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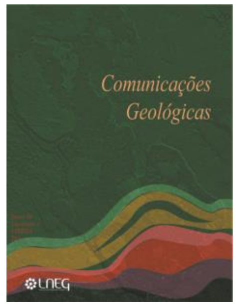
On the relation of geology, natural ventilation and indoor radon concentration: the northern Portugal case study



Relação entre geologia, ventilação natural e concentração de gás radão: caso de estudo no noroeste de Portugal

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Abstract: Alto Minho region, Northwest of Portugal, presents high indoor radon concentrations due to the granitic nature of the soil. Indoor radon concentration is related to the amount of uranium and radium in the building foundation soil. According to the World Health Organization, it is proved that radon exposure in poorly ventilated buildings enhances lung cancer risk. An assessment campaign in a set of granitic buildings in the Alto Minho region, based on short-term measurements, was carried out with a specific focus on the influence of occupancy and ventilation actions performed by residents on the variation of radon concentration, indoor air temperature, and relative humidity. Results attained show to exist an influence of the air renovation on the reduction of radon concentration, therefore, buildings with low occupancy and reduced ventilation present higher indoor radon concentration and poor thermal comfort conditions. 67% of the evaluated buildings show radon concentrations below the reference value of 300 $Bq.m^{-3}$ suggested by Portuguese regulation, highlighting the importance of human occupancy – mostly through passive ventilation processes – as a radon concentration mitigation factor. On the other hand, buildings sporadically occupied and, therefore, badly ventilated show higher indoor radon concentrations. Likewise, building where occupants reveal to have a lack of ventilation routine, present also high indoor radon concentrations.

Keywords: Radon, granitic soil, ventilation, occupancy, indoor air quality

Resumo: A região do Alto Minho, Noroeste de Portugal, apresenta altas concentrações de gás radão em ambientes interiores devido à natureza granítica do solo. A concentração no ar interior de gás radão está relacionada com a quantidade de urânio e rádio no solo de fundação do edifício. De acordo com a Organização Mundial de Saúde, está provado que a exposição ao gás radão em edifícios mal ventilados incrementa o risco de cancro do pulmão. Foi realizada uma campanha de instrumentação tendo como objeto de estudo um conjunto de edifícios graníticos na região do Alto Minho, baseada em medições de curta duração, tendo como foco específico, a influência da ocupação e da ventilação dos edifícios na variação da concentração de gás radão, temperatura do ar interior e humidade relativa. Os resultados obtidos mostram existir uma influência das ações de ventilação na redução da concentração de gás radão. Deste modo, edifícios com baixa ocupação e, portanto, com menor renovação do ar, apresentam elevada concentração de gás radão e deficientes condições de conforto térmico. De facto, 67% dos edifícios avaliados apresentam concentrações de gás radão abaixo do valor de referência de 300 $Bq.m^{-3}$ indicado na regulamentação portuguesa, evidenciando a importância da ocupação humana e dos processos de ventilação natural adotados, como fator de mitigação da concentração de radão. Por outro lado, edifícios esporadicamente ocupados e, portanto, mal ventilados apresentam concentrações mais elevadas de radão. Da mesma forma, edifícios onde os ocupantes não têm hábitos de ventilação apresentam de igual forma concentrações de gás radão mais elevadas.

Palavras-chave: Radão, solo granítico, ventilação, ocupação, qualidade do ar interior

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1. Introduction

Radon is a naturally occurring inert gas formed from the radioactive decay of elements of the uranium series, which is found in small quantities in rocks and soil, as well as in building construction materials (Darby *et al.*, 2001). The indoor radon level is influenced by the radium content in the building foundation soil and its geo-morphological properties, soil permeability, and building ventilation systems (natural *versus* mechanical air exchange) (BEIR VI, 1999; WHO, 2010). The gas is colorless, odorless, and tasteless with a half-life of 3.8 days (WHO, 2010; Darby *et al.*, 2005). After radon inhalation, a fraction decays in solid particles, such as isotopes of polonium, bismuth, and lead, which have a very short half-life, decaying within only a few minutes, emitting during this process, alpha radiation that may damage human tissue (BEIR VI, 1999; WHO, 2010; Darby *et al.*, 2005). Radon is the second most important risk factor for lung cancer after smoking (BEIR VI, 1999; WHO, 2010; Darby *et al.*, 2005; EPA, 2003; BRE, 1999; WHO, 2010 (2); WHO, 2000). It is estimated that the annual mortality from exposure to radon in buildings represents 9% of all deaths from lung cancer, and 2% of all cancer deaths, in Europe (Darby *et al.*, 2005).

The declaration of radon as a potential human carcinogen by the International Agency for Research on Cancer (IARC), led the United States Environmental Protection Agency (EPA) and the European Commission (EC), to establish the so-called action level at 4 pCi/L (148 $Bq.m^{-3}$) and 400 $Bq.m^{-3}$, for existing dwellings, or 200 $Bq.m^{-3}$, for new dwellings, respectively (EPA, 2003; EUROATOM, 1990). The action level is considered as the level of radon above which is recommended to take corrective measures to reduce exposure. The UK Radiation Protection Division of the Health Protection Agency established an action level of 200 $Bq.m^{-3}$ for domestic properties (O'Riordan, 1990), the International Commission on Radiation Protection (ICRP) have recommended an action level for dwellings in the range of 200 to 600 $Bq.m^{-3}$ (ICRP, 1994). This range is very wide however, it is broad enough to cover a significant amount of buildings that require remediation. In Luxemburg the action level is 150 $Bq.m^{-3}$, in Ireland is 200 $Bq.m^{-3}$ like in UK (Åkerblom, 1999; Denman *et al.*, 1998). Most European countries use 300 $Bq.m^{-3}$ as an action level, both for existing homes and new houses. In Portugal, due to the granitic nature of the subsoil and the tradition of using granite as a construction raw material for houses in the countryside, the Centre and the North regions present high radon concentrations. Portuguese granites, especially muscovite and two-mica granites, present average levels of uranium and thorium considerably higher than the average crustal values, which convert these rocks in a high potential risk for radon emanation (Neves *et al.*, 1996). Due to local geology, Viana do Castelo is the second most prominent region in the North of Portugal, in terms of indoor radon concentration (Faísca *et al.*, 1992; Teixeira *et al.*, 1992). For this region, according to the Portuguese legislation regarding protection against exposure to ionizing radiation, the reference level is 300 $Bq.m^{-3}$ (DL n.º 108/2018, 2018). The presence of radon in domestic houses, when the referred thresholds are exceeded, determines the urgency of the implementation of radon mitigation solutions (EPA, 1992; EURATOM, 1990).

Concerning the Portuguese case, regulation over radiological protection is already in force since April 3, 2019 (DL n.º 108/2018, 2018). This general regulation results from the transposition of the 2013/59/Euratom Directive (EURATOM, 2014), and is binding the Portuguese State to ensure effective enforcement of protecting employees and the general public towards radon exposure. Following the so-called reference level for workplaces and buildings, when the concentration limit exceeds the legal threshold, it is mandatory to take steps to remediate high indoor radon concentration and, therefore, assure occupants´ safety (DL n.º 108/2018, 2018).

Ventilation control is an important issue concerning radon mitigation (Allison *et al.*, 2008; Denman *et al.*, 2007). The lack of ventilation of the houses has a strong potential to increase concentrations of pollutants arising from sources inside or underneath the buildings, as is the case of radon (Allison *et al.*, 2008; Denman *et al.*, 2007). Radon is a continuous source, which is therefore not responsive to the intermittent ventilation techniques that can be used to deal with other indoor air pollutants (Allison *et al.*, 2008; Denman *et al.*, 2007).

Requirements for indoor air quality (IAQ) in buildings are defined by existing ventilation standards (EN15251, 2007; Asikainen *et al.*, 2016). Those standards define ventilation requirements to meet comfort requirements of building´s occupants but don´t reflect more serious health impacts like asthma, allergies, chronic obstructive pulmonary disease, cardiovascular diseases, lung cancer, and acute toxication that are caused by exposures to pollutants that are present in indoors (Asikainen *et al.*, 2016). There are no European guidelines to recommend how the buildings should be ventilated to reduce the health risks of the occupants exposed to indoor air pollutants, like radon for instance (Asikainen *et al.*, 2016).

On the other hand, the reduction of the emission of greenhouse gases in the housing sector, determined by improving buildings energy efficiency, imposes a tighter control of the ventilation schemes, leading therefore to a reduction of the ventilation rates (Asikainen *et al.*, 2016; Milner *et al.*, 2014). When dealing with radon mitigation issues, the reduction of ventilation rates can lead to public health problems like the Sick Building Syndrome (Asikainen *et al.*, 2016; Milner *et al.*, 2014).

The occupancy of the buildings as well as their ventilation schemes and schedules are quite relevant to indoor radon air concentration. The main purpose of this study is to compare the effect of ventilation on the indoor radon concentration of a set of 9 granitic buildings located in the Alto Minho region, Northwest of Portugal, including 7 single-family residential buildings, a school laboratory and an olive-oil mill, on which radon monitors were installed on the ground floor. All the buildings are based on granite bedrock, and their pavements, walls, and partitions are mainly built also with granite materials. Some of the instrumented buildings were ventilated during a well-defined period along the experimental period, and some others were badly ventilated. The behavior towards radon air concentration, indoor air temperature, and relative humidity, of both groups of buildings is quite different. Those differences are analyzed and discussed in this paper and related to local geology.

2. Some related works

There have been some studies regarding the analysis of the indoor radon concentration using *in situ* measurements. Some of those studies compared indoor radon concentration with the limits specified in the regulations, before and after mitigation processes. Some other studies highlight the importance of ventilation on indoor radon air concentration, and others studied the effect of occupancy and lifestyle on radon concentrations. There are, however, few studies focused on the variability of indoor radon air concentration with the ventilation, with particular focus on residential buildings.

In fact, regarding this subject, Denman, *et al.* analyzed the radon concentration data from a set of thirty-four homes situated in Northamptonshire, UK, known to exhibit high radon levels. The authors (Denman *et al.*, 2007) concluded that in single-story and two-story dwellings of conventional construction, it is realistic to assume that the observed variability on radon concentration in bedrooms and living rooms can be reliably attributed to differences in the occupants' lifestyles, heating, and ventilation. The investigation showed that occupancy characteristics are important for indoor radon concentration. Similarly, a study developed in the UK (Milner *et al.*, 2014), highlighted the potential problems that may be caused by energy efficiency measures that target heat losses from uncontrolled ventilation. Concerning radon, environmental exposure to this gas is changed by increasing the airtightness of dwellings. According to the authors (Milner *et al.*, 2014), the optimization of ventilation strategies for health issues is more complex if all relevant exposures are considered, and not only thermal or energetic issues. (Groves-Kirkby *et al.*, 2008) studied pre-remediation and post-remediation radon concentrations, measured in a set of 170 homes situated in high radon areas in the U.K., remediated using sub-slab-depressurization technology. The research confirms that 100% of the homes remediated achieves reduction to values below the U.K. Action Level of 200 $Bq.m^{-3}$. The same authors concluded that the indoor radon concentration within a dwelling can be linked to two different sources: the ground radon, emanating from the subsoil entering the dwelling through its foundations, as a component of the soil-gas and capable of being attenuated by sub-slab-depressurization or radon-barrier remediation, and a second contribution attributed to radon emanating from materials used in the construction of the dwelling.

In the North of Spain, Barros-Dios *et al.* studied the factors that influenced residential radon concentration. To this end, after analyzing 983 homes in Galicia, concluded that 21.3% of dwellings have a radon concentration above 148 Bq.m^{-3} and 12% have a concentration above 200 Bq.m^{-3}. The main factors that influence radon concentration were the following: the age of the dwelling, the construction building material, and the story. The study (Barros-Dios *et al.*, 2007) showed that in high-rise buildings, radon levels are appreciably less on the upper than on the lower stories. Nevertheless, there are other variables than those analyzed in the study, and that is fundamental for the analysis of the residential radon concentration, like ventilation. Also relating to residential buildings, (Curado *et al.*, 2017) have assessed radon concentration in 3 single-family typical houses built with granitic stone in Barcelos, Northwest region of Portugal. The Northwest region of Portugal given the granitic nature of the soil is subject to high indoor radon exposure risk. Final results (Curado *et al.*, 2017) revealed the importance of ventilation on indoor air quality. The higher the ventilation rates, the lower the indoor radon risk. This assessment (Curado *et al.*, 2017) allowed concluding that radon gas which arises from ground soil plays an important role in the increment of indoor concentration, particularly evident in poorly ventilated rooms. In Azores islands, Portugal, a volcanic region where radon is predominant, Silva *et al.* surveyed indoor radon concentration in a set of buildings located in Furnas and Ribeira Quente villages, both villages located within degassing areas of Furnas volcano. Furnas volcano is referred to be a polygenetic trachytic volcanic centre with a caldera that shows secondary manifestations of volcanism, recognized by the presence of fumarolic grounds, thermal springs, CO_2 rich mineral waters, and several soils diffuse degassing areas of carbon dioxide (CO_2) and radon (^{222}Rn). The indoor radon concentration measurements were undertaken both in winter and summer periods to control the influence of meteorological conditions and building ventilation in the final results (Silva *et al.*, 2014). For both locations, the measured values far exceeded the legal limits defined by Azores legislation (150 Bq.m^{-3}). The highest values were measured during the winter season due to meteorological conditions and lack of building ventilation. The indoor measurements allowed the development of a radon risk assessment for human exposure in the Furnas volcano region by integrating soil radon susceptibility and vulnerability maps (Silva *et al.*, 2014). The obtained maps revealed that the majority of local buildings show a strong exposure risk to radon.

Regarding radon assessment in school buildings, Madureira *et al.*, after measuring radon concentrations in 45 classrooms from 13 public primary schools located in Porto, Portugal, observed that in 92.3 and 7.7% of the measurements, the limit of 100 and 400 Bq.m^{-3}, established by WHO IAQ guidelines and in the Portuguese legislation, respectively, was exceeded (Madureira *et al.*, 2016). The study confirmed the granitic soil influence as the main source for indoor radon. Still, on the same subject, Lopes *et al.* instrumented radon concentration in a monastery adapted to a school in Ponte de Lima, Northwest of Portugal. A set of 17 classrooms and offices were subject to in-situ monitoring during two different periods of 2017, based on short-term measurements (Lopes *et al.*, 2018). The assessment made clear the influence of ventilation on indoor radon concentration. In fact, during the summer period, when there is natural ventilation, the reduction of radon concentration is much effective (Lopes *et al.*, 2018).

Concerning radon assessment in workplaces, Martin Sánchez *et al.* surveyed to determine indoor radon concentration in offices and meeting rooms, evolving more than 200 measurements corresponding to about 130 companies in Extremadura, Spain. The results show that 34% of the monitored companies presented values that may need mitigation processes, and 16% of the instrumented workplaces presented levels above 400 Bq.m^{-3} (Martín Sánchez *et al.*, 2012). The values obtained in places with low ventilation rates like museums are particularly high, due to their closed-in nature, usually needed to preserve artworks (paintings, sculpture, jewelry, etc.).

Some geological studies about soil emissions in critical areas concerning radon propagation revealed the importance of air renovation in reducing indoor radon concentration. Silva *et al.* evaluated the radon levels in 74 rooms of a building located in Ponta Delgada city, São Miguel Island, Azores (Silva *et al.*, 2014). The results revealed radon concentrations above the legal limits according to Azores regulation. To characterize the soil diffuse degassing emissions in the area, temperature, radon, and carbon dioxide (CO_2) concentration, as well as soil temperature measurements, were performed. Temperature and CO_2 values were below the background value of São Miguel Island (Silva *et al.*, 2014). Soil radon concentration varied between 889 and 24000 Bq.m^{-3}. A dilution test was also performed. Radon concentration measurements were performed at 60 cm depth, at the soil surface, and 1m above the soil surface. The results obtained allowed us to realize that there is an efficient dilution of the gas. The authors (Silva *et al.*, 2014) refer that the opening of windows was normally enough to promote an efficient decrease in the indoor radon concentration. Identically, Lamas *et al.* analyzed a deep borehole drilled in Almeida, Centre Region of Portugal, to measure a set of radiological parameters, mainly: ^{226}Ra activity, radon gas activity, and exhalation rate (Lamas, *et al.*, 2015). The analyzed samples belong to two distinct groups depending on the degree of alteration of the rock induced by metasomatic processes (scarce and significant). The results (Lamas, *et al.*, 2015) show some similarity between both groups in terms of ^{226}Ra activity but a significant difference in average radon gas exhalation rate in both groups, with the higher values in the most metasomatized group. The distribution of radiological parameters does not vary significantly with depth. The study shows that the degree of alteration of the granite rock influences the distribution of radiological parameters (Lamas, *et al.*, 2015).

Some specific indoor radon assessment studies were developed in critical areas of Portugal, namely in the Guarda region. In this respect, Louro *et al.* studied human exposure to indoor radon in a set of 185 dwellings located in a potentially high-risk area of the Guarda region. Results attained allowed concluding to exist a large dispersion of results with an annual average concentration of 860 Bq.m^{-3}, which the authors attributed to a combination of factors: geochemical nature of the soil, building material, and ventilation conditions. Regarding radon exposure, residents are subjected to an effective dose of 15 mSv y^{-1} which is considerably above the estimated dose for Portugal (Louro *et al.*, 2013).

In Guarda region, Portugal, Antão assessed indoor radon concentration in Instituto Politécnico da Guarda (IPG) in the winter and summer seasons. Results attained show to exist different indoor radon concentrations between both seasons – higher in the winter season when room´s ventilation is lower and states the effect of people occupation on the concentration level –

less occupied rooms tend to have higher radon concentration (Antão, 2014).

Sousa *et al.* measured radon concentration in three nurseries and a primary school in a rural area of Bragança, North of Portugal, to assess radon variation during the daytime. Differences between occupied and non-occupied periods were analyzed to check the effect of occupancy on indoor radon concentration. The authors state to exist a broad variability in radon concentrations between all assessed rooms, largely exceeding the recommended values presented on national legislation. An extended radon measurement campaign all over Portugal is strongly recommended to reduce exposure (Sousa *et al.*, 2015).

Neves *et al.* assessed for 6 months indoor radon concentration along with some other variables, such as air temperature, relative humidity, air pressure, and rainfall, in a test room located in an administrative building of the University of Coimbra. The room was not regularly occupied and the building foundations were placed on Triassic red sandstones with low uranium. Despite the observation of low indoor radon concentration, daily variation seems to be correlated to outdoor air temperature and rainfall (Neves *et al.*, 2009).

To allow online monitoring of indoor radon concentration and therefore promote some active mitigation measures, a platform to implement a Human-in-the-Loop Cyber-Physical system was designed (Lopes *et al.*, 2018). The deployment of this technology allowed permanent monitoring of the radon gas concentration and the adoption of on-time active mitigation actions.

3. Case study

The selected case study is constituted by a set of 9 buildings located in the Alto Minho region, nearby the city of Viana do Castelo, Northwest of Portugal. The buildings have different periods of construction, are mainly for residential purposes, and were selected due to their granitic construction and the granitic nature of the soil where are placed. The characteristics of the façade walls, inner partitions, and slabs of the selected buildings are representative of the typical granite one-story houses in the Alto Minho region. Despite some buildings are not residential, they were selected for *in situ* measurements due to their type of occupation. Ventilation schemes were also an important issue to choose the buildings which make part of the selected case study. Table 1 shows the 9 samples considered for instrumentation, including the building type, the monitored compartment, and its occupation schedule.

Figure 1 shows the places in the Alto Minho region where the 9 measured buildings are located. By the analysis of the plan, it is possible to observe a predominant spot of buildings located in central Viana do Castelo. There are however two samples in figure 1, representing samples D and E, respectively, located East and North from outside Viana do Castelo.

Table 1. Considered samples for *in situ* instrumentation.

Tabela 1. Amostras consideradas para instrumentação *in situ*.

Samples	Location	Building type/ Compartment	Occupation
A	Viana do Castelo (Santa Maria Maior)	School Lab	In periods of one hour by about 30 persons
B	Viana do Castelo (Darque)	Residential Building Bedroom	During night period by 2 persons
C	Viana do Castelo (Meadela)	Residential Building Bedroom	Not frequent
D	Viana do Castelo (Santa Marta de Portuzello)	Residential Building Storeroom	Not frequent
E	Viana do Castelo (Carreço)	Residential Building Bedroom	Not frequent
F	Ponte de Lima (Freixo)	Residential Building Living Room	During evening period by 2 persons
G	Viana do Castelo (Meadela)	Residential Building Bedroom	During night period by 2 persons
H	Viana do Castelo (Meadela)	Olive-Oil Mill	Not frequent
I	Viana do Castelo (Santa Maria Maior)	Residential Building Living Room	During evening period by 2 persons

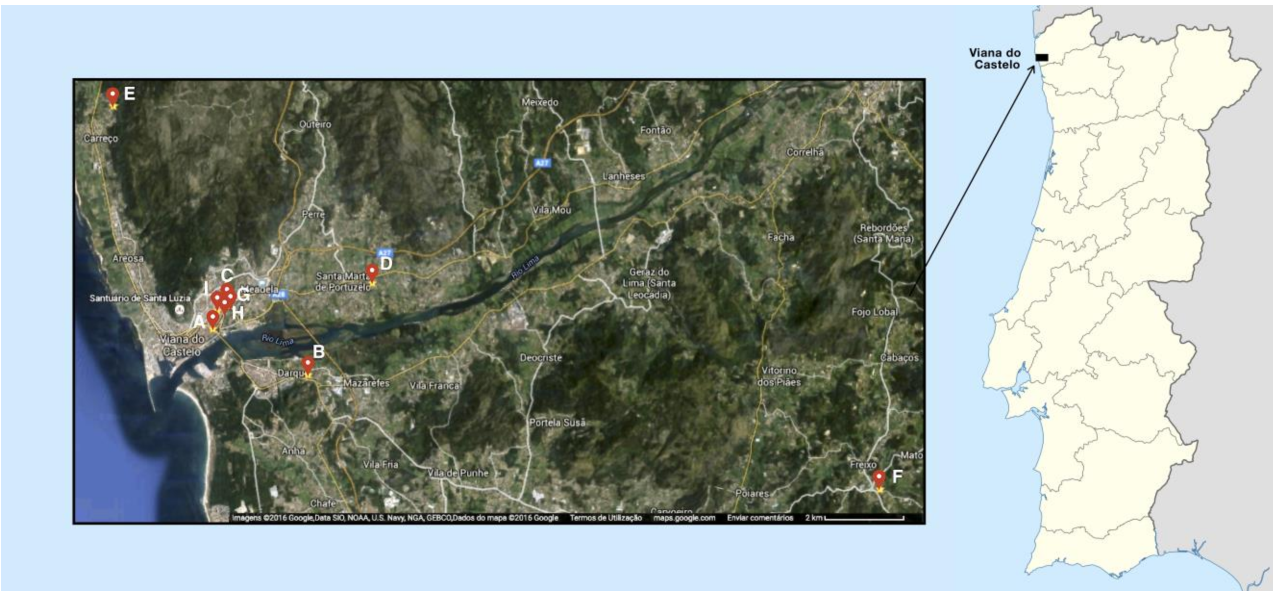

Figure 1. Alto-Minho region, Portugal, where the samples were collected.

Figura 1. Localização das amostras instrumentadas na região do Alto-Minho, Portugal.

By the analysis of table 1, it is possible to observe that part of the instrumented buildings are residential households, most of them occupied during the night period. To study potential differences between buildings, occupation schedules, and ventilation schemes, two other different types of buildings, with distinct occupations and diverse ventilation regimes, were also instrumented. A school lab with a peak occupation during short periods, and an olive-oil mill only occupied by the operator during the running of the whole system, for very short periods, have highlighted the importance of both occupancy and ventilation rates on indoor radon concentration, air temperature, and relative humidity variation, In short, all instrumented buildings share a similar type of construction, identical characteristics of the foundation soil, but different occupancy regimes and ventilation rates.

4. Alto Minho geological characterization

The study area is in the northwest of Portugal in the province of Minho. The area is located on sheet 5-A Viana do Castelo of the Geological Chart of Portugal at a scale 1:50 000 (Teixeira *et al.*, 1972). This region is part of the Galicia-Trás-os-Montes Zone (GTMZ) of the Hesperian Massif (Fig. 2) (Chaminé, 2000), which is predominantly composed of Variscan granitoids and metasedimentary formations of Paleozoic age (Pamplona *et al.*, 2013; Dias *et al.*, 2013). This zone, with allochthonous to parautocthonous and allochthonous materials over the Central Iberian Zone (CIZ), is considered a separate zone of the Hesperian Massif subzone (Arenas *et al.*, 2004). These two zones represent the westernmost segment of the European Variscan of the Gondwana and Laurentia (J.R. Martínez Catalán *et al.*, 1996), with three main phases of Variscan deformation (Ferreira *et al.*, 1987; Dias *et al.*, 2013; Meireles *et al.*, 2014; Ribeiro *et al.*, 1990).The geological formations existing in this area (Fig.2), include Cenozoic materials mostly formed by alluvial and fluvial terraces, Palaeozoic metasediments from Ordovician, Silurian, Devonian, and Cambrian ages, and granitic formations from Variscan age. Several faults cross the region, as well as a large shear zone with an NW-SE direction (Malpica-Lamego shear zone in figure 2).

The Cambrian formations are autochthones and the Silurian and Devonian ones are autochthones to parautothones, and more recently are considered as allothones (Meireles *et al.*, 2014; Ribeiro *et al.*, 1990; Pereira, 1992). A few veins of aplites and pegmatites cut the granites and the country-rock metasediments. The granitic rocks emplaced in the Palaeozoic formations show a wide variety of types with diverse mineralogical and textural composition. It is possible to find two mica granites (Viana do

Castelo sin-orogenic granite), biotitic sin-orogenic granites (Ponte de Lima granite), and biotitic tardi to pos-orogenic granites (Barcelos granite) (Ferreira *et al.*, 1987).

The alkaline fine to medium grain granite, sometimes with coarse grain, is abundant in the Meadela area (sample location C, G, and H, Fig. 3) and Santa Maria Maior area (sample location A and I, Fig. 3). It is a two-mica granite with the predominance of muscovite over biotite and abundant alkaline feldspar. The percentage of quartz in these granites is very low for a granitic rock, highlighting his alkaline behavior (Teixeira et al., 1972). The mineral biotite shows pleochroic halos that are related to the presence of zircon.

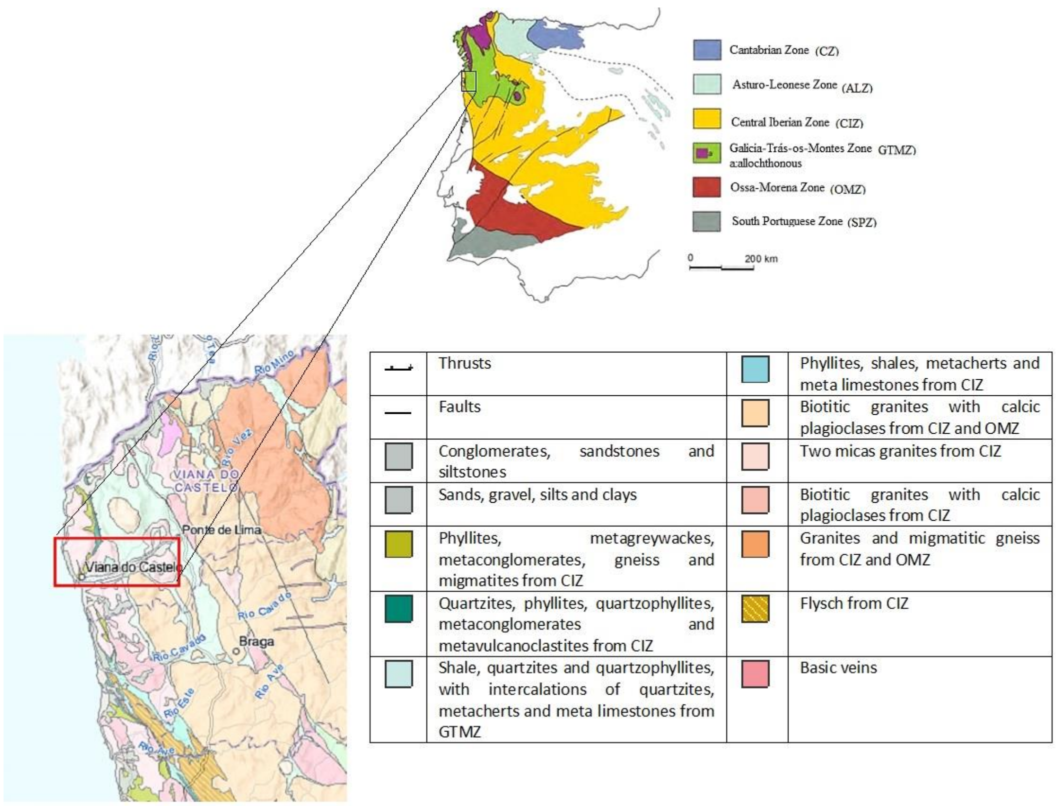

Figure 2. Simplified geological map of the area of Viana do Castelo with the location of the samples – adapted from Meireles *et al.* (2014) – and its insertion in the geotectonic zones of the Iberian Peninsula – modified from Teixeira *et al.* (1972).

Figura 2. Mapa geológico simplificado da zona em estudo (adaptado de Pereira *et a*l., 1989) e sua inserção nas zonas geotectónicas da Península Ibérica (modificado de Teixeira *et al*., 1972).

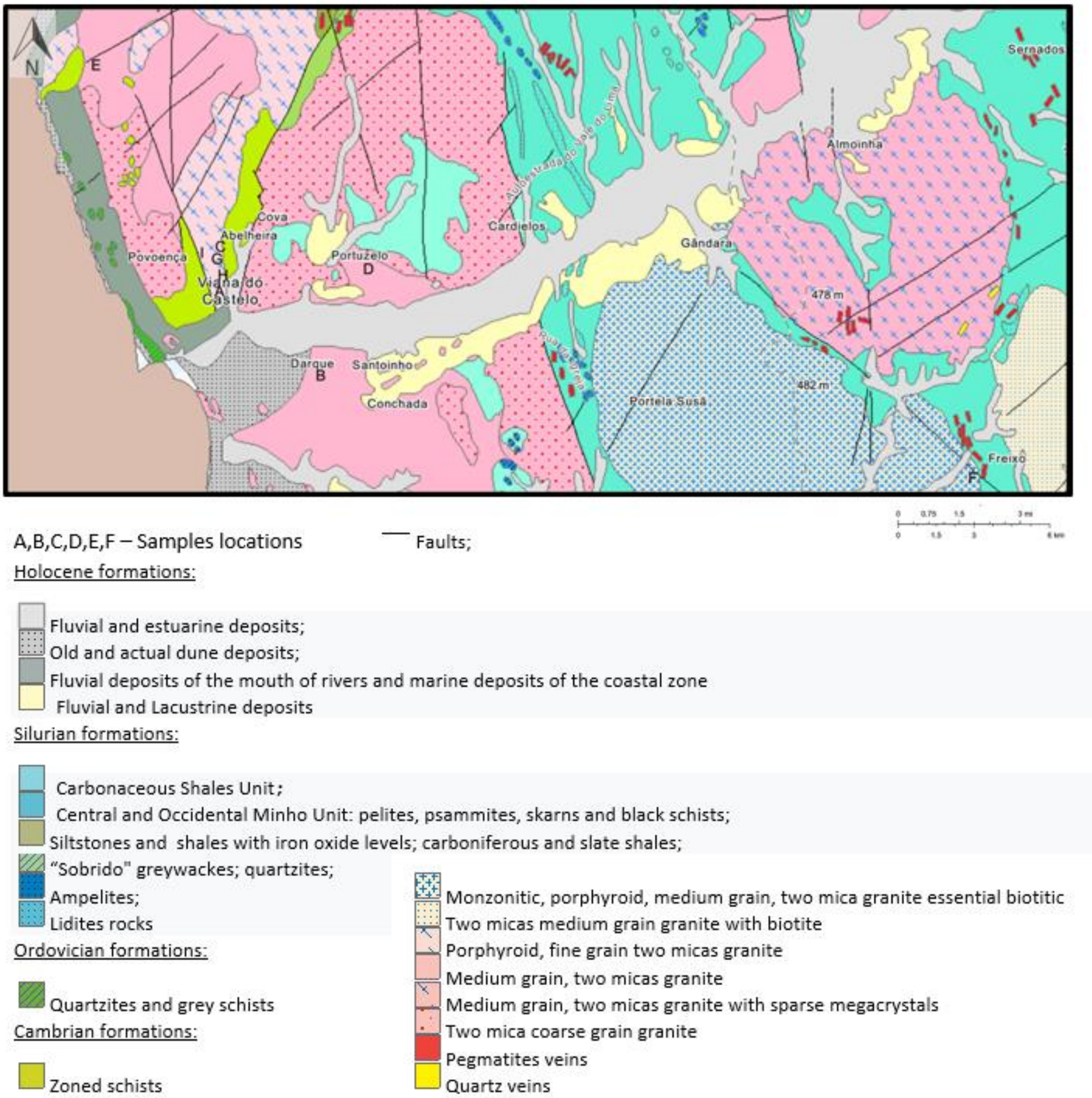

Figure 3. Geological map of the area with sample location (adapted of Pereira *et al.*, 1989) (caption at https://geoportal.lneg.pt/mapa/#).

Figura 3. Mapa geológico da zona em estudo (adaptado de Pereira *et al.*, 1989) com a localização dos locais estudados.

In local B (Darque in figure 1 and South to Viana do Castelo in figure 3), outcrops a leucocratic granite, medium to coarse grain, with quartz, microcline, and albite-oligoclase plagioclases. The main accessory mineral of this rock is the muscovite, appearing biotite and apatite in minor percentages.

The sample F (Figs. 1 and 3) is in the boundary between granitic formations and a metasedimentary phyllite and quartz-phyllite unit (The Tibães formation), where the presence of aplite pegmatitic veins is very common (Meireles *et al.*, 2019). This granitic formation is a two mica, medium grain rock, slight porphyroid, with zoned feldspars and abundant oligoclase-albite plagioclases. The apatite is frequent as an accessory mineral. Sample E is in Carreço area (Figs. 1 and 3), a region where occurs medium to fine granite with quartz, abundant microcline, albite-oligoclase plagioclases, biotite with pleochroic halos and muscovite. In Northeast Carreço the rock formation is very fractured (Fig. 3). In sample location D, the granite formation shows a coarse to medium grain texture similar to Darque area (sample B).

5. Methods

A monitoring campaign that lasted the months of March and April 2016 was carried out to assess indoor radon concentration in a set of 9 buildings in the Alto Minho region, Viana do Castelo.

To evaluate radon air concentration, as well as indoor air temperature and relative humidity, experimental measurements, with 1-hour resolution, were performed continuously using digital radon monitors with incorporated data logger devices from Canary Pro Series. The specifications in detail of the devices used for data acquisition can be found in (Canary, 2016) and are shortly summarized in table 2.

Table 2. Main technical specifications (Canary, 2016).

Tabela 2: Principais especificações técnicas do equipamento de instrumentação (Canary, 2016).

Radon sampling	Passive diffusion chamber
Detection method	Alpha spectrometry
Operation environment	Temperature: +4 ºC to +40 ºC
	Relative humidity: <85%
Measurement range	Lower display limit: 0 Bq.m^{-3}
	Upper display limit: 9999 Bq.m^{-3}
Accuracy/Precision at 200 Bq.m^{-3} (typical)	7 days – 10%
	2 months – 5%

Two data-loggers were placed in strategic spots of each room to evaluate the air breathed by the occupants. Each piece of equipment was not directly exposed to sunlight or moisture and was installed leastwise 0.50 m above floor level, and over 1.50 m from the closest window, door, air vent, and radiation source or electronic equipment. The device was not moved during measurements to allow accurate measurements.

The experimental campaign was implemented in the spring of 2016, based on short-term measurements, during which mild outdoor air temperatures were recorded, thereby facilitating natural air renovation. As such, in the course of the monitoring, no heating or cooling systems were operated by the occupants, and ventilation actions were taken by regular windows opening during very limited periods which varied from 1 to 8 hours, whilst rooms´ occupation period. Buildings were monitored continuously for about one week, and additionally, manual registration of the ventilation periods was performed using a specific paper form available in each room under monitoring. In that sense, users were told to record – as accurate as possible – the periods of ventilation, by registering the period (start and end) of the ventilation actions.

As expected, rooms' occupancy played an important role in the monitored parameters (indoor radon concentration, air temperature, and relative humidity). Despite buildings´ rchitectural features and the way they are constructed can play a great influence on the variation of the instrumented parameters, since all monitored buildings have similar construction (reinforced concrete pavements with walls and partitions made of granite stone) and foundations, occupancy plays a major role on its behavior.

Despite long-term measurements are suitable to identify potential radon health hazards, short-term assessment is generally used to provide in-situ evidence of radon levels. When the long-term measurement is not possible for technical reasons or for being a human-demanding process, short-term assessment can give a straightforward diagnosis by applying a 1-week measurement procedure and it may provide relevant information about the existence (or not) of a radon-related problem. On the other hand, long-term assessment is mandatory for effective radon risk analysis.

6. Results and discussion

From the set of 9 granitic buildings evaluated, 5 were occupied during most of the day and ventilated (samples C, E, F, and H, Fig. 1), and the remaining 4 had a residual occupation and were not constantly ventilated (samples A, B, G and I, Fig. 1). Concerning sample D, despite the occupation of the building is not frequent (Tab. 1), the instrumented room (a storeroom) is permanently ventilated. To avoid moisture and mold formation on the room's inner surfaces (walls and ceilings), there are permanent openings to promote the room air renovation.

Figure 4 shows the evolution in time for the radon concentration and the thermo-hygrometric measurements from sample C. In this example, the occupants performed three ventilation actions, which are directly identified in the plot.

From the data in figure 4, it is possible to observe a reduction of the radon concentration as a result of the ventilation actions. Moreover, it is also possible to observe the cyclic and inverse evolution of the thermo-hygrometric measurements. The cyclic behavior is directly related to the outdoor environmental changes, *i.e.* changes between day and night, for the period under evaluation. Another important observation is related to the increase of the radon concentration during the night, where the temperature tends to decrease, and in opposition, relative humidity tends to increase.

Sample C corresponds to a ground-floor building placed on soils formed of alkaline fine to medium grain granite, sometimes coarse grain. It is a two-mica granite with the predominance of

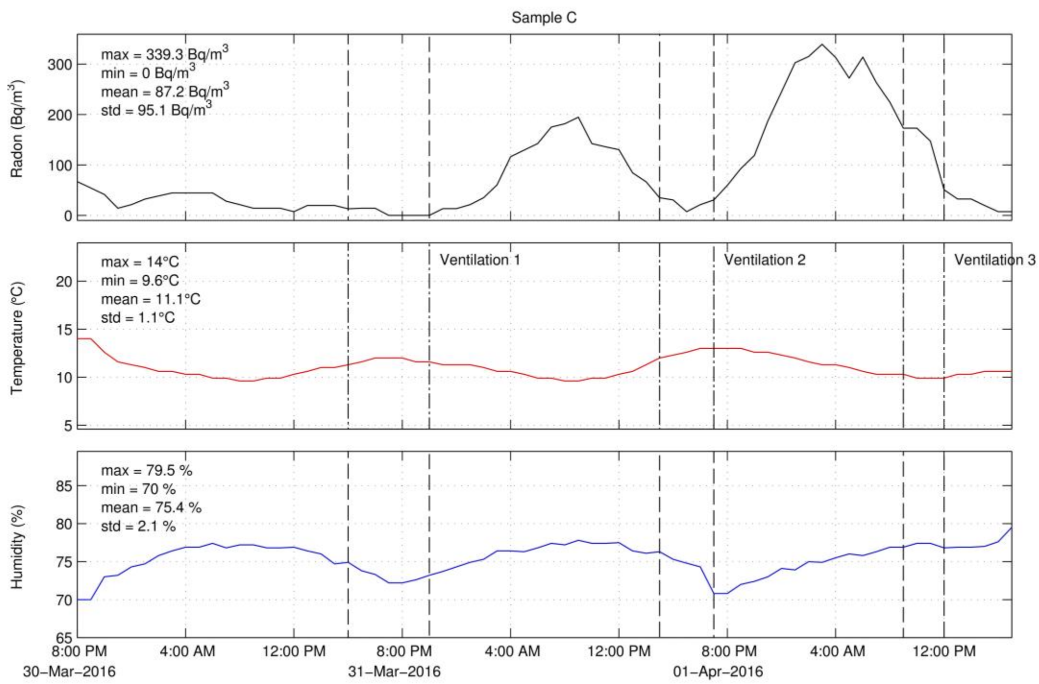

Figure 4. Radon concentration and thermo-hygrometric measurements for sample C.

Figura 4. Concentração do gás radão e medição dos parâmetros higrométricos para a amostra C.

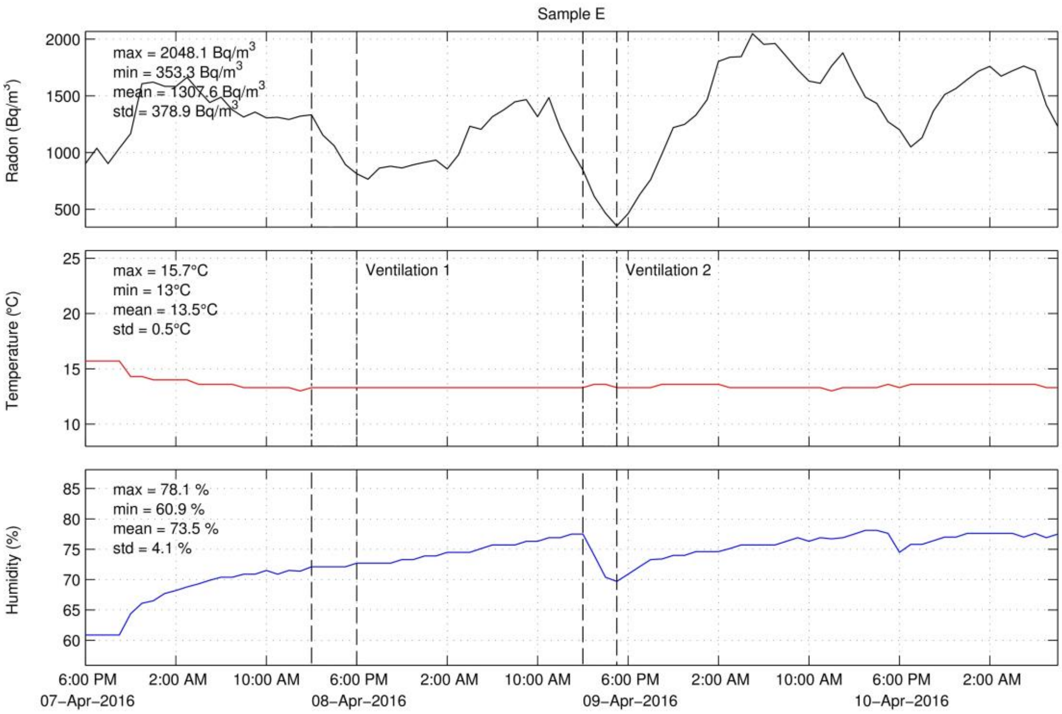

Figure 5. Radon concentration and thermo-hygrometric measurements for sample E.

Figura 5. Concentração do gás radão e medição dos parâmetros higrométricos para a amostra E.

muscovite over the biotite, and abundant alkaline feldspar. The percentage of quartz in these granites is very low for a granitic rock, showing its alkaline behavior. The biotite shows pleochroic halos which could be related to the presence of zircon (Teixeira *et al.*, 1972). The experimental results show that the indoor radon concentration, during some measurement periods, rises above thePortuguese reference level of 300 Bq.m^{-3}, mainly when there are no ventilation actions performed by the occupants. The results presented in figure 4 indicate that buildings placed on granite substrates, poorly ventilated, tend to present higher indoor radon concentration during periods of low air renovation. Another example of the evolution in time for the radon concentration and the thermo-hygrometric measurements can be observed in figure 5. In this case, data corresponds to sample E, and two ventilation actions, directly identified in the plot, were performed.

From the data presented in figure 5, it is also possible to observe a considerable reduction of the radon concentration as a result of the two ventilation actions. Temperature and relative humidity also present an inverse evolution with an abrupt decrease in second ventilation action, which can be justified by a considerable difference to the outdoor environmental conditions in the time interval that the ventilation action was performed.

Sample E refers to a ground-floor building, built upon a medium to fine granite soil foundation, with quartz, abundant microcline, oligoclase-albite plagioclases, biotite with pleochroic halos, and muscovite. Tourmaline mineral was found in a very small percentage. The bedrock appears very fractured what explains the high indoor radon concentration during the instrumented period (Fig. 5). Fractured granite soils with low air renovation lead to a mean value of indoor radon concentration more than 4 times above the legal limit (Fig. 5).

Figure 6 shows the overall statistical results of the thermo-hygrometric measurements using a boxplot representation. In this type of plot the space between the different parts of the box (quartiles) indicates the degree of dispersion of data with relation to the median, being the outliers plotted as individual points.

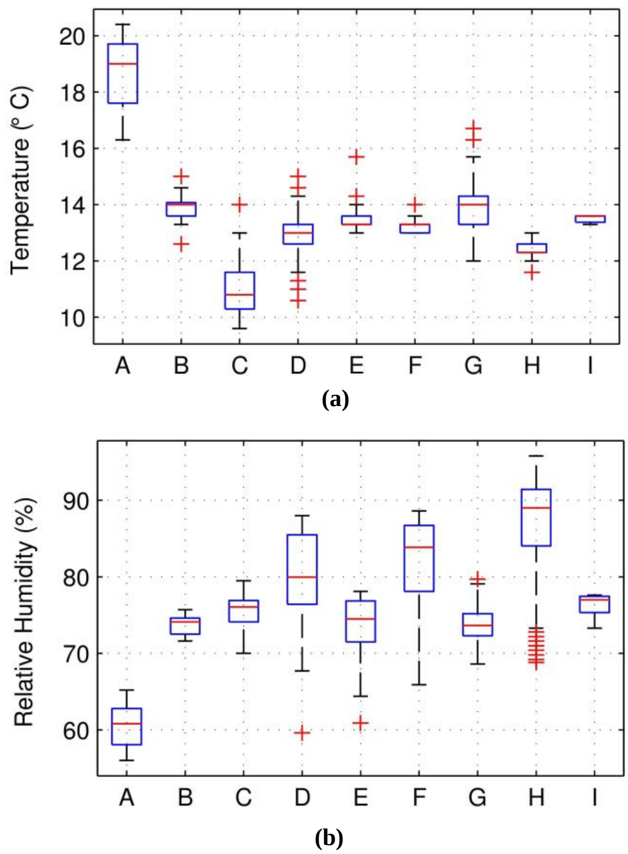

Figure 6. Overall thermo-hygrometric statistical results: a) temperature; b) relative humidity.

Figura 6: Estudo estatístico dos parâmetros higrométricos: a) temperatura; b) humidade relativa.

Data in figure 6, is in line with the information of the ventilation processes identified when the experiments were designed. For example, sample A represents data from a room with a fan exhaust vent performing continuous active ventilation. All the other buildings that were monitored did not have any type of active ventilation system acting. Excluding sample A, the median indoor temperature for the residential buildings under monitoring was in the interval between 11 ºC and 19 ºC, which is normal for the region in the spring season, and the relative humidity was found to present median values in the interval between 70% and 90%, which was expected given the proximity to the sea.

Using the same type of data representation, figure 7 illustrates the overall statistical results for the radon concentration for all the buildings under monitoring. These results show that 67% of the evaluated buildings have radon concentrations below the maximum value of 300 Bq.m^{-3} suggested by Portuguese regulation. In these cases, the human occupancy – mostly through passive ventilation processes – works as a radon concentration mitigation measure.

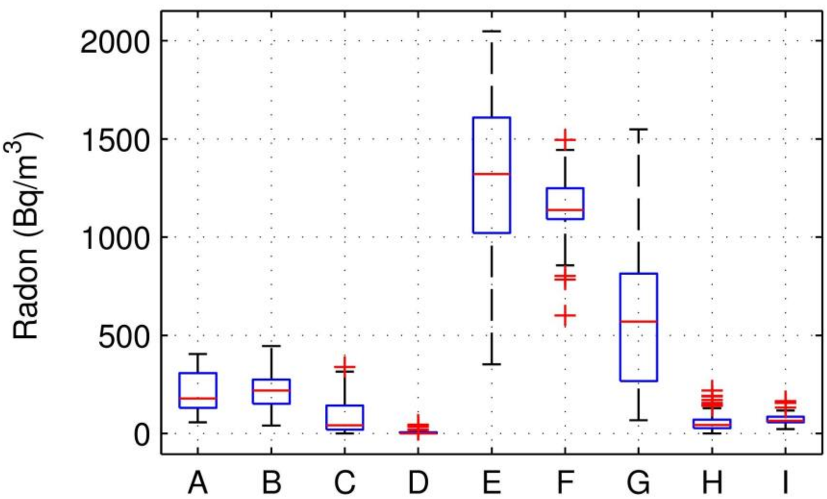

Figure 7. Overall radon concentration statistical results.

Figura 7. Estudo estatístico da concentração do gás radão.

Three samples E, F, and G, exceeded the Portuguese reference level of 300 Bq.m^{-3} with median values of approximately 1300, 1150, and 600 Bq.m^{-3}, respectively. The obtained results are in line with what was expected – three monitored rooms were residually ventilated during the period of instrumentation-. Room E is sporadically occupied. On the other, despite being occupied, the occupants of rooms F and G do not have ventilation routines. Besides that, the three rooms have granitic walls and floors, some of them not covered with plaster and completely facing the indoor environment.

7. Conclusions

In this study, the indoor air quality was evaluated in 9 buildings located in Viana do Castelo area, with a focus on parameters as the room's occupancy, the ventilation, and the relation to local geology. Indoor radon concentration was measured by an active method and, simultaneously, a thermo-hygrometric evaluation was carried out that allowed to correlating thermal comfort and indoor air quality. The measurements were performed during the spring of 2016, in a period of mild outdoor conditions.

The results show that indoor air temperature varied between 11 ºC and 19 ºC, which is normal for the region in the spring season, and the relative humidity between 70% and 90% (median values), which was expected given the proximity to the sea. Regarding radon concentration, the results show that in 67% of the evaluated buildings the values are lower than the reference level of 300 Bq.m^{-3}, as stated in the Portuguese legislation, highlighting the importance of human occupancy – mostly through passive ventilation processes – as a radon concentration mitigation measure. On the other hand, buildings sporadically occupied, therefore poorly ventilated, or when the residents do not adequately ventilate their homes, show higher indoor radon concentrations.

Natural ventilation, as the opening of the windows, can work as an effective radon concentration mitigation process. The mitigation strategy for existing buildings must include air dilution and pressure change, by applying, in the subsoil, a pressure-modifying sump associated with an extraction fan (Allison *et al.*, 2008; Denman *et al.*, 2007). Still in existing buildings, the installation of a natural under-floor ventilation system is an adequate remediation solution (suspended flooring, or a passive sump below the level of the ground-floor). The mitigation strategy for new buildings is simpler since the application of a radon-proof membrane across the building foundation level is a very effective solution (Allison *et al.*, 2008; Denman *et al.*, 2007).

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References

Åkerblom, G., 1999. Radon legislation and national guidelines. *Proc. International Workshop on Radon in the Living Environment*, Athens, Greece, 30.

Allison, C. C., Denman, A. R., Groves-Kirkby, C. J., Phillips, P. S., Tornberg R., 2008. Radon remediation of a two-storey UK dwelling by active sub-slab depressurisation: Effects and health implications of radon concentration distributions. *Environment International*, **34**: 1006-1015.

Antão, A. M., 2014. Assessment of Radon Concentrations Inside a High School Building in Guarda (Portugal): Legislation Implications and Mitigation Measures Proposed. International workshop "Uranium, Environment and Public Health", UrEnv 2013. *Procedia Earth and Planetary Science*, **8**: 7-12. DOI: 10.1016/j.proeps.2014.05.003.

Arenas, R., J. R., Martínez Catalán, Díaz García, F. (Coords.), 2004. Zona de Galicia Trás Os Montes. *In*: Vera, J. A. (Ed.), *Geología de España*, Sociedad Geológica de España, Instituto Geológico y Minero de España, Madrid. 133-165. ISBN 84-7840-546-1

Asikainen, A., Carrer, P., Kephalopoulos, S., de Oliveira Fernandes, E., Wargocki, P., and Hänninen, O., 2016. Reducing burden of disease from residential indoor air exposures in Europe (HEALTHVENT project), *Environ Health*, **15**: S35. DOI: https://doi.org/10.1186/s12940-016-0101-8.

Barros-Dios, J. M., Ruano-Ravina, A., Gastelu-Iturri, J., Figueiras, A., 2007. Factors underlying residential radon concentration: Results from Galicia, Spain, *Environmental Research*, **103**: 185-190.

Building Research Establishment, 1999. Radon: guidance on radon protective measures for new dwellings. *BRE Report BR211*, ISBN 0-85125-511-6.

CANARY pro Digital Radon Monitor System, 2016. CORENTIUM AS, Parkvn, 53b, Oslo, Norway.

Chaminé, H., 2000. *Estratigrafia e Estrutura da Faixa Metamórfica de Espinho-Albergaria-a-Velha (Zona de Ossa-Morena): Implicações Geodinâmicas*. Tese de Doutoramento, Departamento de Geologia, Faculdade de Ciências, Universidade do Porto, 497.

Committee on Health Risks of Exposure to Radon (BEIR VI), 1999. *Health effects of exposure to radon*. Washington DC: National Academy Press. ISBN 0-309-05645-4.

Curado, A., Silva, J. P., Carvalho, L., Lopes, S. I., 2017. Indoor Radon Concentration Assessment in a Set of Single-Family Houses: Case Study held in Barcelos, North of Portugal. *Energy Procedia*, **136**: 109-114. DOI: https://doi.org/10.1016/j.egypro.2017.10.295.

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J. M., Baysson, H., Bochicchio, F., Deo, H., 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *BMJ* (published 21 December 2004), 6.

Darby, S., Hill, D., Doll, R., 2001. Radon, a likely carcinogen at all exposures. *Ann Oncol*, **12**: 1341-51.

Decreto-Lei n.º 108/2018 de 3 de dezembro da Presidência de Conselho de Ministros. Diário da República: 1.ª série, N.º 232. Lisboa, Portugal. https://data.dre.pt/eli/dec-lei/108/2018/12/03/p/dre/pt/html.

Denman, A. R., Groves-Kirkby, C. J., Coskeran, T., Phillips, P. S., Crockett, R. J. M., Allison, C. C., Tornberge, R., 2008. A Review of the Factors Affecting the Cost Effectiveness and Health Benefits of Domestic Radon Remediation Programmes. *12th Congress of the International Radiation Protection Association*, Buenos Aires, Argentina.

Denman, A. R., Groves-Kirkby, N. P., Groves-Kirkby, C. J., Crockett, R. G. M., Phillips, P. S., Woolridge, A. C., 2007. Health implications of radon distribution in living rooms and bedrooms in U.K. dwellings - A case study in Northamptonshire. *Environment International*, **33**: 999-1011.

Dias, R., Ribeiro, A., 2013. O Varisco do sector norte de Portugal. *In*: Dias, R., Araújo, A., Terrinha, P., Kullberg, J. C. (Eds.), *Geologia de Portugal*, **1**: 59-72.

Dias, R., Ribeiro, A., Coke, C., Pereira, E., Rodrigues, J., Castro, P., Moreira, N., Rebelo, J., 2013. Evolução estrutural dos sectores setentrionais do Autóctone da Zona Centro-Ibérica. *In:* R. Dias, A. Araujo, P. Terrinha, J. C. Kullberg (Eds.), *Geologia de Portugal*, **I**: 73-148.

EN15251: CEN Standard on Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics, 2007. *European Committee for Standardization (CEN)*, Brussels, 52.

EPA, 2003. EPA Assessment of risk from radon in homes. *EPA 402-R-03-003*, United States Environmental Protection Agency.

EURATOM, 1990. 90/143/EURATOM: Commission Recommendation of 21 February 1990 on the Protection of the Public Against Indoor Exposure to Radon.

European Council Directive 2013/59/EURATOM, 2014. *OJ of the EU. L13*; 57: 1–73. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF

Faísca, M. C., Teixeira, M. M. G., Bettencourt, A. O., 1992. Indoor Radon Concentrations in Portugal – A National Survey. *Radiation Protection Dosimetry*, **45(**1): 465-467.

Ferreira, N., Iglesias, M., Noronha, F., Pereira, E., Ribeiro, A., Ribeiro, M. L., 1987. Granitóides da Zona Centro-Ibérica e seu enquadramento geodinâmico. Livro de homenagem a L. C. Garcia de Figuerola: *Geologia de los granitoides y rocas asociadas del Macizo Hespérico*, 37-52.

Groves-Kirkby, C. J., Denman, A. R., Phillips, P. S., Tornberg, R., Woolridge, A. C., Crockett, R. G. M., 2008. Domestic radon remediation of U. K. dwellings by sub-slab depressurisation: Evidence for a baseline contribution from constructional materials. *Environment International*, **34**: 28-436.

International Commission on Radiation Protection (ICRP), 1994. Protection against radon-222 at home and at work. *ICRP Publication 65*. Pergamon Press, Oxford.

Lamas, R., Pereira, A., Neves, L., 2015. Radon gas exhalation rate and ^{226}Ra activity in hercynian granitic rocks from a deep borehole (Almeida, Central Portugal). *Comunicações Geológicas*, **102**(1): 71-74.

LNEG, 2014. Carta Geológica de Portugal (accessed on 4 may 2018 http://geoportal.lneg.pt/)

Lopes, S. I., Cruz, A., Moreira, P. M., Abreu, C., Silva, J. P., Lopes, N., Vieira, J., Curado, A., 2018. On the design of a Human-in-the-Loop Cyber-Physical System for online monitoring and active mitigation of indoor Radon gas concentration. *2018 IEEE International Smart Cities Conference (ISC2)*, 1-8. DOI:10.1109/ISC2.2018.8656777

Lopes, S. I., Silva, J. P., Antão, A., Curado, A., 2018. Short-Term Characterization of the Indoor Air Radon Concentration in a XII Century Monastery converted into a School Building. *Energy Procedia*, **153**: 303-308, https://doi.org/10.1016/j.egypro.2018.10.036.

Louro, A., Peralta, L., Soares, S., Pereira, A., Cunha, G., Belchior, A., Ferreira, L., Monteiro Gil, O., Louro, H., Pinto, P., Rodrigues, A. S., Silva, M. J., Teles, P., 2013. Human exposure to indoor radon: a survey in the region of Guarda, Portugal. *Radiation Protection Dosimetry*, **154(**2): 237-244. https://doi.org/10.1093/rpd/ncs166 .

Madureira, J., Paciência, I., Rufo, J., Moreira, A., de Oliveira Fernandes, E., Pereira, A., 2016. Radon in indoor air of primary schools: determinant factors, their variability and effective dose. *Environ. Geochem. Health*, **38**: 523-533.

Martín Sánchez, A., de la Torre Pérez, J., Ruano Sánchez, A. B., Naranjo Correa, F. L., 2012. Radon in workplaces in Extremadura (Spain). *Journal of Environmental Radioactivity*, **107**: 86-91.

Martínez Catalán, J. R., Arenas, R., Díaz García, F., Rubio Pascual, F. J., Abati, J., Marquínez, J., 1996. Variscan exhumation of a subducted Paleozoic continental margin: The basal units of the Ordenes Complex, Galicia, NW Spain. *Tectonics*, **15**: 106-121.

Meireles, C., Pamplona, J., Castro, P., 2014. Lito e tectono-estratigrafia da Unidade do Minho Central e Ocidental: uma proposta de reclassificação. Litho and tectonostratigraphy of "Minho Central e Ocidental", Unit: a proposal of revision. *Comunicações Geológicas*, **101**, Especial I, 269-273.

Milner, J., Shrubsole, C., Das, P., Jones, B., Ridley, I., Chalabi, Z., Hamilton, I., Armstrong, B., Davies, M., Wilkinson, P., 2014. Home energy efficiency and radon related risk of lung cancer: modelling study. *BMJ 2014*, **348**, f7493.

Neves, L. J. P. F., Barbosa, S. M., Pereira, A. J. S. C., 2009. Indoor radon periodicities and their physical constraints: a study in the Coimbra region (Central Portugal). *Journal of Environmental Radioactivity*, **100**: 896-904.

Neves, L. J. P. F., Pereira, A. J. S. C., Godinho, M. M., Dias, J. M. M., 1996. The radioactivity of rocks as an environmental risk factor in the continental Portuguese territory: a synthesis. *Proceedings of the V National Conference on the Environment Quality*, Aveiro, Portugal, **1**: 641-649.

O'Riordan, M., 1990. Human exposure to radon in homes, Docs. NRPB, 1.

Pamplona, J., Ribeiro, A., 2013. Evolução geodinâmica da região de Viana do Castelo (Zona Centro-Ibérica, NW de Portugal*). In:* Dias, R., Araújo, A., Terrinha, P., Kullberg, J. C. (Eds.), *Geologia de Portugal*, **I**: 149-204.

Pereira, E., Ribeiro, A., Carvalho, G., Noronha, F., Ferreira, N., Hipólito, J., Moreira, A., Lemos, M., Montenegro, A., Assunção, A., Ribeiro, L., Farinha, M., Silva, N., Simões, A., 1989. Folha 1 e Notícia explicativa da Carta Geológica de Portugal na escala 1:200 000. Serviços Geológicos de Portugal. Disponível no geoportal do LNEG em https://geoportal.lneg.pt/mapa/#.

Ribeiro, A., Pereira, E., Dias, R., 1990. Structure in the Northwest of the Iberian Peninsula. *In*: Dallmeyer, R., Martínez García, D. E. (Eds.), *Pre-Mesozoic Geology of Iberia*. Springer-Verlag, Berlim.

Silva, C., Ferreira, T., Viveiros, F., Allard, P., 2014. Indoor radon (^{222}Rn) monitoring in some buildings at Furnas and Ribeira Quente villages (Furnas Volcano, Azores): public health risk assessment. *Comunicações Geológicas*, Fasc. Esp. **101(**II): 927-931.

Silva, C., Gaspar, J. L., Viveiros F., 2014. Soil and indoor radon (^{222}Rn) monitoring in a building located at Ponta Delgada, São Miguel, Azores. *Comunicações Geológicas,* Fasc. Esp. **101**(II): 933-937.

Sousa, S. I. V., Branco, P. T. B. S., Nunes, R. A. O., Alvim-Ferraz, M. C. M., Martins, F. G., 2015. Radon Levels in Nurseries and Primary Schools in Bragança District-Preliminary Assessment. *Journal of Toxicology and Environmental Health,* Part A, **78**(13-14): 805-813. DOI: 10.1080/15287394.2015.1051171.

Teixeira, C., Medeiros, A. C., Pinto Coelho, A., 1972. *Notícia explicativa da Folha 5-A Viana do Castelo da Carta Geológica de Portugal na escala 1/50 000*. Serviços Geológicos de Portugal.

Teixeira, M. M. R., Faísca, M. C., 1992. Concentração de radão em habitações a nível nacional. *III Conferência Nacional sobre a Qualidade do Ambiente*, **II**: 522-531.

US Environmental Protection Agency, 1992. Consumer's Guide to Radon Reduction: How to Reduce Radon Levels in Your Home. *National Service Center for Environmental Publications*, Cincinnati, OH (EPA publication no. 402K92003).

WHO, 2000. Air quality guidelines for Europe. Second edition. World Health Organization, Regional Office for Europe, **91**, Copenhagen, Denmark.

WHO, 2010. Guidelines for Indoor Air Quality: Selected pollutants. World Health Organization, Regional Office for Europe, Copenhagen, Denmark. ISBN978 92 890 0213 4.