BEACH SEDIMENT DYNAMICS FROM NATURAL RADIONUCLIDES POINT OF VIEW

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Abstract – This study is focused on assess the use of radionuclides ^{226}Ra, ^{228}Ra, ^{40}K and ^{210}Pb$_{ex,}$ as well as the ratio ^{226}Ra/^{228}Ra, as tracers of marine sediment dynamic. For this the spatio-temporal variability of the activity concentration of these radionuclides was analysed in Las Canteras beach (Spain). This beach was selected due to its heterogenic composition and marine dynamics. A Cluster analysis and a Principal Component analysis (PCA) were performed to evaluate the spatial variability. The results grouped the samples in three zones related to the sediment distribution under the effects of the marine dynamics that are created by the different geomorphologies of the beach. In the temporal variability analysis, an ANOVA test and Tukey's Honestly Significant Difference (HSD) Test pointed out that the wave action influences the activity concentration found for the different radionuclides during erosion and accumulation periods. In addition, the results of a geochemical analysis of samples from maximum and minimum activity concentration campaigns suggested that the radionuclides studied could be used as tracers of marine sediment dynamic in beach areas.

Introduction

Natural radionuclides in the Earth's crust have different origins. Some of them come from the elements that compose it and others are generated by the interaction of the cosmogenic radiation with the elements in the atmosphere. These last ones are then deposited on the planet surface by different processes. Since all of these elements can be found in the soils of the planet that generate sediments, natural radionuclides could be used to evaluate different sediment dynamics. In the case of beaches, the morphology and sedimentary budget is mainly controlled by sand erosion and accumulation periods. Therefore, monitoring these processes closely is a key factor to a sustainable management of this high-value areas, as well as can be useful to better understand how beaches morphology can evolve with time. Different techniques can be used to evaluate sediment dynamics in beach areas, and among them, natural radionuclides have proven to be an interesting tool in coastal areas [7], [15].

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In this study the use of natural radionuclides has been assessed in Las Canteras beach, in Las Palmas de Gran Canaria, Spain. This beach is very heterogenous in sand composition and marine dynamics that affect it. In addition, the sediment dynamic as well as its sedimentary budget have been very well studied during the years. According to these studies, Las Canteras beach is divided in three arches, and it presents a natural offshore rocky bar that covers the northern and central arch (figure 1). This bar is not a complete block, but it presents fragmentations and openings that are more present in front of the central arch. The southern arch, on the contrary, does not present any bar and it is totally open to the wave action. Due to these different morphological characteristics, Las Canteras beach combines the characteristic dynamic of a closed beach protected against the wave action and that associated with a beach open to it, presenting seasonal variability in its sedimentary budget [1]. During erosion periods, sand is eroded from the southern arch and a lengthwise transport of these sediments can occur to the northern arch. During accumulation periods the sand from submerged sandbars arrive to the beach and, since the northern arch is under a constant accumulation period, some berms can appear and a lengthwise transport of sediments from the northern arch to the southern arch can occur [1].

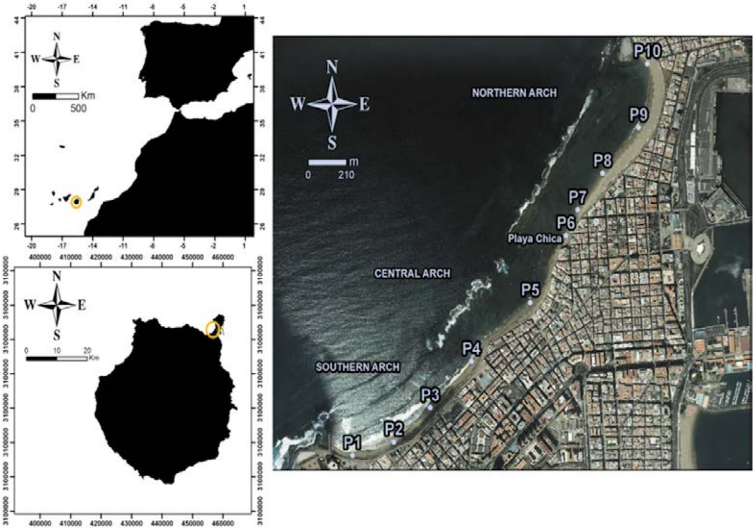

Figure 1 – Location of the study region and the sampling points in Las Canteras beach. Coordinates are in the UTM system [4].

Regarding the sand composition of Las Canteras beach, different sources can be identified: basic volcanic rocks from La Isleta, in the northeast of El Confital bay, phonolitic lava flow from the southwestern side of the bay, basic rocks and magnetite from the mouth of La Ballena ravine in the south part of the beach, submerged sandbars located between the bathymetric curve of 50 m and the beachfront and the natural offshore calcarenite rocky bar

[6], [14]. Furthermore, there are some calcimetry and petrological analyses of the beach sand and the geological composition of El Confital Bay (where Las Canteras beach is located) that identify different materials that can be found along Las Canteras beach. The sand from the northern arch has a higher content of bioclast and calcareous materials, as well as it presents a higher content in calcarenite. This calcarenite displays a higher content of feldspars in its terrigenous part and thus, feldpars seem to accumulate in the northern part of the beach. The southern part of the beach, on the contrary, tends to accumulate clinopyroxenes and other heavy minerals, such as olivine, amphiboles and Fe-Ti oxides that come from the ravine that ends in this part. The lighter lithics that can be found in this part are redistributed along the beach due to erosion and accumulation phenomena [1], [2], [12].

All these differences along Las Canteras beach enabled to evaluate the changes of natural radionuclides associated to the sediments that are transported under different marine dynamics and geological environments. On the one hand the southern arch resembles a beach open to the wave action and with sand composed mostly by heavy minerals. On the other hand, the northern arch presents the characteristics of a beach protected against the wave action and with sediments mainly composed by organic materials and calcarenite. Therefore, the results could resemble to those obtained after assessing the role of natural radionuclides in two different beaches with very different dynamic and geological characteristics. Hence, the results obtained could be expected to be applied in other parts of the world. In this framework, a spatio-temporal analysis of the activity concentrations of natural radionuclides was performed in Las Canteras beach during 2016 and 2019 [4], [5] and it is described in this work. These studies evaluated the role of gamma emitting radionuclides ^{226}Ra, ^{228}Ra, ^{40}K, ^{210}Pb$_{ex}$ and the ratio ^{226}Ra/^{228}Ra as tracers of erosion and accumulation periods in beach areas.

Material and Methods

Samples collection took part monthly from September 2016 to April 2019, with a total of 360 samples collected. For each campaign ten samples were collected in the intertidal zone of the beach during low tide time (Figure 1). At each sampling point, a square of 1 m^2 was drawn in the sand and, after mixing in situ, samples were taken from the superficial sand (between 0 and 5 cm depth). After this, samples were taken to the laboratory, they were dried at 80 ◦C for 24 h. They were then sieved through a 1 mm mesh size to homogenise them and kept inside PVC-trunk conical containers, filled to 40 cm^3. They were sealed with aluminium strips, because they are impermeable to radon gas [4]. Finally, the samples were stored for a duration of approximately one month before measurement to allow secular equilibrium between ^{226}Ra and ^{222}Rn and its short-lived progenies (as ^{214}Pb is used for determining ^{226}Ra).

The determination of radionuclides in sand samples by gamma spectrometry analysis was carried out using a Canberra Extended Range (XtRa) Germanium spectrometer, model GX3518, with 38 % relative efficiency with respect to a 3” x 3” active area NaI (Tl) detector and nominal FWHM of 0.875 keV at 122 keV and 1.8 keV at 1.33 MeV. It works coupled to a Canberra DSA-1000 multichannel analyser with the software package Genie 2000. Efficiency calibration of the system was performed using the Canberra LabSOCS package based on the Monte Carlo method [3], [5], [10], [11]. Calibration was verified using reference standards for IAEA RGK-1 (potassium sulfate), RGU-1 (uranium ore) and RGTh-1 (thorium ore). Energy calibration was carried out using a ^{155}Eu/^{22}Na (Canberra ISOXSRCE, 7F06-9/10138 series) and confirmed using the 1460.8 keV line of ^{40}K (IAEA RGK-1) [3].

The radionuclides of interest were determined from different photopeaks. ^{226}Ra was determined from the ^{214}Pb using the 351.9 keV emission line. ^{210}Pb was directly measured using the emission line of 46.5 keV. The activity concentration of ^{228}Ra was calculated from ^{228}Ac by the emission line of 911.2 keV. Activity concentrations of ^{40}K and ^{137}Cs were directly measured using emission lines 1460.8 keV and 661.8 keV, respectively. The counting time for each sample was around 24 hours. With the values of ^{210}Pb and ^{226}Ra unsupported or excess ^{210}Pb (^{210}Pb$_{ex}$) [9] was calculated.

In order to better understand the role of natural radionuclides as tracers of sediment transport during erosion and accumulation periods, the variations in the chemical and mineralogy composition of 4 sand samples were evaluated. The first 2 samples selected belong to the maximum gamma activity campaign and the other 2 to the minimum one. For this, a multielement analysis using a coupled plasma optical emission spectrometry (ICP-OES), a Powder X-ray diffraction (XRPD) and a single crystal X-ray diffraction (SCXRD) analysis were performed. The X-ray diffraction analysis was selected as a technique to search the minerals that are transported during erosion and accumulations periods and could contain the radionuclides studied. With these techniques, it was expected to identify and better characterize the different sediments and minerals that mix in the sand and are responsible for the activity concentrations found [5].

A cluster analysis (CA) [13] and a principal component analysis (PCA) [16] were carried out in order to evaluate the spatial distribution of the activity concentrations of the radionuclides studied [4]. For the temporal analysis a one-way ANOVA test was performed to evaluate the presence of significant difference among the difference groups. Finally, a Tukey's Honestly Significant Difference (HSD) Test [17] was used to stablish the exact groups among which significant differences were found [5].

Results and Discussion

Figure 2 shows the dendrogram of the hierarchical cluster and the biplot corresponding to the PCA results. The same three groups were observed in both analyses. The first group that will be referred as zone I grouped samples from sampling points P1, P2, and P3, which are located in the open part of the beach in the southern arch. The second group that can be observed, and will be referred as zone III, includes samples from sampling points P7, P8 and P10. This sampling stations are located in the northern arch, in the part of the beach that is completed protected against the wave action by the natural offshore rocky bar. The last group that can be observed combines samples from sampling stations located in both the central arch and the northern arch. It includes samples from sampling stations P4, P5, P6 and P9, that are located in front of the openings of the natural offshore rocky bar. In addition, the biplot points out that the variance of ^{226}Ra, ^{228}Ra, and ^{40}K is mostly explained by PC1. Moreover, these radionuclides appear very close togeher in the biplot, meaning that they activity concentration variance is very well correlated. In the case of ^{210}Pb$_{ex}$ it is load far from the other radionuclides, indicating that its variance is more explained by PC2 and it is badly correlated to them. These seems to suggest that the agent controling the distribution along the beach of ^{210}Pb$_{ex}$ is different from that controlling the spatial distribution of ^{226}Ra, ^{228}Ra, and ^{40}K. Moreover, the presence of the distinct parts of the offshore rocky bar seems to be one of the main influences in the distribution of sediment transport and accumulation of radionuclides along the beach. Therefore, ^{226}Ra, ^{228}Ra, and ^{40}K seem to be tracing marine sediment dynamics [4].

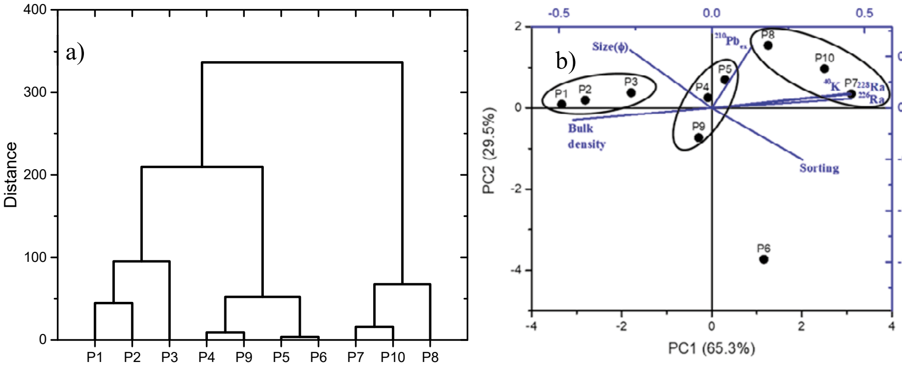

Figure 2 – a) Dendrogram showing clustering for the different sampling points based on their activity concentrations of ^{226}Ra, ^{228}Ra, and ^{40}K. b) Biplot of loading plot with the eigenvectors obtained for the grain size in the phi scale (Size φ), sorting, bulk density of the sample and activity concentrations of ^{226}Ra, ^{228}Ra, ^{40}K and ^{210}Pb$_{ex}$ (blue axes) and scores of observations (black axes) Modified from [4].

Considering the zones described in the spatial analysis, the temporal series of the mean values of ^{226}Ra, ^{228}Ra, ^{40}K, ^{210}Pb$_{ex}$ and the ratio ^{226}Ra/^{228}Ra during the whole study in each zone appear in figure 4. The ratio was also analysed since it had been proposed before as a tracer of erosion/accumulation periods [8]. This is because in the crystal framework of clay minerals both ^{226}Ra and ^{228}Ra can be found, but the carbonate and exchangeable phases contain more ^{228}Ra. Hence accretion or erosion periods could be measured by a change in the ratio between ^{226}Ra and ^{228}Ra. During accumulation periods the ratio would be below 1 due to the higher input of ^{228}Ra in this periods. On the contrary, during erosion events there would be a loss of ^{228}Ra and the ratio would increase above 1. Hence, this ratio was also analysed as tracer of erosion and accumulation periods. In the temporal series of the three zones, it can be appreciated that ^{226}Ra, ^{228}Ra and ^{40}K follow a similar pattern while ^{210}Pb$_{ex}$ behaves diferently. This again suggest that the agents controlling the distribution of the first three radionuclides are different to the ones controlling the distribution of ^{210}Pb$_{ex}$. Regarding the ratio ^{226}Ra/^{228}Ra, it can be observed that for zones I and II it presents values that are above and below 1, while in zone III is always under 1. The zone III is the area protected against the wave action and thus, in this part the ratio would always be below 1 which seems to be what can be observerd in the temporal series. In addition, in zones I and, a bit lesser, in zone II, the maximum values of ^{226}Ra, ^{228}Ra and ^{40}K seem to agree with values of the ratio below 1. All of these seem to agree with what would happen during erosion periods and thus, the temporal series seem to indicate that the three radionuclides, as well as the ratio, are tracing erosion/accumulation periods in the beach.

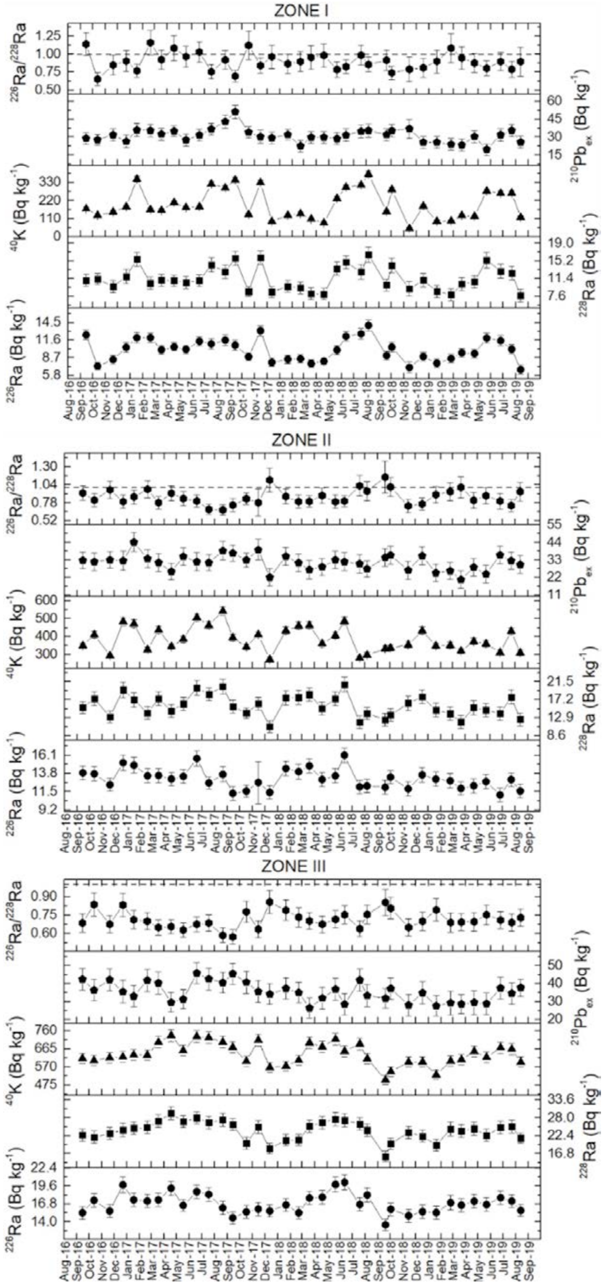

Figure 4 – Temporal series of the activity concentration of ^{226}Ra, ^{228}Ra, ^{40}K, ^{210}Pb$_{ex}$ and the ratio ^{226}Ra/^{228}Ra during the study period for the different zones established in [4] for Las Canteras beach [5].

In order to further analyse the role of the three radionuclides and the ratio as tracers of marine sediment dynamics, the effect of different erosion and accumulation agents such as wave approach direction and significant wave height. In table 1 the results obtained for the One-way ANOVA and the Tukey's Honestly Significant Difference (HSD) Test are shown. The One-way ANOVA identified the presence of significant differences in the temporal series of ^{226}Ra, ^{228}Ra, ^{40}K and the ratio ^{226}Ra/^{228}Ra. The HSD identified the exact groups that present significant differences in relation to the different erosion/accumulation agents studied.

Table 1 – Results of zone I for the one-way ANOVA test and Tukey's Honestly Significant Difference (HSD) Test. Modified from [5].

Area	Field	F	Prob-F	Tuckey's test
^{226}Ra	Significant wave height	9.61900	0.0005110	Low-high (0.0009) Low-medium (0.0114)
	Wave direction	6.02300	0.0194000	NW-NE (0.0194)
^{228}Ra	Significant wave height	19.14000	0.0000030	Low-High (0.0000065) Low- Medium (0.0004618)
	Wave direction	6.67200	0.0143000	NW-NE (0.0142665)
^{40}K	Significant wave height	25.34000	0.0000002	Low-High (0.0000008) Low- Medium (0.0000358)
	Wave direction	9.12100	0.0047700	NW-NE (0.0047708)
^{226}Ra/^{228}Ra	Significant wave height	1.98000	0.1540000	-
	Wave direction	0.21400	0.6470000	-
ANOVA prob-F 0.05 Tuckey's test p-value 0.05				

In the case of the ratio, no significant differences were found for any of the zones. According to the literature [1] the area fully protected by the natural offshore rocky bar (zone III) is in a constant accumulation period. Moreover, zone II is also protected by the bar, so the lack of significant differences can be expected in these two parts of the beach. In addition, some clay minerals have been found in the northern part of the bay where the beach is located [12] so the ratio seems to work in this part of the beach. However, this could not justify the lack of significant differences in zone I and since other minerals could also contain ^{228}Ra, this ratio might not be suitable to use as marine sediment dynamic tracer worldwide, but it could be used in areas with similar characteristics to the northern part of Las Canteras beach [5].

In the case of ^{226}Ra, ^{228}Ra and ^{40}K the results relating to the significant wave height showed significant differences for zone I between the low wave height and the medium and high wave height. According to the polar plots of figure 5, the campaigns with lower values of significant wave height for zone I would present higher activity concentrations values of these three radionuclides. For zones II and III no significant differences were found [5].

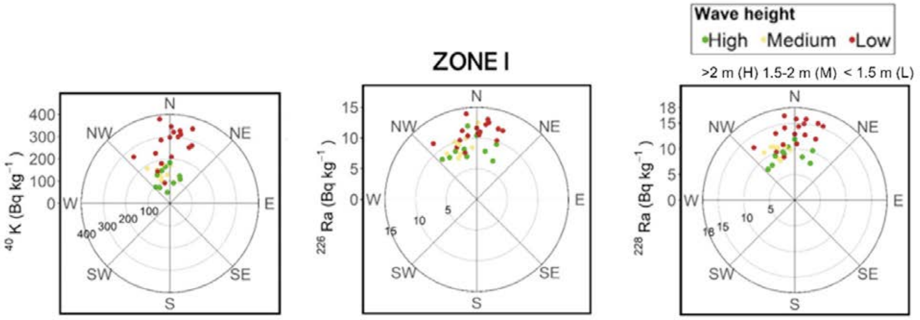

Figure 5 – Azimuth plot of wave height and direction and activity concentration of ^{226}Ra, ^{228}Ra and ^{40}K for the different zones in Las Canteras beach. Modified from [5].

The results relating to wave approach direction also reported significant differences for zone I between the campaign when the wave approach direction was NE or NW. The boxplots of figure 6 represents the activity concentration values of ^{226}Ra (figure 6a), ^{228}Ra (figure 6b) and ^{40}K (figure 6c) for the campaigns with NE and NW wave approach directions. They shows that, in campaigns with a NE wave approach direction, the activity concentration values of these elements were higher. The NE part of the bay and the north part of the beach is where the clay minerals and feldspars were found [2], [12]. Therefore, the results point to the possible influence of the minerals located in the northern part of the beach, in the changes of activity concentration values found in zone I during the whole study period [5]. In this case, zones II and III did not show any significant differences either.

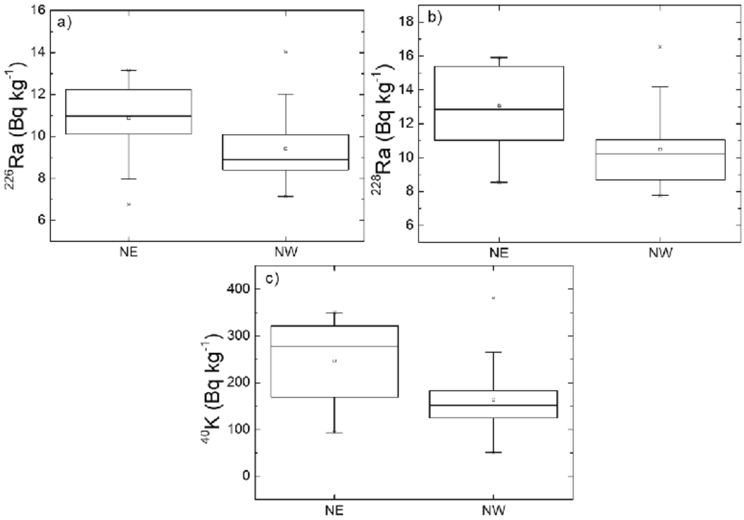

Figure 6 – Boxplot of the activity concentrations obtained for zone I in each campaign for each of the wave approach directions. a) ^{226}Ra, b) ^{228}Ra and c) ^{40}K [5].

In order to comprehend what mineral could be transporting ^{226}Ra, ^{228}Ra and ^{40}K a total of 4 samples were analysed by Powder X-ray diffraction (XRPD). The samples were chosen from two sampling stations (figure 1), one located in the open part of the beach (P2) and another located in the closed part of the beach (P8). From each sampling station a sample from a minimum activity concentration campaign (November 2018) and a sample from a maximum activity concentration value (August 2018) where analyzed. Hence, the samples from November 2018 would correspond to an erosion periods and samples from August 2018 would belong to an accumulation period. In addition, the sample from zone I was analysed by single crystal X-ray diffraction (SCXRD). The results of the X-ray diffraction analysis pointed out the increase of feldspar with potassium content in the samples from the open part of the beach during the accumulation periods. In the case of the samples from the closed part of the beach, this K-feldspar is present in both samples from erosion and accumulation campaigns. It has been described for Las Canteras beach that feldspars arrive to the southern part of the beach and are redistributed along the beach, as well as they are constantly present and accumulated in the northern part of the beach [1], [2]. Therefore, the results of the X-ray diffraction analysis seem to suggest that K-feldspar is the main K-bearing mineral. Hence, ^{40}K seems to be tracing the movement of this feldspar contained in the light fraction of the sand, making it a good tracer of the beach sedimentary dynamics [5]. The results of the multielement analysis showed that total K increases its concentration during accumulation periods and a decrease during erosion periods. In addition, Ba and Ca followed the same pattern as total K. Since it was no possible to measure Ra concentration by this method and, considering Ba has similar chemical properties to Ra, we could be assumed that total Ra follows the same pattern as total K too. Therefore, that would be why ^{226}Ra and ^{228}Ra follow a similar pattern to ^{40}K and could also trace marine sediment dynamics.

Table 2 – Multielement analysis of the total rock composition of each sand sample. Concentrations given in g kg-1 of Ba, Ca and K were analyzed. Modified from [5].

Sample	Ba	Ca	K
LOD of detector	0.0002	0.0552	0.0203
LOB	0.0113	3.1764	0.109
LOD of the method	0.0226	6.3529	0.2181
LOQ	0.0435	11.9209	0.4227
PLC18_8.2	0.3611±0.0047	172±2	16.03±0.10
PLC18_11.2	0.0519±0.0005	25±0	0.65±0.01
PLC18_8.8	0.3805±0.0023	167±1	15.48±0.09
PLC18_11.8	0.3484±0.0021	163±1	22.27±0.08

Conclusions

The assessment of the spatial and temporal variability of activity concentration of ^{226}Ra, ^{228}Ra, ^{40}K and the ratio ^{226}Ra/^{228}Ra in Las Canteras beach suggest that these could be used as tracers of beach sediment. Since this beach encapsulates both the dynamics of a beach protected against the wave action and that open to it, the results could be apply to areas all over the world. Therefore, the main conclusions are:

- The CA and PCA analysis used for the spatial analysis pointed out that samples are grouped in three zones related to the marine dynamics created by the natural offshore rocky bar. The biplot of the PCA also showed that ^{226}Ra, ^{228}Ra and ^{40}K are very well correlated while ^{210}Pb$_{ex}$ is less correlated. Due to the atmospheric origin of ^{210}Pb$_{ex}$, the results of the spatial analysis also suggest that ^{226}Ra, ^{228}Ra and ^{40}K might be tracing marine sediment dynamics.
- The statistical analysis of the temporal variability of activity concentration of ^{226}Ra, ^{228}Ra and ^{40}K suggested that these radionuclides follow a marine sediment dynamic with higher activity concentrations values found for zone I during accumulation periods, when significant wave height was lower. In addition, activity concentrations values would increase with NE wave approach direction, which suggests these radionuclides are also tracing the origin of the sediments that arrive to the beach.
- In the case of the ratio ^{226}Ra/^{228}Ra, no significant differences were found for any of the zones. However, zone III is the area protected by the natural offshore rocky bar and the ratio was below 1 during the whole study period, as it would be expected for a constant accumulation period. Hence, the lack of significant difference could be pointing out the lack of differences between erosion and accumulation periods. Therefore, the ratio could be applied as tracer of sediment dynamics in areas with similar characteristics to the northern arch of Las Canteras beach.
- Moreover, the mineralogical analysis suggested that the activity concentration values found for ^{40}K correspond to the movement of potassium feldspar that are transport in the light fraction of the sand into and along the beach during erosion/accumulation periods. Hence, ^{40}K seems to be the most fitting tracer for sediment dynamics in all the parts of Las Canteras beach. Nevertheless, the multi-element analysis of the composition of the total rock of the sand that can be found in the different parts of the beach in erosion and accumulation periods, indicates that Ba and Ca behave similarly to K. Since Ba has similar chemical properties to Ra, this could explain why ^{226}Ra and ^{228}Ra follow the same pattern as ^{40}K. Thus, these two elements could also be used as tracers of beach sediment dynamics.

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