

THE CHERNOBYL SIGNATURE IN WESTERN ABKHAZIA: ASSESSING ^{137}Cs DEPOSITION VARIABILITY AND APPLICABILITY FOR EVALUATION SEDIMENT REDISTRIBUTION RATES

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ABSTRACT. This study presents the first documented evidence of radioactive contamination in Western Abkhazia linked to the Chernobyl Nuclear Power Plant accident. The data obtained show that the level of ^{137}Cs radioactive contamination in the study area ranged from 50 to 160 kBq/m² in 1986. This corresponds to contemporary values of 25 to 79 kBq/m² when considering the radionuclide's half-life. These measurements are highly consistent with data recorded in the adjacent Sochi region, where contamination levels varied between 40 and 185 kBq/m² in 1986. The local spatial variability of ^{137}Cs fallout was studied at four reference sites, located in different parts of the Mussera upland. All investigated sites demonstrated moderate variability, with value ranges of 17–25%. This heterogeneous distribution pattern is attributed to a combination of factors, including local topography, atmospheric deposition characteristics, and anthropogenic influence. Measurements of ambient dose equivalent rates ranged from 0.01 to 0.05 $\mu\text{Sv/h}$. While no direct correlation was found between dose rates and the age or genesis of the underlying bedrock, a clear relationship was established between dose rates and terrain morphology. Elevated dose rates were consistently recorded in erosional landforms within topographically dissected areas. Analysis of peat cores from the Pitsunda Peninsula lagoon provided conclusive evidence of the Chernobyl disaster's impact on Western Abkhazia, with a measured ^{137}Cs inventory of 20.7 kBq/m² (equivalent to 49.5 kBq/m² when corrected to 1986 values). Application of the non-equilibrium ^{210}Pb dating method yielded a peat accumulation rate of 0.1 cm/year.

The Chernobyl accident resulted in a significant release of ^{137}Cs , leading to widespread radioactive fallout. This document assesses the ^{137}Cs inventory and its impact on ambient dose rates in the affected regions.

KEYWORDS: reference value of Chernobyl-derived ^{137}Cs , dose rate, trend of initial fallout, ^{210}Pb dating, Mussera upland

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INTRODUCTION

Cesium-137 (^{137}Cs), as one of the key anthropogenic radionuclides, shows a high adsorption affinity to soil particles. During initial global fallout events (e.g., following nuclear bomb tests or technological accidents), a primary

contamination field was established (Buraeva et al., 2015; De Cort, 1998; Ivanov et al., 2022; Kuchava et al., 2019; Kuzmenkova et al., 2020; Sedighi et al., 2020; Tsitskishvili et al., 2020). However, subsequent water, wind, and tillage erosion processes lead to the active redistribution of ^{137}Cs across landscapes. The primary mechanisms that govern

the lateral migration rates of this radionuclide include: water erosion, which facilitates soil particle detachment and transport (Evrard et al., 2017; Golosov et al., 2021); aeolian erosion, which promotes fine particle entrainment, wind-driven transport, and redeposition (Van Pelt et al., 2007); and anthropogenic activities, particularly agricultural land use practices (Lobb et al., 1995). These processes, along with other more localised factors, significantly alter the initial radioactive contamination pattern. Notably, secondary accumulation zones emerge with ^{137}Cs inventories substantially exceeding initial deposition levels (Varley et al., 2018). Such anomalies predominantly occur in sedimentary sinks: lower segments of cultivated slopes; unmanaged slope bases; dry valley bottoms; river floodplains and water bodies (Golosov et al., 2018).

The relevance of studying these processes stems from the need to:

- Assess the consequences of radioactive accidents: the redistribution of ^{137}Cs affects the actual contamination levels of territories.
- Predicting contamination dynamics, understanding lateral migration mechanisms enables forecasting changes in radiation conditions.
- Develop rehabilitation measures. Identifying accumulation zones aids in planning risk mitigation strategies.

Moreover, ^{137}Cs has become an important tool in geomorphological studies. The presence of two distinct global fallout peaks (1963 from nuclear weapons testing and 1986 from the Chernobyl accident) can be identified in ^{137}Cs vertical distribution profiles in samples collected from accumulation zones across most of Europe and several regions of the Greater Caucasus. This radiocesium technique enables the dating of deposits and the estimation of sediment accumulation rates for two different time windows (Benoit and Rozan, n.d.; Efimov and Anisimov, 2011; Ito et al., 2020; Izrael, 2007; Łokas et al., 2017; Tashilova et al., 2019). This provides new opportunities for studying the dynamics of erosion-accumulation processes under various landscape conditions. Research on ^{137}Cs redistribution therefore represents an important interdisciplinary field combining radiation ecology, geomorphology, and environmental protection objectives.

The determination of reference inventories serves as the starting point for investigating relative changes in contaminant concentrations across a landscape. To establish the total deposition density of ^{137}Cs within a study area, reference sites are selected (Walling, 1999). These sites represent flat, geomorphologically stable surfaces (the upper parts of slopes, river terraces) where no loss or gain of ^{137}Cs has occurred since its initial deposition (Golosov et al., 2008).

When selecting reference sites, the following conditions must be satisfied:

represent stable lithodynamic zones, meaning soil erosion is negligible, changes in contaminant concentrations are minimal, and the ^{137}Cs inventory can be considered relatively 'undisturbed' (Ivanov, 2017).

Ideally, it should have been free from anthropogenic disturbances (for example, ploughing, soil levelling, or external material input) since the initial atmospheric deposition of ^{137}Cs , which means over the past 70 years.

preferably lack of woody vegetation, with grassland areas being the most suitable.

Verification of a reference site's undisturbed condition is conducted by analysing the vertical distribution profile of ^{137}Cs content, supported by examination of soil profile morphology (Owens, Walling, 1996; Sutherland, 1996; Golosov, 2002; Golosov et al., 2008). The vertical distribution of ^{137}Cs is obtained through layer-by-layer sampling from either a soil pit wall or an extracted monolith of fixed surface area, with typical sampling intervals of 2-5 cm. Analysis of the vertical distribution of radioisotopes within the soil column enables identification of the maximum contamination layer corresponding to the initial deposition event. In undisturbed sites, this layer is typically found in the near-surface horizon at a depth of 2-4 cm (Owens, Walling, 1996; Golosov et al., 2008).

Following the Chernobyl accident, various datasets concerning ^{137}Cs contamination in different European countries and regions were compared. These data had been collected for diverse purposes, leading to significant variations in their resolution and quality. Consequently, the Atlas of Caesium Contamination of Europe and the European Territory of Russia was compiled (Izrael, 2007). However, there remain areas where data continue to be collected through more thorough and extensive monitoring. This is particularly relevant for regions that experienced more substantial contamination. One such hotspot of Chernobyl-derived contamination is the Western Caucasus region (Fig. 1). In Abkhazia, such studies are especially important because the contaminated area remains undelimited, with its boundary coinciding with the state border.

According to the radioactive contamination map, the Western Caucasus region had an inventory of 10-40 kBq/m² as of 1986. This value includes radiocesium from global fallout and deposition from the Chernobyl accident.

The research objectives of the given study are as follows: a) a comprehensive assessment of ^{137}Cs specific activity and inventories in soils of Western Abkhazia, focusing on undisturbed near-watershed areas; b) an evaluation of initial deposition patterns across the Mussera Upland to establish baseline data for sediment accumulation rate

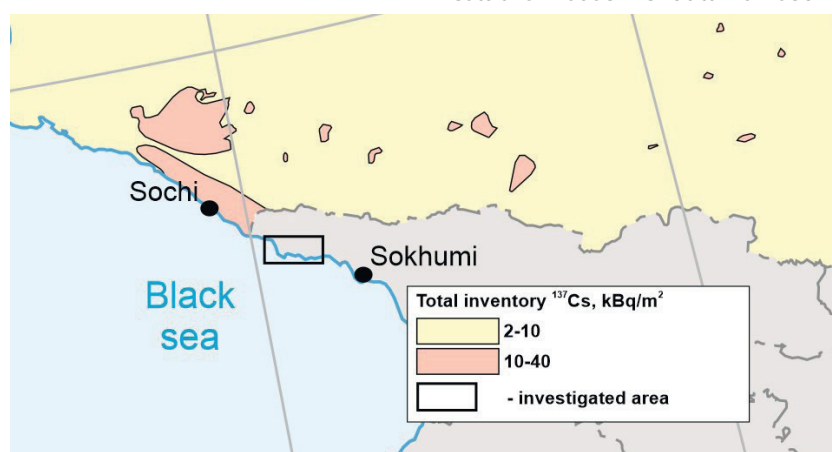


Fig. 1. Section of the ^{137}Cs contamination map of Europe following the Chernobyl NPP accident (Izrael, 2007)

studies; c) the quantification of the Chernobyl impact by determining total ^{137}Cs inventories along the Black Sea coastal zone within Western Abkhazia.

STUDY AREA

The Mussera Upland is a scenic natural and recreational zone characterised by its picturesque landscapes, mild climate, and significant potential for tourism development. Located in Abkhazia on the northeastern coast of the Black Sea, approximately 20 km northwest of Gudauta, the area encompasses the Mussera Nature Reserve, renowned for its pine forests and relict vegetation.

The climate is humid subtropical with warm winters and moderately hot summers. Average January temperatures range from 5 to 7°C, while August temperatures average between 23 and 24.7°C. In the mid-mountain areas, winters are cold, and summers are short and cool. January temperatures range from 2 to -2°C, and August temperatures are between 16 and 18°C. The average annual precipitation is 1400 mm. The soil cover includes subtropical zone soils such as red soils and podzolized red soils, yellow soils, strongly and moderately podzolic soils, weakly podzolic soils, and podzolic-gley soils. Bog and alluvial soils are also found in fragmented areas (Atlas, 1964). Plant communities include pine (*Pinus brutia* var. *pityusa*) stands, which are a relic of Neogene flora. Other communities are liana forests, lowland forests with evergreen undergrowth, foothill oak forests, foothill beech-hornbeam forests, beech forests, chestnut forests, spruce-fir forests, alpine meadows, and bogs dominated by sedge and grass.

The terrain forms a plain that narrows westward, sloping gently southwestward and reaching absolute elevations of 30–35 m. It is bordered by the southern spurs of the Bzyp Range to the north and the Black Sea to the south. This lowland was formed by alluvial-marine accumulation during the Quaternary (Balabanov, 2009). Within the main deltaic areas of the Kodori and Inguri Rivers, the lowland has a Holocene alluvial-marine terrace (5–6 m above sea level, up to 4 km wide). Outside these deltaic areas, the lowland shows a series of Holocene alluvial-marine levels. These surfaces, which slope gently seaward, are cut by small river valleys. The edges and back slopes of these levels are not clearly defined in the relief. Their slightly inclined surfaces

are at absolute elevations of 6–18 m and 26–38 m.

For our study of initial ^{137}Cs contamination variability in Western Abkhazia, four reference sites were selected within the Mussera Upland (Fig. 2). The selection of these reference sites presented challenges due to the extensive tree canopy coverage across the Mussera Upland. The few areas free of tree cover were often anthropogenically modified. However, the relatively flat upper part of slopes, located near the local watershed of the Mussera Upland, are generally not used for agricultural purposes. All selected sites are covered with herbaceous vegetation but border shrub thickets or forest stands. Each reference site featured a relatively flat or gently sloping surface along a watershed divide, preventing any potential redeposition of eroded materials.

A brief description of each of the four reference sites is provided in Table 1.

Additionally, two peat cores were taken from a currently paludified paleolagoon situated in the central and southern parts of the Pitsunda Peninsula. These locations range from 0 to 6 metres above sea level (refer to Fig. 2 for sampling location). The site is within the modern Novochernomorskaya terrace, which features an almost flat, gently undulating surface. The cores were extracted using a manual Dutch auger (Eijkelcamp) from the southeastern edge of the peat bog.

Materials and Methods

At the reference sites, soil pits were excavated to collect incremental samples from areas of 15×15 cm at 3 cm intervals (5 to 13 samples per site) for analysing the vertical distribution profiles of ^{137}Cs . Bulk samples were also collected to determine total ^{137}Cs inventories throughout the soil column. These bulk samples were taken from the surface to a depth of 20–30 cm using an Eijkelcamp cylindrical corer with an inner diameter of 5 cm. Samples for layer sampling were carefully collected from a 10×10 cm area using a spatula. The number of samples and characteristics of the study sites are provided in Table 2. The sampling point arrangement system is shown in Figure 3.

The primary objective of collecting bulk soil samples (0–30 cm depth) at reference sites is to determine the total inventory of ^{137}Cs within a specified soil layer. There was

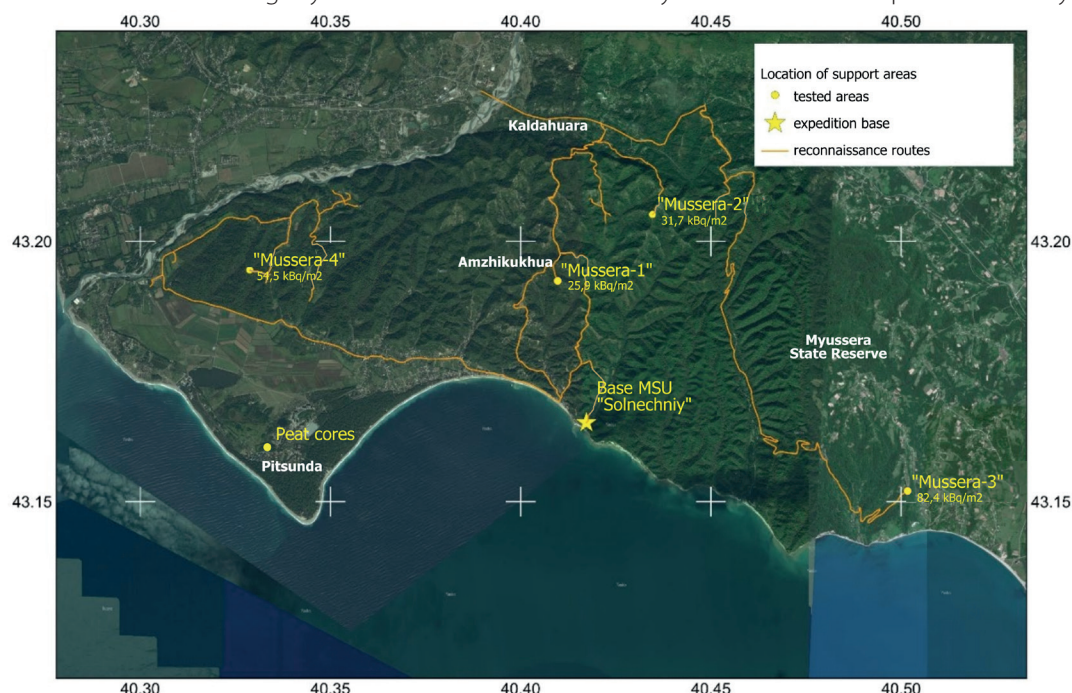


Fig. 2. Location of reference sites on the Mussera Uplands (background - Google Earth satellite image)

Table 1. Location and characteristics of the surveyed reference sites

Reference site	Location	Coordinates	Absolute height of the site, m	Surface character, vegetation and economic use
Mussera-1	interfluvium of the Riapsh and Tsanigvarta Rivers	N 43.19 239E 40.40 967	200-205	Vertex surface of ridge outcrop, herbaceous vegetation, hornbeam, beech and chestnut trees on the periphery of the plot, pasture
Mussera-2	interfluvium of the Mysra and Colchis rivers	N 43.20 523E 40.43 475	250-256	Top surface of rounded ridge, herbaceous vegetation, along the periphery hornbeam trees, pasture
Mussera-3	interfluvium of Ambara and Mchishta rivers, near Mgudzyrhua village	N 43.15 205E 40.50 167	150-156	Top surface of the ridge, herbaceous vegetation and sporadic blackberry bushes
Mussera-4	interfluvium of Bzyb and Adzidu Rivers, in the vicinity of Atsidjkva village	N 43.19 446E 40.32 875	90-95	Top surface of the ridge spur, sparse oak forest with rhododendron and blackthorn, road track and orchard

Table 2. Sampling parameters at the surveyed reference sites

Reference site	Area of sampling site, m²	bulk samples		incremental samples		Sampling point location system
		number of sampling	depths, cm	number of sampling	depths, cm	
Mussera-1	110	10	30 (27)	10	30	in quasi-parallel lines
Mussera-1	450	11	17-20	7	20	in quasi-parallel lines
Mussera-1	300	10	15	5	15	random sampling
Mussera-1	280-300	10	30	13	40	random sampling

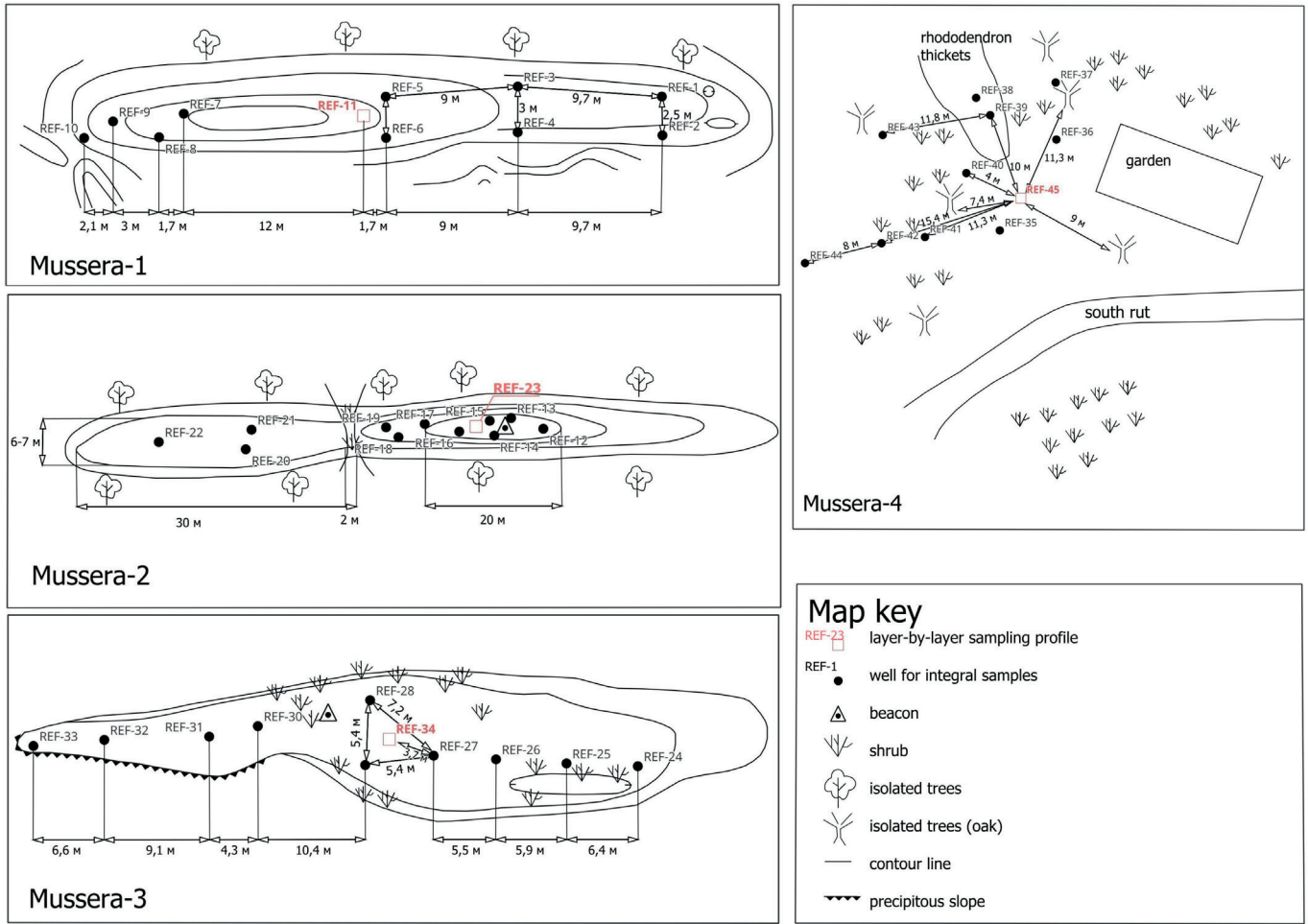


Fig. 3. Location of sampling points at the investigated reference sites (a Mussera-1; b Mussera-2; c Mussera-3; d Mussera-4)

some variability associated with sample collection using a narrow core tube (25 cm² surface area) at the reference sites. It is unlikely that the surface area was exactly 25 cm² for each of the bulk samples collected. It is possible to suggest that the magnitude of such sampling variability is a function of the surface area over which the samples are collected (Martynenko 2003, Loughran et al. 1988; Owens and Walling 1992). In the case of the Mussera upland, with large quantities of gravel and stones, the sampling area factor had a more significant influence. This approach provides crucial data on the local-scale variability of initial radionuclides fallout within each reference site. The observed variability in ¹³⁷Cs inventories at reference sites depends on several factors: (1) local landscape and geomorphic conditions at each sampling point, including microtopography and vegetation characteristics; (2) spatial heterogeneity of initial atmospheric deposition; and (3) methodological subjectivity, encompassing sampling errors, analytical procedures, and calculation methods (Golosov et al. 2008). The greater the local variability in contamination levels, the larger the number of samples required to obtain statistically reliable estimates of mean ¹³⁷Cs specific activity in soils. The minimum necessary number of randomly collected samples can be calculated using the following formula:

$$N_0 = \left[\frac{t_{\alpha, N-1} - C_v}{E_A} \right]^2 \quad (1)$$

The file system, a core component of any operating system, is responsible for organising and managing data on storage devices.

N_0 = minimum number of samples required for statistically reliable determination of ¹³⁷Cs content with permissible error E_A

N = number of collected soil samples

$t(\alpha, N-1)$ is the inverse value of the Student's t -distribution with $N-1$ degrees of freedom and confidence probability α

C_v = coefficient of variation for ¹³⁷Cs content in soil

Typically, for a permissible error of 10% at a 90% confidence level ($\alpha=0.1$), a minimum of 12 composite samples is required (Ivanov, 2017). Verification of reference sites for the absence of external disturbances was performed by analysing the vertical distribution profiles of ¹³⁷Cs content and soil profile morphology (Golosov et al., 2008).

The peat cores extracted from the Pitsunda bog measured 50 cm in length and were sectioned at 2 cm intervals for subsequent sample preparation and analysis. The samples consisted of dark brown, well-decomposed peat containing abundant woody debris. Occasional mineral grains were observed within the peat matrix.

For analysis of gamma-emitting radionuclide content, the samples underwent preparatory processing. Initially, stones and particles larger than 2 mm were separated from each sample using a sieve set. Subsequently, each sample was dried in an oven at 105°C for 8 hours. Following drying, the samples were ground to a powdered state and transferred into standard geometry containers (plastic vials measuring 5×6 cm) for subsequent gamma spectrometric analysis. The content of gamma-active radionuclides was determined using an ORTEC GEM-C5060P4-B gamma spectrometer, which is equipped with an ultrapure germanium (HPGe) semiconductor detector with a beryllium window and a relative efficiency of 20%. Gamma-spectrometric measurements were performed using the certified hardware and software complex

'SpectraLine', which is officially registered in the Russian Federation. The measurements were conducted in strict accordance with the certified methodology (Registration number in the Federal Information Fund for Ensuring the Uniformity of Measurements: FR.1.38.2024.49 576.). The mass of the dried samples ranged from 45 to 130 grams and the measurement time was at least 60 000 seconds. The expanded uncertainty for the activity measurements was 5.1% ($k=2$). This value was derived from a combination of Type A (statistical) and Type B (systematic) uncertainties, with the latter including components for sampling (3%), sample preparation (2%), and instrument calibration (2%). However, the varying and generally quite large inclusion of gravel, fine crushed stone and, in some cases, small pebbles significantly influenced the reliable determination of the density of each sample and, as a result, the estimation of specific activity.

The excess lead (²¹⁰Pb_{ex}) was determined by subtracting the specific activity of ²²⁶Ra from the total specific activity of ²¹⁰Pb. To determine the age of the sediment based on the concentration of ²¹⁰Pb_{ex}, the Constant Rate of Supply (CRS) model was used.

$$t(x) = (1/\lambda) \times \ln[A(\infty)/A(x)]$$

where: $t(x)$ – peat age, years; $A(\infty)$ – is the total unsupported ²¹⁰Pb inventory in the core, Bq/m², $A(x)$ – is the cumulative unsupported ²¹⁰Pb inventory below depth x , Bq/m², λ – radioactive decay constant of ²¹⁰Pb. The accumulation model was developed using the R (rplum) software package. The package considers peat density, the amount of unsupported lead, and the measurement error of the values.

As part of the expedition, dose rate measurements were also made using RadioCode101 and AtomFast dosimeters linked to a smartphone. The dose rate measurements were carried out in accordance with standard field practices. The detector was positioned 1 metre above the ground. The measurement time at each point was at least 2 minutes to ensure statistical significance of the results. For each site, at least 10 point measurements were taken, after which the average value and standard deviation were calculated. The aim of the work was to map the dose rate indicators and explain the revealed regularities, including their connection with the geological and geomorphological structure of the study area. This was carried out in Western Abkhazia for the first time.

At the Mussera-1 site, the highest specific activity values for the isotope and its reserves are recorded in the incremental sample REF-11. Here, a specific activity peak of 520 Bq/kg is observed in the 3-6 cm layer, corresponding to reserves of 15.7 kBq/m² (Fig. 4). The trend of decreasing total inventories can be seen from the southwest to the northeast of the linearly elongated area (see Fig. 3 and Fig. 4, bulk samples). The local variability of the inventories can be explained mainly by the unevenness of atmospheric deposition of the radionuclide, as well as by local site conditions at each sampling point (e.g., microrelief features) (Golosov et al., 2008).

The total ¹³⁷Cs inventory in the selected column averages to that of bulk sample 1, which is 40.9 kBq/m². This is slightly higher than the average for the bulk samples (25.3 kBq/m²). However, in this instance, the total inventory assessment can be considered more accurate because the sampling area was 15 × 15 centimetres. The profile of the vertical distribution of ¹³⁷Cs suggests that this area has not experienced anthropogenic impact, apart from grazing by domestic animals.

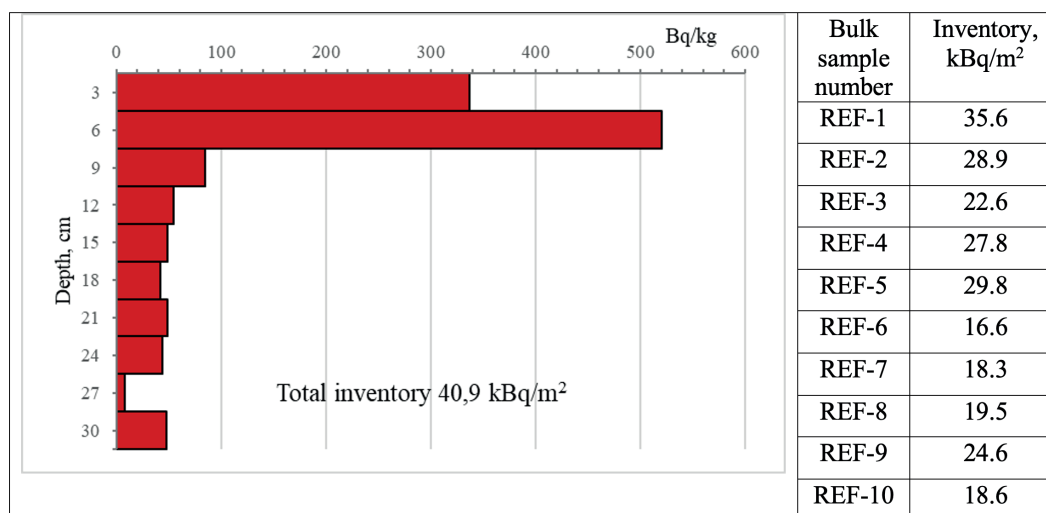


Fig. 4. Depth distribution of specific activity of ^{137}Cs (Bq/kg) in section and inventory in bulk samples of the Mussera-1 (REF-11) site (kBq/m²)

The Mussera-2 site shows a similar trend to the first reference site. Peak values in the REF-23 sample are also observed in the 3-6 cm layer (Fig. 5). In bulk, the total ^{137}Cs inventory in the selected column is on average the same as the average of the integral samples (29.8 kBq/m²), equalling 30.1 kBq/m². The total ^{137}Cs inventory is clearly underestimated, since specific activity in the lower horizons is quite high, and cesium probably penetrated deeper into the soil profile.

Mussera-3 is distinct from other sites due to its highest values of specific activity and inventory. In bulk samples, these reach up to 626 Bq/kg and 27.1 kBq/m² respectively (Fig. 6). The specific activity in layers 0-3 cm and 3-6 cm within sample REF-34 is the highest across the entire study area. The inventory in these layers is considerably lower than in bulk samples, not exceeding 28 kBq/m². The peak inventory occurs in the 3-6 cm layer, similar to previously considered sites. The ^{137}Cs reserve in the section matches the average of the bulk samples (78.8 kBq/m²), equalling 80.2 kBq/m².

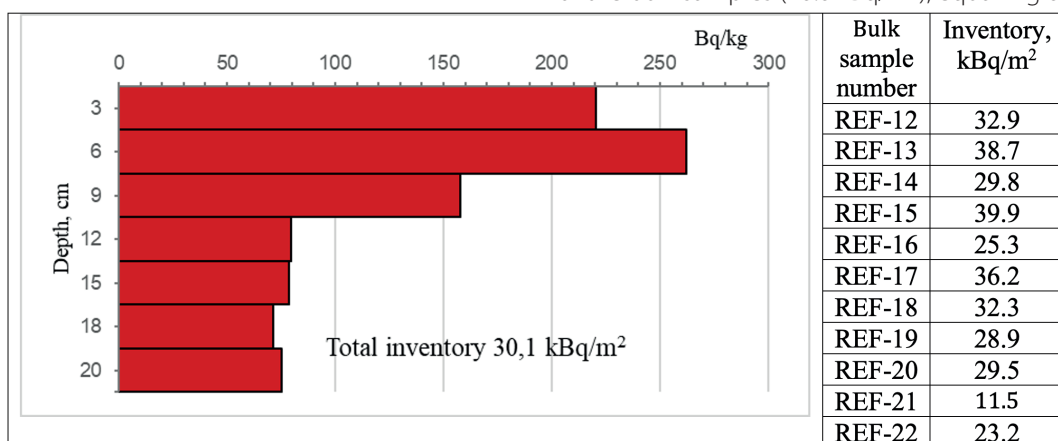


Fig. 5. Depth distribution of specific activity of ^{137}Cs (Bq/kg) in section and inventory in bulk samples of the Mussera-2 (REF-23) site (kBq/m²)

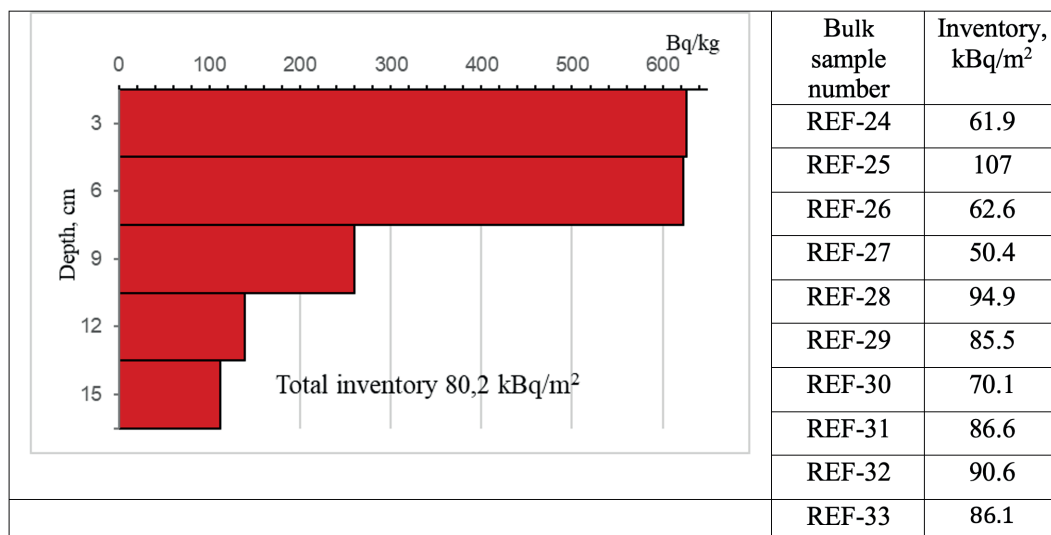


Fig. 6. Depth distribution of specific activity of ^{137}Cs (Bq/kg) in section and inventory in bulk samples of the Mussera-3 (REF-34) site (kBq/m²)

At the Mussera-4 site, specific activity values for all composite samples exceeded 100 Bq/kg, except for REF-44 (33 Bq/kg). Inventories ranged from 30 to 84 kBq/m². The vertical distribution of inventories shows a characteristic trend common to all samples: specific activity and inventories decrease with depth (Fig. 7). The peak concentration occurs in the surface layer (0-3 cm).

The total inventory throughout the soil profile is 55.6 kBq/m², while the current average across bulk samples is 52.3 kBq/m². These findings strongly suggest that this soil profile developed in an area subject to anthropogenic influence, likely including tillage operations. Field observations further indicate the sampling point's proximity to an abandoned orchard, supporting the hypothesis of historical agricultural use at this location.

The variability of bulk inventory values for all sites averaged 17-25%, indicating moderate variability (Table 3). Comparison with the Atlas of Radioactive Contamination of European Russia (De Cort, 1998), which reports values of 40-185 kBq/m² for the Sochi region in the Caucasus, reveals that our measurements for Western Abkhazia range from 50-160 kBq/m² for 1986 (equivalent to 25-79 kBq/m² at present). These findings provide compelling evidence of Chernobyl-derived contamination in Abkhazia, which had previously been known only to a limited circle of scientists. The contamination is associated with heavy precipitation events and air mass trajectories in May 1986. The established ¹³⁷Cs deposition patterns, combined with identified regional trends, enable the use of this radionuclide as a tracer for quantifying the proportional contributions of various sediment sources to the sediment flux in rivers draining the upland area.

For the paleolagoon cores, the total ¹³⁷Cs inventory was determined to be 20.7 kBq/m² for core 1 and 20.2 kBq/m²

for core 2 at present. This is equivalent to 49.7 kBq/m² for 1986. These values closely align with those obtained from the Mussera-1 reference site. Specific activity ranged from 30 to 240 Bq/kg. Both cores, sampled in close proximity to each other, exhibit relatively similar ¹³⁷Cs depth distribution (Fig. 8), confirming proper sampling methodology.

The cesium peaks have a broad, irregular shape, indicating that the water in the marsh is constantly rising and falling. A zero value was not reached, suggesting that the total inventory may be underestimated. Oldfield et al. (1995) provide data supporting the view that ¹³⁷Cs profiles in recent ombrotrophic peat may be displaced by both movement in solution and active biological uptake.

Examination of the distribution of ²¹⁰Pb_{ex} showed a peat formation rate of 0.1 cm/yr (Figure 9). Non-equilibrium lead with minor fluctuations is observed down to the 14th horizon. This indicates that a period of 150-180 years is reached at this horizon, allowing for an accurate calculation of the peat formation rate.

For column 1, a small loss of the upper part of the core was established, which is related to sampling and proves the necessity of core duplication.

The dose rate in the studied region ranges from less than 0.05 µSv/h to 2 µSv/h (Fig. 9). The background radiation level for the area can be determined to be within the range of 0.01-0.5 µSv/h. The distribution of radiation indicators is heterogeneous. On the watershed ridges of the Mussera Upland, the values generally do not exceed 0.5 µSv/h. Maximum values (2.3 µSv/h) were found in the western part of the Mussera Upland, in the basin of the Bzyb River on a ridge near an anthropogenic object (building). Elevated radiation dose rates are also observed in the area between the Ryapsh and Mussera rivers (1.32 µSv/h). In the valley of the Ryapsh River, values were recorded at 1.74 µSv/h near a stable and 1.32 µSv/h upstream on a landslide terrace, near a dirt road.

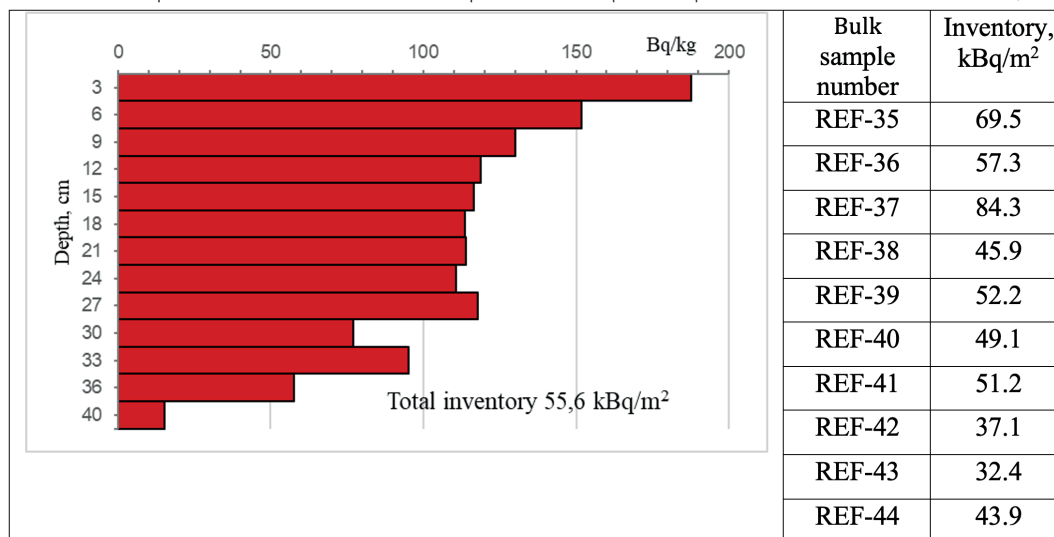


Fig. 7. Depth distribution of specific activity of ¹³⁷Cs (Bq/kg) in section and inventory in bulk samples of the Mussera-4 (REF-45) site (kBq/m²)

Table 3. Statistical results of ¹³⁷Cs specific activity and ¹³⁷Cs inventory measurements in bulk samples

Reference site	Specific activity, Bq/kg		Inventory, kBq/m ²		CV, %	Inventory, kBq/m ² *		CV*, %	Inventory, kBq/m ² (1986)	
	mean	min-max	mean	min-max		mean	min-max		mean	min-max
Mussera-1	97.4	40.5-245	24.9	16.6-35.6	25	25.9	28.3-35.6	25	50.2	33.6-71.9
Mussera-2	139	61.5-311	29.8	11.5-39.9	26	31.7	23.2-39.9	17	60.3	23.2-80.6
Mussera-3	296	176-471	78.8	50.4-107	23	82.4	61.9-107	23	159	102-216
Mussera-4	126	33.1-175	52.3	32.4-84.3	25	54.5	37.1-84.3	22	105.6	65.4-170

without extremes

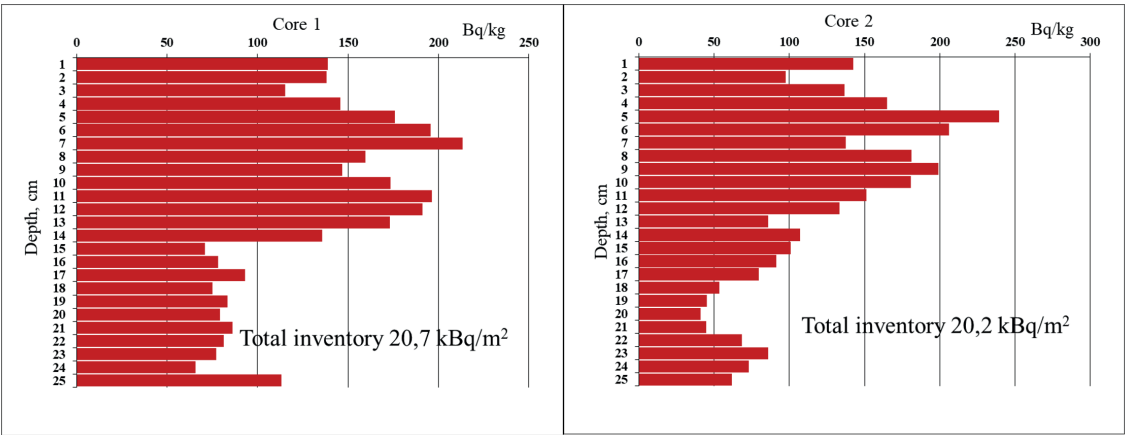


Fig. 8. Specific activity of ^{137}Cs (Bq/kg) in sections and inventory in bulk samples of the peat cores (kBq/m²)

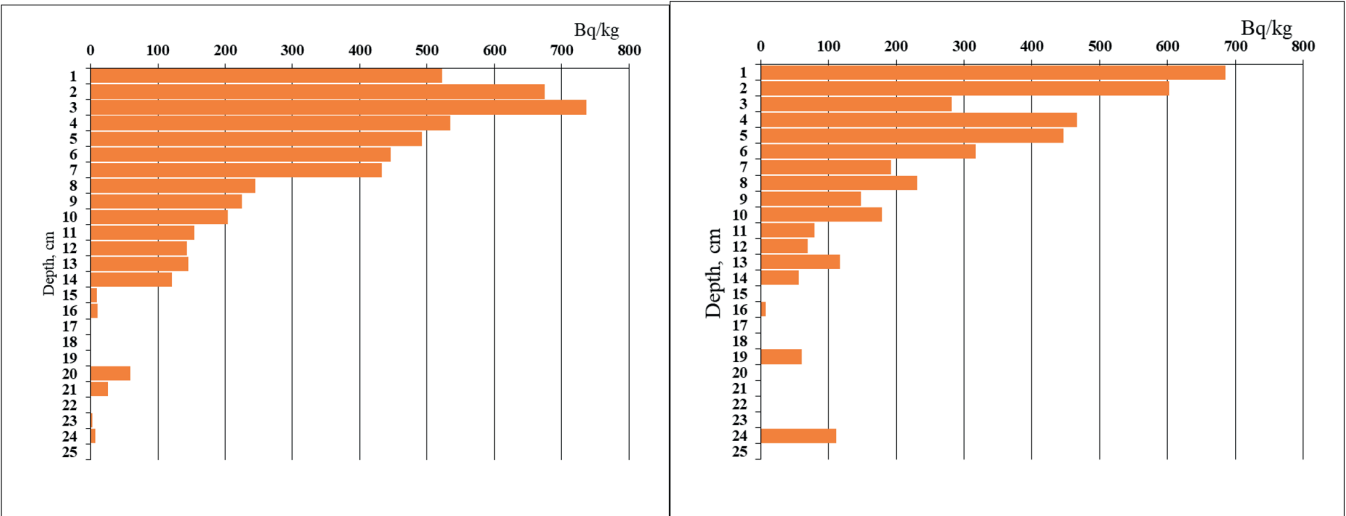


Fig. 9. Specific activity of $^{210}\text{Pb}_{\text{ex}}$ in cores 1 and 2 of Pitsunda palaeolagoon, Bq/kg

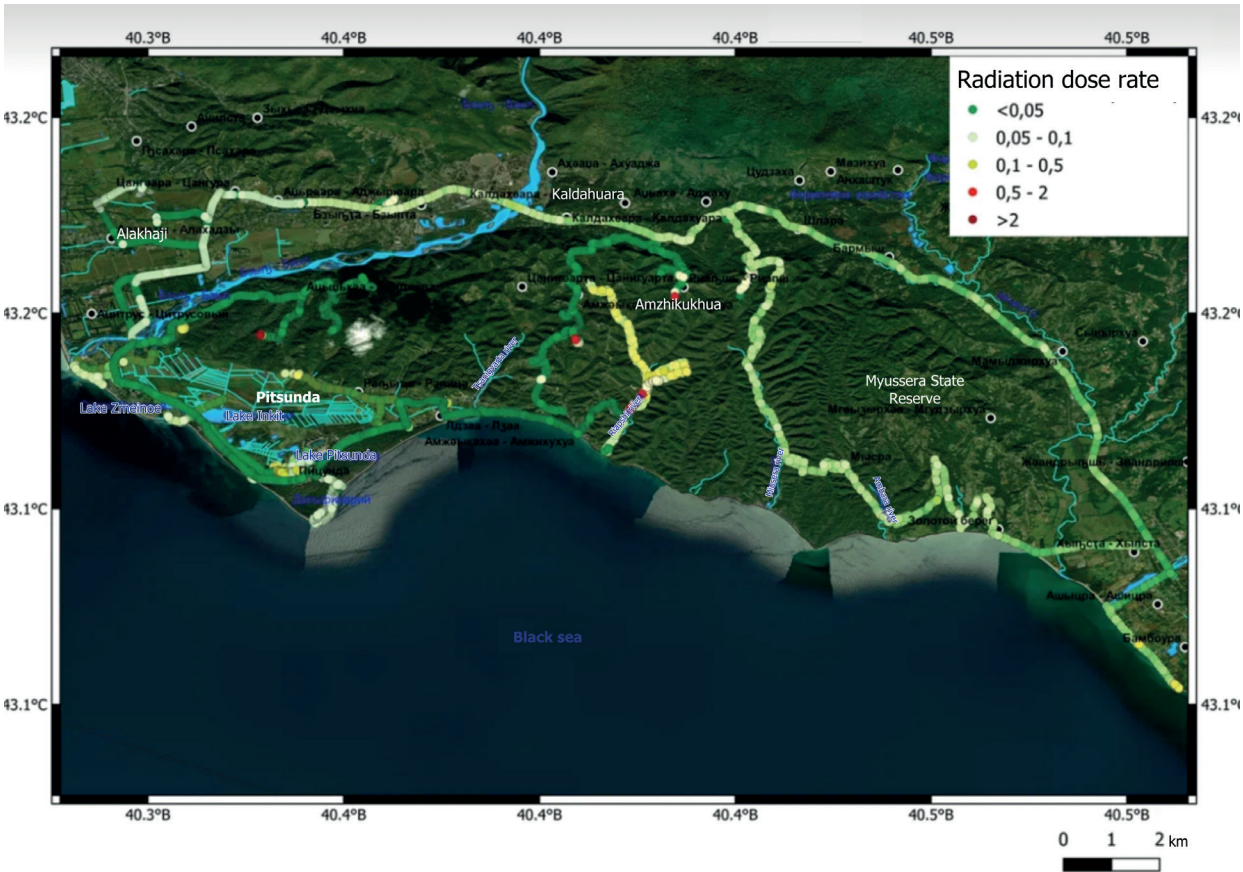


Fig. 10. Dose rate of the investigated area of Mussera Upland

The western part of the study area, near the town of Pitsunda, is the region with the lowest average radiation doses (less than 0.05 $\mu\text{Sv/h}$). However, there are localised increases of up to 0.1–0.5 $\mu\text{Sv/h}$ in the central part of the town. These might be linked to human activity, such as artificial road and building surfaces containing natural radioactive elements like uranium and thorium. Slightly elevated values are also seen near the coast, which is attributed to the presence of pebble beaches containing naturally occurring radionuclides (uranium and thorium) in the rocks.

DISCUSSION

It should be noted that the average values of ^{137}Cs reserves calculated on the basis of reserves in bulk samples for three of the four reference sites were close to the total reserves of caesium-137 in the pits. The only exception is reference site 1, where the reserves in the pit were higher than the average value calculated for the bulk samples. This indicates that the obtained values of average reserve values are reliable. In the case of reference site 1, the differences are due to a very large amount of gravel and small stones in the bulk samples.

There are few sources of observed variability in ^{137}Cs inventories at the reference sites, including random spatial variability, systematic spatial variability, sampling variability, and measurement precision (Owens and Walling, 1996). Random spatial variability is associated in this case with differences in soil bulk density, porosity, the number of stones, plant roots, and vegetation cover. The latter may particularly influence the reference sites at Mussera Upland because some bushes were located at different distances from the sampling points. Topography is another key reason for the random variability, particularly in the cases of reference sites 1 and 2, which are located on narrow, gently sloping surfaces (Fig. 3 a, b). It can be assumed that some of the caesium-137 at these sites was lost with surface runoff before being fixed on soil particles. The lower total ^{137}Cs inventories at sampling points located relatively higher than others support this assumption.

Systematic spatial variability is associated with variations in precipitation. This is particularly typical for mountain areas (Higgitt et al., 1992; Kirchner, 2013) and for areas where Chernobyl-derived ^{137}Cs fallout occurred (Golosov, 2002; Golosov et al., 1999). The Chernobyl-derived ^{137}Cs fallout was associated with one, or at most, two rain events (Izrael, 2007; Kuzmenkova et al. 2023). Consequently, the radioactive contamination pattern reflects the pattern of rain that fell on the studied area. The reference site Mussera-3 is located closest to the sea. It can be assumed that more precipitation fell here compared to other sites.

The exceptionally high ^{137}Cs specific activity (627 Bq/kg) recorded at Mussera-3 in surface soil layers demands particular attention. The elevated levels likely reflect intense rainfall events in May 1986, which scavenged airborne radionuclides from the Chernobyl plume. Similar patterns were observed in Alpine regions (Smith et al., 2000) and Scotland (Bunzl et al., 1995), where localised 'hotspots' formed due to orographic rainfall. The predominant northwest-to-southeast transport of contaminated air masses (Izrael, 2007) explains why Mussera-3, located in a topographically exposed position, received higher deposition than coastal sites. Comparable trends were documented in France (Foucher et al., 2015), where mountainous areas intercepted more fallout than

lowlands. The observed decline in total ^{137}Cs inventories toward the coast is consistent with the dilution of global fallout by marine aerosol deposition and specific coastal wind patterns. This pattern is evident in New Zealand's coastal peatlands, where the already low ^{137}Cs signal from mid-20th century nuclear weapons testing is further suppressed in coastal areas (Pearson et al., 2019).

The availability of data on ^{137}Cs reserves at reference sites allows the radiocesium method to be used to solve various problems in assessing the redistribution of sediments by erosion-accumulative processes in the study area. In particular, differences in the ^{137}Cs content in surface soil horizons, landslide bodies, and eroded river banks allow us to assess their proportional contribution to the total sediment load of rivers, as is done in other mountainous countries (Förstner et al., 2018). Increasing extreme rainfall (IPCC, 2023) may accelerate the rate of erosion on the Mussera upland, as is already observed in Europe (Fulajtar et al., 2017).

The radiocesium method also allows estimation of accumulation rates in various sediment sinks such as reservoirs, river floodplains, and the lower parts of slopes (Linnik et al., 2005; Linnik, 2011). However, the radiocesium technique cannot be used for swampy water bodies because in an acidic environment, a significant portion of ^{137}Cs dissolves (Kudelsky et al., 1996). In this context, the atmospheric component of ^{210}Pb was used as a chronomarker for the accumulation rate in a swampy lagoon on a seaside terrace in the Pitsunda area. Peat accumulation rates (0.1 cm/yr) are slower than in Alpine bogs (0.15–0.3 cm/yr; Le Roux et al., 2012), possibly due to faster decomposition rates in Abkhazia (Fig. 11). The mean accumulation rate (0.1–0.2 cm/yr) is consistent with ombrotrophic bogs in temperate regions (e.g., 0.05–0.1 cm/yr in New Zealand; Pearson et al., 2019), but is slower than in Alpine peatlands (0.15–0.3 cm/yr; Le Roux et al., 2012). Lower organic productivity occurs due to warmer decomposition rates in subtropical climates (Chambers et al., 2010). Limited mineral input is indicated by low Al values, contrasting with minerotrophic European bogs (Shotyk et al., 2002). The unsupported ^{210}Pb peak (250–290 Bq/m²/yr) likely records 20th-century industrial aerosol deposition, mirroring trends in Swiss peat cores (Roos-Barraclough et al., 2002). The memory parameters (mem.strength: 10) suggest bioturbation or gradual compaction, similar to Finnish peatlands (Tolonen et al., 1992). This differs from abrupt deposition in floodplain lakes (Oldfield et al., 1997), highlighting Pitsunda's stable hydroclimate.

It was found that the radiation dose rate, even though remaining relatively low, appreciably depends on the geomorphological position of the measurement point. In the bottoms of canyon-like ravines and gorges of river valleys the dose rate increases, while on watershed ridges it decreases. This is due to the different potential for sediment accumulation and erosion characteristic of these geomorphological positions, which affects the concentration of radionuclides in the surface layer. Thus, in gorges with steep slopes the sources of natural radioactivity (rocks) surround the measurer from three sides, while on watershed ridges only from one side. The absence of correlation with bedrock age or genesis contrasts with findings in New Zealand's volcanic terrains (Herman et al., 2010) but aligns with studies emphasising topography-driven radionuclide redistribution (Golosov et al., 2021). This reinforces the dominance of surface processes over lithology in controlling dose rates.

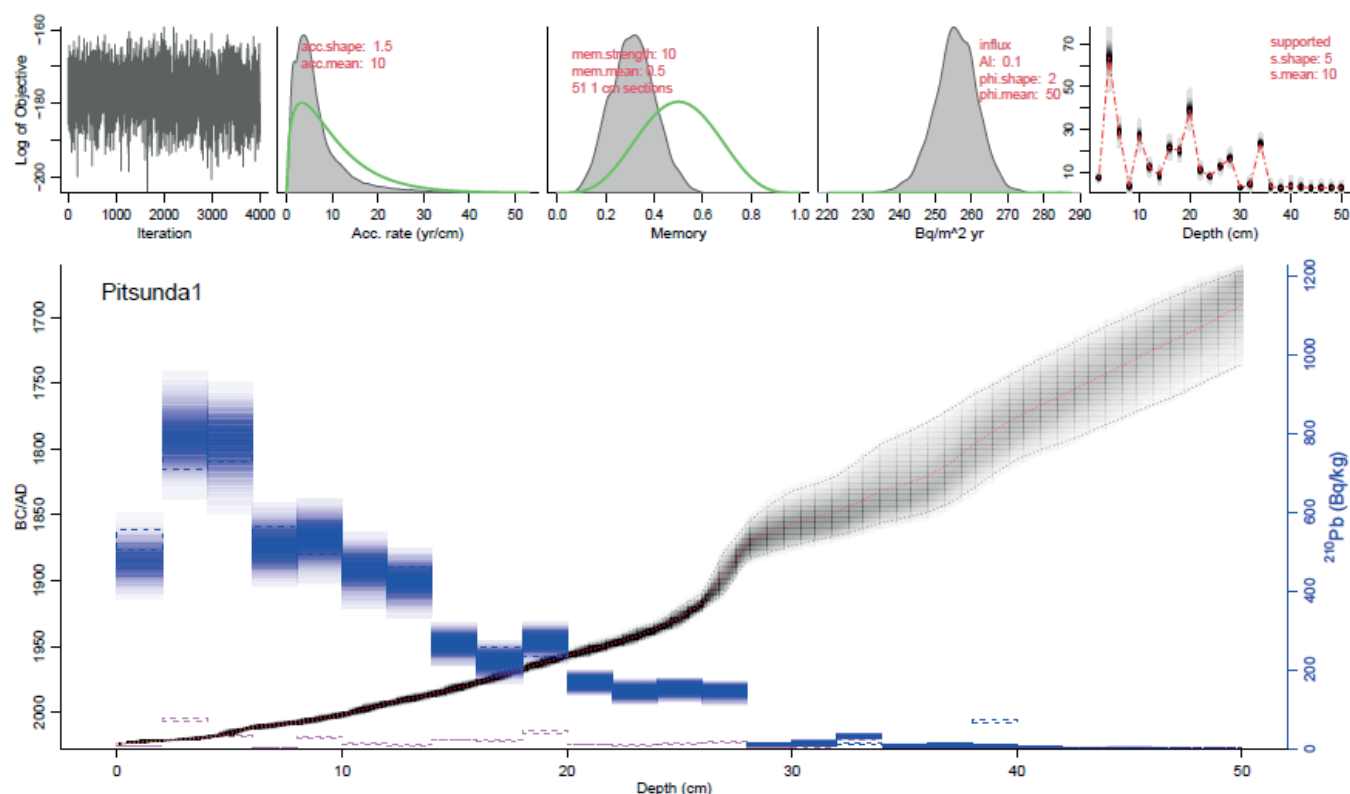


Fig. 11. Variation of sedimentation rate in column 1 obtained with the Rplum package

(Aquino-López et al., 2008). Blue bars: Measured unsupported $^{210}\text{Pb}_{\text{ex}}$ activity data. The height of the bar represents the activity value, and the width represents the depth interval of the sampled sediment section. Solid black line: The model's prediction of the $^{210}\text{Pb}_{\text{ex}}$ activity profile based on the measured data. Grey shaded area: The 95% confidence interval (or uncertainty range) of the model's activity prediction. Red dashed vertical lines: Reference horizons used to validate the model. Modeled ages (on the secondary x-axis) show the sediment accumulation timeline derived by the model. 'BC/AD': This label refers to the calendar year scale on the age axis (X-axis of the chronology panel). 'BC' stands for Before Christ and 'AD' for Anno Domini.

The findings indicate no direct correlation between the geological structure of the area and the measured dose rate levels. For example, outside of deeply incised river valleys, the values recorded on the Mussera Upland, which is composed of Neogene conglomerates, and those on the Pitsunda Lowland are comparable. This can be attributed to the fact that both landforms are made up of denudation products originating from the southern macro-slope of the Greater Caucasus Range, with no significant differences observed in the petrographic composition of the loose and cemented sedimentary rocks found there.

CONCLUSION

For the first time, the ^{137}Cs inventory for the territory of Western Abkhazia has been established for four reference sites. It is 25–79 kBq/m² for the year 2024. The elevated ^{137}Cs inventories are likely largely associated with Chernobyl fallout, considering the chronology and geographical proximity of the study area to the affected zone of the Chernobyl accident. The variability of values for the reference sites is moderate, so they can be considered indicative for the estimation of the total ^{137}Cs inventory.

Using a non-equilibrium lead analysis, the peat formation rate in the Pitsunda palaeolagoon was determined to be 0.1 cm/year. The total ^{137}Cs inventory, measuring 20.4 kBq/m² in 2024, confirmed the values established for the reference sites and the impact of the Chernobyl disaster on Western Abkhazia.

The background dose rate in the area of the expedition operations was determined to be 0.01–0.5 $\mu\text{Sv/h}$. The highest values were observed in the central part of the Musser Upland, specifically in the Ryapsh River valley (approximately 0.1 – 0.5 $\mu\text{Sv/h}$). The lowest values were found in the south-eastern part of the Musser Reserve and on the Pitsunda Peninsula, in coastal areas (approximately <0.05 $\mu\text{Sv/h}$). No direct link between the dose rate and the age or origin of the underlying rocks in the study area was established. However, a direct relationship was found between the dose rate and the territory's relief. Higher dose rates were measured in areas with more dissected relief and within the bottoms of erosion forms.

This study not only fills the knowledge gap regarding radioactive contamination in Abkhazia but also presents new opportunities. These include the application of the radiocesium technique to study sediment redistribution rates and to evaluate the proportional contribution of different sediment sources to the total sediment load of regional rivers. The data acquired can provide a foundation for future research focused on reconstructing the history of modern landscape formation and assessing the intensity of exogenous processes.

The results obtained are of great practical importance as they allow ^{137}Cs to be used as a reliable chronomarker for assessing the intensity of sediment accumulation processes in the region's sediment sinks. The spatial heterogeneity of the radionuclide distribution revealed should be considered, which requires a careful approach to the selection of reference sites for such studies. ■

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