^{90}Sr level and behaviour in the terrestrial environment of Spitsbergen

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Abstract

The research was focused on the level and distribution of ^{90}Sr in various parts of the terrestrial environment of Spitsbergen. The mean activity concentrations were noted lower in peats and soils than in cryoconite. Analysis of vertical variation of ^{90}Sr for soils and peats as well as isotopic ratios of $^{137}\text{Cs}/^{90}\text{Sr}$ and $^{239+240}\text{Pu}/^{90}\text{Sr}$ for cryoconite clearly showed substantial migration or depletion of the considered radionuclide. Due to the large dispersion of isotopic signatures, the ^{90}Sr provenance was difficult to identify in the examined region. However, observed high mobility of the ^{90}Sr might indicate the global fallout origin.

Keywords Radiostrontium · Spitsbergen · Radionuclide migration · Cryoconite · Soil · Peat

Introduction

The radioactive fission product ^{90}Sr has a sufficient half-life ($T_{1/2} = 28.8$ y, $E_{\text{max}} = 546$ keV) to be detected for a long time period after it has appeared in the environment. Due to chemical similarity to calcium, ^{90}Sr is uptaken and easily accumulated by various objects of animate and inanimate nature. The radiotoxic effect of ^{90}Sr is additionally increased by progeny— ^{90}Y ($T_{1/2} = 64$ h, $E_{\text{max}} = 2285$ keV)—, which exists in equilibrium with ^{90}Sr for most environmental samples. Therefore radiostrontium may be considered as a highly hazardous anthropogenic radionuclide.

The worldwide presence of ^{90}Sr , to at least measurable extent, has been caused intentionally or accidentally since the 1940s, as a consequence of various human nuclear activities. For the High Arctic terrestrial environment, the most significant release is associated with the stratospheric global fallout (GF) [1, 2, 48]; i.e., far-reaching radioactive contamination injected into the atmosphere during nuclear weapons testing (1945–1980). The AMAP group estimated that the total inventory of ^{90}Sr from the global fallout was around 21.9 PBq (decay corrected to 1995) over the land north of 60° N [1]. One of the largest yield test sites was located in the Arctic on the island of Novaya Zemlya. From 1955 to 1990 this territory was used by the Soviet Union for 88 atmospheric, 39 underground and 3 underwater nuclear explosions [23]. Despite an extensive nuclear programme, major tests were carried out at high altitudes, minimizing local and enhancing global fallout [48].

Chernobyl NPP's accident has become an important source of ^{90}Sr after 1986. Due to the different mode of the explosion, than during weapons testing, radiostrontium dispersion occurred in a relatively small range reaching mainly immediate vicinity of the Chernobyl. More specifically, the bomb derived deposition of ^{90}Sr was lower (about 30–35%) than ^{137}Cs , whereas in the Chernobyl fallout the fraction of ^{90}Sr was much lower, approximately in the range of 1–10% of ^{137}Cs , depending on the distance from accident zone [26]. In total, the released activity of ^{90}Sr from the Chernobyl NPP's failure exceeds slightly 1% of the weapons test

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fallout [26]. The Arctic archipelago of Svalbard is generally believed to be relatively unaffected by the post-Chernobyl radiostrontium [38].

Of lesser concern, but still worthy of consideration nonetheless, is the possible contribution of the sea-to-land transfer of marine contaminants. The main radioactive discharges into the Arctic Ocean derived from the nuclear fuel reprocessing plants located in Western Europe (Cap de La Hague, France, and Sellafield, UK) and from nuclear facilities in Russia (Mayak PA; SCC, Tomsk; MCIC, Zheleznogorsk) placed within catchments of the Ob and the Yenisey rivers—major freshwater inflows of the Arctic seas [22, 25]. Furthermore, dumped nuclear waste, sunken nuclear submarines in the Arctic Ocean comprise other potential sources of ^{90}Sr , once any leakage occurs [18, 40, 45].

The original distribution of radionuclides stored in the ecosystem changes over time. For the Arctic region, these changes may be, particularly, related to soil erosion, snow or marine aerosols, sea currents, an ice pack or iceberg drift and, finally, deposition of contaminated faeces (guano) by animals (predominantly birds) [11]. Different physicochemical forms of radionuclides (i.e., radionuclide species) affect their transport/mobility and bioavailability [41]. The modern issue is that the Arctic's climate and weather patterns are changing most rapidly [4]. Rising air, surface and ocean temperatures are accelerating the decline of ice (including glaciers) and snow cover, as well as inducing direct and indirect effects on the interconnected physical, chemical and biological systems in the Arctic. Thus, global warming may be a significant factor triggering or enhancing both spatial and temporal variations in the distribution of contaminants trapped in the polar region [2, 3].

To identify and verify the levels, trends as well as dispersion and migration pathways of the contaminants accumulated or released by various elements of ecosystems, only selected environmental media are being commonly used. In recent years cryoconite holes have begun drawing attention among matrices known to be efficient in accumulating of radioisotopes and typically adopted for radioecological monitoring, such as lichens, mosses, peats, soils, sea and lake sediments. Cryoconite is a small size repository of a high level of pollutants on the glacier surfaces [9, 46]. These aggregates of mineral and organic components are associated with biological consortia. They decrease an ice-albedo and are responsible for the formation of water-filled holes. Research on heavy metals and radionuclides in different environmental media showed that cryoconite absorbs most of the analysed elements in high concentration [9, 42]. The hypothesis by Łokas et al. [30, 32] assumes that such material might be transferred into the proglacial zones while glaciers retreating, causing secondary contamination of the initial soils.

As established so far, the level of contamination in Spitsbergen appears to be lower than in temperate zones [10, 13, 15, 44]. This is a simple consequence of the fact, that major human activities (e.g., production and release of radionuclides) took place outside of the polar region. Although, Svalbard archipelago, as the Arctic region in general, remains particularly vulnerable to radioactive contamination. Due to large organic matrix content, the High Arctic environment may be considered as a 'sponge' for captured particles with significant retention and accumulation [12].

This study was dedicated to determining the ^{90}Sr content as well as tracking its behaviour in cryoconite, proglacial soils and peat profiles from Spitsbergen, Svalbard archipelago. The specific goals were to verify the ^{90}Sr mobility relative to other radionuclides (e.g., ^{137}Cs , Pu isotopes) and the possible transfer of pollutants from melting glacier to proglacial zones. Because of the limited knowledge in this area, the article provides scarce data on radiostrontium in various terrestrial ecosystems of Spitsbergen.

Material and methods

Study area and sampling

Svalbard (70° N, 20° E) is the Arctic archipelago placed north of the Arctic Circle between Greenland and Franz Josef Land. The meteorological conditions are temporally and spatially diverse due to the location at the confluence zone between cold and dry polar air masses from the north and warm and humid air masses from the Atlantic currents to the southwest [34]. Therefore, Svalbard has an extremely sensitive climate among other regions of the world [39]. The total glaciated area on Svalbard is 34,560 km² (57% of the entire territory). There are six major islands, of which Spitsbergen is the largest and the most alpine one, having small cirque glaciers, extensive ice fields and valley glaciers.

Sampling was done during seven field campaigns into the different regions of the Spitsbergen within 10 years (from 2005 to 2015). The research material comprised 49 cryoconite samples, 3 proglacial soil profiles, 1 tundra soil profile and 3 peat profiles. The cryoconite was collected from each sampling site, whereas the soil and peat profiles were derived only from the Werenskiöld area. The details of scientific expeditions into the Werenskiöld, Kafføyra and Kongsfjord areas and the description of the fieldworks were presented elsewhere [28, 29, 32, 33, 43]. Samples taken from the other study areas (i.e., Calypsobyen and Sørkapp Land), as a part of a wider scientific project, will be characterised in a future paper. Herein we consider only selected aspects, that

Fig. 1 The map of the Arctic archipelago of Svalbard with tagged study sites (black squares) and satellite pictures of the explored glaciers

Table 1 The details of the sampling positions

Region of Spitsbergen	Glacier	Type of sample	n
Kongsfjord	VESTRE BRØGGERBREEN	Cryoconite	13
	MIDTRE LOVÉNBREEN	Cryoconite	3
Kaffiøyra	WALDEARBREEN	Cryoconite	12
Calypsobyen	SCOTTBREEN	Cryoconite	5
	RENARDBREEN	Cryoconite	5
	BLOMLIBREEN	Cryoconite	2
	RECHERCHEBREEN	Cryoconite	2
	WERENSKIOLDBREEN	Cryoconite	5
Werenskiold		Soil profile	3
		Proglacial	
		Tundra	1
Sørkapp Land	SYKORABREEN	Peat profile	3
		Cryoconite	2

are common for all mentioned above Spitsbergen regions and research material. The locations of study sites are shown in Fig. 1 and the short sampling description is provided in Table 1.

Experimental

Strontium fraction was extracted from the sample matrix after gamma radiation measurement (^{137}Cs) by applying the sequential radiochemical treatment [35, 49]. As a result, the Pu, Th, Sr, Am and U fractions were obtained. The detailed information regarding the laboratory works was described by Łokas et al. [28, 31].

Detection of beta particles emitted by ^{90}Sr and ^{90}Y was based on the electron-scintillation conversion method [36]. The maximum beta energies of both nuclides are as high as follows: 0.54 MeV and 2.28 MeV, respectively. At least 2 weeks after separation, when the radioactive equilibrium between ^{90}Sr and ^{90}Y was reached, Sr fraction was mixed with the liquid organic scintillator followed by measurements on Wallac 1414-003 spectrometer. With the typical counting time of 30,000–45,000 s, the detection limit averaged at 5 mBq per sample.

Calculation

We computed activity concentrations C (Bq/kg) and total inventories I (Bq/m²) for ^{90}Sr as well as isotopic ratios for selected pairs of radionuclides. These parameters were estimated with the aid of commonly known, simple equations [27]. Results were presented for the dry weight. The decay correction to the reference date 2020-01-01 was applied.

To infer the contamination origin, obtained isotopic ratios were compared to the signature typical for the global fallout (Table 2).

Table 2 Reference isotopic ratios of activity concentrations for the global fallout (decay corrected to 2020-01-01)

	$^{137}\text{Cs}/^{90}\text{Sr}^1$	$^{239+240}\text{Pu}/^{90}\text{Sr}^1$
Global fallout NH, 2020	1.5	0.07

¹[48]

The law of propagation of uncertainty and the standard deviation of the mean [47] were used to estimate the errors associated with calculated parameters (only 1 σ was taken).

Evaluation of the analytical quality was performed by the analysis of IAEA reference materials (soil 375, moss-soil 447) using the same procedure as for the sample set. These results were presented by Łokas et al. [28, 31].

Results and discussion

Activity concentration of ^{90}Sr in cryoconite

The highest individual and mean activity concentrations were observed for cryoconite from Werenskiold (Table 3), that is the most southern study site along the west shoreline of Spitsbergen. Moreover, the widest range of results was also noted in Werenskiold (Fig. 2a). In contrast, the most southern Sørkapp Land, placed on the east coastline of Spitsbergen, together with Calypsobyen and Kongsfjord, characterised the lowest mean activity of ^{90}Sr for cryoconite (Table 3). For the latter regions rather high consistency of result ranges was observed (Fig. 2a).

The data by Łokas et al. [31] revealed the average activity concentration of ^{90}Sr at 57 ± 8 Bq/kg for cryoconite collected from Hans glacier, Hornsund fjord (SW Spitsbergen). Our results were slightly lower, although represented the same order of magnitude for cryoconite from Kongsfjord and other studied regions, except Werenskiold.

Fig. 2 The box-whisker plots illustrating the ranges of ^{90}Sr activity concentrations (a) and dispersions of the isotopic ratios of $^{137}\text{Cs}/^{90}\text{Sr}$ (b), and $^{239+240}\text{Pu}/^{90}\text{Sr}$ (c) for the investigated Spitsbergen sites

Table 3 The mean, min and max values of ^{90}Sr activity concentration for examined Spitsbergen sites

Region	Glacier/type of sample	n	^{90}Sr ($\text{Bq}\cdot\text{kg}^{-1}$)		
			Min	Mean	Max
Kongsfjord	VESTRE BRØGGERBREEN/cryoconite	16	8.0 ± 1.3	35.8 ± 5.8	85.2 ± 8.2
	MIDRTE LOVÉNBREEN/cryoconite				
Kaffiøyra	WALDEMARBREEN/cryoconite	12	11.9 ± 3.1	60 ± 14	151 ± 21
Calypsobyen	SCOTTBREEN/cryoconite	14	15.6 ± 2.6	36.4 ± 3.8	63 ± 18
	RENARDBREEN/cryoconite				
	BLOMLIBREEN/cryoconite				
	RECHERCHEBREEN/cryoconite				
Werenskiöld	WERENSKIOLDBREEN/cryoconite	5	18.4 ± 4.1	107 ± 17	215 ± 19
	WERENSKIOLDBREEN/proglacial soil profile	3	4.11 ± 0.20	5.31 ± 0.69	6.50 ± 0.52
	WERENSKIOLDBREEN/peat profile	3	7.42 ± 0.60	12.7 ± 2.9	17.36 ± 0.70
Sørkapp Land	SYKORABREEN/cryoconite	2	26.3 ± 4.9	35.9 ± 9.6	45.6 ± 9.1

Therefore, one might claim, that the level of radiostrontium was relatively similar for both projects.

However, analysing Table 3; Fig. 2a, the considerable difference between results for cryoconite as well as soil and peat profiles derived from Werenskiöld could be noted. Activity concentrations for the latter were even two orders of magnitude lower than in cryoconite samples. This observation corresponds to the previous findings. Namely, cryoconite granules are considered as highly rich in natural (unsupported ^{210}Pb) and artificial radioisotopes, significantly more radioactive than other environmental matrices routinely used in radioecological monitoring [9].

Activity concentration and inventory of ^{90}Sr for soil and peat

Peat profiles, collected from the strandflat adjacent to the proglacial zone of Werenskiöld, were named as P3, P5 and P6 [29]. Proglacial soil profiles were coded as GA, GB, GC—according to decreasing distance from the Werenskiöld glacier terminus—, whereas H1 represented the only one tundra soil core [32]. To better interpret ^{90}Sr results, we included also information on ^{137}Cs and $^{239+240}\text{Pu}$ activity concentrations for each profile, already analysed and published elsewhere [29, 32].

Table 3 provides the means and ranges of ^{90}Sr activity concentration and Table 4 presents ^{90}Sr inventory for each core. Generally, the inventories varied between $128.1 \pm 4.9 \text{ Bq/m}^2$ (P3) and $1082 \pm 104 \text{ Bq/m}^2$ (GC). The UNSCEAR report [48] estimated the deposition of ^{137}Cs over the globe due to weapons testing, distinguishing

different Earth's regions. Assuming 1.5 is the isotopic ratio of $^{137}\text{Cs}/^{90}\text{Sr}$, deposition of radiostrontium derived from the global fallout, should have reached approximately 0.63 kBq/m^2 for $70\text{--}80^\circ \text{ N}$ latitude belt (decay corrected to the year of 2020). The above assessment provided a reference point, which was relatively compatible with inventories for P5, H1, GA and GB. This might suggest the global fallout as prevailing source of radiostrontium for the Werenskiöld area, but the more profound analysis is necessary to infer the origin.

^{90}Sr inventory discrepancies between peat profiles P5 and P3, P6 were, most likely, caused by the lithological heterogeneity of the examined samples. Upper intervals of P3 and P6 consisted of fresh moss-peat, whereas lower layers were strongly humified. In contrast, the bottom part of the profile P5 contained considerable amounts of mineral matter as expressed by the lower loss on ignition (LOI) values [29]. Such conclusion was additionally confirmed by analogous behaviour of ^{137}Cs for mentioned peat profiles [29].

Activity concentrations were higher in the case of the peats (Table 3), but total inventories turned out to be greater for the soil profiles (Table 4). The main reason for such inversion could be related to notably larger surface mass density (kg/m^2) for soil layers and entire cores; the mass data was presented by Łokas et al. [29, 32]. On the other hand, peat accumulates pollutants more efficiently than soil (hence higher activity concentrations), which could somewhat compensate lower bulk density of peats for inventory estimation. The analysis of ^{137}Cs inventories in peat [29] and soil profiles [32] by Łokas et al., revealed large differences between tundra samples (soil and peat) and proglacial material (soil). Namely, results for initial soils GA, GB and

Table 4 Inventory of ^{90}Sr for peat and soil profiles collected from Werenskiöld, Spitsbergen

Sample code	P3	P5	P6	H1	GA	GB	GC
^{90}Sr I (Bq/m^2)	128.1 ± 4.9	691 ± 57	234.0 ± 9.6	465 ± 22	586 ± 28	558 ± 45	1082 ± 104

GC reached significantly higher levels of ^{137}Cs in comparison with profiles H1, P3, P5 and P6, whereas for the latter ones ^{137}Cs inventories were rather less varied. Therefore, we cannot linkage dissimilarities of activity concentrations and total inventories of ^{90}Sr between examined peat and soil profiles with LOI values only. The problem seems to be more complex and affected by other factors.

Further interpretation of the data set requires understanding the mode of pollutant deposition for initial soil as well as tundra soil and peat profiles. Generally, the tundra is rather exposed for fresh fallout (i.e., suspended airborne particles, aerosols), which might be captured and accumulated almost continuously, in accordance with temporal flux variations of the given radioisotope. (Other processes of radionuclide supplies could also take place, however, atmospheric deposition is assumed as dominating). If so, such media should record, layer-by-layer, the history of the fresh radioactive fallout. In contrast, the proglacial zone was covered by the ice cap for most of the time, thus the ground was unavailable for suspended airborne particles. It is only when the glacier begins to melt that proglacial soils open up to the direct atmospheric fallout. Therefore, the radionuclide content within recent initial soils is derived mostly from melted ice, as the pollutants are deposited on its surface (e.g., in form of cryoconite). This mode of contaminant pathway throughout the ecosystem may be called secondary transport. No temporal changes of the radioactive fallout (i.e., changes with the core depth) are preserved correctly in such samples (unless they would become uncovered early enough to record fresh air deposition).

Following Fig. 3, the diversity of vertical radionuclide variations for proglacial and non-proglacial cores is evident. Tundra profiles P3, P5, P6 and H1 preserved temporal fallout oscillations over the Spitsbergen territory, but only for ^{137}Cs and $^{239+240}\text{Pu}$. The observed peaks of ^{137}Cs and $^{239+240}\text{Pu}$ have been already linked to the Partial Nuclear Test Ban Treaty in 1963 [29, 32]; till then the nuclear weapons testing was the most intensive. The position of the maximum within the given profile depended mainly on the mass accumulation rate, which apparently varied from profile to profile. The initial soils GB and GC appeared to contain ^{137}Cs and $^{239+240}\text{Pu}$ from secondary sources only. However, the soil GA, collected from the longest distance from the glacier front position, had to be exposed early enough to record the maximum of the global fallout.

In contrast, vertical variations of the ^{90}Sr activity were distinctly inconsistent with ^{137}Cs and $^{239+240}\text{Pu}$ deposition records (Fig. 3). Even if the maximum of ^{90}Sr activity occurred (e.g., for P6), it was shifted relative to ^{137}Cs and $^{239+240}\text{Pu}$ peaks. Overall, ^{90}Sr profiles seemed to be strongly disturbed.

We claim, that the above described discrepancy resulted from enhanced mobility of ^{90}Sr compared to ^{137}Cs and

$^{239+240}\text{Pu}$. This phenomenon has been observed and reported by many researchers for a variety of soil types and environmental conditions since the 1950s [5, 6, 14, 19–21, 24]. For the Arctic tundra regions, the presence of thick lichen-moss layers on the ground surface prevents the substantial penetration of deposited radionuclides into the deeper layers of the vegetation-soil carpet. However, Sr can migrate faster, than Cs and Pu, from the upper to the lower moss-lichen sections and further down into the soil surface [16].

Environmental mobility of radiostrontium relative to radiocaesium, and particularly to plutonium, could be more intense when radionuclides occur in the ionic form attached to aerosols (e.g., atmospheric nuclear tests' origin). For the places contaminated by local and on-site fallout, no principle differences in depth distributions for anthropogenic radionuclides in soil were found even 30–40 years after the deposition [7, 17]. This is explained by the presence of radiostrontium and other fission or activation products in the form associated with small fuel particles that are rather stable for natural weathering and chemical treatment [37].

Taking into account the behaviour of radiostrontium in the tundra samples from Werenskiold (peats P3, P5, P6 and soil H1) as well as presented above theory regarding its mobility, the global fallout origin of ^{90}Sr is highly possible.

Variation of $^{137}\text{Cs}/^{90}\text{Sr}$ and $^{239+240}\text{Pu}/^{90}\text{Sr}$ isotopic ratios

To recognize the potential sources of environmental radioactive contamination, isotopic signatures were examined. In general, both $^{137}\text{Cs}/^{90}\text{Sr}$ and $^{239+240}\text{Pu}/^{90}\text{Sr}$ varied over wide ranges for each studied region of Spitsbergen (Fig. 2b, c). For cryoconite and, to a minor scale, for initial soils the mean values of ratios were extremely higher than reference values of the global fallout (Fig. 2b, c; Table 2). The overall analysis of $^{137}\text{Cs}/^{90}\text{Sr}$ and $^{239+240}\text{Pu}/^{90}\text{Sr}$ results shed no light on the provenance of ^{90}Sr in glacial and proglacial zones. The enormous excess of Cs and Pu relative to Sr could not be assigned for any known releases of radioactivity. On the other hand, tundra samples (peats and soil) from Werenskiold were characterised by the range and mean values rather consistent with the weapons tests (Fig. 2b, c; Table 2).

The previous investigation for the Arctic archipelago of Svalbard concluded that the terrestrial environment was primarily contaminated with bomb-derived Pu isotopes and ^{137}Cs , and, to a lesser extent, by ^{137}Cs originating from the Chernobyl accident in 1986 [15]. For initial soils and cryoconite unexplained deviations from the weapons testing were noted, but mainly for $^{238}\text{Pu}/^{239+240}\text{Pu}$ and $^{240}\text{Pu}/^{239}\text{Pu}$ activity and mass ratios, respectively [29, 31, 33].

The studies by Bossew et al. [8], Tieber et al. [46] and Łokas et al. [31] showed the strong depletion of Sr activity in cryoconite media. $^{90}\text{Sr}/^{137}\text{Cs}$ and $^{90}\text{Sr}/^{239+240}\text{Pu}$ activity

Fig. 3 The plots present activity concentrations of ^{90}Sr , ^{137}Cs and $^{239+240}\text{Pu}$ versus core depths in soil and peat profiles from Werenskiöld (a—tundra, b—proglacial zone)

ratios, received by Łokas et al. [31] for SW Spitsbergen, varied from 0.04 ± 0.01 to 0.90 ± 0.13 and from 2.2 ± 0.8 to 48.5 ± 18.6 with mean values of 0.26 ± 0.06 and 12.4 ± 4.7 , respectively. Our results indicated even greater excess of Cs and Pu relative to Sr (Fig. 2b, c). Typically, Cs and Pu are more strongly bounded, Cs in clay minerals (omnipresent in cryoconite), Pu also in the organic matter,

whereas high solubility of Sr in water leads to its leaching to a much larger scale. Therefore, we assumed, following Bossew et al. [8], that Sr has been effectively removed from the examined cryoconite samples. This would also explain the loss of Sr relative to Cs and Pu observed for initial soils from Werenskiöld, since the radionuclides

found in proglacial zones, most likely, derived from the cryoconite.

Following the literature data and the observed intensive mobility of ^{90}Sr in the environment, the atmospheric weapons test fallout could be the major source of ^{90}Sr in each studied matrices and the entire examined region. However, isotopic signatures did not support such a thesis for all samples and sites.

Conclusion

Currently, the greatest attention in radiostrontium survey is paid to the dosimetric consideration, somewhat neglecting other environmental monitoring aspects. The presented research attempt was to fill the lack of knowledge regarding ^{90}Sr levels, transfer pathways and trends in various parts of the terrestrial environment of the High Arctic and continue radioecological monitoring in terms of ^{90}Sr .

Our results pointed out the relatively low level of ^{90}Sr activity concentrations in different environmental media of Spitsbergen. In general, the mean activities were higher for cryoconite than for peats and soils. The highest value of ^{90}Sr concentration was received for cryoconite from Werenskiöld. Moreover, the transfer of radiostrontium from retreating glacier to initial soils was noted, that confirms previous findings for Cs and Pu radioisotopes. The total inventory of ^{90}Sr in proglacial zones corresponded to estimation for adequate latitude belt, except the soil profile collected from the closest site to the glacier terminus. However, this value was not significantly higher than the reference level. No hot spot was discovered in terms of ^{90}Sr content in the entire region.

Analysis of the vertical changes of ^{90}Sr in the tundra soil and peat profiles revealed its significant migration throughout the cores. Furthermore, the strong depletion of radiostrontium compared to Cs and Pu for cryoconite matrix was detected.

Due to the large dispersion of both $^{137}\text{Cs}/^{90}\text{Sr}$ and $^{239+240}\text{Pu}/^{90}\text{Sr}$ ratios, the ^{90}Sr provenance could not be identified. Surprisingly, intensive mobility of ^{90}Sr might indicate the global fallout origin, because such property is attributed to ionic form, in which ^{90}Sr was released during nuclear weapons testing.

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