

Radon, Health and Natural Hazards: a signpost for assessment and protection in the 21st century

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Abstract: This volume draws together the final outputs of the five-year UNESCO / IUGS / IGCP Project 571 and presents new data on radon in the built and natural environments, radon as a diagnostic tool of geophysical phenomena, reflections and recommendations on the future of radon research and a critique of radon's asserted use as a therapy. In recent years there has been an increasing interest in radon from a range of different aspects and we would suggest that radon science has the potential to be a useful tool in understanding our environment as well as its impacts on human health.



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The papers in this Geological Society of London special publication represent a cross-section of activities undertaken under the United Nations Educational, Scientific and Cultural Organization, International Union for Geological Sciences and International Geoscience Programme (IGCP) Project 571, *Radon, Health and Natural Hazards*. These activities included a sequence of Project 571-specific sessions at successive European Geosciences Union (EGU) Annual General Assemblies 2009–14, which yielded two special issues of the journal *Natural Hazards and Earth System Sciences* (Gillmore *et al.* 2010; Crockett *et al.* 2012), as well as other Project 571 meetings and workshops in Paris, France, and Bath, UK. In total, these meetings resulted in c. 40 oral and over 100 poster presentations from scientists in more than 20 countries. This special publication represents the culmination of IGCP Project 571 and represents the state of the art at the conclusion of the Project, presenting data obtained in widely different contexts for the first time.

This project focussed on a variety of impacts and hazard-associated manifestations of radon (²²²Rn), which is a colourless, odourless, naturally occurring radioactive gas. Radon, together with its radioactive daughters, principally polonium isotopes ²¹⁸Po, ²¹⁴Po and ²¹⁰Po, has been linked to lung cancer (and perhaps, albeit on a more conjectural basis to date, also to some other cancers). In the UK (population c. 65 000 000), for example, it has been suggested by government agencies such as Public

Health England (see also Darby *et al.* 2005) that between 1000 and 2000 people die each year from radon-induced lung cancer. However, this is not simply a UK problem: the corresponding figure for the USA (population c. 320 000 000) is between 15 000 and 22 000. European-wide research has also suggested that there is no 'safe' lower limit for radon exposure (Darby *et al.* 2005), which perhaps throws into question limits set in various countries. In the UK the domestic and workplace Action Levels are 200 Bq m⁻³ and 400 Bq m⁻³, respectively plus, since 2010, an additional Target Level 100 Bq m⁻³. The introduction of this Target Level in the UK was the UK government agencies' response to World Health Organization guidelines (WHO 2009) which proposed that a limit of 100 Bq m⁻³ would be appropriate in a domestic setting to minimize the health hazard arising from indoor radon exposure.

Raised radon levels have been noted in a number of work environments, in particular water treatment plants, tunnels, caves and mines throughout the world. Links have been made between radon concentrations in mines and the incidence of lung cancer in mine workers (Lubin *et al.* 1995; see also Gillmore *et al.* 2001, 2002).

Other research has demonstrated a link between ocean and earth tides and indoor radon levels in some locations (Yong & Wei 1995; Crockett *et al.* 2006). Whilst such work is a step towards understanding the drivers behind indoor atmospheric

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radon concentrations (and other aspects of crustal deformation), much remains unknown. Similarly, radon is being used as a potential indicator in the monitoring of earthquake and volcanic activity, although not without some controversy, and radon in groundwater wells has been used to monitor such activity in Japan (e.g. Igarashi *et al.* 1995).

Radon hazard assessment is a multi-/inter-disciplinary subject as it requires inputs from a range of academic disciplines, such as geology, geography (physical and human), mathematics/statistics, physics, chemistry and medicine. One of the benefits of Project 571 has been to provide a productive interdisciplinary forum as a basis for better informed decision-making regarding where and when to employ resources to minimize societal risk – both directly from radon gas and its radioactive daughter isotopes and indirectly from radon-indicated natural hazards.

Radon in the built environment

As stated previously, radon (^{222}Rn) has been highlighted by a number of authors as a significant public health concern. For example, it is the second most significant cause of lung cancer after tobacco smoking yet a very high proportion of the general public appears to be unaware of the risk. (Gillmore *et al.* 2017) address this with a comprehensive review of topical radon issues. This assessment of the state of radon research is focussed on the UK as an example of a country where radon has been on the governmental agenda since the late 1970s, but also highlights radon issues throughout the world in, for example, the USA, Europe and Asia.

Radon measurements in the built environment are generally made over sub-annual periods and then seasonally corrected, i.e. scaled by an appropriate seasonal correction factor to provide an estimate of the annual average radon concentration. Seasonal correction factors are statistically derived according to measurement protocols and widely observed seasonal variations in indoor radon concentrations. Crockett *et al.* (2016) take an annual sinusoidal model for variations in radon concentration, as pioneered by Public Health England in the UK, as their starting point. Working with a four-year dataset from Northamptonshire (UK), they characterize the actual annual cycle and revise this model to produce an enhanced version, comprising an annual sinusoid plus second harmonic. This model results in a c. 16% improvement in variance explained over the simple sinusoid, a refinement which has the potential for improved seasonal correction factors.

Whilst radon has generally been regarded as a naturally occurring radiological hazard, Crockett and Gillmore (2016) report measurements of

significant, hazardous radon (and potentially also thoron, ^{220}Rn) concentrations that arise from man-made sources such as radium-dial watches and uranium glass artefacts. Historical artefacts can contain uranium and radium and hence emit radon. In the 1930s and 1940s such items were popular and they are therefore still easily obtainable today – indeed, they are frequently sought after by collectors. The specific watch collection investigated here was shown to be capable of giving rise to radon concentrations two orders of magnitude greater than the UK domestic Action Level of 200 Bq m^{-3} in unventilated or poorly ventilated rooms, indicating a hitherto largely unrecognised radon hazard and an apparent gap in remediation protocols (which are focussed on preventing radon from entering buildings from outside) with regard to internally generated radon hazards.

Moving to the influence of the natural environment on the built environment, Vaupotič *et al.* (2017) report on year-long continuous radon monitoring carried out in a dwelling of high radon levels in a karst region. Two living rooms were selected, one on the ground floor with normal housework activities and the other on the first floor, closed and unattended. The ground-floor seasonal geometric mean radon concentrations ranged from 1.25 kBq m^{-3} (summer) to 9.83 kBq m^{-3} (winter) and the corresponding range for the first floor was 0.168 kBq m^{-3} (summer) to 2.08 kBq m^{-3} (winter). These results, supported by additional data from other rooms in the building and in water in the surrounding environment, indicate an underground karst shaft as the major source of the indoor radon and, as a whole, these results cast new light on the problems posed by this type of underlying geology.

Radon in the natural environment

In many countries, domestic and workplace radon is dealt with by firstly mapping its distribution in the natural environment. Such maps are then used by government bodies, etc., to inform decisions as to where best to deploy their inevitably finite resources. Not surprisingly then, as part of this process, the Geological Survey of Austria undertook a detailed survey of radionuclides in groundwater, rocks and stream sediments, published as an overview map with notes in 2014 (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2014). We are fortunate to be able to include a chapter by Schubert *et al.* (2017) which summarizes this survey. One of the conclusions of this work was to clearly confirm that ^{222}Rn in groundwater depends significantly on the uranium content of the aquifer in question. Interestingly, in the eastern part of Austria high uranium contents in

groundwater (often in excess of $15 \mu\text{g L}^{-1}$) showed a divergent pattern to the uranium in the substratum. This is a region of relatively low precipitation levels but with high agricultural productivity.

Effective ^{226}Ra concentration, $ECRa$, is the product of radium activity concentration, CRA , multiplied by the emanation coefficient, E , the probability of producing a ^{222}Rn atom in the pore spaces. It is generally measured by laboratory accumulation experiments using scintillation flasks to measure radon concentration. **Perrier *et al.* (2016)** report 3370 $ECRa$ values obtained from more than 11 800 such experiments and report that rocks, soils, plants and animal bones have typical $ECRa$ values of 1.9, 7.5, <1 and $>1 \text{ Bq kg}^{-1}$ respectively and conclude that $ECRa$ is a significant factor for radon modelling and health hazard assessment, and also to evaluate the transfer of ^{226}Ra to the biosphere. In a parallel study, **Girault *et al.* (2016a)** report 2143 dissolved ^{222}Rn and ^{226}Ra samples which reveal significant differences between the ^{222}Rn and ^{226}Ra concentrations in (a) ground and surface waters and (b) hot and cold springs. They conclude that, whilst the ^{222}Rn concentrations are, in general, an indicator of ^{226}Ra that is chemically bound into the rocks, the ^{226}Ra concentrations are an indicator of the groundwater–rock geochemistry.

Girault *et al.* (2016b) studied radon (^{222}Rn) and carbon dioxide (CO_2) emissions around four remote Nepalese thermal springs near the Main Central Thrust: Timure and Chilime in the upper Trisuli Valley, central Nepal, and Sulighad and Tarakot in Lower Dolpo, western Nepal.

A total of 949 radon CO_2 fluxes were measured on the ground, complemented by radon concentration measurements in soil and water, and thermal infrared imaging. In Lower Dolpo, the data indicate radon and CO_2 transport dominated by shallow hydrothermal water transport, whereas in the upper Trisuli Valley, the data indicate radon and CO_2 transport dominated by fast gas-transport along fault networks. The authors conclude that radon can therefore yield important and valuable information on the gas transport properties of the shallow continental crust and also that radon flux should be systematically combined with soil radon concentration and CO_2 flux measurements.

Radon as a diagnostic tool

Radon as a diagnostic precursor to volcanic eruptions and earthquakes has been – and continues to be – strongly debated and an underlying factor is the necessity to fully understand the behaviour of fluids in the geological substrate (**Otton 1992; Appleton 2005**). This is illustrated by **Cigolini *et al.* (2016)**, who stress that understanding the

behaviour of fluids in hydrothermal systems is a key factor in volcano monitoring. The authors discuss a collection of data varying from closed to open conduit volcanoes such as Vesuvius and La Soufrière, Stromboli and Villarrica and argue that faults and fracture systems are key controls on radon degassing. However the authors also caution that radon is not the sole precursor and we should not exclusively rely on it but also consider other geochemical and geophysical precursors to help us to improve mitigation of risk.

In the various sites analysed in this volume, better knowledge of the factors of variability and heterogeneity of the radon sources has led to more cautious approaches. This, in turn, will lead to better quantitative models better able to account for the complexity of the problems and, in due course, lead to more reliable forecasts even if precise predictions might remain unattainable owing the degree of complexity.

Radon as a therapy?

This final chapter is intended as a question and to stimulate questioning. As a counterpoint to all the other chapters in this special publication, and also to all the previous publications which originated from IGCP Project 571, we include a chapter by **Przylibski (2016)** which discusses radon's century-plus of use in medicine, based on the radiation hormesis (or radiation homeostasis) theory (e.g. **Feinendegen 2005**). Owing to the radioactive nature of radon and the fact that its alpha-radioactive decay is the source of other radionuclides, its claimed therapeutic application continues to raise serious doubts – and is clearly contradicted by, for example amongst many, World Health Organization advice and guidelines. With regard to the ongoing and still unsettled dispute concerning the beneficial or detrimental impact of radon on human health, the author puts particular emphasis on the necessity of (a) strictly monitoring both the activity concentration of ^{222}Rn and that of its radioactive decay products in media used for therapeutic treatments and (b) monitoring the radioactive dose that is received by persons undergoing radon therapy. Such monitoring should facilitate the assessment of the effectiveness (or detrimental effects) of these treatments, which could contribute to a fuller understanding of ionizing radiation on human health which, in turn, could provide definitive evidence to confirm or reject the radiation hormesis theory.

The future of radon research

This report, as the concluding Project 571 output, builds on the previous Project 571 outputs and

further fulfils the primary project aims and objectives, i.e. to encourage and facilitate dissemination of radon-related information, research results and good practice. Non-governmental organizations such as the World Health Organization need to continue to communicate and liaise with, for example in the UK context, bodies such as the Radon Council, Public Health England and sister bodies in the devolved UK governments, and the Building Research Establishment, and with the corresponding bodies in other countries and legislatures.

Such bodies themselves also need to continue to communicate and liaise with natural-hazards researchers to establish operational practices. Risks arising from radon hazards, and other hazards for which radon is potential indicator/diagnostic, in both the natural and built environments, can and should be mitigated following 'best practice'. Furthermore, this best practice needs to be continually updated as our collective knowledge and understanding of this complex natural – and anthropogenic – phenomenon improves and advances.

It is clear that the papers in this volume bring new data, methods and insights that are of considerable interest to scientists working on radon as a hazard and hazard-diagnostic in the built and natural environments. The publication of this special volume concludes IGCP Project 571 and we hope that this volume both gives a useful snapshot and also provokes questions and further research. In particular, we hope to see arguably neglected aspects of radon research such as indoor sources in the built environment and, controversially perhaps, research into the radiation hormesis theory, can be taken forward as well as the more accepted and established areas of radon research. In any case, radon research will remain connected to heuristic developments in medical research, including oncology, but probably other human health issues as well. Concerning natural hazards, large-scale data analysis and detailed modelling, based on a sound knowledge of the variability and complexity of the natural and human processes, will surely establish radon physics as one of the most reliable tools for the surveillance and the protection of our environment.

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continue to strive – to maintain the momentum generated by Project 571.

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