# THE GABBRO AND SERPENTINIZED PERIDOTITE OF BONASSOLA (BRACCO-LEVANTO OPHIOLITE, ITALY) - AN EXTREMELY LOW NATURAL RADIATION AREA TO IMPROVE *IN SITU* GAMMA SPECTROMETRY

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ABSTRACT

Outcrops of dunite, serpentinized peridotite and clinopyroxene-rich coarse gabbro around Bonassola (Bracco-Levanto ophiolite, NW Italy) have been analyzed for natural radionuclides using γ-spectrometry. The very low activity concentrations of natural radionuclides in the dunite outcrop (< 9.0 Bq kg$^{-1}$ $^{226}$Ra; < 3.5 Bq kg$^{-1}$ $^{228}$Ac and < 25 Bq kg$^{-1}$ $^{40}$K) indicate that this site is characterized by a very low natural radiation for both cosmic (being at sea level) and terrestrial contributions. Before starting a field radiometric survey it is important to assess the local background, i.e. the g radiation that does not originate from rock, in order to correct the measurements for the local background. Contrary to the general practice regarding the background radiation in γ-spectrometry measurements, the investigated mafic-ultramafic outcrops has been used to estimate the detection limits for *in situ* measurement of $^{238}$U, $^{232}$Th and $^{40}$K using sodium iodine (NaI) scintillator detectors. These results have proved useful to quantify the minimum detectable amount of activity (MDA) of $^{238}$U, $^{232}$Th and $^{40}$K for the NaI detector; the MDA points at sub ppm levels for $^{238}$U and $^{232}$Th and 0.01 wt% $K_2O$.

This study also permits to assess the radiological risk of dimension stones that are petrographically similar to the serpentinized ultramafics occurring in the Bracco-Levanto ofiolite. The comparison of the activity concentration index I, defined by the EU Basic Safety Standards Directive and depending on the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K, with other stones used as building material, indicates that the Bonassola mafic-ultramafic rocks provide a negligible contribution to the indoor gamma radiation dose.

## INTRODUCTION

Natural radioactivity is widely distributed in the lithosphere as well as in all the various environmental compartments as a result of nucleosynthesis and biogeochemical cycling, providing the largest contributor to the collective effective dose received by the human population (Eisenbud and Gesell, 1997; UNSCEAR, 2008). Terrestrial radioactivity is mostly produced by $^{238}$U, $^{235}$U, and $^{232}$Th radioactive families together with $^{40}$K, which is a long lived radioactive isotope of the elemental potassium. These terrestrial radionuclides generated during the formation of the Earth and are still present in the Earth's crust. The heat released from them is the major energy source to drive the evolution of Earth and planets, and also the major power to drive the origin and evolution of the continental crust on Earth (Bao and Zhang, 1998).

The detection and measurement of natural radioactivity have a role of primary importance in many aspects of earth and health sciences. Radionuclides are widely used in geochronology and cosmochronology, and they can be very efficient markers for a variety of geochemical and petrological processes (Allègre, 2008). Additionally, γ-ray spectrometry techniques to detect radioactivity in the field, either *in situ* or using airborne detectors, is of interest for geophysical surveys aimed to mineral prospecting, gamma dose rate, natural radioactivity content and radon risk mapping (Chiozzi et al., 2000; Cinelli, 2012; Drolet et al., 2013; 2014; Strati et al., 2014; Guastaldi et al., 2013). *In situ* γ-spectrometry is usually performed with Sodium Iodine (NaI) detector, a good instrument to identify rapidly radionuclides in the environment thanks to the higher efficiency and portability than the more expensive benchtop germanium detectors. *In situ* technique with NaI detector allows much shorter measurement time than collecting samples of rock or soil and analyze them in a standard laboratory system. Before starting a field radiometric survey it is important to assess the local background, i.e. the γ-radiation that does not originate from rock, in order to correct the measurements for the local background. Generally this task is performed by looking for low natural radiation areas, usually represented by low-salinity lakes or rock exposures with very low $^{238}$U, $^{232}$Th and $^{40}$K contents. As rule of thumb, ultramafic rocks with very low bulk U-Th-K contents are the target for background measurements (Chiozzi et al., 2000).

In this work the extremely low background radiation area of the Bracco-Levanto ophiolite (NW Italy, Fig. 1) has been studied with the aim to use these results for improving *in situ* γ-spectrometry performance. In detail, this work aims to identify an extremely low natural radiation area to evaluate the detection limits of the NaI detector, calibrated with the Monte Carlo method (Cinelli, 2012). For these purposes, spectra using NaI detector have been collected on three outcrops (dunite, serpentinized peridotite and coarse-grained gabbro) with good source-detector geometry. Rocks from these outcrops have been sampled and analysed in the laboratory by means of high-resolution gamma spectrometry and x-ray fluorescence to establish which rock has the lowest radionuclides content and hence it is the most suitable to evaluate the NaI detection limits.

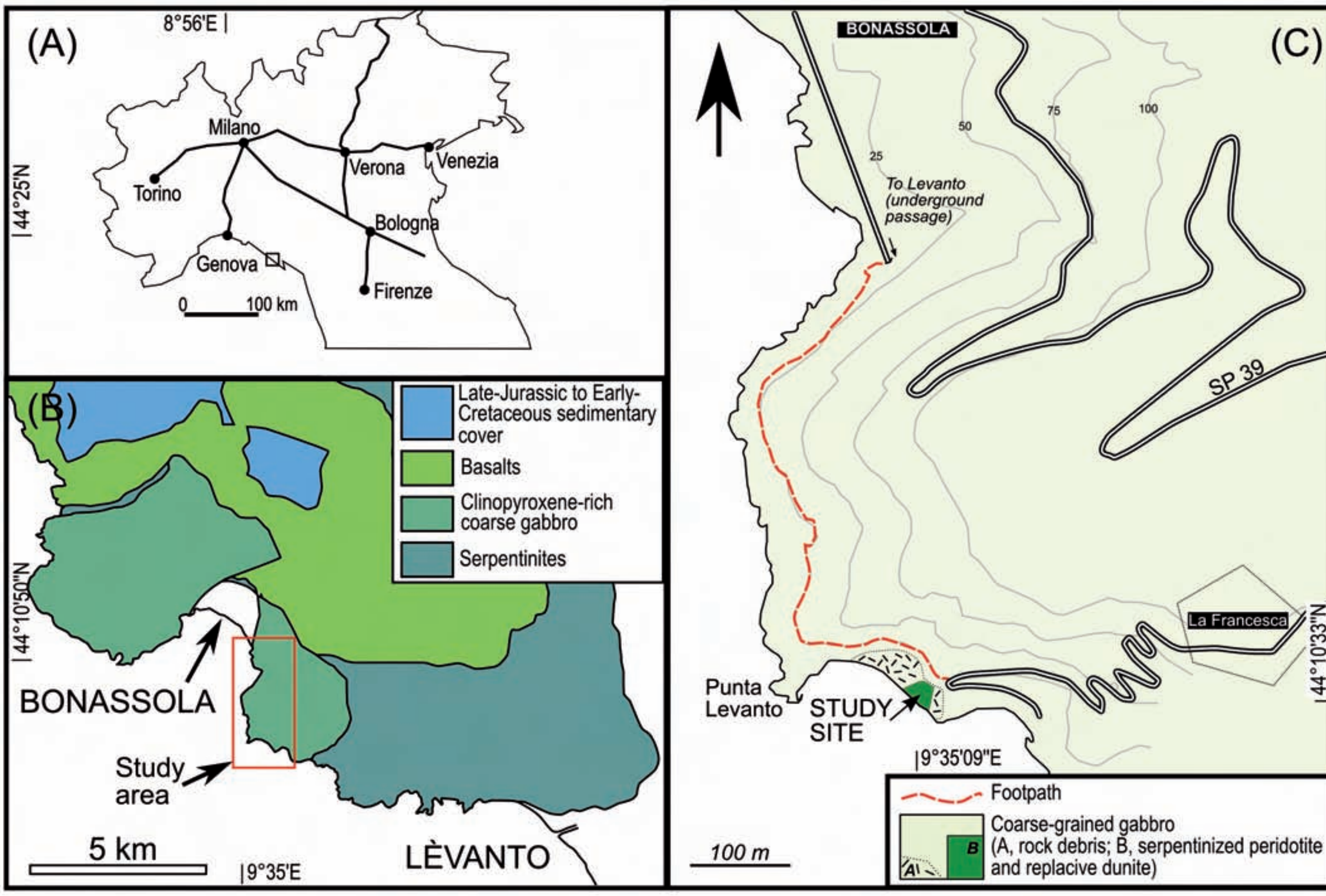


Fig. 1 - (A) index map; (B), simplified geological map from Decandia and Elter (1972); (C) location of the measurement sites in the Bonassola gabbro (Bonassola-Levanto ophiolite). The footpath starts beside the former railway tunnel (now a pedestrian passage) at the southeastern skirts of Bonassola.

The results of this study, moreover, permit to evaluate the radiological risk associated with the use of rocks similar to those occurring in this area as building material, in accordance with the new Directive on Basic Safety Standards by the European Union published in January 2014 (EC, 2013).

## STUDY AREA AND MEASUREMENT SITES

The measurement sites lie SSE of the Bonassola village (Italy: 44°10'32.6''N, 9°35'09.4' E) within the so-called Bonassola-Levanto ophiolite unit that belongs to the Internal Ligurian ophiolites, an association of lower oceanic crust basement with its Late Jurassic-Cretaceous volcano-sedimentary cover. The Internal Ligurides are interpreted as a distal portion of the Ligure-Piemontese basin (Principi et al., 2004). Along the cliff face connecting Bonassola to the La Francesca resort (Fig. 1), only the mafic-ultramafic sequence of the lower oceanic crust crops out. In particular, the chosen site consists of an ultramafic body hosted in the coarse-grained Bonassola gabbro, close to the contact with the serpentinized peridotites. The field relations and the petrography of the different rock types are already described in detail elsewhere (Molli, 1995; Tribuzio et al. 2014 and references therein), and only the main field features of the measurement sites are reported in the following.

The site BON3 occurs within a gray-greenish dunite lens (Fig. 2A) showing diffuse contacts with the surrounding serpentinized peridotite. The dunite, which has a replacive origin (Tribuzio et al., 2014), preserves relics of a tectonite fabric defined by the preferred orientation of spinel trails. The BON4 measurement site corresponds to a dark-gray serpentinized peridotite showing mm-sized pseudomorphs after orthopyroxene as a relic of the primary Spl-harzburgite assemblage (Tribuzio et al., 1997). Finally, the BON5 site consists of coarse-grained, clinopyroxene-rich varitextured gabbro adjacent to the serpentinite body. The gabbro outcrop is characterized by variations in grain-size and modal ratio of clinopyroxene and plagioclase (Fig. 2B), but in the site a definite compositional layering is not present. The primary gabbro mineralogy is not preserved: igneous clinopyroxene is replaced by amphibole (Fig. 3) and plagioclase by low-grade metamorphic minerals (Tribuzio et al., 1997). Veins (≤ 1mm to 10 mm thick) filled with amphibole and/or chlorite (Fig. 3) occur within the measurement sites. Late, open fractures crosscut both the serpentinized peridotite and the gabbro exposures.

## METHODS

*In situ* γ-spectrometry measurements were taken by using a 3 X 3 in. thallium-activated sodium iodide NaI (Tl) scintillator detector. NaI detector has been calibrated using Monte Carlo technique, MCNP code, for *in situ* γ-spectrometry at contact geometry, i.e. placing the NaI(Tl) probe directly on the solid source to be analyzed (Cinelli, 2012). Before acquiring each spectrum, a reference source of $^{137}$Cs

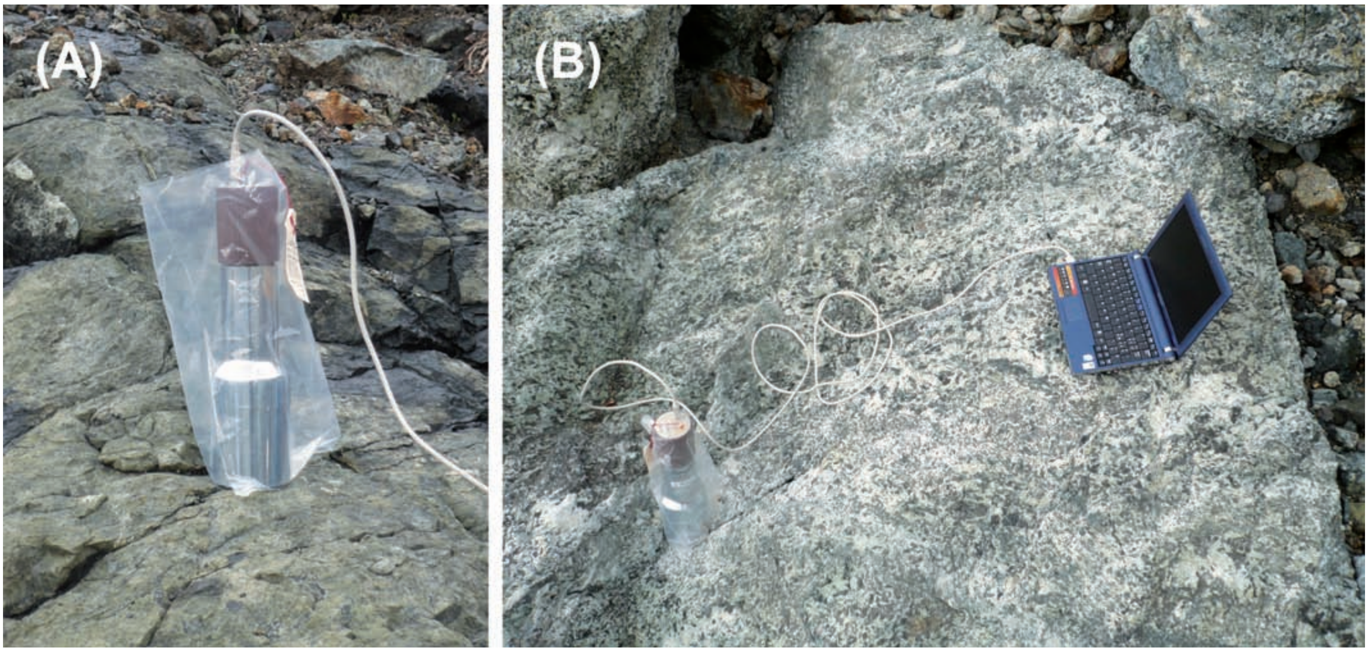


Fig. 2 - Examples of collection of gamma-ray natural background on dunite (A) and coarse-grained gabbro (B). In both locations the NaI detector sits on open fractures. The NaI detector (crystal part, photomultiplier tube and photomultiplier basis) is ca. 30 cm long. A polyethylene bag (0.1 mm thick) is used for protection.

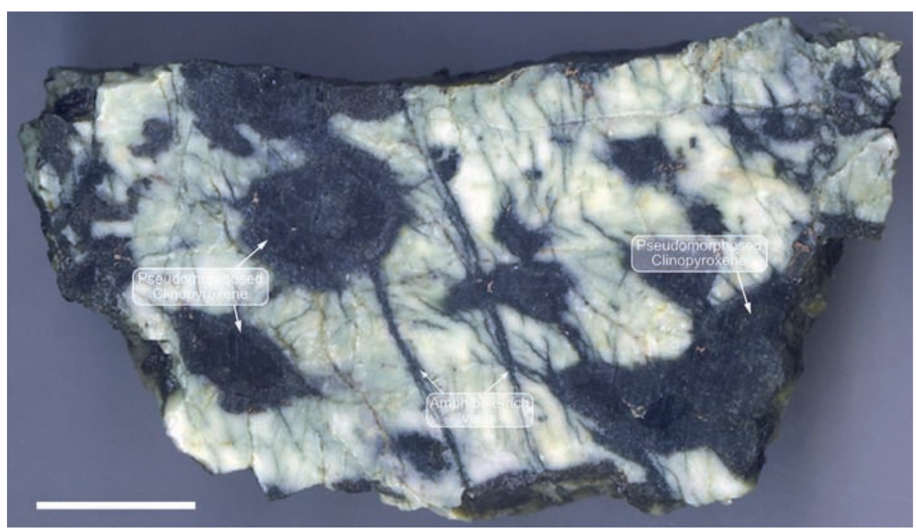


Fig. 3 - Slab surface of a sample of clinopyroxene-rich coarse-grained gabbro (BON5 measurement site). Pseudomorphosed clinopyroxene, now replaced by amphibole, and whitish plagioclase cut by hornblende veins up to 0.5 mm thick. Scale bar represents 1 cm.

is employed to control the system gain and correct any shift caused by temperature effect or component ageing. The measurement site was carefully chosen in order to ensure that only a rock type is within a hypothetical cylindrical volume of about 1.5 m of radius and 50 cm height, estimated as the maximum source volume from which the detector samples the photon flux (Cinelli, 2012). Three different spectra of ca. 900 s were collected on the three outcrops (dunite, serpentinized peridotite and coarse-grained gabbro) described above.

Samples of about 2 kg each of dunite, serpentinized peridotite and coarse-grained gabbro were taken from the same place where the *in situ* γ-spectra have been collected. Samples were crushed and sieved at 2000 micro-mesh size and each sieved sample was divided into two representative aliquots.

The first portion was analysed by high resolution γ-spectrometry with a p-type coaxial and a planar Hyper Pure Germanium crystal detectors (HPGe) at the Laboratory of Radiochemistry of the Bologna University. The system was calibrated for energy and efficiency using a multiple nuclide source (QCY48, Amersham) in a jar geometry (diameter: 56 mm; thickness: 10 mm). Spectra were analysed with the GammaVision-32 software (version 6.07, Ortec). $^{238}$U and $^{232}$Th were determined using the emissions of their radioactive descendants $^{226}$Ra (186 keV) and $^{228}$Ac (911.2 keV), assuming a secular equilibrium between $^{226}$Ra-$^{238}$U and $^{228}$Ac-$^{232}$Th. The correction of the $^{226}$Ra peak at 186 keV was carried out assuming a secular equilibrium between $^{226}$Ra-$^{238}$U and natural $^{235}$U/$^{238}$U isotopic ratio (Gilmore, 2008). Under these two hypotheses the $^{226}$Ra peak was corrected by dividing by 1.7337. To reach appropriate counting statistics samples were counted for more than 80,000 s. Conversion from activity concentration (Bq/kg) to bulk elemental weight fraction was obtained with the following conversion factors (Stromswold, 1995):

1% K = 309.7 Bq/kg
1 ppm U = 12.35 Bq/kg ($^{238}U$ or $^{226}Ra$, both assumed in equilibrium)
1 ppm Th = 4.072 Bq/kg.

The second portion was milled in a motorized agate mill for 10 min to produce an impalpable powder. The mill was cleaned after each milling run using denatured alcohol. Less than a gram of the rock powder of each sample was heated at 950°C overnight to determine the Loss on Ignition (LOI, which combines the loss of $H_2O^+$, $H_2O^-$ and $CO_2$, and possible gain of O if $Fe^{2+}$ is oxidized) by gravimetric analysis. Three grams of powder were pressed using 10 g of boric acid as binder to produce pressed powder pellets (Ø = 37 mm). This procedure ensures 1 mm thick powder film. The pressed powder pellets were analysed on an Axios (PANalytical, Netherlands) wavelength-dispersive XRF spectrometer at the Biological, Geological and Environmental Department (University of Bologna, Italy). For the major elements, the acceleration voltage and beam current were 24 kV, 100 mA for Si, Al, Ca, Na, K and P, and 30 kV, 80 mA for Ti, Fe, Mn, Mg. The operating conditions for the trace elements (As, Co, Cr, Cu, Ni, Pb, Rb, Sr, Th, U, Y, Zn and Zr) were 60 kV and 45 mA, with the exception of V (30 kV, 90 mA). The instrument was calibrated against international standard powders prepared using the same procedure outlined above. Based on repeated measurements, precision for major elements is always better than 3%, with the exception of $P_2O_5$ (9%). As for the considered trace elements, precision is better than 10%. Accuracy was tested against certified reference materials and the results are always within the ranges compiled in the GeoREM database (http://georem.mpch-mainz.gwdg.de). Under the reported instrumental conditions, the limit of detection (LOD, expressed in ppm) is estimated being the double of the LOD calculated by the Panalytical SuperQ® software. For U, Th and $K_2O$, which can be in very low concentrations especially in ultramafic rocks, the LOD is 2, 4 and 32 ppm for U, Th and $K_2O$, respectively.

## RESULTS

The results of high-resolution γ-spectrometry performed in laboratory using the HPGe detectors are reported in Table 1. The values for the three radionuclides of interest ($^{226}Ra$-$^{238}U$, $^{228}Ac$- $^{232}Th$ and $^{40}K$) are reported in term of activity concentrations. In all samples the investigated radionuclides have activity concentration below the detection limit of the instrument, pointing out that the detection limit depends on the measurement time.

The whole-rock chemical compositions of the ultramafic rocks show high contents of MgO (38-43 wt%) and Ni (≥ 2000 ppm), and low $SiO_2$ (35-36 wt%), $Al_2O_3$ (0.7-1.8 wt%) and $Na_2O$ (0.02-0.03 wt%; Table 2). LOI is ~ 13 wt%, in agreement with the large amount of secondary serpentine-group minerals after the primary mineral assemblage. U, Th and K abundances are values always below the detection limit of the XRF technique adopted here. Compared to the Primitive Mantle, the serpentinized ultramafic rocks are enriched in fluid-mobile elements like Rb and Pb, but depleted in Sr. The Zr contents (18-20 ppm) are nearly twice the Primitive Mantle value (Fig. 4A). The major element composition of the coarse gabbro is similar to other gabbroic rocks sampled in the same area (Tribuzio et al., 2014). This sample contains low $K_2O$ (0.07 wt%), and U and Th contents are below the detection limit of the XRF (2 and 4 ppm, respectively). Compared to N-MORB (Fig. 4B), the selected gabbro is enriched in Rb, Pb, Sr and Cu and depleted in Ti.

Using the NaI detector three spectra have been acquired *in situ* on the dunite, serpentinized peridotite and coarse-grained gabbro outcrops where the rock samples analysed above have been collected. In Table 3 the counts per second in the Regions of Interest (ROI) of the investigated radionuclides ($^{40}K$, $^{238}U$, $^{232}Th$) for each acquired spectrum are reported.

## DISCUSSION

### Defining an extremely low natural radiation area

A correction for the local background should always be applied during *in situ* γ-measurements. In general this correction is carried out subtracting the γ-ray background count rate from the γ-ray count rate for each spectrum within each ROI collected. During a geophysical survey, the local background can be measured looking for natural sources with low radioactivity close or within the area considered for the measurement campaign. For example, in view of a radiometric survey in NW Italy, Chiozzi et al. (2000) evaluated the local background in an area characterized by serpentinites, while for a radiometric survey in the Aeolian volcanic arc in an area offshore Lipari, the sea surface was chosen (Chiozzi et al., 2001). In the present work, contrary to the general practices, the extremely low natural radiation area has been identified to quantify the minimum detectable amount of activity (MDA) of $^{238}U$, $^{232}Th$ and $^{40}K$ for NaI *in situ* measurement. In other words we have estimated, in a very low natural radiation area, the smallest signal that can be detected reliably in order to set a "detection limit" for the counting system.

The integration of XRF and HPGe γ-spectrometry can help to assess the rock type with the lowest natural radiation. The XRF results regarding the elements of interest (U, Th and K) in the three rock types (Table 2) are below the instrumental detection limits, which are slightly higher than

Table 1 - Activity concentrations of the measured radionuclides $^{226}Ra$, $^{228}Ac$ and $^{40}K$ in the three sampled rocks and counting times using HPGe detector. Concentrations of U, Th and K assuming secular equilibrium between $^{226}Ra$-$^{238}U$ and $^{228}Ac$-$^{232}Th$.

| Rock Type | Sample | Counting Time (s) | $^{226}Ra$ (Bq/kg) | $^{228}Ac$ (Bq/kg) | $^{40}K$ (Bq/kg) | U (ppm) | Th (ppm) | K (%) |
|---|---|---|---|---|---|---|---|---|
| Dunite | BON3 | 244283 | <9.05 | <3.51 | <25.16 | <0.72 | <0.86 | <0.08 |
| Serpentinized peridotite | BON4 | 86998 | <13.91 | <5.804 | <41.40 | <1.10 | <1.43 | <0.13 |
| Gabbro | BON5 | 169822 | <10.44 | <3.67 | <28.10 | <0.83 | <0.90 | <0.09 |

Table 2 - Major element oxide concentrations reported as wt%, trace elements as ppm.

| | BON3 Dunite | BON4 Serpentinized peridotite | BON5 Coarse-grained gabbro |
|---|---|---|---|
| $SiO_2$ | 36.3 | 35.4 | 50.0 |
| $TiO_2$ | 0.01 | 0.03 | 0.41 |
| $Al_2O_3$ | 0.68 | 1.75 | 15.9 |
| $Fe_2O_3$* | 10.6 | 7.82 | 7.47 |
| MnO | 0.06 | 0.07 | 0.18 |
| MgO | 37.6 | 42.7 | 9.70 |
| CaO | < 0.007 | 0.02 | 8.35 |
| $K_2O$ | < 0.003 | < 0.003 | 0.07 |
| $Na_2O$ | 0.02 | 0.03 | 3.78 |
| $P_2O_5$ | < 0.001 | < 0.001 | 0.06 |
| LOI | 13.2 | 12.7 | 3.88 |
| Sum | 98.5 | 100 | 99.9 |
| Th | < 4 | < 4 | < 4 |
| U | < 2 | < 2 | < 2 |
| V | 18.1 | 37.8 | 95.4 |
| Cr | 1030 | 3267 | 24.0 |
| Ni | 2365 | 1984 | 125 |
| Co | 132 | 100 | 37.8 |
| Cu | 33.2 | 17.1 | 517 |
| Zn | 31.7 | 51.3 | 202 |
| As | < 2 | < 2 | 15.9 |
| Rb | 3.7 | 5.0 | 5.2 |
| Sr | 5.4 | 8.9 | 178 |
| Pb | 3.3 | 7.7 | 2.6 |
| Y | 5.7 | 2.1 | 13.6 |
| Zr | 20.3 | 17.5 | 55.9 |

* Total iron as $Fe_2O_3$.

the detection limits attained by high-resolution γ-spectrometry (Table 1). In particular, the $^{40}K$ activity measured on the dunite outcrop is the lowest compared to the other two measurement sites. The clinopyroxene-rich coarse-grained gabbro is the only rock type with a bulk $K_2O$ content above the XRF detection limit (Table 2), resulting in slightly higher $^{40}K$ activity than the dunite outcrop.

With regard to the contribution U and Th radionuclides to the natural radiation, the dunite outcrop gives the lowest $^{226}Ra$ and $^{228}Ac$ values that are related to the U and Th activity concentrations. The clinopyroxene-rich coarse-grained gabbro has $^{226}Ra$ and $^{228}Ac$ activity concentrations similar to the dunite outcrop, indicating a very low (below the ppm level) bulk U and Th contents. This is confirmed by the available bulk analyses on samples collected from the same outcrop by Tribuzio et al. (2014) by the sensitive ICP-MS technique (0.66 and 0.09 ppm for U; 0.84 and 0.15 ppm for Th). The serpentinized peridotites appear to be the rock type with the highest U activity concentration, possibly due to the presence of U-rich accessories in the hornblende-rich veins (see discussion below).

In summary, the results of HPGe γ-spectrometry, corroborated by the bulk-rock element concentrations by XRF, indicate that the dunite yields the lowest activity concentrations compared to the serpentinized peridotite and the gabbro. The dunite outcrop has been chosen as the site with the lowest natural radiation for both cosmic (being at sea level) and terrestrial contributions.

In Cinelli (2012) the detection limit for the NaI detector has been calculated by the widely used Currie definition (Knoll, 2000) based on the following equation:

$$N_D = 4.653 * \sigma_B + 2.706 \quad (1)$$

where:

$N_D$ is the minimum count rate (corresponding to the detection limit);

$\sigma_B$ ($\sigma_B = N_B^{-1/2}$) is the uncertainty on the background count rate ($N_B$).

In the formula (1) the γ-ray count rate within each ROI for the spectrum collected on dunite outcrop (Table 3) has been considered to estimate the background count rate $N_B$. Hence, following Cinelli (2012), the minimum detectable amount of activity (MDA) of the used NaI detector considering a measurement time of 900 s is:

2.48 Bq/kg for $^{40}K$ (0.01 % K)
1.34 Bq/kg for $^{232}Th$ (0.33 ppm Th)
2.44 Bq/kg for $^{238}U$ (0.20 ppm U).

## Influence of veined ultramafic rocks on the natural radiation

One of the main features of the studied area is the occurrence of hornblende-rich veins crosscutting the coarse-grained gabbro and the serpentinized peridotite. These veins contain accessory zircon along with ilmenite and apatite as documented by optical microscopy (Tribuzio et al., 2014). The presence of Zr-rich accessories is also suggested by the Zr enrichment of serpentinized peridotite and dunite over the Primitive Mantle (Fig. 4A). It is well known that zircon can incorporate U and Th up to thousands of ppm (Harley and Kelly, 2007). Despite the presence of these veins in the analysed gabbro and serpentinized peridotite volumes, the detected amount of U and Th is always below the detection limits of the different instruments. One reason able to explain these analytical results is the possibility that the analysed rock volumes (both *in situ* and in samples considered for

Table 3 - Counting times and counts per second in the ROI's of interest for $^{40}K$, $^{238}U$, $^{232}Th$ in the three spectra collected with NaI.

| Rock Type | Sample | Counting Time (s) | ROI-K (cps) | ROI-U (cps) | ROI-Th (cps) |
|---|---|---|---|---|---|
| Dunite | BON3 | 903 | 0.03 | 0.12 | 0.07 |
| Serpentinized peridotite | BON4 | 969 | 0.12 | 0.09 | 0 |
| Gabbro | BON5 | 912 | 0.13 | 0.02 | 0.03 |

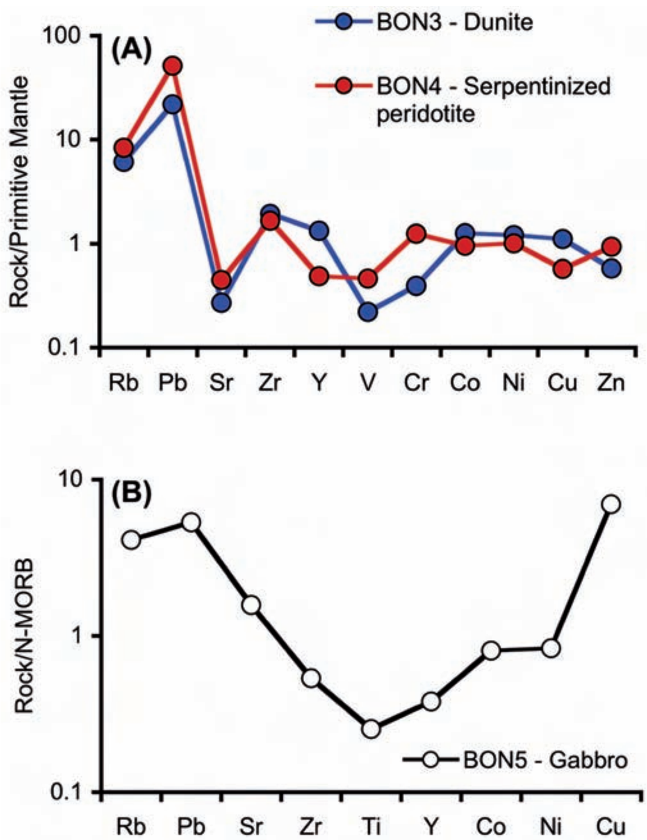


Fig. 4 - (A) Incompatible elements concentration of the serpentinized ultramafic rocks normalized to the Primitive Mantle (McDonough and Sun, 1995). (B) Incompatible trace elements composition of coarse-grained, clinopyroxene-rich gabbro normalized to N-MORB (Hoffman, 1988).

laboratory work) do not contain veins. This hypothesis argues against the simple visual inspection that reveals, for the coarse-grained gabbro sample, a significant amount of Hbl-bearing veins (Fig. 3). In order to take into account the contribution of accessory minerals like zircon to the whole-rock U budget, we considered that: a) the percentage of hornblendite veins in the outcrop is 5 wt%; b) in the veins the percentage of zircon in the veins is ca. 1 vol% and c) the maximum amount of U in the zircon is 500 ppm, considering some of the highest U contents analysed in zircon separated from the early Ordovician gabbro of the Savona Crystalline Massif (Giacomini et al., 2007) or from the Late Jurassic plagiogranites of the Voltri Group, Northern Apennines (Borsi et al., 1996). Assuming these values, the concentration of U related to the hornblendite veins should be maximum 0.25 ppm, in agreement with XRF and high-resolution $\gamma$-spectrometry analyses. Note that doubling all the above values, the percentages of veins in the outcrop and of zircon in the veins and the amount of U in the zircon, the whole-rock U content should be 2 ppm. This value is still acceptable to consider the studied outcrops sites with very low natural radiation ideal to be used as background.

### Estimation of the environmental risk

Serpentinized peridotites and, to a lesser extent, gabbros, are employed as dimension stones in historical and modern buildings (Cavallo et al., 2004). So far, almost all the efforts by local government aim to asses the toxicological risk of serpentine, and other associated mafic rocks associated, that may contain asbestos fibres, e.g., fibrous chrysotile and amphibole (Giacomini et al., 2010). The radiological risk, likewise, needs to be taken also into account. The new European Union Directive on Basic Safety Standards published in January 2014 (EC 2013) establishes a reference level for indoor gamma radiation emitted from building materials. The Directive suggests the use of an index that relates to the gamma radiation dose, in excess of typical outdoor exposure, in a building made of a specified building material. The activity concentration index I is given by the following formula:

$$I = C_{226Ra}/300\ \text{Bq/kg} + C_{232Th}/200\ \text{Bq/kg} + C_{40K}/3\,000\ \text{Bq/kg} \quad (2)$$

where $C_{226Ra}$, $C_{232Th}$ and $C_{40K}$ are the activity concentrations in Bq/kg of the corresponding radionuclides in the building material. An activity concentration index value of 1 can be used as a conservative screening tool for identifying materials that may exceed the reference level for the effective dose fixed at 1 mSv/y. Assuming that the rocks analysed in the present paper will be used as building material, the above index has been calculated for our samples considering the activity concentration of $^{226}Ra$, $^{232}Th$ (in the present work determined using the activity concentration of $^{228}Ac$, see above) and $^{40}K$ estimated by high resolution gamma spectrometry (Table 2). The indexes for other rocks, typically used as building material, have been calculated for comparison using activity concentration values of the three radionuclides of interest available in literature. Remarkably the veined serpentinite (and gabbro) have a I index at least one order of magnitude lower than the I index calculated for other natural stones produced in Italy and commercialized elsewhere (Table 4).

## CONCLUDING REMARKS

- The Bonassola-Levanto ophiolite unit occurring near the Bonassola village can be considered a reference site for low natural radiation background thanks to its characteristics of lowest cosmic radiation and extremely low terrestrial radiation.
- In the present work, contrary to the general practice regarding the background radiation in $\gamma$-spectrometry measurements, the investigated mafic-ultramafic outcrops has been used to estimate the detection limits for *in situ* measurement of $^{238}U$, $^{232}Th$ and $^{40}K$ using a NaI detector.
- The lowest U-Th-K compositions derived from HPGe $\gamma$-ray spectrometry are below the ppm level, the same order of magnitude of ICP-MS analyses.

Table 4 - Activity concentration Index (I) calculated using the formula (2) for different rock types used as stones.

| Rock Type | I |
|---|---|
| Dunite | <0.06 |
| Serpentinized peridotite | <0.09 |
| Gabbro | <0.06 |
| Bolsena Lava [a] | 3.35 |
| Bolsena Tuff [a] | 2.85 |
| Basalto Etneo[b] | 0.44 |
| Peperino Viterbese[b] | 1.44 |
| Porfido Val Cembra[b] | 0.79 |

[a] Capaccioni et al. (2012); [b] Marocchi et al. (2011).

– The occurrence of zircon-bearing hornblende-rich veins crosscutting the coarse-grained gabbro and the serpentinized peridotite should not affect, in this case study, the natural radiation of the area.
– Veined ultramafic and mafic rocks similar to those occurring in the Bracco-Levanto ophiolite unit, if used as building material, provide a negligible contribution to the indoor gamma radiation dose.

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