

Observation of ^3He and ^3H in the volcanic crater lakes: possible evidence for natural nuclear fusion in deep Earth

Songsheng Jiang (ssjiang@ciae.ac.cn)^a, Ming He^a, Weihong Yue^a, Bujia Qi^a, Jing Liu^b

^a China Institute of Atomic Energy, P O Box 275(49), Beijing 102413, China

^b Bonner Nuclear Lab., MS315, Rice University, 6100 Main Street, Houston, TX 77005, USA

Abstract

Mantle helium and other volatiles may be released to volcanic crater lakes. This paper presents the observation of ^3H and mantle helium in the crater Lakes Nemrut (Turkey), Laacher (Germany) and Pavin (France). The presence of excess ^3H in the lakes can be explained as material released from mantle sources because of the correlation of excess ^3H with mantle ^3He and ^4He . The helium concentration was much higher in the bottom layers of the lakes. The ^4He and ^3He concentrations in Lakes Nemrut, Laacher, and Pavin were determined to be 25 and 190; 10 and 50; and 70 and 500 times larger than the atmospheric saturation value, respectively. The isotopic ratio of the excess helium, $^3\text{He}_{\text{ex}}/^4\text{He}_{\text{ex}}$, in Lakes Nemrut, Laacher and Pavin was $(1.032 \pm 0.006) \times 10^{-5}$, $(7.42 \pm 0.03) \times 10^{-6}$ and $(9.09 \pm 0.01) \times 10^{-6}$ respectively. The ratios clearly indicate that large amounts of helium isotopes are released to the lakes from a mantle source. The excess ^3H at the bottom of Lakes Nemrut, Laacher and Pavin is estimated to be 3.7 ± 1.4 TU, ~ 1.4 TU and ~ 4 TU respectively. Detection of tritium in the Earth's interior is key evidence for natural nuclear fusion in the Earth.

We conclude that the excess ^3H in the lakes, after the origin of the excess ^3H from atmosphere and conventional nuclear reactions are excluded, and the correlation of the excess ^3H and mantle ^3He is considered, might be from a mantle source. We also conclude that the ^3H and ^3He are produced by nuclear fusion (d-d reaction) in an environment (condensed matter or plasma) rich in H atoms and (U+Th) at high temperature and high pressure conditions in deep Earth.

1. Introduction

In 1969, Clarke *et al.* discovered mantle ^3He released to the deep Pacific Ocean water^[1]. This excess ^3He was attributed to the leakage of primordial ^3He into the oceans at active spreading centers such as the East Pacific Rise. Then, Krylov *et al.*^[2] found an elevated $^3\text{He}/^4\text{He}$ ratio of ~ 9 RA in oceanic basalt glass, where RA is the $^3\text{He}/^4\text{He}$ ratio in the atmosphere.

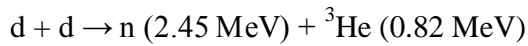
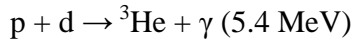
The atomic ratio of the two stable helium isotopes, $^3\text{He}/^4\text{He}$, varies considerably between different components of the geosphere. In the troposphere and hydrosphere the ratio is on the order of 1.4×10^{-6} . The mantle is characterized by a $^3\text{He}/^4\text{He}$ ratio of $\sim 10^{-5}$, while the continental crust is characterized by a $^3\text{He}/^4\text{He}$ ratio of $\sim 10^{-7} - 10^{-8}$. The analysis of helium isotopes in fluids can help to identify the origin of gas fluxes from the interior of the Earth.

Seeking the source of ^3He in the Earth's interior, Gerling *et al.*^[3] and Mamyrin and Tolstikhin^[4] investigated various nuclear processes for ^3He (^3H) production, including spontaneous fission of U and Th, and nuclear reactions induced by neutrons, α -particles and γ -rays. However, the results show the $^3\text{He}/^4\text{He}$ ratios to be less than 10^{-8} , values much lower than the $^3\text{He}/^4\text{He}$ ratios in the mantle. High $^3\text{He}/^4\text{He}$ ratios could be induced by the spallation reaction

from cosmic rays in terrestrial rock^[5], but the effect should be negligible deep under the earth. Therefore, the ^3He in ocean basalts has been explained as having a primordial origin (i.e. ^3He trapped underground at the time of Earth's formation). This is the default explanation, given that no radiogenic or nucleogenic mechanism can be found to produce such high $^3\text{He}/^4\text{He}$ ratio over broad regions of the Earth's mantle.

In recent years, the hypothesis that the ^3He is of primordial origin has been challenged. It seems paradoxical that there is such a narrow distribution of $^3\text{He}/^4\text{He}$ ratios (8 ± 1 RA) in the Mid-Ocean Ridge Basalts (MORB) and in the hydrothermal vent fluids at Mid-Ocean Ridge (MOR)^[6]. Also, the $^3\text{He}/^4\text{He}$ ratio in diamonds is extraordinarily high^[7], exceeding the planetary value of 1.4×10^{-4} .

The hypothesis of natural nuclear fusion occurring in the deep Earth (geo-fusion) goes back to 1980s. Jones *et al.*^[8] supposed that under non-equilibrium conditions, d-d and p-d fusion reactions might occur in the deep Earth with the reactions:



Here ^3H and ^3He are the products of a d-d reaction. ^3He is already known to be released from deep Earth, but this could be of primordial origin. Since tritium decays with a half-life of 12.4 years, a good test of the hypothesis that d-d reactions occur in the Earth would be the detection of tritium emanating from deep Earth and found in magmatic gases and fluids^[9]. ^3H induced by other nuclear reactions in the Earth was estimated to be less than 0.01 TU (1 TU=1 tritium atoms per 10^{18} hydrogen atoms), a value which is under the detectable limit.

Extensive tritium measurements in volcanic products were made to search for evidence for natural nuclear fusion in the Earth. Quick *et al.* tried to measure the tritium concentration in the active P'pO'o crater at Kilauea in Hawaii^[10], they found that the tritium concentration of the samples from inner crater was lower than that of the samples taken simultaneously from the nearby upwind crater rim. The results provide no evidence in support of natural fusion in the Earth's interior. In another experiment, Goff and McMurtry^[11] collected magmatic water samples from 11 active volcanoes around the world. They found that magmatic tritium values were generally as small as the background level, and they concluded there is no evidence that natural fusion in the Earth emits ^3H at a concentration above 0.05 TU. However, from measured data^[11] Jones *et al.* noticed that there were "positive ^3H anomalies" in two sites, Kilauea in Hawaii and the Alcedo "geyser" in the Galapagos Archipelago^[9].

2. Mantle helium and excess tritium in volcanic lakes

The analysis of helium isotopes in lakes can help us to identify the origin of gas fluxes from the interior of the Earth. The ability of volcanic lakes to store magmatic gases can be used to detect mantle degassing. In this work, we report observations of helium isotopes and tritium in volcanic crater lakes Nemrut, Laacher and Pavin

2.1 Lake Nemrut

Lake Nemrut (2247 m a.s.l., in Turkey) is formed from a caldera. It is located at the western border of Lake Van, and has a surface area of 11 km^2 , a maximum depth of 167 m and volume of

0.98 km³. Lake Van is the fourth largest closed-basin lake and the largest alkaline lake on Earth, and it is surrounded by several active volcanoes, situated along a fault running from the north-east to the south-west^[12].

2.1.1 Mantle helium

The most striking feature of the helium concentration measured in Lake Nemrut is the large increase of both helium isotopes with depth (Fig. 1). At the depth of 150 m the ⁴He concentration is 25 times larger than the atmospheric saturation value. For ³He the supersaturation reaches a factor of about 190. The ³He/⁴He ratio at the bottom of the lake equals 10.1×10⁻⁶ and decreases from the bottom to the surface due to mixing. However, the helium excess of both isotopes at different depths are linearly related: ³He_{ex}/⁴He_{ex} = (1.032 ± 0.006)×10⁻⁵ (Fig. 2). The ratio is about 7.5 times larger than the ratio in the atmosphere and clearly excludes the possibility that the excess helium could be of atmospheric origin^[12]. The ³He_{ex}/⁴He_{ex} ratio is consistent with the ratios in MORB and hydrothermal fluids from MOR.

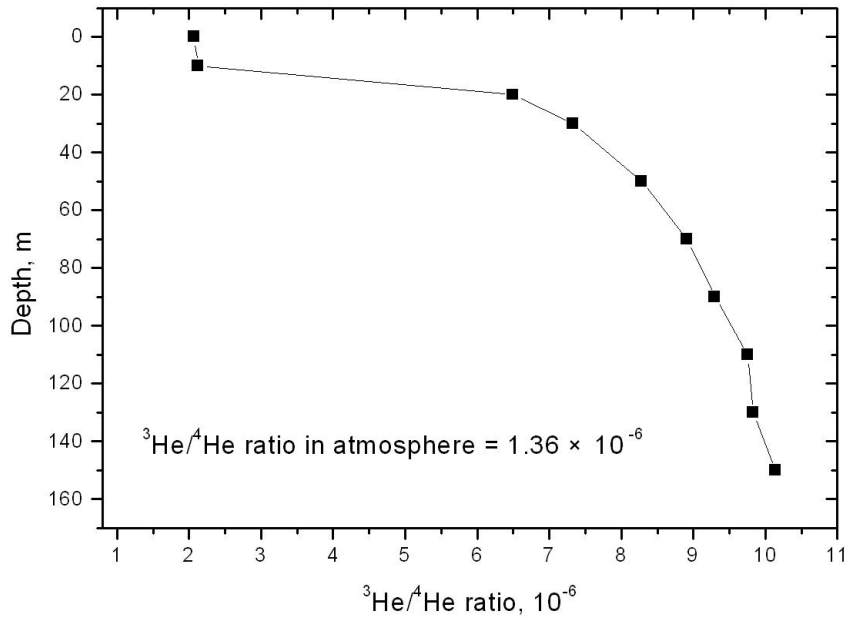


Figure 1. Vertical profile of ³He/⁴He ratio in Lake Nemrut. Due to mixture of water, the ratios decrease with depth. Data are adopted from Ref. 12.

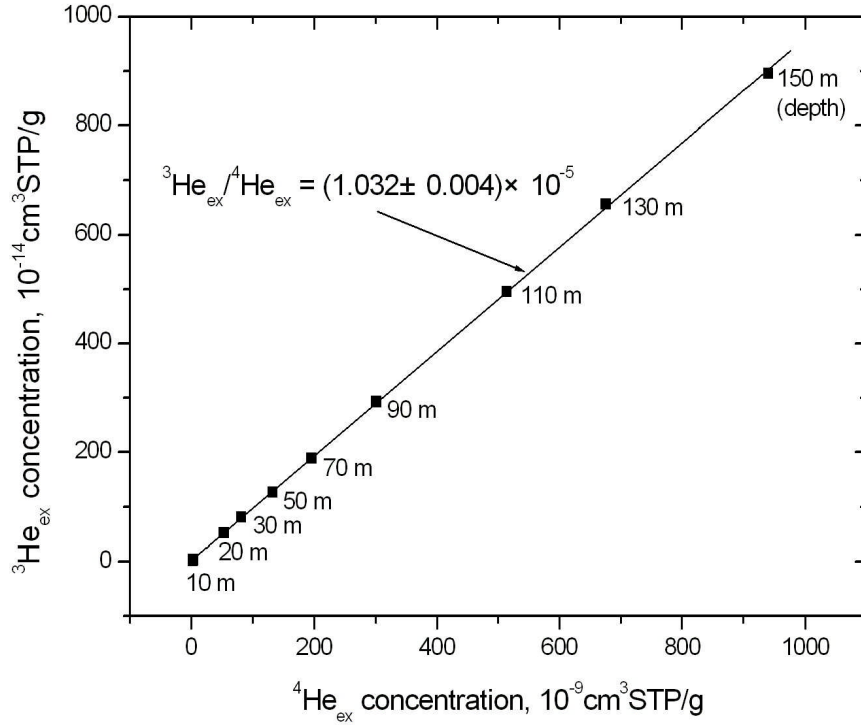


Figure 2. Vertical profile of $^3\text{He}_{\text{ex}}/^4\text{He}_{\text{ex}}$ in Lake Nemrut. $^3\text{He}_{\text{ex}}$ and $^4\text{He}_{\text{ex}}$ are excess ^3He and ^4He respectively. Data are adopted from Ref. 12.

2.1.2 Tritium anomalies in vertical profiles

Tritium is usually added to a lake from the surface by precipitation. When the water is well mixed vertically, nearly homogeneous tritium distribution is found from the surface to the bottom of the lake, as shown in Lake Issyk-kul (Kyrgyzstan)^[13]. On the other hand, with a non-uniform vertical mixture, the tritium concentration will decrease with depth, as observed in the vertical profiles of ^3H concentration in Lakes Van^[12] and Baikal (Russia)^[14].

The different patterns seen in the vertical profiles of ^3H concentration in Lake Nemrut and Lake Van is observed from experimental data in reference 12. The ^3H concentration in Lake Van decreases with increasing depth (Fig. 3a). It decreased by about 20% and 15% respectively in 1989 and 1990 from the surface to the bottom of the lake^[12]. This could be due to the fact that the water in the bottom is not completely mixed. The dashed line in Fig. 3 indicates the ^3H concentration in the surface layer. Unlike the situation when tritium is added to the lake from precipitation, the ^3H concentration in Lake Nemrut was about 10% higher ($> 3 \sigma$) at the bottom than at the surface (Fig. 3b), and all the values below the depth of 10 m were larger than the surface value. These results suggests that in addition to normal atmospheric tritium added to the surface, excess ^3H may also be injected from the bottom of the lake.

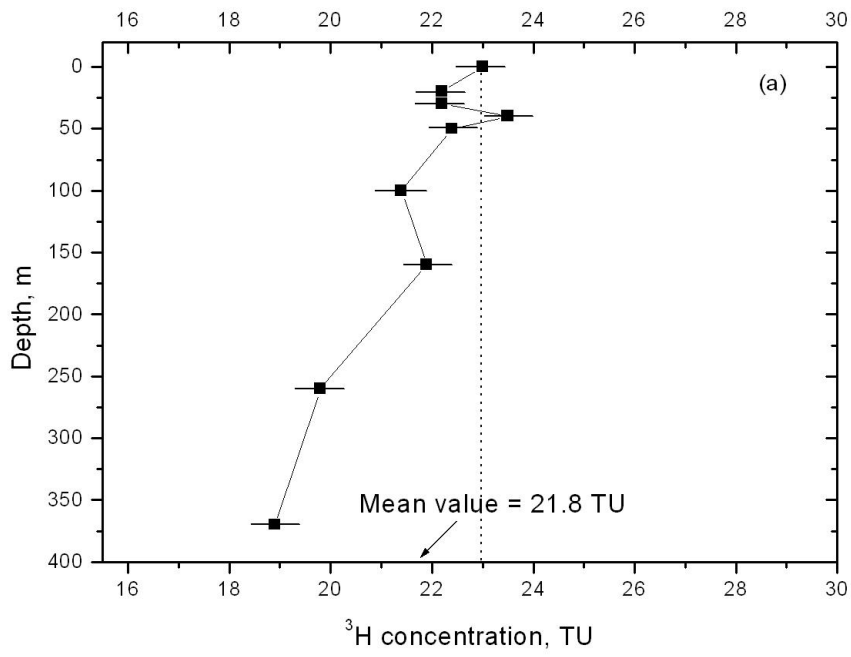


Fig. 3a.

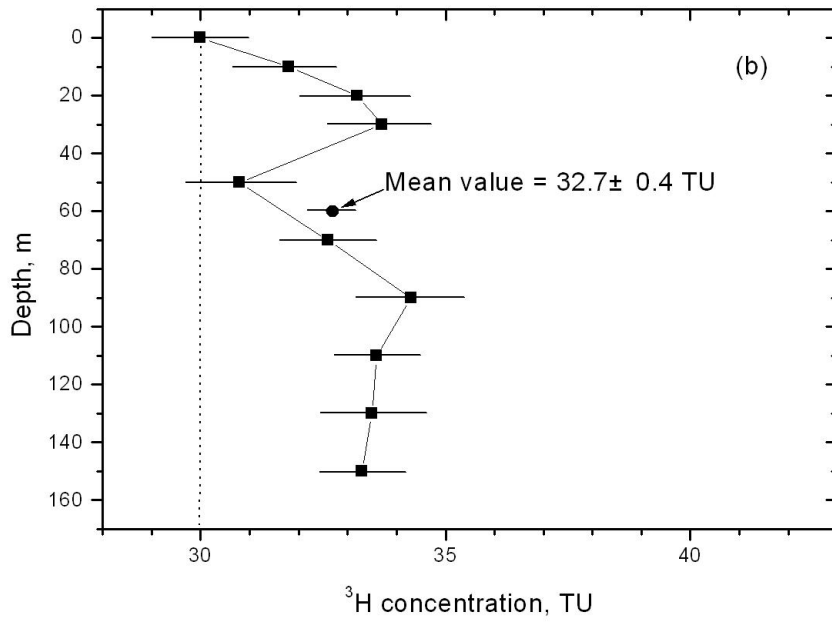


Fig. 3b.

Figure 3. The vertical profiles of ^3H concentration in Lakes Van and Nemrut are given in Fig. 7a and Fig. 7b respectively. The dash line indicates the ^3H concentration in the surface layer; error bar at 1σ . Data is adopted from Ref. 12.

The ^3H concentration is 33.3 ± 0.9 TU at the bottom layer of Lake Nemrut (150 m), and 30.0 ± 1.0 TU at the surface, an error at 1σ level. The difference of the values between the bottom and surface is about +10%, $> 3 \sigma$. The tritium at the surface is mainly from the atmosphere, and the tritium in the deep water is a mixture of tritium from the surface and the bottom. The difference of mean ^3H concentration between the depth of 90 to 150 m and the surface value is about 3.7 ± 1.4 TU, which implies an excess of ^3H . We suppose that ^3H , similar to ^3He , might originate from a mantle source ^[15].

2.2. Lake Laacher

Lake Laacher is located at the east Eiffel volcanic district of the Rhenish Massif with a nearly circular surface ^[16]. The main volcanic activity in the East Eiffel occurred during the Tertiary Quaternary volcanic activity started about 0.7 Ma ago and was essentially confined to the west East Eiffel. The typical craters called maars were formed by steam explosions due to contact of water with a magma chamber near the surface. Some of these maars formed lakes, especially in the West Eiffel. The largest maar lake, Lake Laacher, was found in the East Eiffel as a result of the most recent eruption of a huge volcano, about 11,000 years BP. Lake Laacher caldera has a maximum depth of 52 m and a surface area of 3.31 km².

2.2.1 Mantle helium

In Lake Laacher, the concentration of ^4He and ^3He increase with depth and at the bottom layer of the lake, they reach values up to 10 times (for ^4He) and 50 times (for ^3He) that of the atmospheric equilibrium concentration. The isotopic ratio of the excess helium, $^3\text{He}_{\text{ex}}/^4\text{He}_{\text{ex}}$ is $(7.42 \pm 0.03) \times 10^{-6}$. This indicates the presence of helium from the sub-continental mantle. A plume of bubbles emerging from a funnel was observed at the sediment surface at depth of 31 m, to the eastern shore. The strong mantle helium near station LA2 was detected ^[16]. The helium isotopes and other rare gases emerging from the funnel are from the mantle, which is confirmed by the $^3\text{He}/^4\text{He}$ ratios in the gases (from 7.23×10^{-6} to 7.33×10^{-6}) and very low ^{20}Ne concentration (3 - 60 ppb) compared with atmospheric (16.4 ppm).

The measured $^3\text{He}/^4\text{He}$ ratios (station LA1, near the center of the lake) as a function of the depth present a peak at around 25 m of depth (Fig. 4), which is caused by the existence of a large amount of local helium emerging from the funnel near station LA2. Also, the fact that the helium concentration increases below 30 m implies the presence of additional and deeper mantle sources.

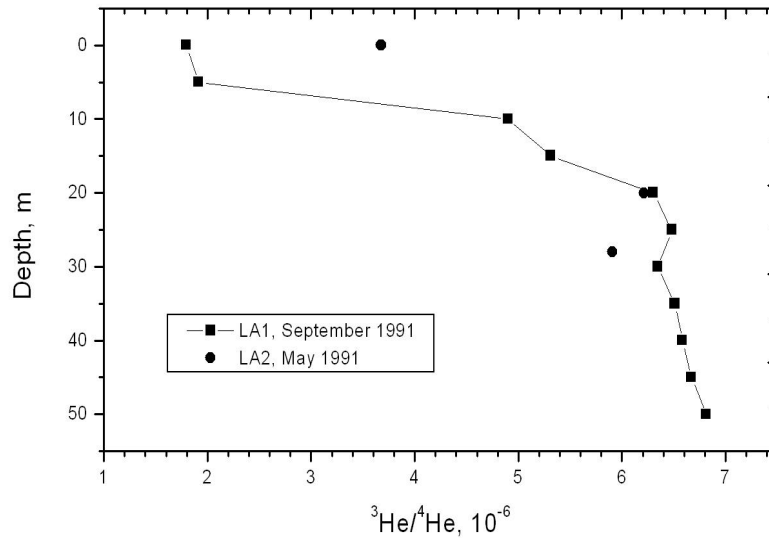


Figure 4. Vertical distribution of the measured $^3\text{He}/^4\text{He}$ ratio in Lake Laacher, data adopted from Ref. 16. The peak is consistent with existence of funnel, emerging gases at the sediment surface at 31 m, to the eastern shore.

2.2.2 Excess ^3H in the lake

As mentioned above, the vertical profile of measured $^3\text{He}/^4\text{He}$ ratios presents a peak at a depth of around 25 m (Fig. 4). A similar peak can be also observed in the vertical distribution of ^3H concentration (station LA1) (Fig. 5).

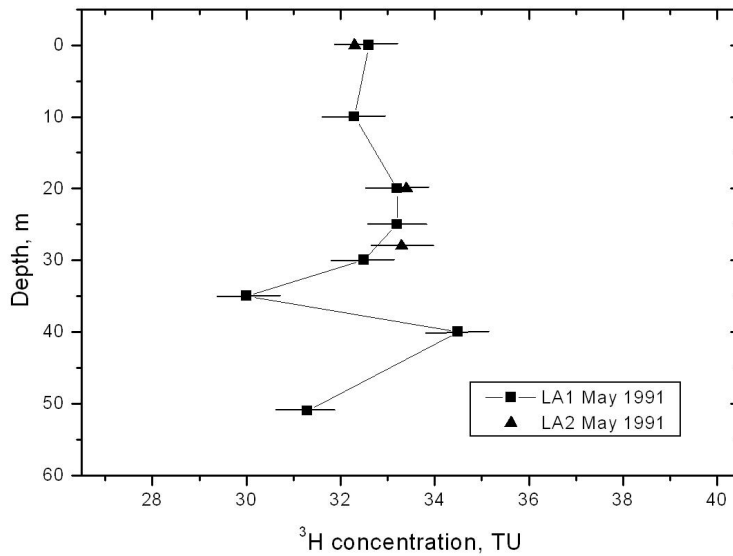


Figure 5. Vertical distribution of the measured ^3H concentration in Lake Laacher, data adopted from Ref. 16. The peak is consistent with existence of the funnel, and also consistent with the peak of $^3\text{He}/^4\text{He}$ ratio at 25 m (see Figure 4).

We consider it likely that the excess ^3He and ^3H at both peaks is all released from the funnel^[16]. Therefore, the excess ^3H , like the ^3He , might also originate from the mantle. The excess ^3H concentration released from the funnel is estimated to be about 1.1 TU. The 3 data points taken from below 30 m are widely scattered (Fig. 5), making it difficult to estimate the vertical variation trend of ^3H concentration in the deep parts of the lake. However, the fact that the $^3\text{He}/^4\text{He}$ ratio increases below 30 m implies the presence of an additional and deeper mantle source (Fig. 4).

In Fig. 6, we summarize all the tritium data listed in Table 1 of reference 16, including all data from LA1, LA2 and LA3, collected in May and September 1991. The tritium concentration measured in September is normalized to that of May. It can be seen that the ^3H concentration in the surface water is consistent for LA1 and LA2 in May and LA1 in September. The average value is 32.2 TU for surface water, shown as a dashed line (Fig. 6). The ^3H concentration between depth 10 and 50 m is higher than that in the surface on average. The data indicate that the excess ^3H concentration (at 20 - 30 m depth) is nearly constant with an average value of 1.1 TU. This excess ^3H correlate well with gases emerging from the funnel. The average value for total excess ^3H concentration between 10 - 50 m depth is 1.4 TU. The result indicates that the residual excess ^3H may be injected into the lake from the bottom and correlates well with mantle ^3He .

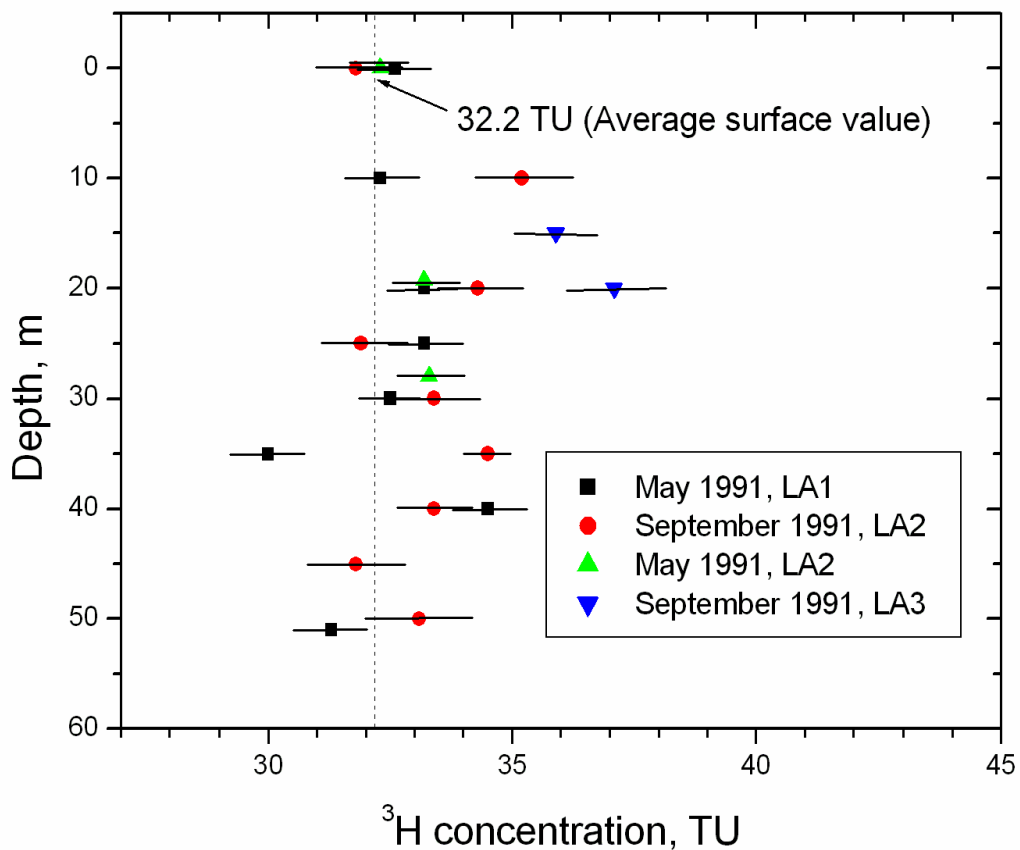


Figure 6. A summary of the data for vertical profiles of ^3H concentration in Lake Laacher. Data adopted from Ref. 16. The dashed line indicates the ^3H concentration in the surface layer. The average value for total excess ^3H concentration between 10 - 50 m is deduced to be 1.4 TU.

2.3. Lake Pavin

Lake Pavin is a small (0.44 km²), but deep (92 m), nearly circular lake located at an altitude of 1197 m in the French Massif Central^[17]. It occupies a maar crater which formed about 6000 years ago. A peculiar property of Lake Pavin is the presence of a stagnant deep water layer; that is, a permanently stratified layer, or “monimolimnion.” The monimolimnion is not affected by seasonal mixing. It is separated from the overlying seasonally mixed layer, or mixolimnion, by a chemocline between about 60 and 70 m in depth. This type of permanently stratified lake is referred to as “meromictic.”

2.3.1 Mantle helium

The ⁴He concentration is nearly at atmospheric equilibrium only in the surface layer of lake (the epilimnion). In the hypolimnion (depths between about 20 and 60 m), the ⁴He concentration is higher by up to a factor of 3, and in the monimolimnion by a factor of 70^[17]. The vertical profiles of the ³He/⁴He ratios and ³He concentration are shown in Figs. 7a and 7b respectively. The ³He concentration in the monimolimnion is higher than the surface layer by a factor of 300. The ³He/⁴He ratio of excess helium is deduced to be $(9.09 \pm 0.17) \times 10^{-6}$, or 6.57 ± 0.01 RA. The value clearly indicates its origin from mantle source and a flux of mantle-derived magmatic gases into the monimolimnion.

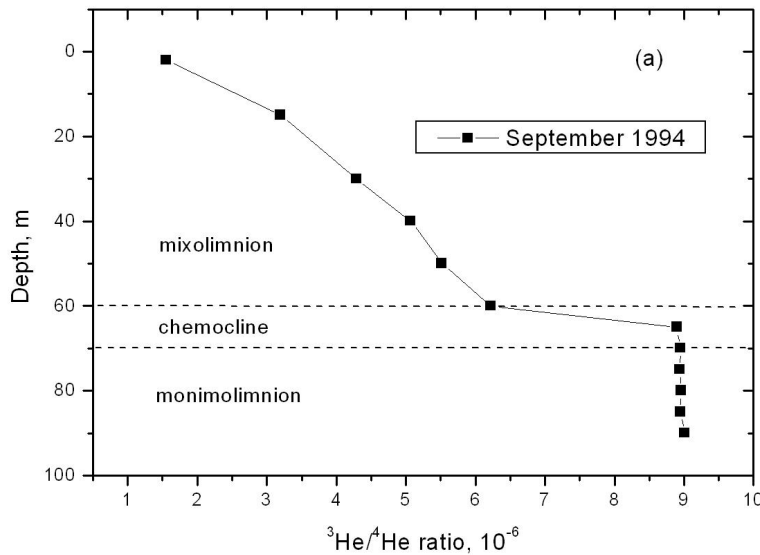


Fig. 7a.

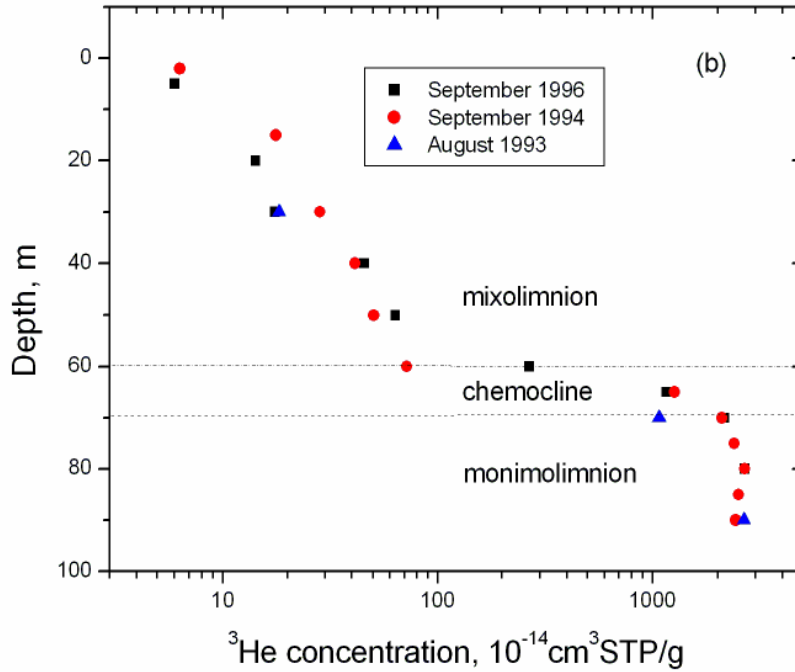


Fig. 7b.

Figure 7. Vertical profiles of $^3\text{He}/^4\text{He}$ ratio (Figure 7a) and ^3He concentration (Figure 7b) in Lake Pavin. The mantle helium was injected to the lake from the bottom and remained nearly constant in the monimolimnion. Data are adopted from Ref. 17.

2.3.2 Tritium concentration in the deep part of Lake Pavin

Lake Pavin is a meromictic crater lake. The chemocline (60-70 m) separates the seasonally mixed mixolimnion (the upper part of the lake) from the monimolimnion, which leads to a long deep-water residence time^[17].

The data listed in Refs. 18 and 19 show clearly the influence of tritium from nuclear testing on the surface water of the lake. The atmospheric tritium input into the lake is from the surface. The tritium concentration had large difference in the upper layer of the lake (mixolimnion) between 1981 and 1996, the tritium concentration varying from ~53 TU to ~12 TU in the mixolimnion. But the tritium concentration in the deep layer of the lake (monimolimnion) appeared to be more or less uniform around 5 TU (Fig. 8). The approximate constant tritium concentration in the deep part of the lake indicates no visible correlation with the variation of tritium concentration in the mixolimnion. Due to separation by chemocline, the ^4He concentration in the monimolimnion is higher than the concentration in the surface layer by a factor of ~ 70 ^[17]. If separation of tritium by the chemocline is similar to ^3He and ^4He , the mixture of atmospheric tritium in the monimolimnion should be less than 1 TU. Therefore, an additional tritium source in the monimolimnion must be considered. A large amount of excess helium with $^3\text{He}/^4\text{He}$ ratio of $(9.09 \pm 0.01) \times 10^{-6}$ in the monimolimnion clearly indicate the input of mantle gases from the bottom. Thus, the presence of a large amount of mantle helium in the monimolimnion suggests that the excess ^3H (about 4 TU) is also from a mantle source.

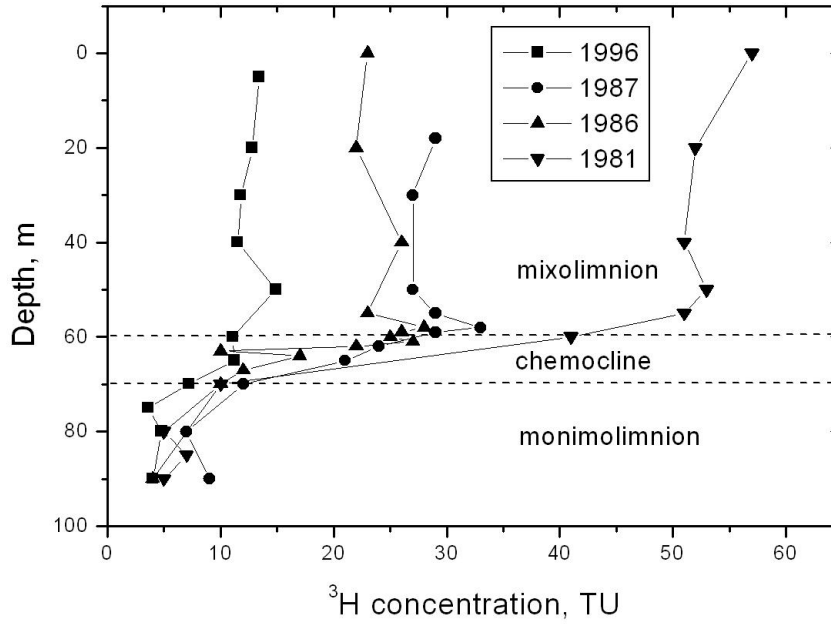


Figure 8. The vertical profiles of ^3H concentration in Lake Pavin, measured in 1996, 1987, 1986 and 1981, data adopted from Ref. 18 and 19. The approximate constant ^3H concentration in the monimolimnion shows no obvious correlation with the large variation of ^3H concentration in the mixolimnion.

3. Discussion

Both mantle ^3He and excess ^3H in Lakes Nemrut, Laacher and Pavin are observed. The data are summarized in Table 1.

Table 1. The observed mantle helium and excess ^3H in the volcanic crater lakes

Lake	$^3\text{He}_{\text{ex}}/^4\text{He}_{\text{ex}},$ 10^{-6}	$^3\text{He},$ concentration, C_{air}	^3He flux, $\text{mol/m}^2 \cdot \text{s}$	Excess $^3\text{H},$ TU	Reference
Laacher (Germany)	7.42	50	1.2×10^{-16}	~ 1.4	[16]
Nemrut (Turkey)	10.1	190	$\sim 1 \times 10^{-16}$	3.7	[12]
Van (Turkey)*	12	1.5	6×10^{-18}	~ 0.9	[12]
Panvin (France)	9	500	9×10^{-18}	~ 4	[17, 18, 19]

C_{air} : ^3He atmospheric saturation value in the water.

Global average ^3He flux: $6.6 \times 10^{-20} \text{ mol/m}^2 \cdot \text{s}$.

* Volcanic lake

The volcanic crater lakes enrich mantle helium. For example, the excess ^3He concentration at the bottom of Lake Nemrut is about 1- 2 orders of magnitude higher than the ^3He concentration in the volcanic crater at Kilauea. If the excess ^3H comes from the mantle, together with ^3He , the

high ^3He concentration might indicate high ^3H concentration in the end-member magmatic fluid. Therefore, the concentration of mantle ^3H in Lake Nemrut should be higher than the volcano areas (e. g. Kilauea). Thus, the volcanic lakes with high mantle-helium concentration are idea sites for testing magmatic gases released from the mantle source.

4. Conclusions

“ ^3H anomalies” in the vertical profiles are observed in Lakes Nemrut, Laacher and Pavin. These profiles have different shapes. The excess ^3H correlate fairly well with mantle helium (^3He) in each lake. Therefore, the excess ^3H is believed to be injected into the lakes from the bottom. We conclude that excess ^3H in the three lakes, after the origin of the excess ^3H from atmosphere and conventional nuclear reactions are excluded, and the correlation of the excess ^3H and mantle ^3He is considered, might be from a mantle source. We suppose that the ^3H and ^3He might be produced by nuclear fusion (d-d reaction) occurring in an environment of enriched H atoms and (U+Th) deep in the earth, at high temperatures and pressure^[15]. The physical mechanism of natural nuclear fusion in the deep Earth, however, remains an open question. Nuclear mechanisms that can explain the excess ^3H released from deep Earth are called for.

Acknowledgements

We would like to express our thanks to the authors for the published data that are used in this research.

This work is supported by President Foundation of the China Institute of Atomic Energy (No. YZ-0602).

References

- [1] W.B. Clarke, M.A. Beg, H. Craig, Excess ^3He in the sea: evidence for terrestrial primordial helium, *Earth Planet. Sci. Lett.* 6(1969)213-220.
- [2] A.Ya. Krylov, B.A. Mamylin, L.A. Khabarin, T.I. Mazina, Yu.I. Silin, Helium isotopes in ocean floor bedrock, *Geokhimiya*, 8(1974)1220-1225.
- [3] E.K. Gerling, B.A. Mamyrin, L N. Tolstikhin, S.S. Yakovleva, Helium isotope composition in some rock, *Geochim. Int.* 8(1971)755-761.
- [4] B.A. Mamyrin, L N. Tolstikhin, Helium isotope in nature 1984, Amsterdam, Oxford, New York, Tokyo.
- [5] M.D. Kurz, Cosmogenic helium in a terrestrial igneous rock, *Nature* 320(1986) 435-439.
- [6] D.L. Anderson D L, a statistical test of the two reservoir model for helium isotopes, *Earth planet. Sci. Lett.* 193(2001)77-82.
- [7] M.G. Zadnik, C.B Smith, U. Utt, F. Begemann, Crushing of a terrestrial diamond: $^3\text{He}/^4\text{He}$ higher than solar, *Meteoritics* 27(1987) 541-542.
- [8] S.E. Jones, E.P. Palmer J.B. Czirr, D.L. Decker, G..L. Jensen J.M. Thorne, S.F. Taylor, J. Rafelski, Observation of cold nuclear fusion in condensed mater, *Nature* 338(1989)740.
- [9] S.E. Jones, J.E. Eilsworth, Geo-fusion and cold nucleosynthesis, 10th International Conference on Cold Fusion, 2003, Cambridge, MA: LENR-CANR.org.

- [10] J.E. Quick, T.K. Hinkley, G.M. Reimer, C.E. Hodge, Tritium concentration in the active Pu'uO'o crater, Kilauea volcano, Hawaii: implications for cold fusion in the Earth's interior, *Phys. Planet. Interiors* 69(1991)132-137.
- [11] F. Goff, G.M. McMurtry, Tritium and stable isotopes of magmatic water, *Journal of Volcanology and Geothermal Research* 97(2000)347-396.
- [12] R. Kipfer, W. Aeschbach-Hertig, H. Baur, M. Hofer, D.M. Imboden, P. Signer, Injection of mantle type helium into Lake Van (Turkey): the clue for quantifying deep water renewal, *Earth Planet. Sci. Lett.* 125(1994)357-370.
- [13] M. Hofer, F. Peeters, W. Aeschbach-Hertig, Rapid deep-water renewal in Lake Issyk-Kul (Kyrgyzstan) indicated by transient tracers, *Limnol. Oceanogr* 47(2002)1210-1216.
- [14] R. Hohmann, M. Hofer, F. Peeters, D.M. Imboden, H. Baur, M.N. Shimaraev, Distribution of helium and tritium in Lake Baikal, *J Phys. Res.* 103(C6)(1998)12, 823-12, 838.
- [15] S-S. Jiang, M. He, Evidence for tritium production in the Earth's interior, *Chinese Science Bulletin* 52(2007)1499-1505, in Chinese, to be published in English version.
- [16] W. Aeschbach-Hertig, R. Kipfer, M. Hofer, D.M. Imboden, R. Wieler, P. Signer, Quantification of gas fluxes from the subcontinental mantle: The example of Laacher See, a maar lake in Germany, *Geochim. Cosmochim. Acta* 60(1996)31-41.
- [17] W. Aeschbach-Hertig, M. Hofer, R. Kipfer, D.M. Imboden, R. Wieler, Accumulation of mantle gases in a permanently stratified volcanic lake (Lac Pavin, France, *Geochim. Cosmochim. Acta* 63(1999)3357-3372.
- [18] P. Olive, J. Boulègue, Biogeochemical study of meromictic lake: Pavin lake, France, *Géomorphologie* 4(2004)305-316.
- [19] W. Aeschbach-Hertig, M. Hofer, R. Kipfer, D.M. Imboden, The physics structure and dynamics of a deep, meromictic crater lake (Lac Pavin, France), *Hydrobiologia* 487(2002)111-136.