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Key Points:
- We analyzed ^3He, ^4He, and ^{20}Ne in the accreted ice frozen to the ceiling of Lake Vostok down to 2 m above the lake-ice interface
- The neon budget of the lake is balanced, the neon supplied to the lake by the melting of glacier ice being compensated by the neon exported by lake ice
- Lake Vostok's waters are enriched by a terrigenic helium source. Its radiogenic value (0.057 × R_a) is typical of an old continental province

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Helium and Neon in the Accreted Ice of the Subglacial Antarctic Lake Vostok

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Abstract We analyzed helium and neon in 24 samples from between 3,607 and 3,767 m (i.e., down to 2 m above the lake-ice interface) of the accreted ice frozen to the ceiling of Lake Vostok. Within uncertainties, the neon budget of the lake is balanced, the neon supplied to the lake by the melting of glacier ice being compensated by the neon exported by lake ice. The helium concentration in the lake is about 12 times more than in the glacier ice, with a measured $^3He/^4He$ ratio of 0.12 ± 0.01 R_a. This shows that Lake Vostok's waters are enriched by a terrigenic helium source. The $^3He/^4He$ isotope ratio of this helium source was determined. Its radiogenic value (0.057 × R_a) is typical of an old continental province, ruling out any magmatic activity associated with the tectonic structure of the lake. It corresponds to a low geothermal heat flow estimated at 51 mW/m^2.

Plain Language Summary Extending over 15,000 km^2 in a deep trough north of Vostok station, Lake Vostok is the largest and the deepest among the many subglacial lakes to have been discovered in Antarctica. Its ice ceiling is tilted, with an ice thickness of 3,750 m in the south and 4,300 m in the north. As the melting point is pressure dependent, the base of the glacier melts on the thick side (northern region) whereas lake water refreezes in the south, where the Vostok station is located. Unlike most gases, helium and neon can be incorporated into the crystal structure of ice during freezing. This property makes helium and neon isotopes in the accreted ice a valuable source of information on the concentration and isotope composition of both gases in the lake water itself. Between 2006 and 2012, we collected 24 samples from between 3,607 and 3,767 m (i.e., down to 2 m above the lake-ice interface) of the accreted ice frozen to the ceiling of Lake Vostok (lake ice) for analyzing helium and neon. Within uncertainties, the neon concentration measured in the lake ice is equal to that in the glacier ice. This indicates that the neon budget of the lake is balanced, the neon supply to the lake by the melting of glacier ice being compensated by the Ne export by lake ice. This confirms earlier suggestions from radar data and GPS measurements of surface ice velocity that the water added to the lake by the melting of glacier ice is balanced by the lake ice, which is exported by the glacier's movement out of the lake. Helium isotopes (^3He and ^4He) are sensitive indicators of tectonic-magmatic activity. In continental areas of recent tectonic-magmatic activity such as geothermal areas, the ratio $^3He/^4He$ is at its highest, accompanied by excess heat flow. On the contrary, in stable continental areas, low $^3He/^4He$ ratios are found. The low $^3He/^4He$ ratio in Lake Vostok clearly demonstrates the absence of volcanic and/or magmatic activity associated with the tectonic structure of the lake, in agreement with the absence of magnetic anomaly. The helium concentration in the lake is about 12 times the concentration measured in the glacier ice. This shows that the Lake Vostok's waters are enriched from beneath by a flux of helium typical of an old stable continental province. Helium isotopes points to a low geothermal heat flow beneath the lake. We estimate this heat flow at 51 mW/m^2. This value is fully consistent with the heat flow map for Antarctica inferred from satellite magnetic data and corresponds to the baseline heat flow in Antarctica. Our data do not allow us to determine the helium flux and the residence time of the lake waters independently, but only as the product of these two quantities. If we adopt the previously determined residence time of 13,300 years based on geophysical inferences, we note that the helium flux value is close to the maximum of the lognormal distribution of continental helium fluxes, corresponding to the maximum likelihood of the continental helium flux.

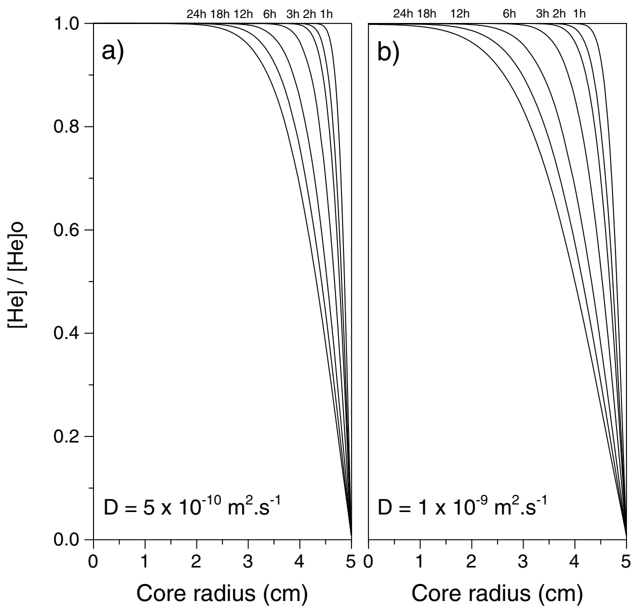

Figure 1. Time series of the helium concentration (relative to the initial concentration) in an ice core (diameter = 10 cm) in contact with the atmosphere for 1, 2, 3, 6, 12, 18, and 24 hr, respectively. The computation is performed with the conditions prevailing at the Vostok site for (a) the lower limit and (b) the upper limit of the helium diffusion coefficient (Haas et al., 1971; Ikeda-Fukazawa et al., 2002; Satoh et al., 1996).

1. Introduction

Antarctic subglacial lakes are formed by the melting of basal ice due to geothermal heat flow below the 3- to 4-km-thick ice sheet. Extending over 15,000 km^2 in a deep trough north of Vostok station, Lake Vostok is the largest and the deepest among the many subglacial lakes to have been discovered in Antarctica (Kapitsa et al., 1996; Siegert et al., 1996, 2005). Its ice ceiling is tilted, with an ice thickness of 3,750 m in the south and 4,300 m in the north. As the melting point is pressure dependent, the base of the glacier melts on the thick side (northern region) whereas lake water refreezes in the south, where the Vostok station is located (Siegert et al., 2000). The boundary between glacier ice and ice accreted through refreezing of lake water occurs at a depth of 3,539 m in the drill hole at Vostok station, corresponding to sharp changes in stable isotope compositions and the gas content of the ice (Jouzel et al., 1999).

Unlike most gases, helium and neon can be incorporated into the crystal structure of ice during freezing. This property makes helium and neon isotopes in the accreted ice a valuable source of information on the concentration and isotope composition of both gases in the lake water itself. Previous measurements obtained in the Vostok ice core (Jean-Baptiste et al., 2001) show a pronounced difference in both the helium concentration and isotope ratio between glacier ice and the refrozen lake water. In the glacier ice, helium concentrations are similar to those measured in the upper layers of the Vostok ice core, with $^3He/^4He$ values close to the atmospheric ratio. Below 3,539 m depth, the helium content of the samples is enriched by up to a factor of 3 with respect to glacier ice and their $^3He/^4He$ ratio exhibit a clear crustal signature, indicating that the accreted ice is enriched by a helium source with a radiogenic isotope signature typical of an old continental province (Jean-Baptiste et al., 2001).

Here we present helium isotopes (^3He and ^4He) and ^{20}Ne measurements from the deepest section of the Vostok ice core. These new data allow us to extend the previous helium profile (Jean-Baptiste et al., 2001) down to 2 m above the interface with lake water.

2. Materials and Methods

Between 2006 and 2012, we collected 24 samples between 3,607 and 3,767 m depth. Owing to the high diffusivity of helium in ice (Haas et al., 1971; Ikeda-Fukazawa et al., 2002; Satoh et al., 1996), appropriate action must be taken to minimize helium loss during core retrieval and sampling. Figure 1 shows helium loss from the ice core during its retrieval. Hence, it is essential that the ice be sampled as soon as it is retrieved from the drill hole and that the sample be taken from the central part of the core to avoid any helium loss. Each sample consisted of a parallelipipedic piece of ice, weighing typically 10 to 20 g, cut from the center of the core immediately following its retrieval. The ice samples were placed in 1-inch-diameter copper tubes sealed at one end with a brazed copper disc. The tubes were evacuated with a primary pump to 10^{-3} Torr for 2 min and closed with two metal clamps placed in series to ensure a tight seal (Figure 2). With this protocol, the estimated helium loss due to sample preparation (approximately 3 min) and pumping was 11.5 ± 2% (see Figure 3), while the residual air contamination was negligible (helium blank $<4.5 \times 10^{-14}$ mol). The estimated neon loss, computed with a diffusion coefficient $D_{Ne} = (9 \pm 3) \times 10^{-11}$ m^2/s (Satoh et al., 1996), was 4 ± 0.5%.

In the lab, helium and neon were transferred to sealed glass tubes using a routine procedure (Jean-Baptiste et al., 1992). Helium and neon measurements were made with a MAP-215 mass spectrometer (Jean-Baptiste et al., 1992, 2010) connected to a high-vacuum inlet line with a low helium blank ($<2.5 \times 10^{-14}$ mol). The analytical accuracy for ^4He, ^{20}Ne concentrations, and $^3He/^4He$ ratio, calibrated against an atmospheric standard, is better than 1%.

Figure 2. Copper tube (1 inch diameter) equipped with two clamps, used for storing the ice sample.

3. Results

The helium and neon results are shown in Figure 4 and Table 1. The isotope ratio $R = {}^3He/{}^4He$ is expressed relative to the atmospheric ratio $R_a = 1.38 \times 10^{-6}$. The average helium concentration (corrected for helium loss during sample preparation and pumping) is $[{}^4He]_{lake\ ice} = 166 \pm 27$ nmol/kg. This is about 15 times the concentration measured in the glacier ice (Jean-Baptiste et al., 2001). The scatter around the average value is probably due to the fact that helium losses during sample preparation and pumping vary depending on the actual geometry and size of the cut piece of ice and on the actual sample preparation time. The mean ${}^3He/{}^4He$ ratio is $0.12 \pm 0.01\ R_a$. This ratio is little affected by helium losses compared to concentrations, thus explaining the better reproducibility. Controlled laboratory experiments on the growth of ice from seawater (Top et al., 1988) suggest that helium is 1.26 times more soluble in ice than in water whereas neon is 10% less soluble. Therefore, helium concentration in Lake Vostok should be ~132 nmol/kg, that is about 12 times more than in the glacier ice. This observation confirms earlier conclusions by Jean-Baptiste et al. (2001) that the lake is strongly enriched in terrigenic helium originating from the lake's bedrock and sediments. This situation is similar to that described, for instance, by Torgersen and Clarke (1978) for Teggau Lake (northern Ontario, Canada) where deep waters show an excess ${}^4He$ with more than five times the solubility and a radiogenic isotope ratio ${}^3He/{}^4He$ as low as $0.24 \times R_a$.

Measured ${}^{20}Ne$ concentrations have a mean value (corrected for neon loss during sample preparation and pumping) $[{}^{20}Ne]_{lake\ ice} = 51 \pm 3$ nmol/kg. The better reproducibility compared to helium concentrations is likely due to the lower diffusivity of neon in ice.

4. Discussion

4.1. Neon Budget of Lake Vostok

Unlike ${}^4He$, ${}^{20}Ne$ is atmospheric in origin (no terrigenic source). Unfortunately, neon concentration in the glacier ice, $[{}^{20}Ne]_{glacier}$, is not known because all the samples collected in the glacier ice (i.e., prior to 2001) were measured with an old VG 3000 mass spectrometer on which, for technical reasons, peak jumping from helium to neon was not feasible. However, it can be estimated from the helium concentration $[{}^4He]_{glacier}$ using the $({}^{20}Ne/{}^4He)$ ratio in the air bubbles trapped in the ice. This ratio is greater than the atmospheric ratio due to elemental fractionation during the process of bubble close-off during which small size molecules are preferentially excluded from the shrinking bubbles (Huber et al., 2006; Severinghaus & Battle, 2006). In their study of gas fractionation in firn air at NGRIP (North Greenland) and Devon Island, Huber et al. (2006) estimated an average close-off fractionation factor of 0.595 for neon and 0.388 for helium, corresponding to a 53% enrichment in neon relative to helium in the trapped air. This corresponds to a $({}^{20}Ne/{}^4He)$ ratio of 4.8 in the air bubbles (compared to 3.14 in the atmosphere). Although this value may not be directly transposable to Vostok due to the differences in temperature and accumulation rate, it corresponds to a ${}^{20}Ne$ concentration in the glacier ice $[{}^{20}Ne]_{glacier} = 4.8 \times [{}^4He]_{glacier} = 53 \pm 8$ nmol/kg (with $[{}^4He]_{glacier} = 11.1 \pm 1.7$ nmol/kg; Jean-Baptiste et al., 2001). Although the actual error bar on the determination of $[{}^{20}Ne]_{glacier}$ is certainly larger due to the uncertainty on the $({}^{20}Ne/{}^4He)$ ratio in the air bubbles, this value is comparable to the mean ${}^{20}Ne$ concentration measured in the lake ice $[{}^{20}Ne]_{lake\ ice} = 51 \pm 3$ nmol/kg. This strongly suggests that the neon budget of the lake is balanced, the ${}^{20}Ne$ supply to the lake by the melting of glacier ice being compensated by the ${}^{20}Ne$ export by

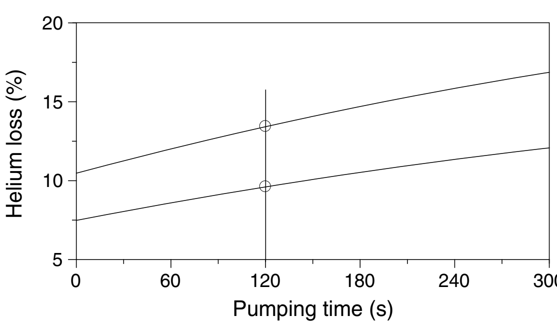

Figure 3. Helium loss from the ice sample (approximated by a 1.8-cm-diameter cylinder) as a function of the pumping time for the lower limit ($D = 5 \times 10^{-10}$ m^2/s) and upper limit ($D = 1 \times 10^{-9}$ m^2/s) of the helium diffusion coefficient (Haas et al., 1971; Ikeda-Fukazawa et al., 2002; Satoh et al., 1996). Helium loss during sample preparation (3 min) is also taken into account in the computation.

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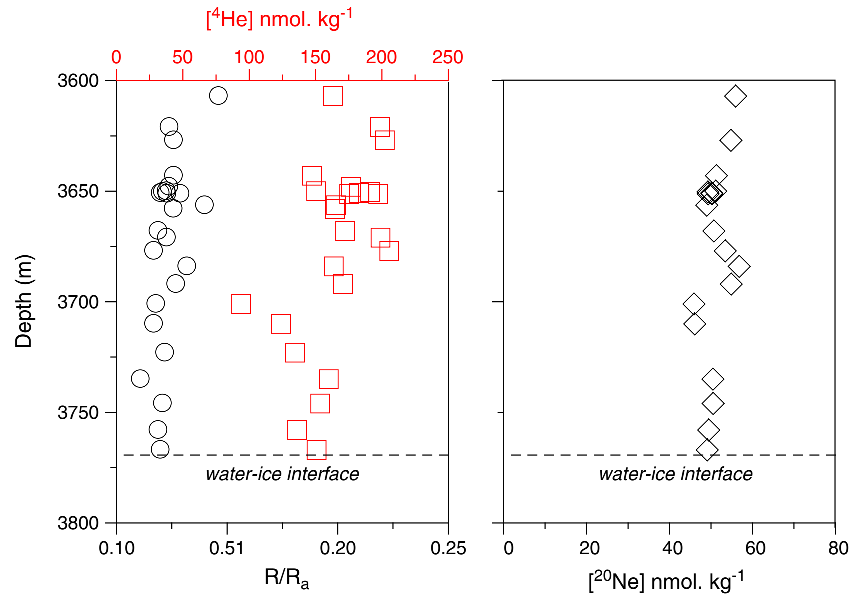

Figure 4. ^{4}He, ^{20}Ne, and ^{3}He/^{4}He vertical profiles (corrected for helium and neon loss during sample preparation and pumping).

lake ice. This balancing is in agreement with geophysical inferences from radar data and GPS measurements of surface ice velocity (Bell et al., 2002), which indicate that the water added to the lake by the melting of glacier ice is balanced by the lake ice, which is exported by the glacier's movement out of the lake.

Table 1
Helium and Neon Results (Corrected for Helium and Neon Loss During Sample Preparation and Pumping)

Depth (m)	R/R_a	[^{4}He] (nmol/kg)	[^{20}Ne] (nmol/kg)
3,607	0.146	163.0	56.0
3,621	0.124	198.4	—
3,627	0.126	202.1	54.8
3,643	0.126	147.3	51.3
3,648	0.124	176.7	—
3,650	0.123	150.4	51.1
3,650.4	0.121	191.1	49.3
3,650.9	0.120	182.6	50.2
3,651.2	0.123	175.3	49.3
3,651.2	0.129	197.1	50.3
3,656.37	0.140	165.4	49.0
3,658	0.126	164.6	—
3,668	0.119	172.2	50.7
3,671	0.123	198.9	—
3,677	0.117	205.4	53.5
3,684	0.132	163.6	56.8
3,692	0.127	170.7	54.9
3,701	0.118	93.9	45.9
3,710	0.117	124.0	46.1
3,723	0.122	134.5	—
3,735	0.111	159.9	50.5
3,746	0.121	153.4	50.5
3,758	0.119	136.0	49.4
3,767	0.120	150.7	49.1
Average	**0.12**	**166**	**51**
Sigma	**0.01**	**27**	**3**

Note. Average and sigma of the data are indicated in bold.

4.2. Helium Budget of Lake Vostok and Terrigenic Helium Flux

Per unit of time, the amount of helium released to the lake by the melted glacier ice together with the amount of crustal helium injected into the lake from the bedrock and sediments must be balanced by the amount of helium that leaves the lake with the exported lake ice, according to the mass balance equation:

$$m/\tau \times \left[{}^{4}\text{He}\right]_{\text{lake ice}} = m/\tau \times \left[{}^{4}\text{He}\right]_{\text{glacier}} + \Phi_{\text{He}} \times S \qquad (1)$$

where m is the total mass of liquid water in Lake Vostok with a residence time τ, Φ_{He} is the helium flux from the bottom, and S the surface area of the lake.

Replacing m by ρ H S in equation (1), where ρ is the water density and H is mean depth of the lake (H~385 m; Siegert et al., 2005; Studinger et al., 2004), the helium flux can be expressed as a function of the residence time of the lake waters in the following simple way:

$$\Phi_{\text{He}} = \rho H \left(\left[{}^{4}\text{He}\right]_{\text{lake ice}} - \left[{}^{4}\text{He}\right]_{\text{glacier}} \right) / \tau \qquad (2)$$

Based on the amount of lake ice exported from the lake, Bell et al. (2002) estimated that the residence time τ should be about 13,300 years. This residence time corresponds to a helium flux of 0.86×10^{11} atom·m^{-2}·s^{-1}. This value is close to the maximum of the lognormal distribution of continental helium fluxes proposed by Torgersen (2010) based on the compilation of all available continental helium flux data (Figure 5). Although this is by no means a proof that the residence time estimated by Bell and coworkers is correct, it is

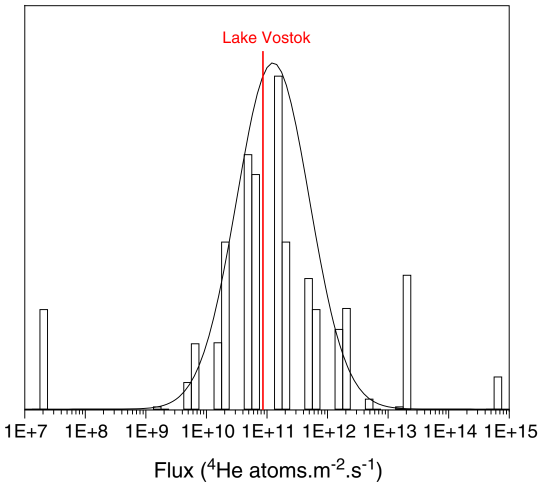

Figure 5. Histogram of continental degassing helium fluxes (Torgersen, 2010), with the plot of the corresponding lognormal distribution. He flux for Lake Vostok (red bar) corresponds to the residence time of 13,300 years determined by Bell et al. (2002).

interesting to note that it corresponds to the maximum probability of the helium flux from the Earth's continental surface.

4.3. Terrigenic ^{3}He/^{4}He Ratio and Geothermal Heat Flow

As shown earlier (Jean-Baptiste et al., 2001) helium in Lake Vostok is a mixture of two components: Atmospheric helium trapped in glacier ice and released into the lake water as the basal layers are melted, with an isotope ratio equal to R_a, and terrigenic helium originating from the bedrock and bottom lake sediments, with an isotope ratio equal to R_{ter}. This is already apparent in equation (2), which can be rewritten as follows:

$$\left[^4\text{He}\right]_{\text{lake ice}} = \left[^4\text{He}\right]_{\text{glacier}} + \left[^4\text{He}\right]_{\text{ter}} \tag{3}$$

with $[^4\text{He}]_{ter} = \tau\Phi_{He}/\rho H$ = 156 nmol/kg.

The same equation can also be written for ^{3}He:

$$R\left[^4\text{He}\right]_{\text{lake ice}} = R_a\left[^4\text{He}\right]_{\text{glacier}} + R_{ter}\left[^4\text{He}\right]_{\text{ter}} \tag{4}$$

where R is the ^{3}He/^{4}He ratio measured in the lake ice (R = 0.12 ± 0.01 R_a).

Combining equations (3) and (4) allows us to determine the value of the ^{3}He/^{4}He ratio of the terrigenic helium component, R_{ter}:

$$R_{ter} = R - (R_a - R) \times \left(\left[^4\text{He}\right]_{\text{glacier}} / \left[^4\text{He}\right]_{\text{ter}}\right) = 0.057 \times R_a$$

The ratio ^{3}He/^{4}He is a sensitive indicator of mantle involvement in crustal thermal activity (Lupton, 1983; Mamyrin & Tolstikhin, 1984). In continental areas of recent tectonic-magmatic activity such as geothermal areas, ^{3}He/^{4}He is at its highest, accompanied by excess heat flow. On the contrary, in stable continental areas, where low ^{3}He/^{4}He ratios are found, the mantle contribution to the heat flow is also low (Polyak & Tolstikhin, 1985). The low ^{3}He/^{4}He ratio of the terrigenic helium flux in Lake Vostok (R_{ter} = 0.057 × R_a) clearly demonstrates the absence of volcanic and/or magmatic activity associated with the tectonic structure of the lake, in agreement with the absence of magnetic anomaly (Studinger et al., 2003) and suggests a low thermal flux at the lake bottom. Based on the empirical correlation between terrestrial heat flow and ^{3}He/^{4}He ratio proposed by Polyak and Tolstikhin (1985), the ^{3}He/^{4}He value of 0.057 × R_a results in a geothermal heat flow estimate of ~51 mW/m^2. This value is fully consistent with the heat flow map for Antarctica inferred from satellite magnetic data (Maule et al., 2005).

5. Conclusions

We have measured helium isotopes (^{3}He and ^{4}He) and ^{20}Ne in the last 160 m of the water frozen to the ceiling of Lake Vostok (lake ice), down to 2 m above the lake-ice interface. Our main conclusions are as follows:

Within existing uncertainties, the neon budget of the lake is balanced, the ^{20}Ne supply to the lake by the melting of glacier ice being compensated by the ^{20}Ne export by lake ice. This is in agreement with geophysical inferences from radar data and GPS measurements of surface ice velocity (Bell et al., 2002), which indicate that the water added to the lake by the melting of glacier ice is balanced by the lake ice, which is exported by the glacier's movement out of the lake.

The helium concentration in the lake (deduced from that measured in the lake ice) is about 12 times the concentration measured in the glacier ice, with a radiogenic isotope ratio ^{3}He/^{4}He equal to 0.12 × R_a. This shows that the Lake Vostok's waters are enriched from beneath by a terrigenic helium source. Helium in the lake is a mixture of atmospheric helium coming from the melting of the glacier ice and terrigenic helium coming from the bedrock and sediments. Its ^{3}He/^{4}He isotope ratio was determined. Its value is clearly radiogenic (0.057 × R_a). This is typical of an old stable continental province, ruling out any magmatic activity associated with the tectonic structure of the lake.

Based on the empirical correlation between terrestrial heat flow and $^3He/^4He$ ratio proposed by Polyak and Tolstikhin (1985), this low $^3He/^4He$ value implies a low geothermal heat flow estimated at 51 mW/m^2.

Our data do not allow us to determine the helium flux and the residence time of the lake waters independently, but only as the product of these two quantities. If we adopt the residence time of 13,300 years determined by Bell et al. (2002) based on geophysical inferences, we note that the helium flux value is close to the maximum of the lognormal distribution of continental helium fluxes proposed by Torgersen (2010), corresponding to the maximum likelihood of the continental helium flux.

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