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Review

Natural Radiation in the Geological Anomaly of Poços de Caldas Plateau, Minas Gerais, Brazil

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The Poços de Caldas anomaly has been subject to attention of geologists for many years. It is an about circular shaped structure of about 30 km diameter, elevated a few 100 m above the surrounding region, formed by an alkaline intrusion including volcanic activity. Within this geological unit there are geochemical anomalies, such as a uranium deposit which has been exploited by a U mine (now under remediation), and the notable Th and RE anomaly Morro de Ferro where ambient dose rate up to several 10 µSv/h is encountered. Several small cities are located in the otherwise rural region with population together about 200,000.

We give an overview on the geological setting and present data of radiometric surveys, which have been performed over the years. In the last years, they have been intensified and include detailed surveys of ambient dose rate, indoor Rn, and since recently, Rn in soil. In a few cases, largely increased indoor Rn concentrations up to above 1000 Bq/m³ were found. In addition, epidemiological data of cancer mortality are available which however require very considerate and restrained interpretation.

Key words: Poços de Caldas geologic and radiometric anomaly, dose rate, indoor radon, soil radon

1. Introduction: The geological anomaly of the Poços de Caldas Plateau

The geological structure of the Poços de Caldas Plateau (Brazil) has interested geologists for long and it has been known as radiological anomaly since the middle of last century. In the 1960s the region, traditionally agricultural with long standing spa tourism (due to mineral springs and the benign climate) has become economically important with the development of the Osamu Utsumi open pit uranium mine, in operation between 1982 and 1995, currently under remediation. Today a large aluminium plant drawing from bauxite deposits is still operational in the Southern outskirts of Poços de Caldas city (about 150,000 inhabitants) but about to be closed too. In this article, recent findings about natural environmental radioactivity will be reviewed.

The Poços de Caldas Plateau is easily recognizable from space by its approximately circular shaped topography, Figure 1. Genetically it is a caldera formed by the collapse of cretaceous elevated subvolcanic intrusions in the surrounding proterozoic crystalline basement. The average altitude of the plateau is about 1200 m a.s.l. (above

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Fig. 1. The Poços de Caldas Plateau in Google Earth. Image (c) 2015 CNES / Astrium; (c) 2015 Google; Image (c) 2015 Digital Globe; Image Landsat. Poços de Caldas City is located about 21°48' South, 46°34' West.

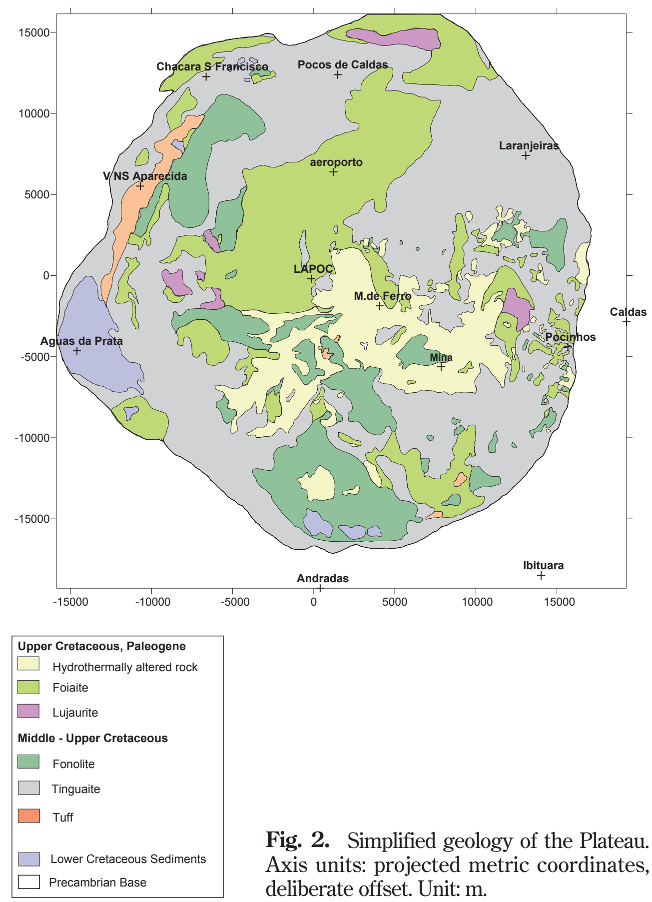

Fig. 2. Simplified geology of the Plateau. Axis units: projected metric coordinates, deliberate offset. Unit: m.

sea level), which is several 100 m above the surrounding region, and the caldera rim is a prominent feature of the landscape. Closer inspection reveals several smaller about circular structures within the large one, believed to be remainders of volcanoes.

The predominant rocks are Tinguaite and Foaite. These are nepheline syenites of which the former is the volcanic and the latter the plutonic version.

Additionally there are fonolitic lavas and pyroclastic rocks (tuff), clastic sediment and arenite, which is an erosion product of more ancient rock. A minor, but radiologically important rock is Lujaurite-Chibinite, a variant of foiaite enriched in the mineral eudalite (Na, Ca, Ce, RE, Fe, Mn, Na, Zr-Silicate including high concentration of U and Th).

The specific feature of the region is, however, hydrothermally alterated rock, formed in most cases from tinguaite and fonolites and sometimes very highly mineral enriched compared to original rock, which has typical background concentrations.

The geology is very complex and the interested reader is referred to literature, e.g. Schorscher and Shea[1] which also contains an extensive bibliography or the "Planalto Project" report[2] for a short version. A detailed study of hydrothermal alteration is Garda[3]. A simplified geological map is shown in Figure 2.

Two particularly notable mineral deposits are the Osamu Utsumi U mine and the Morro do Ferro. The mine is the only U occurrence on the plateau, which was large enough to be of economic importance. For details on the geological setting, see the report by Waber *et al.*[4]. Environmental problems consist in seepage of acid drainage water from waste rock deposits[5-7].

Morro de Ferro (translated "iron hill") is a quite unique Th – Rare Earths deposit, located on the slope of a hill; it is only a few 10 m thick and has been formed by a sequence of intense hydrothermal alteration and weathering, forming a laterite-kind structure covered by magnetite. The details are complicated, see e.g. the studies by Waber *et al.*[8] and by Linsalata *et al.*[9]. The site has been investigated thoroughly as a natural analogue of a nuclear waste deposit, where transport mechanisms of certain elements can be studied[10]. The deposit has so far been considered too small to be of economic importance. On the surface of the otherwise unspectacular hill, today covered by eucalypt forest, locally ambient gamma dose rate of several 10 μSv/h can be encountered.

2. The "Poços de Caldas Project"

The *Projeto Planalto* (2004-2013) (Planalto project) has been coordinated by the Health Secretariat of the State of Minas Gerais. Its objective was to establish a database of natural radiation (ambient dose rate and indoor radon-222 concentration) and of cancer incidence. (Henceforth radon-222 will be abbreviated simply as "Rn".)

In its first phase, 2004-2009, documented in a report[2], ambient dose rate was measured and demographic and epidemiological data were acquired. The main objective of the second phase, 2010-2013, was indoor radon, motivated by epidemiological knowledge about the effects of Rn and international activities in Rn surveying. The results can be found in the second project report[11].

Indoor radon is the main concern from a radiological point of view, as in most cases it contributes overwhelmingly to the dose budget of people. Epidemiological studies have shown a cancerogenic effect starting from relatively low exposure[13] and it is believed that no threshold of the effect exists. Therefore, internationally much effort has been, and continues to be devoted to assessing indoor Rn by surveys and planning and implementing countermeasures aimed to reducing the risk of lung cancer. This includes regulation, such as the recent Basic Safety Standards (BSS) of the European Union[12], which also cover Rn. For a good introduction to indoor Rn, in particular health effects, and literature, the reader is referred to the Radon Handbook issued by the WHO[13].

Among additional activities accompanying the project without being part of it proper, are first attempts of surveying soil Rn. This started in 2014 only but no results have been available by mid-2014.

3. Review of the results of the project

The figures quoted in the following are mostly taken from the project reports[2,11], with some additional calculations performed by the authors. The maps, Fig. 2 to 7, were created by the authors.

3.1. Ambient dose rate

The raw values of ambient dose rate measured by car borne survey on the plateau and in its surroundings are plotted in Figure 3. The database consists of about 530,000 records. The outline of the plateau is clearly visible. Cosmic radiation has not been corrected for but the altitude difference between the plateau and the surrounding lower region accounts for a few nSv/h only. Also the equipment used (plastic scintillometer) is little sensitive for cosmic radiation.

Statistical analysis, presented at a recent conference[14] shows that geology is a controlling factor for dose rate. Modelling by ordinary kriging including geology as external deterministic predictor leads to the map shown in Figure 4. The areas with relatively high dose rates (yellow, red and purple zones) are essentially the ones underlain by hydrothermally altered rocks and Lujaurite. The crescent or semi-circular structure within the plateau distinguished by high dose rate is believed to be the remainder of another volcano. However, geological units are very heterogeneous with respect to dose rate.

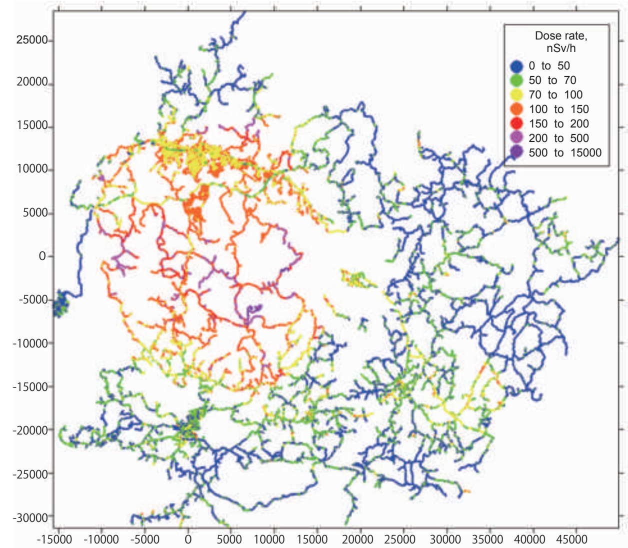

Fig. 3. Ambient dose rate, raw values of the carborne survey. Coordinates as in Figure 2.

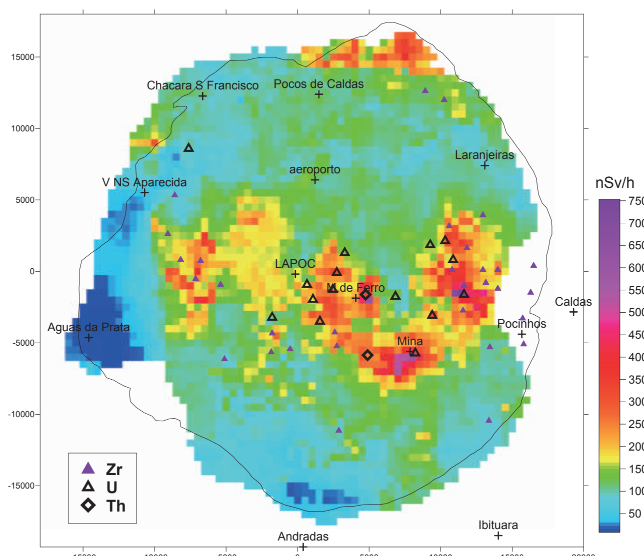

Fig. 4. Ambient dose rate modelled by ordinary kriging (estimation support: 500 m×500 m cells) using geology as external predictor and mineral occurrences. The analysis has been restricted to the Poços de Caldas Plateau; blank areas within: insufficient data. Coordinates as in Figure 2.

One reason may be that dose rate largely depends on the degree of hydrothermal alteration, while a binary classification "alterated yes-no" conveys relatively little information. In fact, it appears that dose rate is a fair predictor of the degree of alteration, compared to the inverse, "altered y/n" as predictor of dose rate.

Figure 4 also shows the locations of known mineral occurrences or anomalies of three types. For a further description see a report[3].

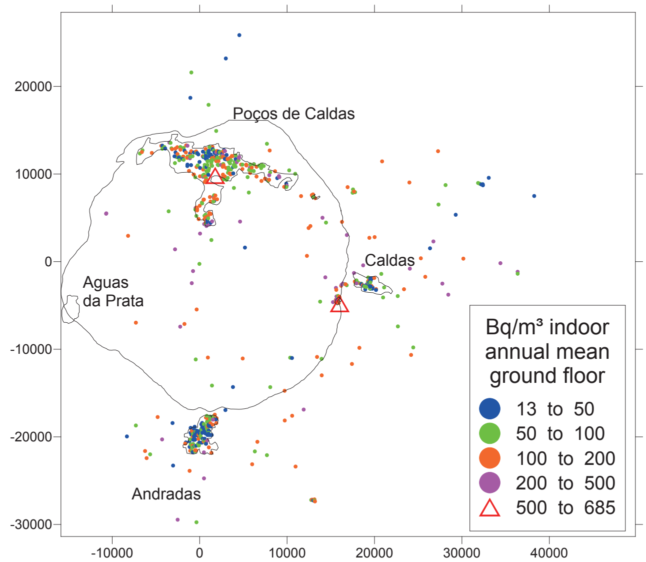

Fig. 5. Indoor Rn measurements. The point density reflects population density. Coordinates as in Figure 2.

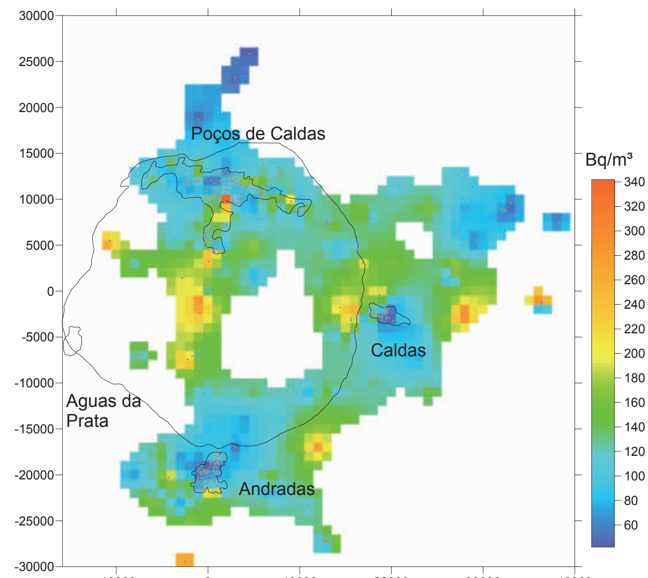

Fig. 6. Indoor radon map: 1 km × 1 km cells, standardized indoor concentrations (for technical details see text). Grey points: sample locations. Coordinates as in Figure 2.

3.2. Indoor radon

Houses were selected to be about demographically representative by randomly picking from the smallest administrative unit which is the “setor censitário” (census tract) in Brazil, and which can be as small as some blocks in a city or tens of km² in rural regions. Rn was measured with standard track etch detectors, in one living and one sleeping room per household, and in two consecutive half-yearly periods.

Altogether, we have 577 data of annual mean indoor concentrations, 464 of them in ground floor rooms. For the sake of comparability, only the latter have been evaluated for the following results. The maximum annual mean equals 685 Bq/m³, with seasonal values in particular rooms up to over 1600 Bq/m³. The mean is the arithmetic mean over two rooms and two seasons, i.e. 4 values. High variability between seasons and between rooms has been observed in some cases. The locations of measurements are shown in Figure 5 as classed post plot. Together with the detectors extensive questionnaires were distributed which allow identifying factors that contribute controlling indoor Rn levels; for details see annex 2 of the project report[10].

The regional arithmetic mean (AM) and the standard deviation (SD) of all original values (n = 577) are 104 ± 81 Bq/m³, geometric mean (GM) and geometric standard deviation (GSD), 81 Bq/m³ */ 2.0. The distribution is approximately log-normal (LN). Empirical exceedance probabilities are prob(C>100 Bq/m³) = 40%, prob(C>300 Bq/m³) = 3%. Assuming LN, the theoretical values are 38.4% and 3.3% for the thresholds 100 and 300 Bq/m³, respectively.

In an additional step, the raw data were rendered more demographically representative by adjusting them for the population number within the “setores censitários”. The adjusted AM and GM are 101 and 90 Bq/m³.

An interpolated map of standardized indoor Rn concentrations is shown in Figure 6. Rn values were standardized in order to obtain a more homogeneous dataset (for reducing short range variability which may obscure the spatial structure) as follows: living and sleeping rooms in ground floors of buildings in contact with the ground (i.e. not over basements or suspended), sleeping rooms included only if the inhabitants indicated that they sleep with closed windows.

This can be considered a conservative selection in the sense that other choices lead to lower Rn concentrations, in general. The interpolation technique is ordinary block kriging, based on a mean variogram from 10 random realizations of randomly declustered data.

One can observe a spatial tendency but it is difficult to interpret in relation to geology, also due to the fact that indoor Rn samples, selected as demographically representative, are not so with regard to geological units.

Generally, the Rn concentrations tend to be higher inside the caldera, but there are also high-Rn areas outside, e.g. in an area East of Caldas town. Possible geological reasons have not been identified so far. In addition, a regional trend in building styles – which contribute strongly to indoor Rn – may exist, but closer investigation is still missing. Especially heterogeneous is the distribution of indoor Rn in Poços de Caldas city, with a tendency towards somewhat higher concentrations over Foiaite.

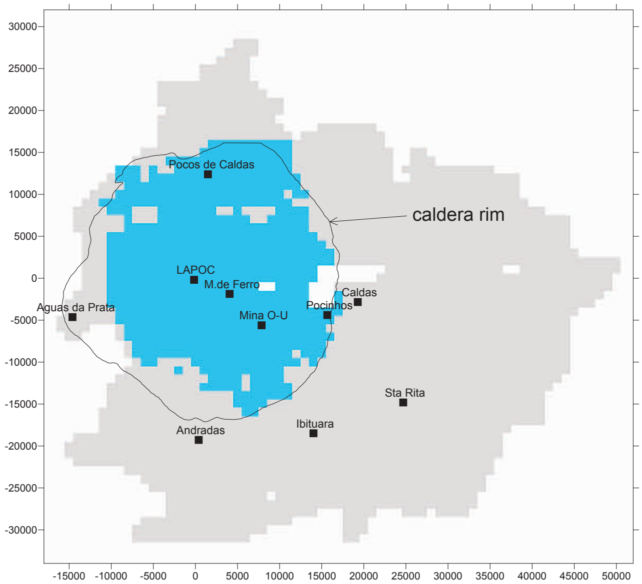

Fig. 7. radon prone areas defined by threshold of ambient dose rate dr^{opt}=92 nSv/h derived from criterion $E(C_{in})$>100 Bq/m³ in 1 km × 1 km cells. The caldera rim encircles the plateau of Poços de Caldas. The city is located in the Northern part. Dark (blue) shaded: RPA, light grey: non-RPA; white: missing predictor data. Coordinates as in Figure 2.

Table 1. Approximate population adjusted mean radon concentrations in ground floor rooms in different European countries compared to the Poços de Caldas project

Country	estimated mean in ground floor Bq/m³
Austria	133
Czech Republic	258
Denmark	96
Finland	260
Lithuania	59
Macedonia	120
Netherlands	23
Norway	135
Slovenia	166
Spain	118
Switzerland	200
U.K.	89
Pocos de Caldas Project	108

3.3. Relations between dose rate and indoor radon

Although correlation between ambient dose rate and indoor Rn concentration is weak, by applying a classification method dose rate can be used as a predictor of whether a cell on the map should be considered radon prone area (RPA). The method has been shown in a report[15] and applied to the Poços de Caldas data in a report[16]. Basically, from a pre-set criterion of indoor Rn, here: expectation (estimated as arithmetical mean) of indoor Rn concentration (restricted to living rooms in ground floor) in a 1 km × 1 km cell to be > 100 Bq/m³, a threshold of the predictor, here ambient dose rate, is derived through optimized binary classification. The threshold of dose rate, which defines a RPA according this logic, has been found 92 nSv/h. The affected area is shown in Figure 7. Clearly, a different choice of the criterion would lead to a differently delineated RPA.

3.4. Exposure

External exposure

Areas with high ambient dose rate, in particular the uranium mine and Morro de Ferro, are not populated. However also in some residential areas, notably in the Southern part of Poços de Caldas city, dose rate well above average is encountered. The population-adjusted dose amounts to about 1 mSv/a in this city, whereas for the other towns (Andradas, Caldas, Ibitiúra and Santa Rita) this figure is between 0.54 and 0.66 mSv/a. In certain places in the region theoretical annual doses (supposing residence in that place) could amount up to almost 100 mSv/a.

Indoor Radon

Using the population-adjusted mean concentration, and assuming an occupation factor of 0.8, an equilibrium factor 0.4 and the dose conversion factor 9 nSv/(Bq h/m³), from ICRP 65[17], this leads to a mean Rn dose of 2.55 mSv/a, with some variability between municipalities. Applying the new dose conversion factors probably to be adopted by the ICRP in the near future, the dose would be three or more times as high[18].

The mean exposure to indoor Rn is medium high in the investigated region, although in certain areas and certain houses high doses can be expected. In Table 1 approximate mean Rn concentrations in ground floor rooms from different countries are compared. The data were taken from the database of the European indoor Rn map[19, 20], adjusted by taking weighted means over cells. Weights are the number of measurements per cell, which in case of representative sampling (more or less the case for the selected countries) are approximate surrogates of population density. For Poços de Caldas the mean over all ground floor rooms was taken.

4. Conclusions and consequences

The Poços de Caldas Plateau is a region of elevated natural radiation and a large part of it can be considered radon prone area. Although a dense data base of dose rate and indoor Rn exists, relations between these quantities

and with geology are not sufficiently understood yet. We hope that the planned investigations of soil Rn will help clarify some issues.
In spite of elevated radiation levels, no increased cancer incidence is observed in the region, compared to other Brazilian regions[11].

In May 2014, the First Latin American Radon symposium together with the Second Brazilian Radon Seminary was held in Poços de Caldas. Connected to it was an exercise of measuring Rn concentration in soil. The presentations can be found in the conference web site[21]. A main topic was presentation of the results of the Poços de Caldas Project, some shown in this article, which, apart from its importance by itself, given the relatively high levels of ambient radiation in the region, is considered a pilot project for larger Rn surveys in Brazil.
In the affected Poços de Caldas region, a longer-term task will certainly consist in developing strategies for radon prevention in new buildings and remediation of existing ones. Experience mainly from Europe and North America shows that this involves not only inclusion of the expertise of construction industry but also regulatory and administrative work, and not least, educational work and communication with the public.

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