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^{137}Cs dating of lake cores from the Nahuel Huapi National Park, Patagonia, Argentina: Historical records and profile measurements

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Historical records of short lived (^{140}Ba, ^{131}I, ^{103}Ru and ^{95}Zr+^{95}Nb) and long-lived (^{137}Cs and ^{90}Sr) fission products by fallout measurements performed in Argentina since 1959 were analyzed in order to define the main characteristics of ^{137}Cs fallout time evolution in the Nahuel Huapi National Park, Patagonia, Argentina. Sedimentary cores were sampled from Lake Nahuel Huapi and Lake Morenito, which are located within Nahuel Huapi National Park. ^{137}Cs specific activity profiles were measured and ^{210}Pb dating was performed in each core. The time evolution of ^{137}Cs fallout shows different characteristics than records taken in the Northern Hemisphere.^{137}Cs specific activity profiles of the cores studied reproduce the fallout time sequence observed in the historical records, and the chronology obtained shows excellent agreement with ^{210}Pb dating.

Introduction

Lake sediments contain valuable historic information and can be considered as environmental archives that can be read employing different analytical techniques. The events affecting the natural ecosystem during the last 200 years, such as population increase, massive deforestation, desertification, dam construction, introduction of exotic species, extensive use of agrochemicals, etc., have modified the natural evolution processes, changing sediment composition and sedimentation rate. These changes are recorded in the sediment sequence, and the occurrence of natural and historical events can be traced back through the study of sedimentary cores sampled from the lake. In these studies, it is of the utmost importance that the chronology of the sedimentary sequence should be established with good reliability. The most widely used dating technique for the time period of interest, is the measurement of the specific activity profile of the natural radioactive isotope ^{210}Pb ($T_{1/2} = 22.3$ y).[1,2] However, it is useful to determine the occurrence in time of known events which can be related to definite points in the sediment sequence, thus establishing absolute dates in the ^{210}Pb activity profile. These definite events are also useful in those cases where ^{210}Pb dating can not be applied to evaluate mean sedimentation rates and chronology. The releases of anthropogenic radioactivity to the atmosphere are events registered in the sedimentary sequence, that can be identified in a specific activity profile.

Atmospheric nuclear weapon tests and the Chernobyl nuclear power plant accident produced regional and global radioactive fallout. The deposition of fission products, activation products, and weapon residuals was strongly associated in time with the events that produced them. The accumulation of these radioactive elements with the sediments in the water body allow us analyzing the specific activity profile of these anthropogenic radionuclides, to relate the date of the event to definite core layers. The radionuclides studied for this purpose are the long lived fission products ^{137}Cs ($T_{1/2} = 30.07$ y) and ^{90}Sr ($T_{1/2} = 28.78$ y), the activation product ^{241}Am ($T_{1/2} = 432.2$ y),[3] and the weapon residuals ^{239}Pu and ^{240}Pu.[4] But the most widely used radionuclide is ^{137}Cs. It can be measured easily by direct low background gamma-ray spectrometry while ^{90}Sr is only a β^--emitter, ^{239}Pu and ^{240}Pu are measured through their α decay after radiochemical separation, and the sediment ^{241}Am specific activity is much lower because of its longer half-life and low yield in nuclear tests.

The onset of relevant anthropogenic radionuclide inputs in the biosphere is due to the widespread atmospheric testing of nuclear weapons, starting in 1954, with the 1959–1960 and 1963–1964 intervals being reported as maximum ^{137}Cs fallout period in the Northern Hemisphere,[3,5] while negligible amounts were deposited before 1954.[4] The Chernobyl accident (1986) is also clearly registered in ^{137}Cs core profiles in the Northern Hemisphere.[6] Most atmospheric nuclear events have taken place in the Northern Hemisphere, with only the South Pacific atmospheric nuclear weapon testing, from 1966 to 1974, were placed in the Southern Hemisphere. Also, most authors have studied the records of nuclear event depositions in different regions of the Northern Hemisphere, correlating the radioactivity core profiles and deposition with the dates of the nuclear events that occurred in that hemisphere. In the present work we analyze the information available on the anthropogenic radioactive fallout in Argentina, and correlate these data with the measurement of ^{137}Cs profiles and ^{210}Pb dating of two cores sampled from Lake Nahuel Huapi, and another from Lake Morenito, both lakes within Nahuel Huapi National Park.

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Anthropogenic radioactive fallout in Argentina

Anthropogenic radionuclides from atmospheric fallout have been measured in Argentina since 1959 to present to study radiological effects on the population.[7–9] Different materials, sampled from different regions, were analyzed in the past 40 years. Since we want to relate the deposition records, and their dates, to the radioactive profiles measured on sediment cores, we shall only focus on the results on direct fallout, which was only collected in Buenos Aires City (34° 27' S, 58° 22' W), and also on the results obtained from milk samples collected in Buenos Aires, Bariloche (41° 9' S, 71° 19' W), and Salta (24° 48' S, 65° 25' W), because they represent the deposition in distant regions of Argentina, including our region of interest, the Nahuel Huapi National Park, where Bariloche City is located.

Direct fallout was sampled by collecting water deposits in recipients during a month. The samples were concentrated by evaporation and extracted by ion exchange before measurement by γ-spectrometry and β-counting. Also aerosols sampled daily from surface air by pumping through filters, were analyzed.

Argentina has received mainly stratospheric fallout from the nuclear events carried out in the Northern Hemisphere, like the atmospheric nuclear weapon tests at the end of the fifties and early sixties (except for little short half life fallout registered, associated with the Equatorial series of nuclear tests, at Navidad Islands, from April to July, 1962).[10] But the nuclear tests in the Southern Hemisphere, from 1966 to 1974, induced tropospheric fallout in Argentina, as discussed in next section. These two facts, the stratospheric fallout from Northern Hemisphere nuclear events and tropospheric fallout from Southern Hemisphere nuclear tests, mark clear differences in the radioactive records obtained in sediment cores sampled in Argentina as compared to those obtained in the Northern Hemisphere.

Tropospheric fallout in Argentina from nuclear tests in the South Pacific

Atmospheric nuclear weapon tests were performed from 1966 to 1974 in the South Pacific Ocean, generating tropospheric fallout in Argentina. The tropospheric fallout has transport times ranging from days to few weeks, while the radionuclides have residence times in the order of years in the stratosphere. Thus, the tropospheric fallout can be distinguished by measuring short-lived fission products generated in the nuclear events. The short-lived fission products detected in measurements of fallout samples,[11–14] collected monthly in Buenos Aires City, were ^{131}I ($T_{1/2}$ = 8.02070 d), ^{140}Ba ($T_{1/2}$ = 12.752 d), ^{103}Ru ($T_{1/2}$ = 39.26 d) and ^{95}Zr+^{95}Nb ($T_{1/2}$ = 64.02 d and $T_{1/2}$ = 34.997 d) (all half-lives are from Reference 15).

Fallout measurements started when ^{140}Ba activity was detected in air samples. The air samples, collected daily, also showed that the mean time for radionuclide transport was 10 days, for the tests performed in the period 1966–1970.[11]

The specific activity of the shorter lived fission products, ^{131}I and ^{140}Ba, shows sharp peaks immediately after nuclear tests (Fig. 1), and vanishes shortly. The longer lived fission products, ^{103}Ru and ^{95}Zr+^{95}Nb, also show sharp peaks at the same dates but remain longer in time (Fig. 2). A specific activity peak of these two fission products is observed in the winter of 1969. This peak shows a higher relative intensity, as compared to the previous peak, in the ^{95}Zr+^{95}Nb fission product, with a 64 day half-life, than in the case of the ^{103}Ru, with a half-life of 39 days; and does not show up in the case of the shorter lived fission products ^{131}I and ^{140}Ba. A possible explanation for this delayed peak can be found in the seasonal increase of rains in Buenos Aires City during the winter time, causing a strong increase of atmospheric washing. This would also explain the different behavior of short (^{131}I and ^{140}Ba) and long (^{103}Ru and ^{95}Zr+^{95}Nb) lived fission products: radionuclides produced in nuclear tests remain in the troposphere for many months, gradually diminishing by atmospheric washing, atmospheric transport, and nuclear decay. A further study of Figs 1 and 2 shows that the peak intensity in all four measured isotopes follow the same trend. This shows that the behavior of the different fission products is similar during transport and deposition, a conclusion that we will use later on in our analysis.

The release of ^{131}I to the atmosphere is one of the most important radionuclides as far as human radiological protection is concerned. Its path to human intake starts with tropospheric fallout, followed by grass contamination, cattle feeding from that grass, and incorporation into milk. For this reason milk samples, collected daily during 1966, 1967 and 1974 in Buenos Aires City and in two other distant points in Argentina, were measured, starting when ^{140}Ba activity was detected in air samples.[11,14] The results are shown in Figs 3, 4, and 5. An analysis of the measurements performed in Buenos Aires City during the period 1966–1970 shows that ^{131}I has a 2-day mean transfer time from fallout to milk, with a mean transfer factor of ^{131}I of 230 (pCi·d/l)/(mCi/km^2).[11] The strong correlation between fallout and ^{131}I milk specific activity that these results show, allows us to consider activity measurements in milk to be a good indicator of deposition evolution in places where fallout had not been measured.

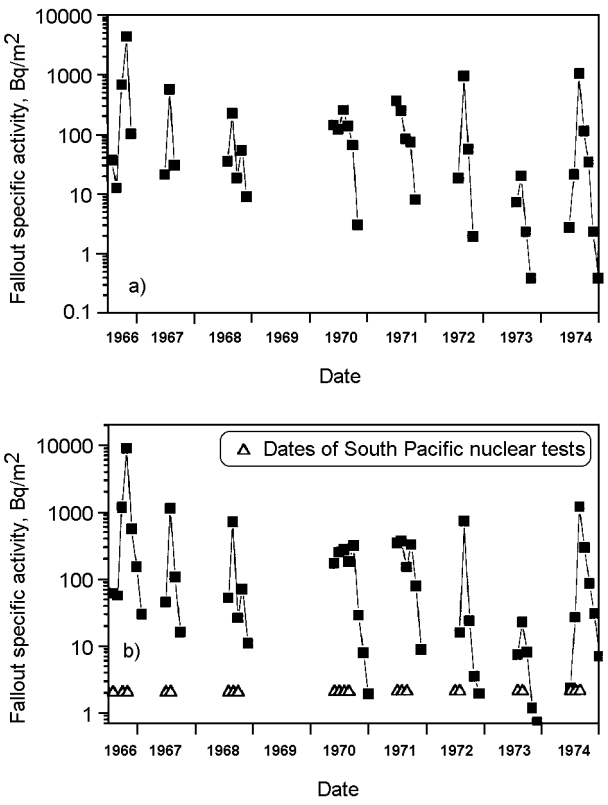

Fig. 1. Specific activity of ^{131}I (a) and ^{140}Ba (b) fallout. The samples were collected in Buenos Aires City

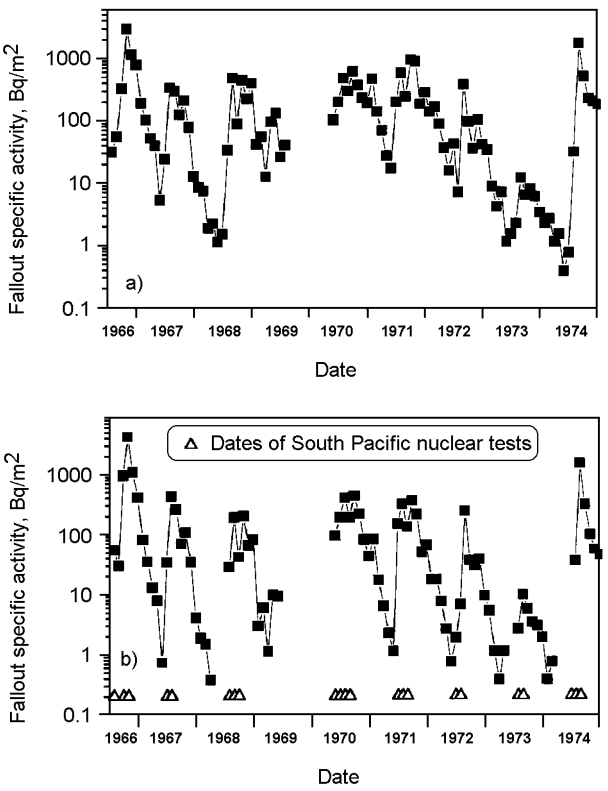

Fig. 2. Specific activity of ^{95}Zr+^{95}Nb (a) and ^{103}Ru (b) fallout. The samples were collected in Buenos Aires City

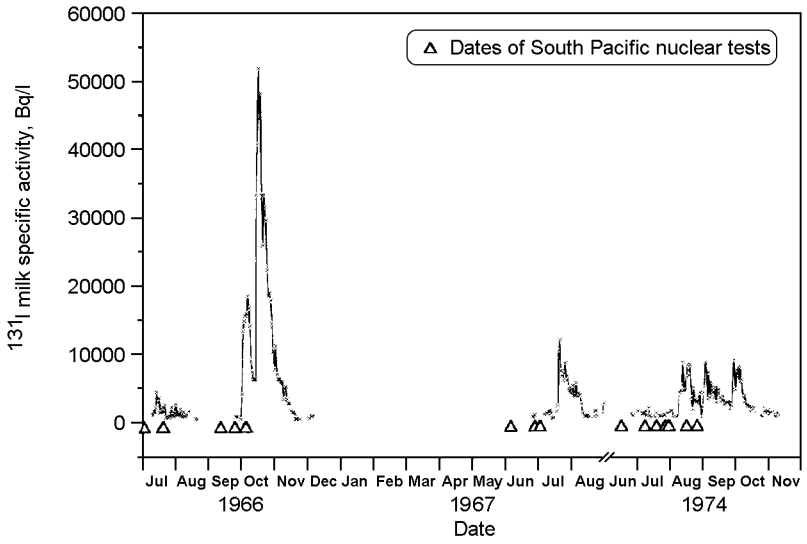

Fig. 3. Specific activity of ^{131}I in milk. The samples were collected daily in Buenos Aires City (34° 27’ S, 58° 22’ W)

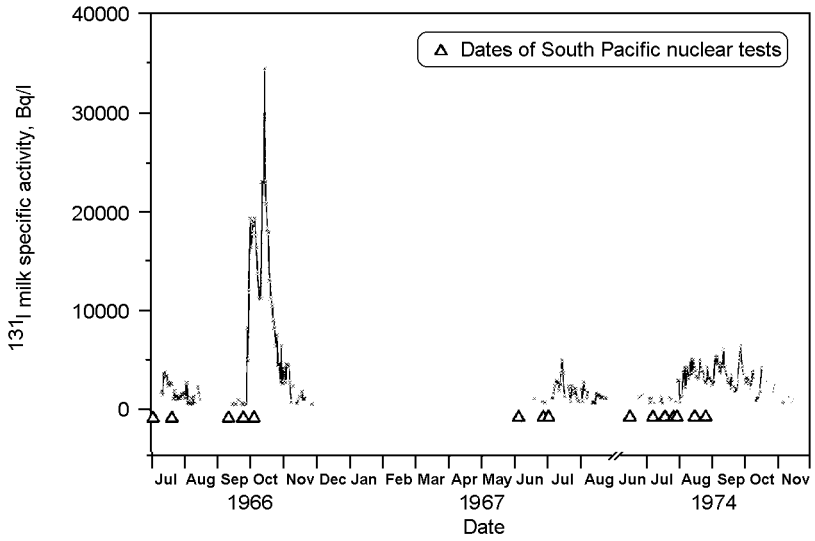

Fig. 4. Specific activity of ^{131}I in milk. The samples were collected daily in Salta City (24° 48' S, 65° 25' W)

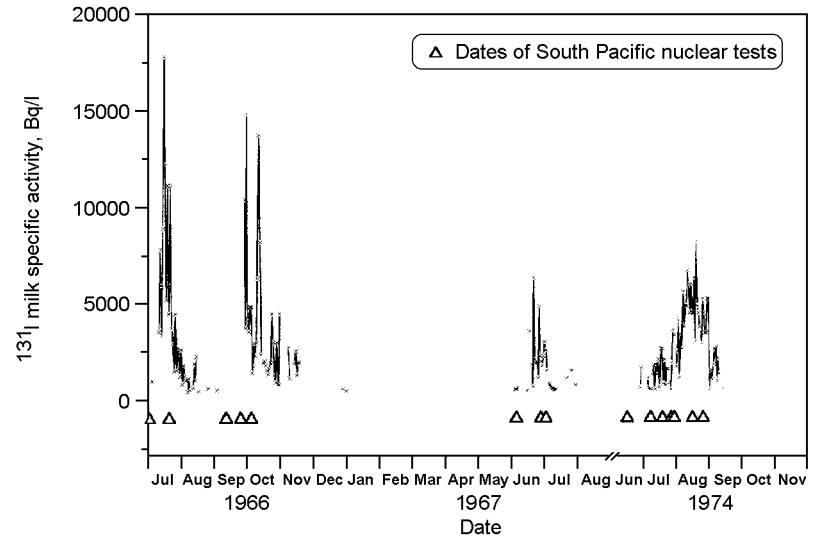

Fig. 5. Specific activity of ^{131}I in milk. The samples were collected daily in Bariloche City (41° 9' S, 71° 19' W)

Figures 3, 4, and 5 show that ^{131}I activity was detected in milk samples after each nuclear test in the three sampling points. The mean delay time between the tests and the start of ^{131}I detection in milk sampled in Buenos Aires City was 12 days.[11] Similar time delays can be observed in Figs 4 and 5 for the other sampling points, Salta and Bariloche cities. Since ^{131}I activity in milk is associated with fallout, we can evaluate fission products deposition by analyzing the relative intensity of the peaks observed in Figs 3, 4, and 5. Samples from Buenos Aires and Salta (Figs 3 and 4) show similar behavior, with the highest peak, of similar intensity, taking place between October 13 and October 19, 1966, while the test series of July, 1966, June–July, 1967, and June–August, 1974, had little contribution to fallout in these places. Figure 5, when compared to Figs 3 and 4, shows that in the samples taken in Bariloche the highest specific activity is associated with the test series of July, 1966. Also observed is a similar fallout contribution from the test of September 11, 1966, June–July, 1967, and June–August, 1974, and lower fallout intensity in the tests of September 24 and October 4, 1966.

We conclude from the analysis of ^{131}I in milk samples that, despite the different fallout intensity attributable to differences in local weather conditions during radionuclides transport and deposition, the three sampling points, Buenos Aires, Salta and Bariloche cities, received tropospheric fallout fission products associated with the nuclear tests in the South Pacific.

It is, therefore, reasonable to assume that most part of the Argentinian territory received this fallout with similar behavior, except for regions with strong differences in weather conditions that affect transport and deposition. We can also conclude that the general remarks that can be obtained from the analysis of fallout sampled in Buenos Aires City are valid also in the other two places, taking into account the fallout intensity differences.

The analysis of the four short lived fission products in fallout sampled in Buenos Aires City, shows that all nuclear test series from 1966 to 1974 produced tropospheric fallout, with different intensity. The behavior of the fallout specific activity of the four radionuclides studied is similar, showing similar behavior during transport and deposition, so that, as mentioned before, we can expect the same behavior of other fission products, like ^{137}Cs ($T_{1/2}$ = 30.07 y)[15] and ^{90}Sr ($T_{1/2}$ = 28.79 y).[15] The previous analyses of ^{95}Zr+^{95}Nb and ^{103}Ru show that the fission products remain in the troposphere for months, and are released by fallout, atmospheric transport and nuclear decay. Due to their long half-life, this last effect is negligible for ^{137}Cs and ^{90}Sr.

Fallout of long-lived fission products

Anthropogenic fission products of long half-life had been measured in fallout sampled at Buenos Aires City.[8,9] Fallout specific activity of ^{90}Sr was measured since 1959, while ^{137}Cs was measured since 1964. Figure 6 depicts the specific activity of ^{137}Cs and ^{90}Sr accumulated per year, without nuclear decay correction, showing the same pattern for both fission products.

The early ^{90}Sr measurements show a fast increase of the specific activity, that can be associated with stratospheric and tropospheric fallout of fission products derived from the nuclear test series starting in the second half of the sixties in the case of the tests at Navidad Islands. Activity measurements of 1959 and 1960 correspond to the previous atmospheric nuclear test series, that started in 1954. Given the similar behavior of both fission products from 1964 to 1976, it is only reasonable to assume that ^{137}Cs fallout behaved in the period 1959–1963, as ^{90}Sr did. BENINSON et al.[7] reported that the behavior of ^{137}Cs fallout in that period is similar to that of ^{90}Sr, but direct ^{137}Cs measurements are not reported. Their work also reports that the ratio, ^{137}Cs/^{90}Sr, of the mean specific activities for the two fission products in the period 1959–1963 was 1.8±0.4, a value that is in good agreement with the relation of fission product yields in nuclear explosions.[7] In the period 1964–1976 this relation keeps constant, 1.33± 0.15, with a lower mean value and lower dispersion.

The highest fallout contribution of ^{137}Cs and ^{90}Sr was registered in the period 1964–1966 (Fig. 6). This coincides, except for a delay of one year, with the year 1963, which was the period of maximum ^{137}Cs fallout from nuclear tests registered in sediment cores sampled in the Northern Hemisphere.[2,5,6] Figure 7 shows the peak registered in 1963 in a core sampled in Switzerland. In the measurements performed in Argentina (Fig. 6), the ^{137}Cs and ^{90}Sr deposition contents in 1964 and 1965 could be explained as due to stratospheric fallout from nuclear tests performed in the Northern Hemisphere. However, the specific activity contents in 1966 show an increase over the previous year that, in the case of ^{137}Cs, led to the highest measured value. This increase, not registered in the Northern Hemisphere, could only be due to tropospheric contributions from the South Pacific nuclear tests which, according to Figs 1 and 2, gave rise in 1965 to the maximum fallout of short-lived fission products. After 1966 the specific activities decreased rapidly due to less intense tropospheric fallout from the South Pacific tests of 1967 to 1969 and also due to little contribution from stratospheric fallout. The fallout specific activities of ^{137}Cs and ^{90}Sr from 1970 to 1974, as observed in Fig. 6, can be ascribed solely to the South Pacific nuclear tests, and are consistent with those observed in the case of the short lived fission products. This last statement is backed by the following observations:

(1) In 1970, an increase in specific activity (only ^{137}Cs), due to the eight South Pacific tests carried out during that year. Notice that the fallout specific activity for ^{95}Zr+^{95}Nb had similar or higher values in 1970 than in 1968 (Fig. 2) but ^{137}Cs values are higher in 1968 than in 1970 (Fig. 6). This is most likely due to stratospheric and residual tropospheric contributions from the five 1968 explosions, while there were no tests performed during 1969.

(2) The fallout specific activity of ^{95}Zr+^{95}Nb had similar or, if any, higher values in 1971 than in 1970. This fact, plus the atmospheric accumulation from the tests performed during 1970, would explain the increase in the case of ^{90}Sr and ^{137}Cs.

(3) A specific activity decrease of fallout in 1972, and a sharper decrease in 1973, clearly observed in Fig. 2 for ^{103}Ru and ^{95}Zr+^{95}Nb, are faithfully repeated in the behavior of ^{90}Sr and ^{137}Cs in Fig. 6.

(4) An increase in 1974, due to a much higher relative fallout intensity than in the previous year, is clearly observed also for ^{103}Ru and ^{95}Zr+^{95}Nb (Fig. 2).

^{137}Cs and ^{90}Sr fallout contents decreased rapidly after 1974, and they were below detection limits after 1976. It should be remarked that the ^{137}Cs and ^{90}Sr fallout described in this work for the period 1970–1974, has not been observed in sediment cores sampled in the Northern Hemisphere (Fig. 7).[2,5,6] After 1980 detection techniques were improved and small ^{137}Cs and ^{90}Sr fallout contents were measured. The Chernobyl accident in 1986 produced little stratospheric ^{137}Cs fallout in Buenos Aires City, in any case negligible for dating

purposes. This is another relevant difference with the Northern Hemisphere records, where the Chernobyl accident is clearly registered (Fig. 7).[6]

^{137}Cs dating in sedimentary cores from Nahuel Huapi National Park

Analyses were performed of sedimentary cores sampled from lakes Nahuel Huapi and Morenito. ^{210}Pb dating was performed in each core to compare the result with ^{137}Cs profiles. Low background, high resolution gamma-ray spectrometry was used for ^{210}Pb dating,[1,16–18] applying the CRS model.[1,19,20]

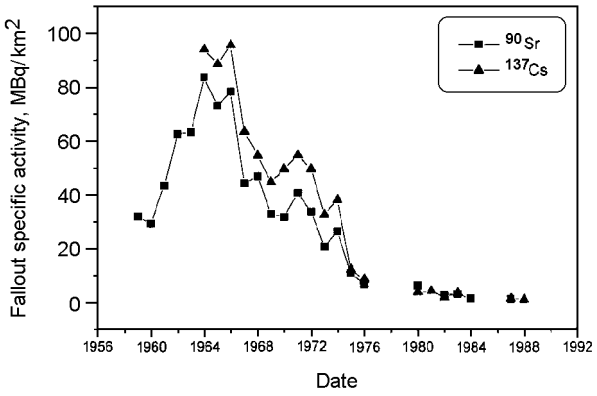

Fig. 6. Specific activity of ^{137}Cs ($T_{1/2}$ = 30.07 y) and ^{90}Sr ($T_{1/2}$ = 28.79 y) fallout measured monthly and accumulated per year without decay correction. The samples were collected in Buenos Aires City

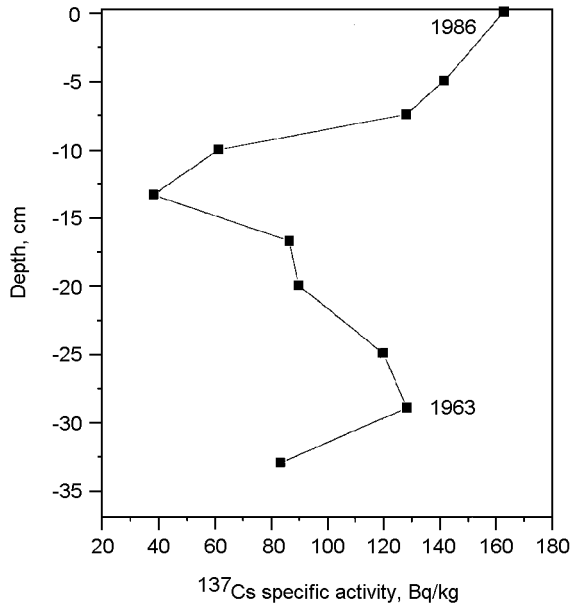

Fig. 7. Specific activity of ^{137}Cs measured in a core sampled from Lake Lobsigensee, a small eutrophic shallow near Bern, Switzerland.[6] The two peaks correspond to 1963 nuclear tests and 1986 Chernobyl accident

^{137}Cs profiles were determined by high resolution gamma-ray spectrometry, measuring the 661.66 keV gamma-ray. A high purity germanium (HPGe) detector, 30% relative efficiency, was used. Data collection and gamma-ray spectra processing were performed respectively with an EG&G Ortec DSPec electronic system and with the Ortec Gamma Vision-32 program. Spectra were taken in 4096-channels. Self attenuation correction factors were computed according to the methodology presented by CUTSHALL et al.[21] Long counting background runs were performed, and no 661.66 keV activity was detected. The detection limit of the system is around 1 Bq/kg, depending on sample mass and counting time. The efficiency calibration for the 661.66 keV peak was performed using three standard reference materials, with different ^{137}Cs specific activity: IAEA-300 Baltic Sea Sediment (1067 Bq/kg), NIST Fresh Water Lake Sediment (59.2 Bq/kg), and NIST Peruvian Soil (0.33 Bq/kg). The SRM NIST Peruvian Soil was used only to check the detection limit of the system.

Sediment cores were extracted with a messenger activated gravity type corer. They were cut open, visually inspected, and sub-sampled every 1 or 2 cm. Each sample was freeze-dried, homogenized in an agate mortar, weighted, placed in the counting containers and sealed.

Lake Morenito

Lake Morenito (41° 4’ S, 71° 32’ W) is a small closed basin, with a maximum depth of 6 m. This lake was a branch of western Lake Moreno until 1960, when an artificial dam closed the system establishing the new lake. Its connection to Lake Moreno depends on the Moreno water level fluctuations, and water inputs are mainly due to small mountain streams. The human-induced disturbances occurred during the last few decades have strongly affected Lake Moreno-Morenito ecosystem, producing an accelerated eutrophication. Lake Morenito is a highly productive closed environment, with porous sediments (density is around 0.1 g/cm^3) and up to 30% organic matter. A sedimentary core was sampled in May 1997, at 6 m depth. It was 73 cm long, and it was sub-sampled every 1 cm.

The ^{210}Pb dating of Lake Morenito core allowed the identification of accumulation periods of the eight upper layers (Fig. 8). The 1947–1997 average sedimentation rate obtained is (23.08±0.71) mg·cm^{-2}·y^{-1} ((0.2004±0.0060) cm·y^{-1}).[18] The activity has an approximately exponential behavior except in the upper layers. This behavior gives evidence of phenomena like biodisturbation or diagenesis, that were reported in other works.[1,2,6,17,22,23] These phenomena might be respon-sible also for disturbances in ^{137}Cs profile in these layers.

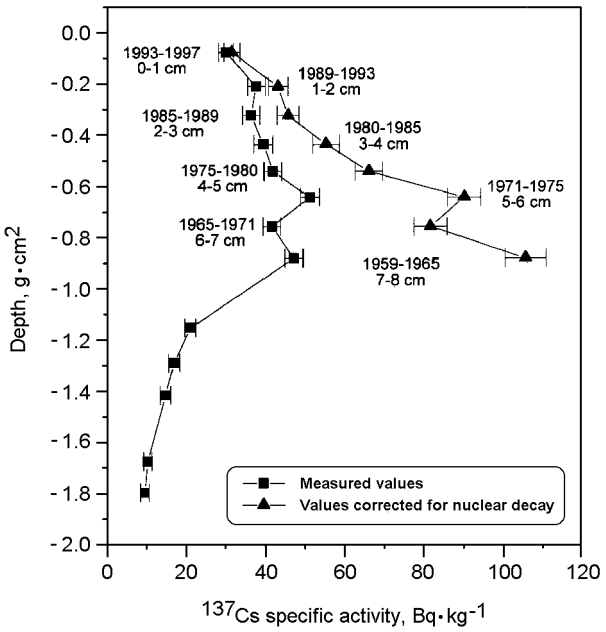

Fig. 8. ^{137}Cs specific activity profile of Lake Morenito core. The sediment accumulation periods were calculated by ^{210}Pb dating

Figure 8 shows the measured ^{137}Cs specific activity profile of Lake Morenito, and the same values after correction for nuclear decay for the layers where ^{137}Cs contents is mostly due to sediment deposition, as opposed to diffused ^{137}Cs.

Lake Nahuel Huapi

Lake Nahuel Huapi has a total area of 557 km^2, a maximum depth of 464 m and it is 764 meters above sea level. It is a glacial lake and its only discharge is the Limay river. Although it can be considered as an ultraoligotrophic system, the lake shows some mesotrophic areas located near Bariloche City and also near Villa La Angostura due to waste discharges. In the area surrounding the lake there is a strong vegetation gradient, from dry grassland (ecotonal forest) in the East to dense rainforest (mainly *Nothofagus dombeyii* and *Austrocedrus chilensis*) in the West. The East to West precipitation gradient is also steep, from less than 1000 mm to about 3500 mm. In the area of interest the precipitation is 949 mm (1975). San Carlos de Bariloche, located in the southern margin of Lake Nahuel Huapi, is the largest human settlement of the area, with about 80000 people.

Two cores, designated as NHS and NHN, were taken from Lake Nahuel Huapi. One in July 1998, NHS, sampled on the southern side of the lake (41° 7' S, 71° 15' W) near Bariloche City, and the other in October 1998, NHN, on the northern side (41° 3' S, 71° 22' W). Core NHS was 70 cm long and was taken at a depth of 42 m. Two 1 cm-layers were sub-sampled from the upper end of the core, and thereafter the core was sub-sampled every 2 cm. Core NHN was 72 cm long and was taken at a depth of 40 m. It was sub-sampled every 2 cm. Figures 9 and 10 show the uncorrected specific activity profiles measured for cores NHS and NHN, respectively. Also shown in these figures are the same profiles after correction of nuclear decay for those layers where ^{137}Cs content is mostly due to sediment deposition.

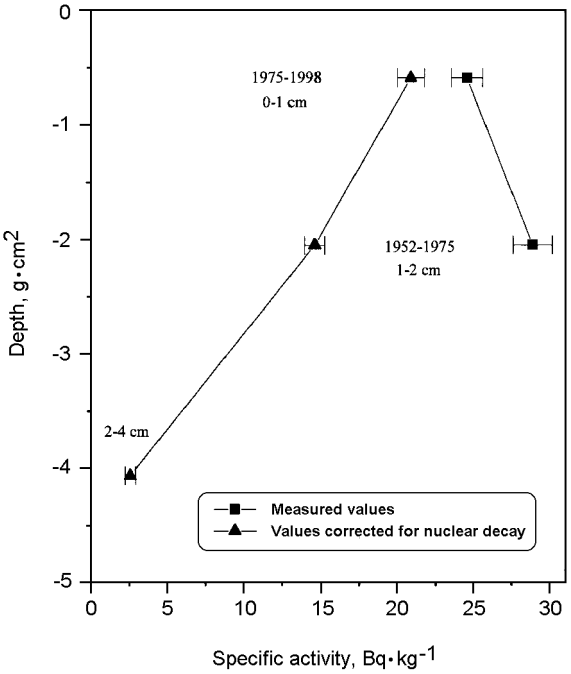

Fig. 9. ^{137}Cs specific activity profile of core NHS, Lake Nahuel Huapi. The sediment accumulation periods for the upper layers were estimated by ^{210}Pb dating

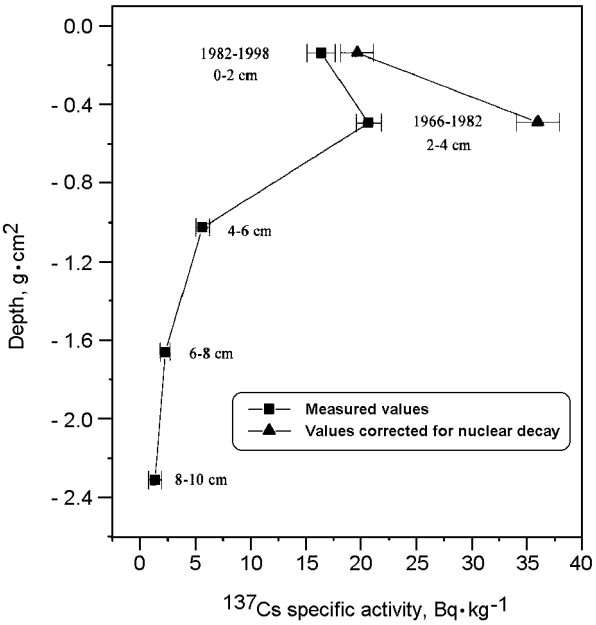

Fig. 10. ^{137}Cs specific activity profile of core NHN, Lake Nahuel Huapi. The sediment accumulation periods for the upper layers were estimated by ^{210}Pb dating

^{210}Pb dating of Lake Nahuel Huapi cores gave only an estimate of the sedimentation rates and the accumulation period of the upper layers. ^{226}Ra, that represents the supported ^{210}Pb activity, coincides with the total ^{210}Pb contents of layer 2–4 cm in core NHS, and layer 6–8 cm in core NHN, and all subsequent layers. Therefore, the unsupported ^{210}Pb activity is significant only in the upper layers. ^{210}Pb dating of the core layers was not possible under these conditions. However, with the data available for the upper layers, it was possible to estimate the mean sedimentation rate.[18] The mean sedimentation rate estimated in the last 50 years is 59 mg·cm^{-2}·y^{-1} (0.043 cm·y^{-1}) for core NHS,[18] hence the estimated accumulation periods for layers 0–1 cm and 1–2 cm were 1975–1998 and 1952–1975, respectively. The mean sedimentation rate estimated in the last 32 years is 22 mg·cm^{-2}·y^{-1} (0.123 cm·y^{-1}) for core NHN, hence the estimated accumulation period for layers 0–2 cm and 2–4 cm are 1982–1998 and 1966–1982, respectively.

Discussion

It is well known that Cs moves along the sediment column after deposition, altering the time sequence associated to the specific concentration profile. Changes in environmental conditions, like pH, oxygen concentration or water salinity, produce adsorption or desorption of Cs onto, or from, the sediment surface, allowing the transport by diffusion through the interstitial water. Biodisturbance and physical mixing of the sediment are other phenomena that alter the sediment content sequence. Most ^{137}Cs specific activity profiles reported in the literature show ^{137}Cs detection in core layers that should not have it, and this detection can be explained by the phenomena mentioned above. There are cases where ^{137}Cs mobilization within the sediment is so important that the activity profile has an exponential form, thus completely loosing the time sequence.[24] For dating purposes, only the profile peaks are considered. The profiles measured in this work show ^{137}Cs contents even in deep layers, with a strong decrease in specific concentration values (Figs 8, 9 and 10). This behavior can be explained by ^{137}Cs mobilization. The graphs of the ^{137}Cs specific activity profiles (Figs 8, 9 and 10) also show the measured values corrected by nuclear decay, using ^{210}Pb dating, to properly evaluate the time sequence. The correction was only performed for those layers where we considered that the measured ^{137}Cs content is mostly associated to sediment deposition.

The low resolution of core NHN and NHS sub-sampling, combined with the low sedimentation rate, does not allow to distinguish the ^{137}Cs fallout peaks in the activity profile. However, these profiles are consistent with the ^{210}Pb sedimentation rate estimations, regarding the ^{137}Cs fallout time evolution in the study region. In core NHS (Fig. 9) the presence of ^{137}Cs in the two upper layers, plus the strong decrease in layer 2–4 cm, and its disappearance in the subsequent layers, are consistent with the ^{210}Pb sedimentation rate estimation. The ^{137}Cs stratospheric and tropospheric inputs are registered in the 1–2 cm layer (1952–1975, according to ^{210}Pb dating), the highest value after decay correction, while mainly tropospheric inputs are registered in the 0–1 cm layer (1975–1998, according to ^{210}Pb dating). An activity peak can be observed in layer 2–4 cm of core NHN profile (Fig. 10), with a strong decrease in deeper layers. The ^{137}Cs stratospheric and tropospheric inputs are registered in the 2–4 cm layer (1966–1982, according to ^{210}Pb results) and stratospheric inputs are partially registered in 4–6 cm layer, while weak stratospheric inputs are registered in the 0–2 cm layer (1982–1998, according to ^{210}Pb results). The peak intensity of layer 2–4 cm of core NHN relative to the upper layer (activity relation: 1.8) is higher than in core NHS (activity relation: 1.2), after decay correction. This fact is consistent with the deposition chronology stated above, because layer 2–4 cm of core NHN received almost all relevant ^{137}Cs fallout, while the activity of layer 0–2 cm is composed of weak fallout and contributions from Cs mobilization. In core NHS, layer 1–2 cm received most stratospheric fallout, while tropospheric inputs were shared with layer 0–1 cm.

The ^{137}Cs profile of Lake Morenito (Fig. 8) shows excellent agreement with ^{210}Pb dating and fallout time evolution described (Fig. 6). Figure 8 shows activity peaks in layers 5–6 cm (1971–1975, according to ^{210}Pb dating) and 7–8 cm (1959–1965, according to ^{210}Pb dating), that, respectively, correspond to the secondary peak of the tropospheric fallout and stratospheric plus tropospheric inputs (Fig. 6). The activity relation of the peaks, after decay corrections, is also consistent with the deposition chronology stated above.

Conclusions

The specific activity of ^{137}Cs fallout samples collected in Buenos Aires City shows different characteristics than records taken in the Northern Hemisphere. The most intense fallout peaks were registered in 1964, 1965, and 1966. These peaks were produced by the combination of stratospheric and tropospheric fallout, with the tropospheric contributions coming from the South Pacific nuclear tests. We should expect these peaks to show up as the deepest and most intense specific activity peaks found in sedimentary core of ^{137}Cs specific activity profiles. Another ^{137}Cs peak, associated mainly with tropospheric fallout, was detected in the period 1970–1972, with a secondary peak in 1974. No other relevant ^{137}Cs fallout was observed, furthermore, the Chernobyl nuclear power plant accident

in 1986 produced little stratospheric ^{137}Cs fallout in 1987 and 1988, negligible for dating purposes. The analysis of short lived fission products in fallout sampled in Buenos Aires City clearly demonstrates that tropospheric fallout originated in the South Pacific nuclear tests was received in Argentina from 1966 to 1974. Fallout observations were closely followed in Buenos Aires City but not in Nahuel Huapi National Park (located about 1600 km South West of Buenos Aires City) where our study of lake cores was performed. However, the analyses of milk sampled in Bariloche City and in Salta City show that the fallout covered most of the territory of Argentina with a similar time pattern, showing in particular that fallout did indeed reach Nahuel Huapi National Park where Bariloche City is located. We do not expect that the stratospheric fallout has substantial differences between Bariloche and Buenos Aires. With these arguments we conclude that the time behavior of ^{137}Cs fallout in the Nahuel Huapi National Park was similar to that in Buenos Aires, and followed the description stated in the previous paragraph. This behavior is represented in Fig. 6.

^{137}Cs specific activity profile of a core taken from Lake Morenito reproduces the fallout time sequence observed in the region, thus allowing for the determination of both the sediment deposition chronology in the 1959–1998 period, and the evaluation of the sedimentation rate. The chronology obtained shows excellent agreement with ^{210}Pb dating. ^{137}Cs specific activity profile of Lake Nahuel Huapi cores can also be associated with the fallout time sequence, despite the low resolution of the sub-sampling and the low sedimentation rate. The ^{137}Cs chronology of two Lake Nahuel Huapi cores shows good agreement with ^{210}Pb dating.

In brief, the conclusions stated above show that ^{137}Cs specific activity profiles of sediment cores sampled from lakes of the Nahuel Huapi National Park are a useful tool for dating purposes.

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