Po and Pb cycling in a hydrothermal vent zone in the coastal Aegean Sea

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Abstract

To quantify the potential enhancement of naturally-occurring 210Po and 210Pb that may result from the high sulfur-reducing and sulfur-oxidizing regimes associated with hydrothermal vents, sinking particles from both inside and outside vent areas and benthic molluscs grazing on or living near bacterial mats in the vent zone were collected off Milos Island (Aegean Sea) and analyzed for their 210Po and 210Pb content. There was no significant difference in the range of 210Po specific activities measured in particulate material collected by sediment traps in a control area and in the vent area; the resultant 210Po levels were of the same order of magnitude as literature values reported for other Mediterranean coastal areas. 210Pb levels in sinking particles from the control site tended to be higher than those measured in the vent zone, as demonstrated by the lower 210Po/210Pb ratios observed in particles from the control site. Nevertheless, these 210Pb levels were also comparable with similar 210Pb data reported for the northwestern Mediterranean Sea. The 210Po and 210Pb vertical particulate fluxes were, on average, higher in the vent zone as a consequence of the higher particle flux. This observation indicates that vents can indirectly control the flux of these natural radionuclides by affecting the types and amount of particles produced in hydrothermal areas. The 210Po levels measured in a gastropod and a bivalve living on or near the microbial mat in the vent zone were higher than values reported for non-vent gastropods and bivalves from the NW Mediterranean Sea, an observation which suggests that an enhanced food chain transfer of 210Po may occur in the vicinity of vents off Milos Island. Nevertheless, the lack of a general enhancement of 210Po and 210Pb in the marine particulate samples collected indicates that any input of these radionuclides through venting activity may have a minimal effect in the surrounding environment. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Natural radioactivity; Food chain transport; Particle flux; Molluscs

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1. Introduction

Naturally-occurring $^{210}$Po is present in the marine environment primarily as a result of the decay of $^{210}$Pb following atmospheric deposition and by the outgassing of $^{222}$Rn from sediment and submarine formations such as hydrothermal vents. Polonium-210 is strongly accumulated by a variety of marine organisms (Cherry and Shannon, 1974) and it is known also to be the major contributor to the natural radiation dose received by these organisms (Cherry and Heyraud, 1982). UNSCEAR (1988) has reported that $^{210}$Po and $^{210}$Pb are estimated to contribute approximately 8% of the natural internal radiation dose to man from seafood ingestion, and a more recent assessment has confirmed that the dominant contribution to dose received by man ingesting seafood is $^{210}$Po derived from Po in fish and shellfish (Aarkrog et al., 1997). In addition, $^{210}$Po and $^{210}$Pb are often used as oceanographic tracers and have proven useful in delineating particle transport processes in the oceans (Shannon et al., 1970; Bacon et al., 1980; Cherry and Heyraud, 1988; Radakovitch et al., 1998). Because of their differing chemistry in aquatic systems, the $^{210}$Po/$^{210}$Pb ratio is a particularly useful indicator of biogenic and lithogenic processes, both of which act as a source of particulate material in coastal areas.

While vent fluids are known to be highly enriched in natural series radionuclides (Kadko and Moore, 1988; Harada et al., 1989) including $^{210}$Po and its grandparent $^{210}$Pb, only very few data exist on $^{210}$Pb and $^{210}$Po levels in vent organisms (Cherry et al., 1992). The specific radioactivity of particles depends upon the production rate; however, if the vents are acting as a source of hydrothermal waters enriched in $^{210}$Po and $^{210}$Pb, then particles in the vent field might also be expected to be enriched in these radionuclides, leading to a potential enhancement of their food-chain transfer in areas adjacent to the vents. In order to assess the impact of shallow water hydrothermal inputs on the biogeochemical cycling of $^{210}$Po and $^{210}$Pb in the coastal marine environment, sediment trap material and soft tissues of benthic molluscs grazing on or living near microbial mats were collected within the sulfur-rich vent zone off Milos Island (Aegean Sea) and analyzed for their $^{210}$Po and $^{210}$Pb content.

2. Material and methods

Sinking particles were collected at a shallow depth (60 m) during eight different periods in summer 1996 using sediment traps moored at two different locations in the Aegean Sea, viz. in the vent zone of Palaeochori Bay off the southeast coast of Milos Island and in a nearby area off Provates Bay presumed to be free of the influence of hydrothermal fluids emitted from the vents (see Miquel et al., 1998; Miquel et al., in preparation).

Other samples of bottom sedimentary material and marine organisms were collected by Scuba diving in close proximity to the vents in Palaeochori Bay, an area some several hundred meters wide. Two replicate samples of the top few millimeters of microbial mats, which formed a whitish floc layer over the sediment, were collected at the same site during June and another sample was taken during September from a different location in the eastern sector of the bay. The top layer of yellow, sulfur-containing sand adjacent to the vent opening was also collected by syringe. Samples of the gastropod *Cyclope neritea* which was always found grazing on the microbial mat and a bivalve *Tellina tenuis* living in the sand near the mats were depurated and dissected into shell and soft parts. The soft parts of the two molluscs, surface sediments, microbial mat and sediment trap material were freeze-dried and 35 ± 2 MBq of $^{209}$Po ($T_{1/2} = 103$ y) tracer were added to each sample as a yield determinant. Using a standard procedure (Flynn, 1968) modified by Carvalho (1988) and Cherry et al. (1992), the samples were acid-digested in Teflon beakers using a mixture of hot concentrated HNO$_3$–HF or HNO$_3$, and H$_2$O$_2$ and HCLO$_4$ for sedimentary material and marine organisms, respectively. The acid digest was treated by repeated evaporation with the corre-
sponding mixture followed by concentrated HCl. The residue was subsequently taken up in 100 ml of 0.5 N HCl. Polonium was allowed to spontaneously deposit for 4 h (at 80°C in the presence of 10 mg of ascorbic acid) on one side of a polished silver disc placed in a spinning holder and immersed in the solution. After the first deposition of polonium, the solution was evaporated in the presence of a piece of silver to ensure that all the ^{210} Po remaining in the solution was removed. The plating solutions were stored for approximately 6 months to allow the ingrowth of ^{210} Po from ^{210} Pb present in the sample. A second plating was then performed to calculate the ^{210} Pb activity in the original sample (35 ± 2 mBq of ^{209} Po tracer was added to each sample as a yield determinant).

Alpha counting was performed using silicon surface-barrier detectors (R type, 300 mm², 100 μm depletion depth) connected to an 8-dual module alpha spectrometer. The ^{210} Po and ^{210} Pb contents were calculated on a dry weight basis and corrected for ^{210} Pb decay from the collection date. The counting times were adjusted to yield propagated counting errors < 5%.

The organic carbon content of the biota and sediment samples was measured using a Heraus CHN analyzer following the methodology described by Miquel et al. (1994).

### 3. Results and discussion

#### 3.1. ^{210} Po and ^{210} Pb levels in settling particles

The ^{210} Po and ^{210} Pb contents in sediment trap material collected in the vicinity of vents and in a ‘control’ area presumed to be free of the influence of hydrothermal fluids are presented in Table 1. ^{210} Po specific activities ranged from 1.19 ± 0.11 Bq g⁻¹ dw to 3.60 ± 0.09 Bq g⁻¹ dw in the vent zone, and from only 1.73 ± 0.05 Bq g⁻¹ dw to 2.49 ± 0.15 Bq g⁻¹ dw in the control zone. These levels are in the same order of magnitude as the average ^{210} Po specific activity 1.02 Bq g⁻¹ dw reported by Heussner et al. (1990) for sediment trap material collected during the summer in the coastal northwestern Mediterranean Sea, far from any vent influence. Our data were also comparable to the mean ^{210} Po specific activity 0.9 Bq g⁻¹ dw obtained by Radakovitch et al. (1999) for sediment trap material collected at a 100-m depth on the northwestern Mediterranean margin and to the range of ^{210} Po specific activities 0.42–0.72 Bq g⁻¹ dw obtained in pelagic sediment trap material from the East Pacific (Harada and Tsunogai, 1986).

<table>
<thead>
<tr>
<th>Site</th>
<th>Sampling period 1996</th>
<th>Mass flux (g/m²/d)</th>
<th>^{210} Po (Bq/g)</th>
<th>^{210} Po flux (Bq/m²/d)</th>
<th>^{210} Pb (Bq/g)</th>
<th>^{210} Pb flux (Bq/m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2–14 Jul</td>
<td>0.026</td>
<td>1.84 ± 0.15</td>
<td>0.05</td>
<td>0.48 ± 0.04</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>7–19 Aug</td>
<td>0.05</td>
<td>2.49 ± 0.15</td>
<td>0.13</td>
<td>0.32 ± 0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>19–31 Aug</td>
<td>0.46</td>
<td>2.42 ± 0.07</td>
<td>1.12</td>
<td>0.19 ± 0.01</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>31 Aug–12 Sep</td>
<td>0.34</td>
<td>2.18 ± 0.06</td>
<td>0.75</td>
<td>0.57 ± 0.019</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>12–24 Sep</td>
<td>1.01</td>
<td>1.73 ± 0.05</td>
<td>1.75</td>
<td>0.57 ± 0.02</td>
<td>0.57</td>
</tr>
<tr>
<td>Vents</td>
<td>20 Jun–2 Jul</td>
<td>2.44</td>
<td>3.60 ± 0.09</td>
<td>8.81</td>
<td>0.13 ± 0.01</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>2–14 Jul</td>
<td>5.90</td>
<td>1.23 ± 0.05</td>
<td>7.29</td>
<td>0.06 ± 0.006</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>14–26 Jul</td>
<td>1.60</td>
<td>1.36 ± 0.06</td>
<td>2.18</td>
<td>0.05 ± 0.006</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>26 Jul–7 Aug</td>
<td>0.04</td>
<td>1.90 ± 0.16</td>
<td>0.07</td>
<td>0.14 ± 0.02</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>7–19 Aug</td>
<td>0.02</td>
<td>1.19 ± 0.11</td>
<td>0.02</td>
<td>0.17 ± 0.03</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>31 Aug–12 Sep</td>
<td>4.76</td>
<td>3.09 ± 0.07</td>
<td>14.70</td>
<td>0.17 ± 0.01</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>12–24 Sep</td>
<td>2.88</td>
<td>3.19 ± 0.07</td>
<td>9.21</td>
<td>0.37 ± 0.01</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Counting errors at 1 S.D. are also given.
When specifically comparing $^{210}$Po levels in settling particles collected during the same period at the control site and the vents area, there was no significant evidence ($P = 0.05$; paired $t$-test) from the trap data that the sulfur-rich environment in the vicinity of vents was enhancing $^{210}$Po levels in the settling particles (Fig. 1).

$^{210}$Pb levels in sediment trap material varied from $0.19 \pm 0.01$ to $0.57 \pm 0.02$ Bq g$^{-1}$ dw in the control area and from $0.05 \pm 0.006$ to $0.37 \pm 0.01$ Bq g$^{-1}$ dw near the vents. The range of $^{210}$Pb specific activities measured in our study was in agreement with the average $^{210}$Pb level of 0.2 Bq g$^{-1}$ dw obtained by Heussner et al. (1990) for particulate material collected in the northwestern Mediterranean basin. Our $^{210}$Pb specific activities in the settling particles from the control site were also comparable to the mean $^{210}$Pb level $0.255 \pm 0.006$ Bq g$^{-1}$ dw obtained by Wei and Murray (1994) for sediment trap material collected at a shallow depth in the Black Sea. Like $^{210}$Po, $^{210}$Pb levels showed no enhancement in particulate matter collected in the vent zones (Fig. 2). When tested for the same time periods, particles from the ‘control site’ tended to contain significantly ($P = 0.025$) more $^{210}$Pb than those in the vent zone, a fact which is reflected in the lower range of $^{210}$Po/$^{210}$Pb ratios observed in the ‘control’ particles (Table 2). The range of ratios we obtained for the vent particles was higher than the average ratio in particles reported for the northwestern Mediterranean (Heussner et al., 1990) and for the Black Sea, i.e. 0.68–1.13 (Wei and Murray, 1994). According to Radakovitch et al. (1997), the $^{210}$Po/$^{210}$Pb ratio depends not only on the settling transit time, but also on the nature of the particles. The ratio is generally close to 1 in sediments, approximately 2 in fecal pellets, 7 in

![Fig. 1. $^{210}$Po levels in settling particles collected during similar periods in the control and vent areas. Errors represent the counting error at 1 S.D.](image-url)
phytoplankton and 30 in zooplankton detrital material. In addition, the behavior of $^{210}$Po in the ocean differs from that of $^{210}$Pb, especially because of the higher affinity of $^{210}$Po for organic matter (Wei and Murray, 1994; Radakovitch et al., 1998). Therefore, the nature and the fluctua-

Table 2
Ranges of $^{210}$Po and $^{210}$Pb vertical fluxes (Bq m$^2$ d$^{-1}$) and $^{210}$Po/$^{210}$Pb ratios associated with the flux of settling particles observed during the sampling periods at the control area and in the vents area compared to literature data

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Aegean Sea control area</th>
<th>Aegean Sea vents</th>
<th>NW Mediterranean Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical fluxes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>0.048–1.75</td>
<td>0.021–14.7</td>
<td>0.745 (Heussner et al., 1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.12–0.96 (Tateda et al., 1997)</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>0.012–0.576</td>
<td>0.003–1.07</td>
<td>0.120 (Heussner et al., 1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5–0.20 (Tateda et al., 1997)</td>
</tr>
<tr>
<td><strong>Ratio</strong></td>
<td>$^{210}$Po/$^{210}$Pb</td>
<td>3.0–7.8</td>
<td>7.0–20.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.21 (Heussner et al., 1990)</td>
</tr>
</tbody>
</table>

*Range include only values from Table 1 for comparable sampling periods at both sites.
tions of the relative proportion of organic and inorganic fractions in sinking particles may have a greater influence on resultant 210Po and 210Pb levels than any input from vent emissions.

3.2. 210Po and 210Pb fluxes

Vertical fluxes of 210Po and 210Pb through a 60-m depth were computed from the 210Po and 210Pb specific activities in settling particles and the mass flux measured by Miquel et al. (1998). The radionuclide fluxes measured at the control site and the vent area off the coast of Milos Island given in Table 1 are comparable with the values reported for sediment trap material collected in the northwestern Mediterranean Sea in summer (Heussner et al., 1990) and autumn (Tateda et al., 1997).

When comparing the particulate 210Po and 210Pb vertical fluxes measured during the same periods in the vent and in the control area (Table 1), it appears that the range of fluxes of these two radionuclides tended to be, on average, higher in the vent zone, even if the difference is not significant at the 0.05 level (paired t-test). According to our results, this difference is not due to high radionuclide levels in the settling particles near the vents, but rather to the high particle flux in the vent zone. Clearly, productivity and the resultant biogenic particle fallout are enhanced near the vents (Miquel et al., 1998; Miquel et al., in preparation), which in turn, increase the downward radionuclide flux. Therefore, vents can indirectly regulate the radionuclide flux by affecting the types and amount of particles produced in hydrothermal areas.

3.3. 210Po and 210Pb levels in biota and sediment samples

In this particular ecosystem where high sulfur-reducing and sulfur-oxidizing regimes are associated with the vents (Dando et al., 2000), it is expected that given the similar chemical characteristics of sulfur and polonium, sulfur-rich vents could also be highly enriched in polonium, leading to a potential enhancement of polonium levels in biota present in adjacent areas.

Surface sediment in the vicinity of vents were horizontally stratified in distinct concentric colored layers: an inner yellow sediment layer immediately around the vent outlet (not always visible), an intermediate white layer (microbial mat), and a dark-green external layer surrounding the vent (not analyzed). A black sediment layer was underlying the white layer (Aliani et al., submitted). In some cases, the black sediment was uncovered since the mat had been scoured by current or storm action. The results of 210Po and 210Pb content of some of these layers are shown in Table 3. Specific activities of both radionuclides were consistent in the two microbial mat samples at approximately 1 Bq g⁻¹ 210Po and 0.12 Bq g⁻¹ 210Pb. The yellow and black sediments contained variable, but generally low levels of both radionuclides compared to that in the microbial mats.

Table 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Collection dates</th>
<th>210Po (Bq/g)</th>
<th>210Pb (Bq/g)</th>
<th>210Po/210Pb</th>
<th>C org % dry wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow sediment</td>
<td>20 Jun 96</td>
<td>0.10 ± 0.01</td>
<td>0.02 ± 0.002</td>
<td>5.0</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Black sediment</td>
<td>20 Jun 96</td>
<td>0.06 ± 0.008</td>
<td>0.01 ± 0.002</td>
<td>6.0</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Black sediment under mat</td>
<td>20 Jun 96</td>
<td>1.00 ± 0.08</td>
<td>0.23 ± 0.03</td>
<td>4.3</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Black sediment under mat</td>
<td>29 Sep 96</td>
<td>0.20 ± 0.01</td>
<td>0.05 ± 0.004</td>
<td>4.0</td>
<td>0.17</td>
</tr>
<tr>
<td>White microbial mat layer</td>
<td>20 Jun 96</td>
<td>1.02 ± 0.13</td>
<td>0.12 ± 0.02</td>
<td>8.5</td>
<td>4.9</td>
</tr>
<tr>
<td>White microbial mat layer</td>
<td>20 Jun 96</td>
<td>0.81 ± 0.08</td>
<td>0.12 ± 0.02</td>
<td>6.8</td>
<td>4.7</td>
</tr>
<tr>
<td>Gastropod Cyclope neritea</td>
<td>29 Sep 96</td>
<td>0.23 ± 0.02</td>
<td>0.07 ± 0.006</td>
<td>3.3</td>
<td>23.1</td>
</tr>
<tr>
<td>Bivalve Tellina tenuis</td>
<td>20 Jun 96</td>
<td>1.92 ± 0.16</td>
<td>0.04 ± 0.01</td>
<td>48</td>
<td>27.9</td>
</tr>
</tbody>
</table>

Errors represent the analytical error at 1 S.D.
One of the black sediment replicates contained higher $^{210}$Po and $^{210}$Pb levels suggesting possible contamination from mat material; however, the uniformly low carbon content of all the sediment samples indicated that this was not the case. It is, perhaps, noteworthy that the $^{210}$Pb activity in the white microbial mat samples, $0.12 \pm 0.02$ Bq g$^{-1}$, fell within the range of total $^{210}$Pb level $0.10\,\text{to}\,0.22$ Bq g$^{-1}$ measured in the top 1-cm layer of a vertically stratified microbial mat produced under specific conditions of winds and waves in the Ebro Delta (NW Mediterranean Sea) where atmospheric input is considered to be the sole source of this radionuclide (Sanchez-Cabeza et al., 1999).

The so-called microbial mat is really a white mineral precipitate containing micro-organisms comprising mainly of various types of bacteria (Dando et al., 2000). Despite this biological component, the mats also have a significant inorganic content as demonstrated by the relatively low organic carbon fraction in them (i.e. $\sim 5\%$, Table 3). The benthic organism Cyclope neritea, a herbivorous gastropod, was always observed to be grazing on the abundant, whitish microbial mats present around the vents (Southward et al., 1997). Likewise, the small clam Tellina tenuis, a facultative deposit feeder which, depending on food bioavailability, can feed on either suspended or deposited material, was found in the sediment near the mats. It was, therefore, of interest to analyze $^{210}$Po and $^{210}$Pb levels in the mats and soft parts of the molluscs living in the vent area to assess a possible enhancement in the concentrations of these natural radionuclides and to evaluate their resulting food chain transport (Table 3). The $^{210}$Po and $^{210}$Pb levels measured in the gastropod Cyclope neritea were similar to the median values $0.27$ Bq g$^{-1}$ and $0.01$ Bq g$^{-1}$ dry weight of numerous data compiled from the literature for various non-vent organisms (Cherry et al., 1992). The $^{210}$Po level observed in Cyclope neritea from the Milos vent area was one order of magnitude higher than the other available data for gastropods collected in the NW Mediterranean Sea, i.e. $^{210}$Po specific activity of $0.02$ Bq g$^{-1}$ dry weight measured in Buccinum sp. (Boisson and Carvalho, in preparation). However, this gastropod, being principally a carnivore, has a different feeding behavior than Cyclope neritea.

Likewise, the $^{210}$Po level measured in the bivalve Tellina tenuis, viz. $1.92$ Bq g$^{-1}$ dry weight, was compared to data available for bivalve species (filter feeders) collected in the NW Mediterranean Sea. The average specific activity in Tellina tenuis was higher than the range of values reported for mussel soft parts, i.e. $0.17\text{--}1.29$ Bq g$^{-1}$ dry weight (Heyraud et al., 1994), and one order of magnitude higher than the levels $0.07$ Bq g$^{-1}$ dry weight and $0.08$ Bq g$^{-1}$ dry weight measured in Cerastoderma glaucum and Crassostrea gigas, respectively (Boisson and Carvalho, in preparation). More specifically, the $^{210}$Po content found in soft parts of Tellina tenuis was significantly higher than the average value ($0.234 \pm 0.003$ Bq g$^{-1}$ dw, unpublished data) obtained for Tellina sp. originating from the NW Mediterranean Sea outside the influence of any vent activity.

Therefore, although the data are very limited, the ingestion of bacteria associated with these mineral mats may result in an enhancement of $^{210}$Po levels in certain benthic molluscs living near the Milos vents. However, this does not appear to be the case for Pb, as evidenced by the very low $^{210}$Pb specific activity ($0.04$ Bq g$^{-1}$) and high $^{210}$Po/$^{210}$Pb ratio (48) in Tellina tenuis, which is typical of non-vent organisms (Cherry et al., 1992). This is interesting in that Cherry et al. (1992) found significant $^{210}$Pb enhancement in deep water hydrothermal vent polychaetes (0.42--15.1 Bq g$^{-1}$ dry weight) and attributed this to the ingestion of sulfide mineral particles. Hence, the lack of $^{210}$Pb enrichment which we noted, particularly in the bivalve Tellina tenuis, may reflect a different feeding strategy, digestive physiology and Pb assimilation efficiency compared to that of Alvinellid polychaetes.

In an earlier radiological survey carried out around Milos Island by Florou and Kritidis (1991), thorium and radium nuclides were analyzed in marine flora and fish. With the exception of somewhat elevated levels of $^{228}$Th and $^{228}$Ra in the sea grass Posidonia oceanica, they found no apparent enhancement of these natural radionu-
clides in any of the macroalgae or fish examined. Although those authors did not measure $^{210}$Po and $^{210}$Pb in their samples, our results indicating a lack of overall enhancement of $^{210}$Pb in the marine samples from Milos Island generally support the findings and conclusions of the earlier survey.

4. Conclusions

The nature and fluctuations of the relative proportion of organic and inorganic fractions in sinking particles may have a greater influence on $^{210}$Po and $^{210}$Pb levels than any input from vent emissions. Thus, the downward radionuclide flux is increased near the Milos vents primarily by the increased productivity and resultant biogenic particle fallout rather than by any enhancement of $^{210}$Po and $^{210}$Pb levels in the surrounding waters. In this manner, vents can indirectly regulate the radionuclide flux by affecting the types and amount of particles produced in underwater hydrothermal areas. In addition, $^{210}$Po levels in the local marine food chain, represented by benthic molluscs, tended to be somewhat enhanced by the venting activity. Considering the available data, the hydrothermal emissions in the shallow Aegean Sea off Milos Island do not appear to have any major effect on the biogeochemical cycling of the natural radionuclides $^{210}$Po and $^{210}$Pb in the water column; however, a possible influence on their enhancement and subsequent transfer in the local marine food chain should be considered. Nevertheless, further studies are needed to provide additional comparative data on $^{210}$Po and $^{210}$Pb levels in different types of biota living in the vent area and outside any hydrothermal influence in order to confirm the preliminary observations reported here.

Acknowledgements

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