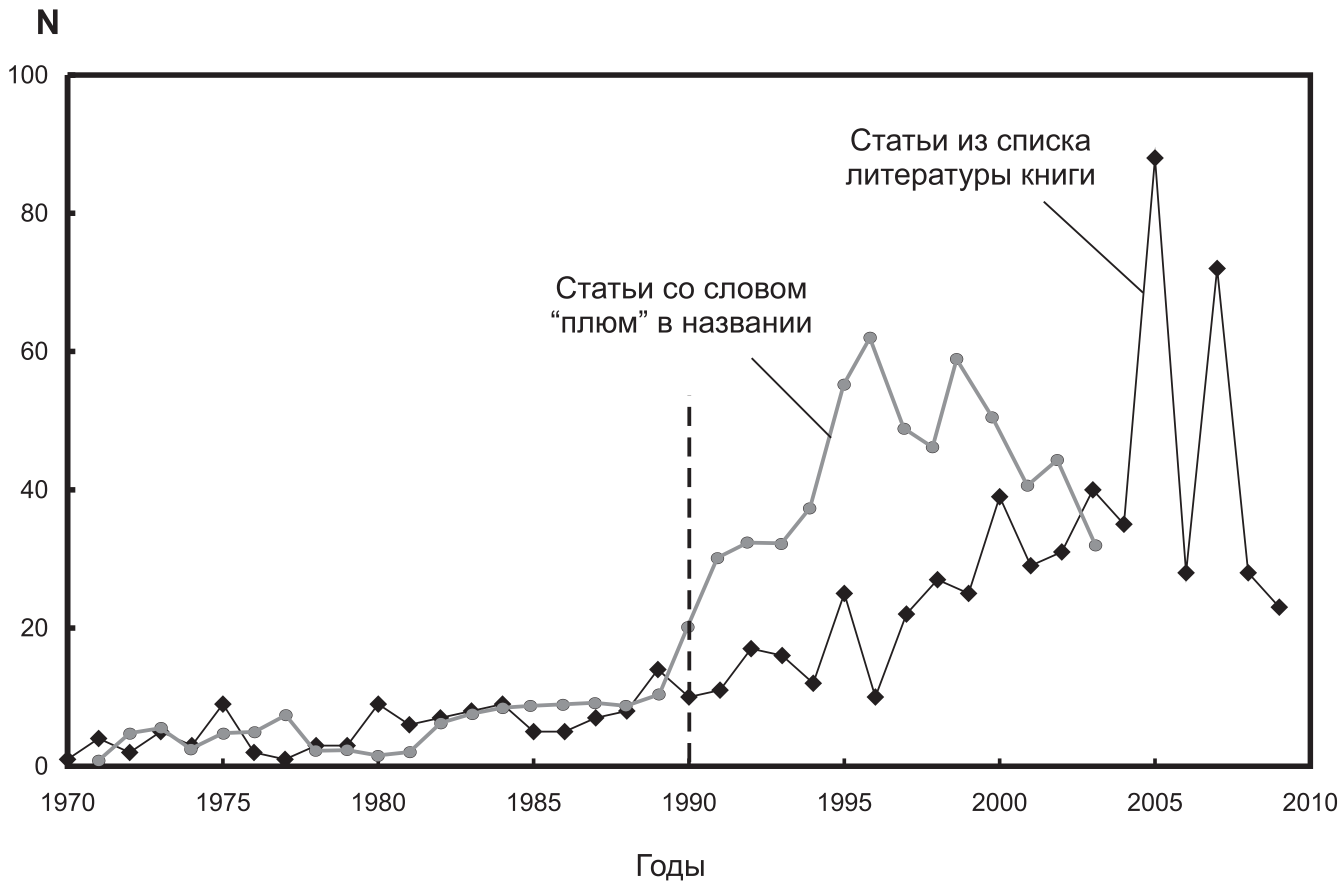

Fig. 2. Temporal variations of N – numbers of published papers on the plume topic and numbers of papers from references in the book by Foulger [*2010*]. The dashed vertical line shows the increase of publications on plumes in 1990. The number of references used in the book for that time persistently increases and reaches a maximum in 2005 and 2007 as a result of the published Geological Society of America special volumes: «Plates, plumes, and paradigms» and «Plates, plumes, and planetary processes». Thus, Foulger's book uses information based on papers that were published mostly in the last two decades. The line with the word «plume» in the title, plotted according to the Georef data base is taken from Fig. 1.8 of the book.

Рис. 2. Сопоставление по годам вариационных линий N – числа опубликованных работ по плюмовой тематике и числа статей (всего 699 наименований), цитированных в книге Дж.Р. Фулджер [*Foulger*, *2010*]. Штриховой вертикальной линией (1990 г.) отмечено заметное возрастание количества публикаций по плюмам. Количество статей списка цитированной литературы книги в это время последовательно повышается и дает максимумы 2005 и 2007 годов в результате опубликованных сборников статей специальных томов Геологического Общества Америки: «Плиты, плюмы и парадигмы» и «Плиты, плюмы и планетарные процессы». Таким образом, книга Дж.Р. Фулджер подготовлена по опубликованным работам главным образом двух последних десятилетий. Вариационная линия числа статей со словом «плюм» в названии приведена по рис. 1.8 книги Дж.Р. Фулджер, по данным Georef data base.

subsequent sections, it is helpful to look first through the list of «exercises for the student». These, to me, are mostly unexpected and often puzzling. What is «normal» and what is «anomalous» volcanism? Can an ordinary volcanologist answer to this question?

2. From plate tectonics to plumes and back again

An introductory section lays out terminology and the history of the hypotheses of plate tectonics and mantle plumes. Examination of geodynamics focuses on the origin and uniqueness of volcanism as a reflection of deep processes in the Earth. At the end of the section, the student is offered six exercises. None of them concerns a comparison between the hypotheses. The main collision is yet to come. So far, the teacher spares the student.

When reading the section, the student learns that a mantle plume is a column of material that rises from the base of the mantle to shallower depths, up to the eruption on the earth's surface in the form of magmatic liquid. High temperature in a magmatic source predicted by the plume hypothesis is observed only in Hawaii. Magmatic sources of other ocean islands show no elevated temperatures. This is the reason Foulger chose to exclude the term «hot spot», that was used by Wilson prior to the plume hypothesis, and to replace it by the neutral term «melting anomaly».

Initially, the plume hypothesis was based on six predictions:

1) plumes are fixed relative to one–another,

2) time-progressive volcanic chains emanate from them,

3) they are rooted in the deep mantle, whence they transport relatively primordial mantle upward,

4) they break up continents,

5) they drive plate tectonics, and

6) they are hot.

The number of publications on plumes increased in the early 1990s[1] (Fig. 2). Over time, the initial plume hypothesis evolved. A modern standard plume model suggests five basic predictions:

1) precursory domal uplift,

2) flood basalt eruption,

3) a narrow conduit to the core–mantle boundary,

4) a time-progressive volcanic chain, and

5) high temperatures within the magmatic source.

Similarly, the original version of plate tectonics has been modified also. Now, it is obvious that the lithospheric plates are not rigid. In many cases, interplate boundaries are uncertain[2]. Nevertheless, the basics of the hypothesis of plate tectonics have been used successfully in geological reconstructions. This reliability emphasizes the comparative level of plume inconsistency.

In the two decades after publication of the plume hypothesis, alternative processes that could cause intraplate volcanism were discussed also, such as propagating cracks, internal plate deformation, membrane tectonics, self-perpetuating volcanic chains, recycled subducted slabs, and continental break-up. Foulger shows that the plume hypothesis gave an oversimplified version of natural processes, so that new information from specific areas failed to confirm its predictions. Intraplate volcanism found a more satisfactory explanation by models of lithospheric extension and local convection in the shallow mantle.

Data on plumes are tabulated, starting with the Afar melting anomaly, that demonstrates almost all features of a plume. No volcanic areas of Asia are included[3]. North America is represented by Yellowstone and Raton[4].

[1] At that time I obtained geochronological data that demonstrated a stepwise westward shift of volcanism in the Eastern Sayans and interpreted this as evidence for eastward motion of South Siberia over a mantle plume in the past 21 Ma with an average velocity of 0.9 cm yr^{-1} [*Rasskazov, 1991, 1994a, 1994b*].

[2] For example, Asia was subdivided into microplates [*Zonenshain, Savostin, 1981*] and into mobile systems of orogenic and rift types [*Rasskazov et al., 1998*].

[3] Analysis of the volcanism in Central Mongolia showed reliability of only one of the five plume criteria listed by Courtillot et al. [*2003*], i.e. the general northward shift of volcanism [*Rasskazov et al., 2007*].

[4] The former is characterized by a progression of calderas [*Morgan, 1971; Pierce, Morgan, 1991*]. The latter is a part of the Jemez lineament and shows no time progression and therefore is rarely considered to be a plume locality.

3. Vertical motions

The section is preceded by an epigraph from Kozma Prutkov: «If, on the cage with a tiger, you see a sign reading «elephant», do not believe your eyes». The meaning of the epigraph becomes clear at the end of the section where the student is presented with 19 exercises. Only seven of them are of the traditional type. Exercise No 7 concerns Asia. The student is offered the topic of developing a plate model for the Emeishan basalts in China.

In the text of the book, one reads that the earliest basaltic eruptions occurred in Emeishan at ca. 260 Ma in a shallow marine basin on an active carbonate platform. Published data on local erosion of the platform before the eruptions are regarded as unreliable. Since there was no washout, there was no uplift of the area that may have been the predicted precursory dynamic activity due to a plume. To gain an understanding of the role of magmatic processes in the Emeishan complex of Permo–Triassic events, the student may read additional papers[5].

The three other exercises related to the area of my continental interests are numbers 12, 15, and 16. What caused uplift of the Colorado plateau? Can the vertical motions in the Red Sea–Afar–Gulf of Arabia region be accounted for by continental break-up? What is the timing of uplift relative to volcanism and rifting in the Afar region?

The Colorado Plateau was at sea level in the Late Cretaceous. At that time, shallow marine sediments were deposited. At present, these sediments are at an altitude of >2 km. The surface of the plateau is deeply eroded. What caused it? It is assumed that the rise relates to Laramide orogeny, which took place between 80 and 40 Ma due to structural reorganization at the interplate boundaries to the west of the plateau. As a result, subduction processes were replaced by transform motion. It is inferred that the 400 m elevation accounts for the effect of rapid erosion, exceeding sedimentation, and 300 m for isostatic uplift.

4. Volcanism, time progressions, and relative fixity of melting anomalies

The section «Volcanism» finishes with 21 exercises for the student, eight of which are traditional and seven of which are on Iceland. Exercise No 20 concerns the excess volcanism at the Afar triple junction. In the section «Time progressions and relative fixity of melting anomalies», eight exercises are included, four of which are traditional and the other four related to the Pacific region. The section presents data only for well expressed volcanic progressions.

The development of volcanism in rift structures of Af-

[5] Data on the Permo–Triassic boundary are of special interest [*Rasskazov et al., 2005, 2010a; and references therein*].

rica, Asia, and North America is not discussed[6]. The section provides an overview of large igneous provinces, relations between eclogite and peridotite sources of flood basalts, and other topics. The facts presented in this section are combined with those from other sections and extend general understanding of melting anomalies. The information on the spatial-temporal distribution of volcanic activity in Asia, East Africa, and North America is extended by references to papers on the website www. mantleplumes. org.

The data are complicated and confusing[7].

5. Seismology

The section is preceded by the quote from Confucius «Wise people are honest about what they know and what they don't know». These words seem to relate primarily to Foulger herself as an expert who realizes capabilities and limitations of the modern seismological methods. The section is one of the most valuable in the book. It focuses on identification of melting anomalies and transitions from them to plumes that underlay the anomalies. Only seismology can be used to detect a conduit that extends to the core–mantle boundary.

The section provides 18 exercises for the student, 11 of which are traditional. Two exercises are formulated for North America: If the low-wave-speed seismic anomaly beneath the Yellowstone region were interpreted solely in terms of temperature, how would the deduced temperatures vary throughout the body? What is the true depth extent of the low-seismic-wave-speed anomaly that tilts to the north from beneath Yellowstone?

6. Temperature and heat, petrology and geochemistry

The sections «Temperature and heat» and «Petrology and geochemistry» are closely related to each other. The former contains 11 exercises, eight of which are traditional, one concerns Iceland and two deal with Hawaii. The latter chapter provides 20 exercises, including 12 of which are traditional ones and six related to oceanic islands, i.e. Iceland and Hawaii. Asia and North America are not considered. The only exercise, which touches my direct interests, sounds, alas, non-petrologic: What is the relationship between structure and volcanism in East Africa[8] ?

The original plume hypothesis says that the primordial material rises from the deep mantle to the asthenosphere, where it partially melts and erupts in the form of melting anomaly. A primordial composition was adopted for plume material to explain a geochemical contrast between basalts from oceanic islands (OIB) and mid-ocean ridges (MORB). The key innovation of the hypothesis was that OIB geochemistry was attributed to a particular source, that is deeper than that of MORB [*Morgan, 1971*]. The hypothesis gained new meaning when it was postulated that subducted slabs sink to the bottom of the lower mantle and accumulate there in a "slab graveyard". This material is subsequently captured by plumes ascending from the core-mantle boundary. Anomalous geochemical signatures are formed due to recycling of delaminated continental crust and lithospheric mantle.

For a long time it was assumed that the primary magma must be in equilibrium with peridotitic mantle and have Mg# = $Mg/(Mg+Fe^{2+})$ >70. But from Ni–Mg and Fe–Mn relations, it was found that the erupted melts may be produced by a non-peridotite source with low Mg#. Respectively, the heat balance of deep processes in the sources of such melts may be significantly different from those in peridotite plumes.

The critical attitude of Foulger to prospects of petrology and geochemistry of isotopic end-members for deciphering processes of mantle dynamics reflects a natural reaction to uncertainties in speculations presented in many papers. In the popular textbook on isotope geology [*Dickin, 2005*], one can find a harmonious model for end-members of oceanic basalts, but a pessimistic comment on the isotope geochemistry of continental rocks: «*Ocean volcanics, which are expelled through a thin, young lithosphere, provide information about the asthenosphere and the deep part of the mantle. In contrast, continental basalts and mantle xenoliths, infiltrated through thick, old lithosphere, can tell us about the nature of the deep crust and lithospheric mantle and the evolution of magma during the ascent to the surface ... Unfortunately, continental magmatic rocks are difficult to interpret. This is due to the fact that they can acquire enriched elemental and isotopic characteristics from the three possible sources of mantle plumes, continental lithosphere and crust. The separation of these components together in continental volcanics and*

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[6] The melting anomalies in the Baikal, Rio Grande, and East African rifts show both similarities and differences [*Rasskazov et al., 2003, 2010a, 2010b*].

[7] This particular feature of the Late Cretaceous through Cenozoic volcanism in Central Mongolia - its northward shift - was established by Devyatkin [*1981*]. Later on this volcanic migration was interpreted as denoting the motion of the Mongolian lithosphere above a mantle plume, by Yarmolyuk et al. [*2007*]. The volcanism was inferred, however, to occur simultaneously along zones as long as 500 km. Therefore, the zones cannot be compared with oceanic progressions of volcanic chains and appear to reflect specific conditions of volcanic evolution similar to those in the Tibetan plateau [*Chuvashova et al., 2010; Rasskazov et al., 2010a*].

[8] Rasskazov et al. [*2003*] present geochronological data on the initial volcanic episode of 19–17 Ma in the Rungwe Province of the Western Rift. Identification of this episode is important for understanding the general evolution of volcanism and rifting in East Africa. According to $^{40}Ar/^{39}Ar$ and approximate K–Ar ages, these processes began during the Eocene in the Turkana saddle, which separated the Ethiopian and East African plateaus. In the former plateau, a strong thermal impact on the lithosphere was expressed as voluminous volcanic eruptions distributed in its central part along the Ethiopian rift at ca. 30 Ma. In the latter plateau, thermal erosion of the lithosphere began beneath its periphery, in the Kenyan rift, at 23 Ma, and in the Western rift at 19 Ma.

plutons have been discussed over the last few decades. Significant progress was made, but a large number of variables, making each event unique ... It is difficult to generalize the approach to the study of continental magmas and to make illustrations for the fundamental principles of private research approach[9]» [*Dickin, 2005, p. 174*].

Understanding the systematics of magmatic sources is impossible without representative and reliable determinations of trace elements and isotopes in geochronologically constrained volcanic sequence. Comments by Foulger on magmatic sources are not accompanied by any results of the studies of this kind. Her viewpoint on the common isotopic component as a result of a single phase melting is not supported by actual data, which, in principle, would indicate its existence. To define the role of melting anomalies in continents, additional studies of volcanic rocks should be done yet for proper applications of their isotopic and trace-element signatures.

7. Synthesis and conclusions

The final section includes four exercises of traditional type, that encourage the student to think over what future is waiting for geodynamics. The proposed exercise to falsify the plume and plate hypotheses essentially leaves the student a choice – either to use a scientific approach to the analysis of facts and to not go beyond the interpretation that follows from them, or join the belief in rising plume material from the core–mantle boundary.

On the whole, the book «Plates vs. plumes: a geological controversy» is definitely intended for the advanced students who are not satisfied with interpretations of intraplate volcanism in publicaitons that predominately assume plumes. From the presented systematic descriptions of the geological controversy on the plate and plume hypotheses, it follows that, unlike predictions of the former, those of the latter have not been confirmed by observations.

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[9] I agree with the thesis of Dickin on the whole, but note that, besides the three mentioned enriched sources, one of convecting asthenospheric mantle might be also isotopically enriched. If a component like this is identified in magmatic liquids from a continental region, it is helpful for identification of other mantle and crustal components similar to a tracer in the isotope dilution technique [*Rasskazov et al., 2011*].

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