

This discussion paper is/has been under review for the journal Solid Earth (SE).
Please refer to the corresponding final paper in SE if available.

Radon signals at the Roded site, southern Israel

G. Steinitz and O. Piatibratova

Geological Survey of Israel, 30 Malkhe Israel St. Jerusalem 95501, Israel

Received: 18 May 2010 – Accepted: 14 June 2010 – Published: 22 June 2010

Correspondence to: G. Steinitz (Steinitz@gsi.gov.il)

Published by Copernicus Publications on behalf of the European Geosciences Union.

SED

2, 161–193, 2010

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Temporal variations of radon in the geological environment (upper crust) are frequent and recognized as unique in terms of the signals encountered and for the lack of substantial and generally applicable explanations. The phenomena observed at the Roded site, located in arid southern Israel, emphasize this situation. Monitoring of radon during more than 10 years is carried out in massive meta-diorite of the Precambrian basement block of Roded. Measurement is conducted using an alpha detector at a resolution of 15-min, lowered in a borehole at a depth of 9 m, within a PVC casing to that depth. Systematic temporal variation patterns, manifesting large relative signals are composed of sub-daily (SDR) radon, multi-day (MD) and annual (AR) signals. The overall variation is dominated by the intense SDR signals which occur in some days, and may vary from background levels (5 counts or less) to peak values (attaining >1000 counts) and back to background in an interval of 6 to 12 h. Intervals of up to several tens of days without significant SDR signals interchange with times of intense daily occurrences of such signals. Their occurrence indicates very fast variations of radiation from radon at the point of measurement. The peak times, within the diurnal 24-h cycle of SDR signals occur preferentially in the interval of 14–16 h (UT+2). Spectral analysis indicates: (a) A diurnal periodicity composed of a primary 24-h and a secondary 12-h periodicity, which are attributed to the solar tide constituents S1 and S2. Tidal constituents indicative for gravity tide (O1, M2) are lacking; (b) An annual periodicity. A compound relation among the diurnal and annual periodicity is indicated by: (a) Wavelet (CWT) analysis showing an overall annual structure with a modulation of the S1 and S2 periodicities; (b) FFT analysis using consecutive 21.3-day long time intervals shows that the amplitudes of S1 and S2 vary in an annual pattern, with relatively high values in summer. The phase of S1 and S2 and S3 shows a systematic multi-year variation. Existing frames of reference of geophysical processes cannot explain the highly systematic phenomena. It is suggested that the significant signatures of the periodic phenomena and their modulations are reflecting a direct link with solar radiation tide.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 hampered by the complex patterns of the measured signals (for a recent review see Cicerone, 2009). Radon time series display a compound temporal pattern of variation spanning multi-years to several hours, and exhibit both periodic and non-periodic patterns. Furthermore, radon time series exhibit non-stationary features in both mean and variance and clear nonlinear characteristics (Barbosa et al., 2007). The understanding of the origin of the different radon signals and its geophysical interpretation is a challenging task, on one hand due to the complexity and multi-scale properties of the signals, on the other due to the different and interacting physical processes influencing radon transport in the natural environment. The nature of the physical processes driving the temporal patterns observed in radon time series is not clear, particularly the extent to which environmental parameters, such as temperature, atmospheric pressure and humidity, can influence radon level. It is assumed that the temporal patterns of radon in the geogas phase are due to processes affecting its exhalation from the country rock and/or gas transfer processes in the complex consisting of rock porosity and subsurface air space. Environmental influences, particularly atmospheric pressure and temperature, have been proposed for the origin of the periodic signals observed in radon time series (Shapiro et al., 1985; Ball et al., 1991; Pinault and Baubron, 1997; Finkelstein et al., 2006). However, other studies (Aumento 2002; Groves-Kirby et al., 2006; Crocket et al., 2006, Weinlich et al., 2006) indicate that a consistent meteorological influence cannot be identified as giving rise to variability in radon time series, and suggest gravitational tides as an influencing factor on radon variability, since both earth tides and ocean tidal loading may drive periodic radon exhalation via crustal expansion/compression and geophysically-driven groundwater level variations.

25 Monitoring of Rn is performed since 1995 in the frame of Israel Geophysical Radon Project (IGRnP) in upper crustal rock systems from the Dead Sea to the Gulf of Aqaba. Several signal types are recognized, recurring in time and at different stations, ranging from multi-year to sub-diurnal scales which are periodic and non-periodic (Steinitz et al., 1992, 1996, 1999, 2007). Following the prevailing approaches and models it was attempted to determine the potential of non-periodic signals as a proxy of active

Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



seismically related geodynamics (Steinitz et al., 2003; Begin and Steinitz, 2005). Further effort to advance along this track did not result in progress, and on the other hand it became clear that an overall understanding of the unique behavior of radon was required, and specifically the driver(s) of the associated periodic signals. Detailed and advanced geophysical analysis of the radon phenomena at two key sites (Steinitz et al., 2007, Steinitz and Piatibratova, 2009) demonstrated that: (a) the large scale of relative variation of the superimposed signals and the temporal structure of the data is characteristic (unique) for radon time series in the subsurface; (b) the periodic and non-periodic patterns in radon time series display compound patterns of variation spanning multi-years to several hours; (c) local atmospheric influences cannot explain the observed patterns, and (d) the signals cannot be explained in term of known local active geodynamics. The outcome of the results from the field sites in Israel (see below) indicate that unrecognized dynamic processes are driving the radon signal in the geogas in the subsurface to a depth in the order of 100 m. The source of the radon is due to its release from the country rock. It is suggested that the significant S1 and S2 tidal signatures of the daily radon (DR) signal, and their variations and modulations, are related to the rotation of earth around its axis and around the sun. This indicates a direct link between a component in the solar irradiance (= solar radiation tide) as a driver of the periodic radon signals.

Radon time series display a compound temporal pattern of variation spanning multi-years to several hours, and exhibit both periodic and non-periodic patterns. The large scale of relative variation of the superimposed signals and the temporal structure of the data is characteristic (unique) for radon time series in the subsurface environment. So far establishing the geodynamic nature of the signatures and signals relies on negation of atmospheric influence, analyzing radon signatures in the geological, spatial, time and frequency domains, and primarily by establishing correlation with geophysical phenomena, and specifically the correlation to earthquakes (Steinitz et al., 2003; Begin and Steinitz, 2005).

Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In general the understanding of the nature and the processes driving the formation of radon signals in subsurface geogas is uncertain and disputed. The diversity of the observations, the complexity of the phenomena and the span of the suggested mechanisms render the overall picture as unresolved, hampering utilization of radon as a significant proxy of geodynamic processes. This contribution describes and examines the temporal patterns, at a scale of hours to years, of the radon signal at the Roded site, Southern Arava. A framework for interpreting the temporal patterns of radon is set by combining (i) qualitative description of the occurrences; (ii) application of time series analysis and signal processing approaches to long (multi-year) and high-resolution (< 1 h) radon time series for the extraction and description of the signal patterns; and (iii) comparative analysis of environmental and eventual geophysical influences on the radon time series.

2 Geographic and geological setting

The Roded site (Israel Grid 142350/898000; elevation 285 m) is located in the Roded massif, southern Arava, on a block of Precambrian basement, tectonically uplifted along the western margin of the southern segment of the DST (Fig. 1). Massif Roded is influence by arid climate (< 50 mm/year) and the whole area is a rock desert devoid of soil cover.

The local lithology is gneiss and schist intruded by rhyolitic and medium to basic dikes, all belonging to the Precambrian basement. Local metallic mineralization (including low U mineralization) was prospected in the late 1980's (Bogoch et al., 1990), and a prospecting drill hole was placed at the site (Shirav and Bogosh, 1995). The borehole, dipping 70° and 51–56 m deep, cuts mainly gneiss and some basic dikes. Presently the hole is blocked (rock fall) at a depth of 9 m. A PVC pipe (3") is introduced as casing to this depth and the radon sensor is lowered to its end. The PVC pipe is blocked at its upper end to inhibit exchange of air in the pipe with the atmosphere.

Initial monitoring of radon in the Southern Arava indicated temporal variations of radon in the Precambrian basement rocks (Shirav et al., 1999). Monitoring using high-time resolution measurements in this scenario is also performed at three locations covering a sector of around 20 km along the western margin of the Arava valley – the Roded, Amram and Elat Granite (ELTGR) sites (Fig. 1). The phenomena at ELTGR are described in detail by Steinitz et al. (2007) and Barbosa et al. (2007) and initial results from Amram are described by Barobsa et al. (2009). The time series from Roded site, located between these sites, exhibits a temporal pattern which differs from both latter sites. Preliminary monitoring of radon utilizing the SSNTD technology (integral measurements lasting from a week up to one month; Shirav et al., 1999) already indicated the temporal variation of radon level at the shallow depth of 50 cm at the Roded site.

3 Methods

Detection of radon ($= {}^{222}\text{Rn}$) at the Roded site is performed with a nuclear alpha which was replaced during the monitoring (Table 1; Fig. 2). Monitoring was initiated with an alpha detector (Alphameter 611; AlphaNuclear Inc., Canada) based on a 400 mm^2 silicon junction diode, immersed in a sensing volume open to the geogas, and equipped with an integral datalogger. Later measurements (since 11 November 2004) are performed with an alpha Barasol BT45 detector (400 mm^2 Si diode; Algade Inc., France), connected to a datalogger (CR10; Campbell Inc). In both types of instruments the detector is protected from the environment by a thin, aluminized Mylar anti thoron ($= {}^{220}\text{Rn}$) membrane. Radon enters the sensing volume, in order of 50 cc, by diffusion. The alpha radiation impulses are recorded (as counts) every 15-min. The sensitivity of the instruments is in the order of 50 Bq/m^3 per impulse/h. Results of temporal variation in ensuing figures are shown on a decimal-day scale (Days since 1 January 1992).

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4 Results

Visual inspection of the radon signal measured at the depth of 9 m (Fig. 3) exhibits a recurring temporal variation pattern dominated by intense and very fast relative variations and signals. The span of radon variations is from low background levels (0–5 counts per 15 min) up to hundreds and more than a thousand counts per 15 min. This variation pattern is consistent over more than ten years, and is independent of the specific sensor utilized. Part of the overall irregularly appearing is due in part to time intervals, lasting from single and several days, and up to tens of days, where a very low signal level is encountered, which is at or below the threshold of the sensor sensitivity (see Fig. 5). These low level intervals interchange with periods where the overall radon level is varying intensely and is extremely high.

Detailed inspection shows that this overall irregular appearing pattern contains systematic temporal variation types spanning from parts of a day to multi-years. These consist of: (a) Long term annual (and semi annual) variations; (b) Medium term multi day variations and (c) diurnal and sub-diurnal radon variations. These different types are observed mainly in the time domain and also in the frequency-time domain.

A weak annual variation is evident in some years (Fig. 3). The annual radon (AR) signal is clearly shown in a five year detail using daily averages (Fig. 4), manifested mainly as a superposition on the upper edge of the envelope of the intense variation. Compared with the lowermost baseline levels this variation is actually very large. More ever, a semi-annual constituent is also indicated in some years (2006, 2008; Fig. 4). These annual and semiannual variations are rather obscured due to the intense daily variations discussed below. The long time series (above 10 years) collected in Roded also allows examining the multi-year periodic pattern of the radon time series. Figure 5 shows the FFT spectra of the whole data set covering the years 1999–2009. An annual periodicity is indicated in 4 the spectrum.

Non-periodic multi-day (MD) signals are described and investigated from radon time series from Elat (Steinitz et al., 2007) and Gavnunim (Steinitz and Piatibratova, 2010).

SED

2, 161–193, 2010

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



At Roded MD signals occur as groups of sub-daily signals occurring in a train of consecutive days (Fig. 6).

The daily radon (DR) signal at Eilat and Gavnunim sites (op. cit.) is a significant component of the variations and has basically a semi sinusoidal form. In Roded the DR signal is the major and the dominant component of the variation. At this site the daily signal is developed only in a part of the day, and its form is actually highly non-sinusoidal. Such signals have been termed as Sub Diurnal radon (SDR) signals (Steinitz and Piatibratova, 2010). They occur in some days – as groups of SDR signals (Fig. 6) or at single and isolated days (Fig. 7). The features of the SDR signal at Roded are:

- Very fast increase lasting up to several hours from background level to a sharp peak that typically lasts less than one hour (generally only 15 min) followed by a similar fast decrease. The whole time interval from initiation to termination of the SDR signal is generally from 6 to 12 h. The amplitudes of daily peak of the SDR signals vary from several tens of counts to more than one thousand counts per 15-min. Visual inspection of the time series already indicates that SDR signal tends to occur at specific hours within a day, indicating a 24-h periodicity.
- Generally one SDR peak occurs in a day. Infrequently a double SDR signal occurs within a single day (Fig. 7 – Right). This is an indication for 12-h periodic cycle, in addition to the primary 24-h cycle (see below).

For further examination of SDR signals the time of 810 peaks above 100 counts were extracted from the measured time series. This allows analyzing the timing of the peak-time within the 24-h daily cycle, as shown in Fig. 8 – Top. The SDR extreme events, which do not occur every day, exhibit a clear preference to occur between 15–16 Hr (UT+2), and possibly also around 3–4 Hr. This pronounced timing within the daily cycle is the same for SDR signals of low and high amplitude (Fig. 8 – Bottom). In both cases a similar distribution of peak time occurs, indicating that there is no relation between peak-time and their intensity.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The peak shape of SDR signals above 100 counts/15-min was investigated. More than 64% of the peaks are characterized by a decreasing flank which is steeper than the rising flank (Fig. 9 – Left). This asymmetry is accentuated when taking into account only SDR signals of higher amplitude (Fig. 9 – Right). The intense variation in the SDR signal, reflected in the very fast increase followed immediately by a similar fast decrease is further analyzed in Fig. 10, showing three typical strong SDR signals with a relatively faster decreasing limb. As shown, correcting for radioactive decay of radon from peak-time (also shown) does not alleviate this asymmetry.

The diurnal periodicity is further examined using spectral analysis (FFT). Using a long time series at 15-min resolution clearly resolves three periodicities (Fig. 11) at 1-, 2- and 3-cycles per day (CPD). These primary periodic constituents reflect the S1 (24 h), S2 (12 h) and S3 (8 h) tidal frequencies (Wilhelm et al., 1997). The diurnal tidal constituents typical for gravity O1 and M2 are absent in the spectra of Roded site.

Relations among the different signals, as compounded phenomena, are highlighted by applying Continuous Wavelet Transform to the long time series. The result in Fig. 12 shows a clear annual structure, strongly related to the 1 CPD frequency and also to the 2-CPD. Furthermore, a semiannual pattern occurs, the relative intensity of which varies among the years. At the diurnal scale, the amplitudes of the daily signal, and possibly a semi-daily constituent are accentuated as a discontinuous horizontal band.

The time series of radon at Roded is clearly non-stationary, indicated by the fact that the mean value changes considerably with time, a situation also encountered in other radon time series (Barbosa et al., 2007). This sets known limitations on the application of Fourier spectral analysis in the combined frequency and time domain to such time series. Thus further insight on compounded phenomena is gained by addressing a series of shorter time windows and evaluating the spectrum relatively to the specific time interval. Therefore a moving-time-window Fourier spectral analysis is applied to estimate the “local in time” spectrum, as applied by Steinitz et al., (2007) and Steinitz and Piatibratova (2010). The amplitudes of the cyclic pattern are extracted from FFT calculated per 512-h long consecutive intervals (2048 time points = 2^{11}) and

plotted relative to the centre of each interval. The resulting time series of the long-term temporal variation of the amplitudes of the daily cyclic constituents is shown in Fig. 13, and for the phase in Fig. 14. The resulting time series exhibits a concordant temporal variation of the amplitude of the diurnal (S1) and semidiurnal (S2) and S3 constituents. All three constituents vary in an annual pattern with maxima in summer, which is accordance with the result of the CWT analysis (Fig. 12). A gradual long term (multi-year) variation is exhibited in the corresponding time series of the phase of the three periodic constituents. These parallel trends are clearer from 2003 onwards (probably related to improved continuity of the sampling – compare Fig. 2) and are most clearly depicted in the pattern of S2.

5 Discussion

The temporal variation of radon in the geological subsurface of southern Israel was recently evaluated in detail at the Elat Granite (ELTGR; Steinitz et al., 2007) and at Gavnunim (GAV; Steinitz and Piatibratova, 2010). The Roded site is located between these sites, some 17 km north of the ELTGR (Fig. 1). A joint evaluation is justified as they: (a) belong to the same geographic and climatic zone, (b) measurements are performed in massive magmatic hard rocks, (c) measured in boreholes at depths of up to 100 m, and (d) are from the unsaturated zone at a considerable level above a local water table.

Instrumental effects to explain the phenomena are ruled out based on (a) change of sensors and (b) the systematic of the variation patterns, especially in the frequency domain.

The eventual influence of atmospheric parameters – primarily barometric pressure and ambient temperature on the temporal variation – was dealt with separately and in detail for the case of the ELTGR and GAV sites, and similar arguments and conclusion are applicable for the Roded site which is located in the same arid climatic zone. A priori, within the specific geographic and geologic regime, there is no reason to assume

SED

2, 161–193, 2010

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



sensing volume of which is in the order of 50 cc. Radon enters the sensing volume by diffusion from the immediate vicinity – from the geogas around the bottom end of the PVC pipe in the case of this site. In such a scenario the concentration of radon in the sensing volume reflects the concentration in the adjacent volume of geogas. The local background due to emanation from rocks in the vicinity of the sensor is probably represented by the low level readings (in the order of 50 Bq/m³) during longer intervals of up to several tens of days. Initiating the extremely fast rise of the signal is incompatible with diffusion rates and must mean a flow of radon rich geogas from another zone, to the immediate vicinity of the sensor, which is followed by a similar flow of geogas with no radon – where the (interpreted) concentration differences attain several orders of magnitude. Two end member patterns of flow can be thought off: a continuous flow of a carrier geogas with highly varying concentrations of radon or, alternatively, a discontinuous flow alternating between radon rich and radon deficient concentration. Flow patterns with such variability are highly improbable on the following grounds:

1. The flow patterns which always generate an extremely short peak time lasting an hour or less are highly improbable.
2. If exist such flow patterns exist they are not limited to the site (borehole) alone and must be of extensive scale. No geological or geo-environmental evidence is known to support this.
3. The highly significant daily periodicity of the supposed flow events, the timing of which is determined by an external above surface driver.

Negating a flow regime involving very regular temporal features raises the possibility that the SDR signal does not reflect actual variation in the concentration of radon in the adjacent geogas but rather changes in the radiation from radon within the sensing volume. This is further discussed below.

SDR signals have also been documented from the GAV site, where they are recoded (by a similar detector) at a depth of 85 m. In both Roded and GAV sites the signals occur in some days and reflect sub-daily intense variations. A central property common

for both occurrences is their unambiguous proffered occurrence within the 24-h cycle. A major difference is that at GAV a bi-modal daily distribution is observed while at Roded a uni-modal pattern is observed. Subsurface geophysical periodic drivers are not known. At both sites such daily patterns must be reflecting an above surface periodic geophysical driver possessing typical tidal frequencies. This conclusion is supported by the spectral analysis which demonstrates that the involved periodicities are the tidal constituents S1, S2 and S3. If a common such a common feature is at hand then the differences in occurrence and timing pattern among the two sites may be attributed to local, i.e. geological, interactions.

In terms of fundamental properties the signal types and phenomena at Roded are in accordance with variation patterns found at the other locations in Israel. The source of the radon in the geogas is from the local country rock. In general the drivers so far suggested for explaining such radon signals are: (a) a process acting on the rock and affecting the release (emanation and exhalation) of radon from the solid and its transfer into the gas phase; (b) Processes affecting the level of radon in the gas phase, such as mass transfer and transport, mixing, dilution and adsorption. The above mentioned considerations suggest that such processes are incompatible for the generation of the described radon signals. On the other hand the patterns of temporal variation of radon place them within the realm of features observed in geophysical time series. Having excluded both subsurface geodynamic processes and above surface atmospheric influences a different option is considered to explain features in the temporal variation of radon at Roded. In the case of the ELTGR and GAV sites (op. cit) it was suggested that the generation of the periodic phenomena in radon time series is linked to an interaction with a component in solar radiation tide. This suggestion is further substantiated for the signal patterns at Roded, using similar criteria based on the characteristics of the radon time series in the frequency and frequency-time domains:

- The peak times of SDR signal clearly indicate a diurnal periodicity.
- Predominance of the S1, S2 and S3 periodicities, and

SED

2, 161–193, 2010

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- the lack of diurnal periodicities indicative for gravity tidal interaction (O1, M2).
- Generation of diurnal periodicities in the radon system is related to the rotation of Earth around its axis.
- The amplitude of the diurnal frequencies S1, S2 and S3 are co-modulated in an annual pattern, with high amplitudes in summer. Generation of this periodicity, as a compounded feature in the frequency-time domain, is related to the rotation of Earth around the sun.

These features at Roded are communal to similar features at ELTGR and GAV. In line with the interpretation suggested for the latter cases it is therefore concluded that this is also in the case of the Roded site.

Acknowledgements. N. Gazit, L. Michaeli and U. Malik assisted with the data collection and in initial processing. We would like to thank our colleagues H. Zafir and S. Barbosa for their joint discussions. The project is supported by Israel Science Foundation grant ISF 524/05.

References

- Alparone, S., Behncke, B., Giammanco, S., Neri, M., and Privitera, E.: Paroxysmal summit activity at Mt. Etna (Italy) monitored through continuous soil radon measurements, *Geophys. Res. Lett.*, 32, L16307, doi:10.1029/2005GL023352, 2005.
- Aumento, F.: “Radon tides” on an active volcanic island: Terceira, Azores. *Geofísica Internacional*, 41, 499–505, 2002.
- Ball, T. K., Cameron, D. G., Colma, T. B., and Roberts, P. D.: Behavior of Radon in the geological environment: a review., *Q. J. Eng. Geol.*, 24(2), 169–182, 1991.
- Barbosa, S. M., Steinitz, G., Piatibratova, O., Silva, M. E., and Lago, P.: Radon variability at the Elat granite, Israel: Heteroscedasticity and nonlinearity, *Geophys. Res. Lett.*, 34, L15309, doi:10.1029/2007GL030065, 2007.
- Barbosa, S. M., Steinitz, G., Zafir, H., Malik, U., and Piatibratova, O.: Radon variability in a subsurface stable environment – insights from continuous monitoring at the Bloch Geophysi-

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Immè, G., La Delfa, S., Lo Nigro, S., Morelli, D., and Patane, G.: Soil radon monitoring in the NE flank of Mt. Etna (Sicily), *Appl. Radiat. Isotopes*, 64, 624–629, 2006.
- Monin, M. M. and Seidel, J. L.: Radon in soil-air and groundwater related to major geophysical events: a survey, *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 314(2), 316–330, 1992.
- Pinault, J. L. and Baubron, J. C.: Signal processing and diurnal and semidiurnal variations in radon and atmospheric pressure: A new tool for accurate in situ measurement of soil gas velocity, pressure gradient and tortuosity, *J. Geophys. Res.*, 102, 18101–18120, 1997.
- Segovia, N., Mena, M., Seidel, J. L., Monnin, M., Tamez, E., and Pena, P.: Short and long term radon in soil monitoring for geophysical purposes, *Radiat. Meas.*, 25(1–4), 547–552, 1995.
- Shapiro, M. H., Rice, A., Mendenhall, M. H., Melvin, J. D., and Tombrello, T. A.: Recognition of environmentally caused variations in Radon time series, *Pure Appl. Geophys.*, 122, 311–326, 1985.
- Shirav, M. and Bogosh, R. Preliminary report on borehole cores, Roded prospect area, *Isr. Geol. Surv., Rep. GSI/14/95*, 12 p., 1995.
- Shirav, M., Steinitz, G., and Vulkan, U.: Feasibility of Rn monitoring in a tectonic context – testing in the Elat area, *Isr. Geol. Surv. Rep. TR-GSI/4/99*, (in Hebrew), 8 p., 1999.
- Steinitz, G., Vulkan, U., Lang, B., Gilat, A., and Zafrir, H.: Radon emanation along border faults of the Rift in the Dead Sea area, *Israel J. Earth. Sci.*, 41, 9–20, 1992.
- Steinitz, G., Vulkan, U., and Lang, B.: Monitoring of the tectonically related radon flux in Israel, *Isr. Geol. Surv. Current Res.*, 10, 148–153, 1996.
- Steinitz, G., Vulkan, U., and Lang, B.: The Radon flux at the northwestern segment of the Dead Sea (Dead Sea Rift) and its relation to earthquakes, *Israel J. Earth. Sci.*, 48, 283–299, 1999.
- Steinitz, G., Begin, Z. B., and Gazit-Yaari, N.: A Statistically Significant Relation between Rn Flux and Weak Earthquakes in the Dead Sea Rift Valley, *Geology*, 31, 505–508, 2003.
- Steinitz, G., Piatibratova, O., and Barbosa, S. M.: Radon daily signals in the Elat Granite, southern Arava, Israel, *J. Geophys. Res.*, 112, B10211, doi:10.1029/2006JB004817, 2007.
- Steinitz, G. and Piatibratova, O.: Radon signals in the Gavnunim intrusion, Makhtesh Ramon, *Israel Geophys J. Int.*, 180, 651–665, 2010.
- Toutain, J. P. and Baubron, J. C.: Gas geochemistry and seismotectonics: a review, *Tectonophysics*, 304, 1–27, 1999.
- Trique, M., Richon, P., Perrier, F., Avouac, J.-P., and Sabroux, J.-C.: Radon emanation and electric potential variations associated with transient deformation near reservoir lakes, Na-

Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

ture, 399, 137–141, 1999.

Weinlich, F. H., Faber, E., Bouskova, A., Horalek, J., Teschner, M., and Poggenburg, J.: Seismically induced variations in Mariánské Lázně fault gas composition in the NW Bohemian swarm quake region, Czech Republic – A continuous gas monitoring, *Tectonophysics*, 421, 89–110, 2006.

Wilhelm, H., Zürn, W., and Wenzel, H. G.: Tidal phenomena, *Lectures in Earth Sciences* (Springer), 66, 1997.

SED

2, 161–193, 2010

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



SED

2, 161–193, 2010

Radon signals at the Roded siteG. Steinitz and
O. Piatibratova[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)**Table 1.** Sensors used for radon monitoring at Roded site.

| Sensor | S/N | Date | Installed | Serial Day |
|----------------------|------|------------------|-----------|------------|
| Alpha Nuclear AM-611 | #50 | 4 February 1999 | | 2592 |
| Alpha Nuclear AM-611 | #49 | 7 January 2003 | | 4024 |
| Barasol BT45 | #018 | 11 November 2004 | | 4698 |

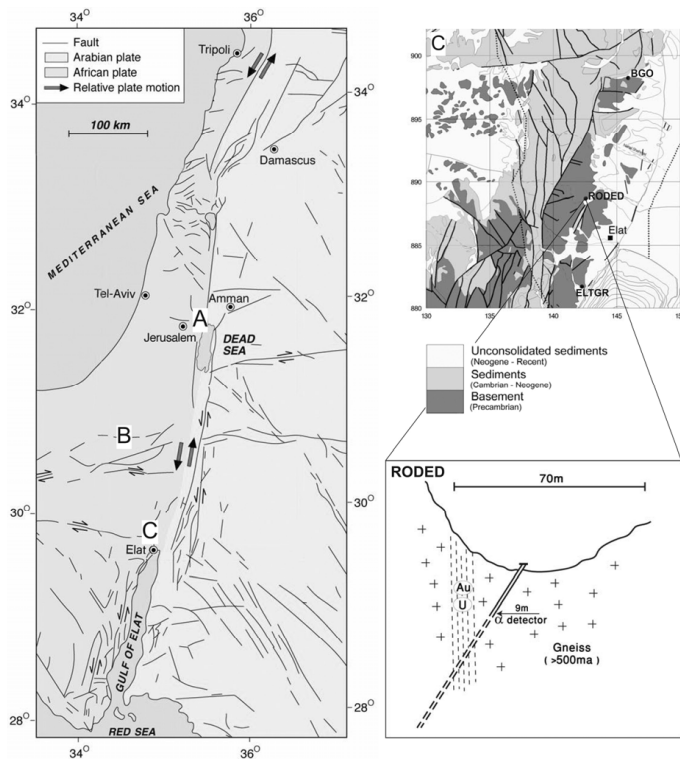


Fig. 1. Location map of arrays of radon monitoring sites along the southern sector of the Dead Sea Transform (DST), separating the Sinai subplate and the Arabian plate. **(A)** – Radon monitoring at the NW shore of the Dead Sea **(B)** – Radon monitoring at Gavnumim, Makhtesh Ramon, **(C)** – Southern Arava monitoring array: Eilat Granite (ELTGR) sites, Bloch Geophysical Observatory (BGO) in tunnel at Amram, and the RODED site **(D)** – The RODED site – detailed cross section and monitoring borehole. Alpha detector is inserted into the bottom (9m) of the PVC casing. The PVC pipe is blocked at the top to minimize exchange with the atmosphere.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

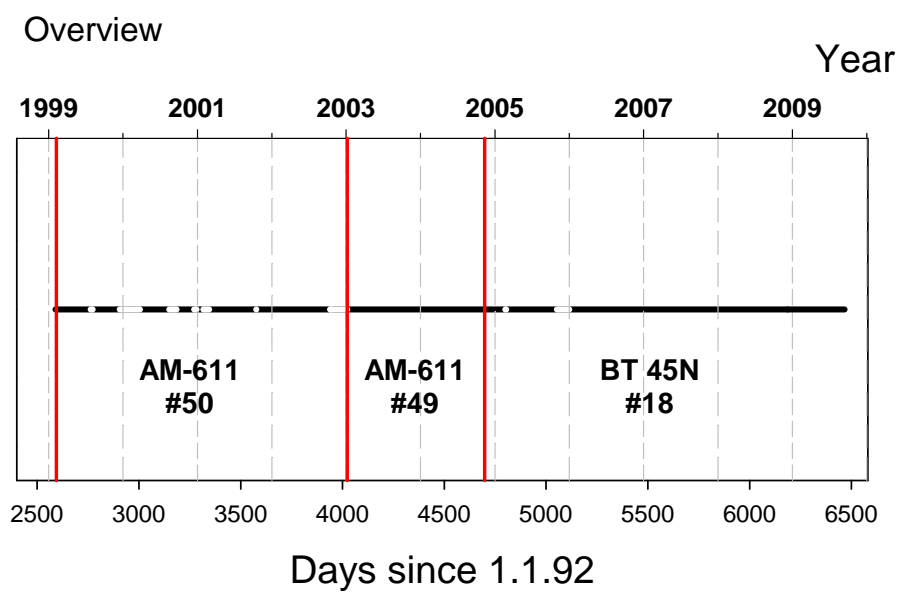


Fig. 2. Overview of the span of the recorded data and the implementation of the different sensors.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



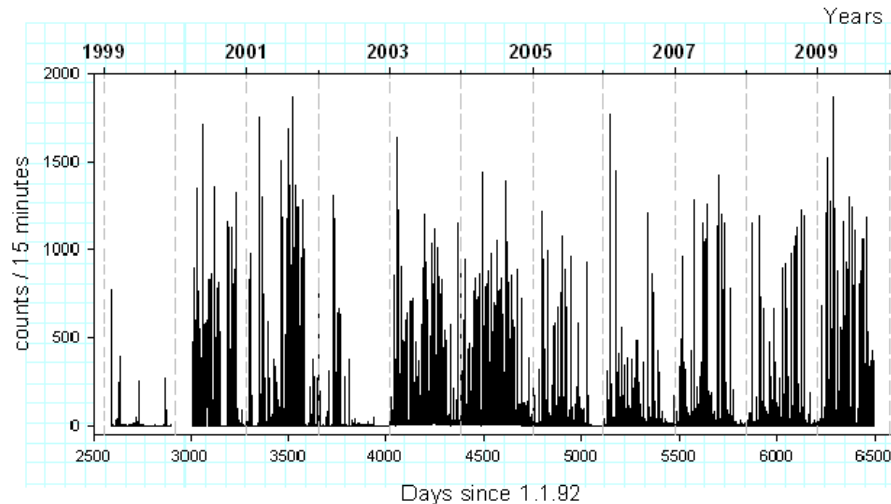


Fig. 3. Time series of radon during 11-years at the Roded site showing the overall variation pattern. Intervals of very low level alternate with times of highly varying signals composed of very strong (SDR) signals. A weak annual modulation is superimposed on this pattern.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



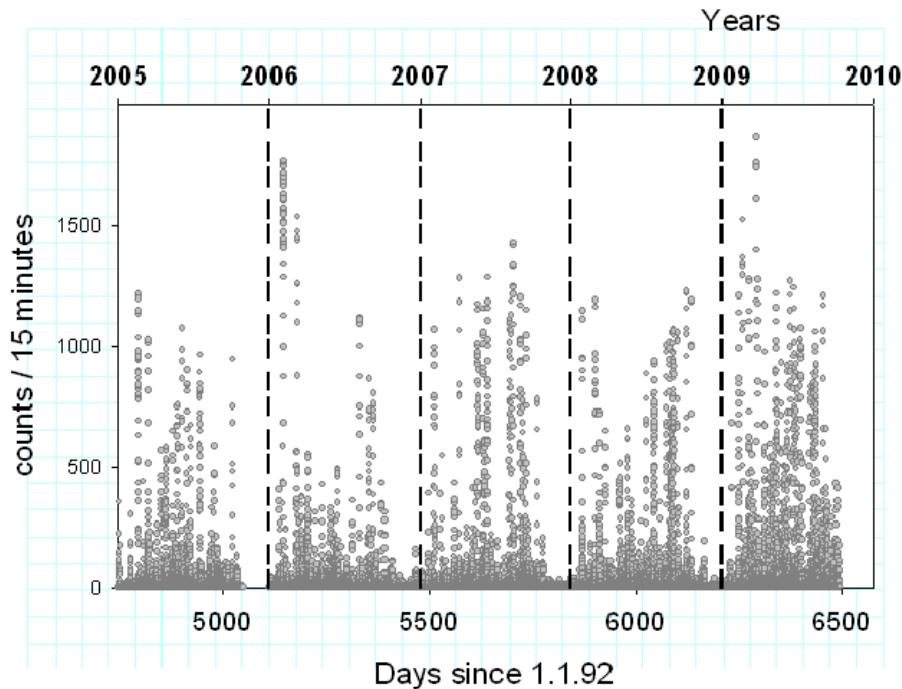


Fig. 4. Five years of the radon time series at Roded shown using daily averages. The complex and intensively varying signal obliterates an underlying annual radon (AR) signal, which is traceable in the upper envelope of the variation. A semiannual pattern is observed in 2006 and 2008.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



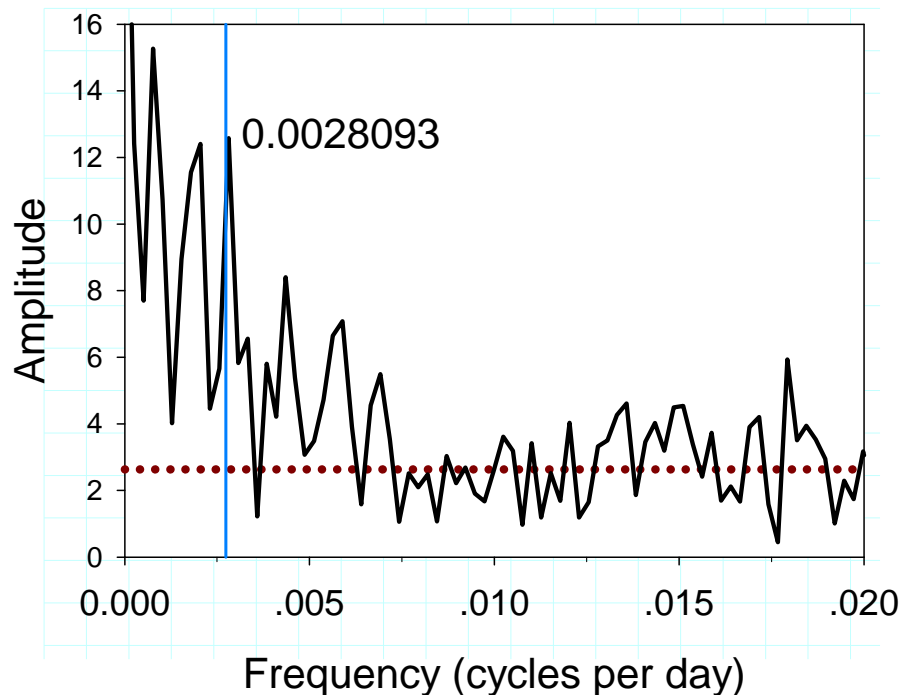
Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

Fig. 5. FFT spectra for an 11-year interval at Roded site. The peak of 0.0028093 cycles per day is a frequency corresponding to the annual periodicity ($1/365=0.0028397260$, indicated as a vertical line).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

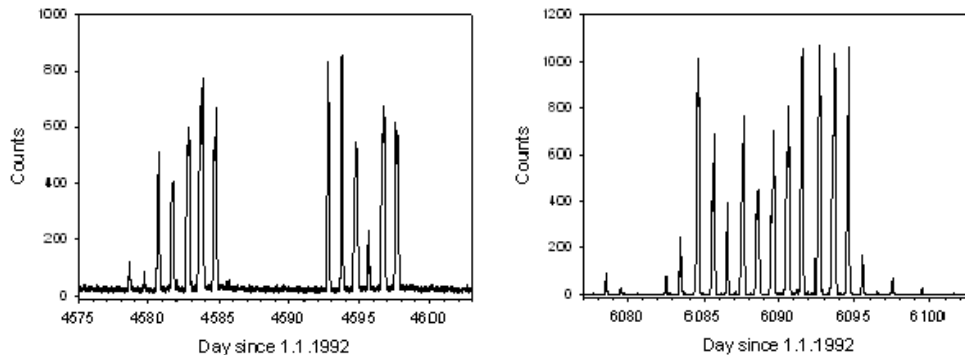


Fig. 6. Overview of the span of the recorded data and the implementation of the different sensors

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

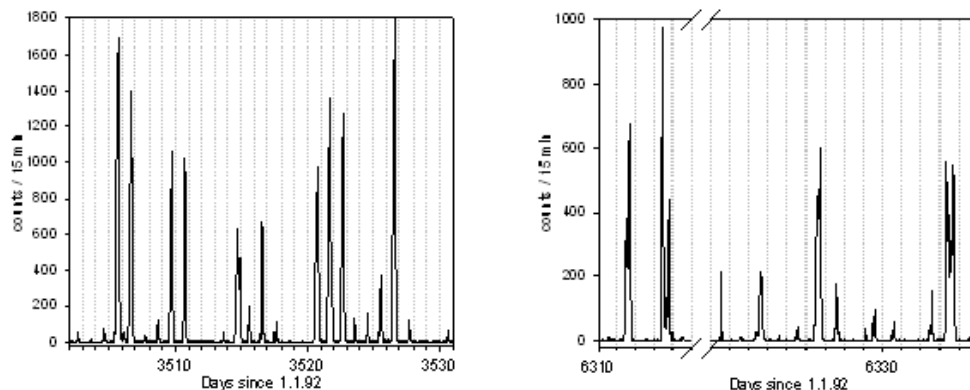


Fig. 7. Time intervals showing isolated and grouped SDR signals with intervening days without any signal (Left). In some cases two peaks occur within a day (Right).

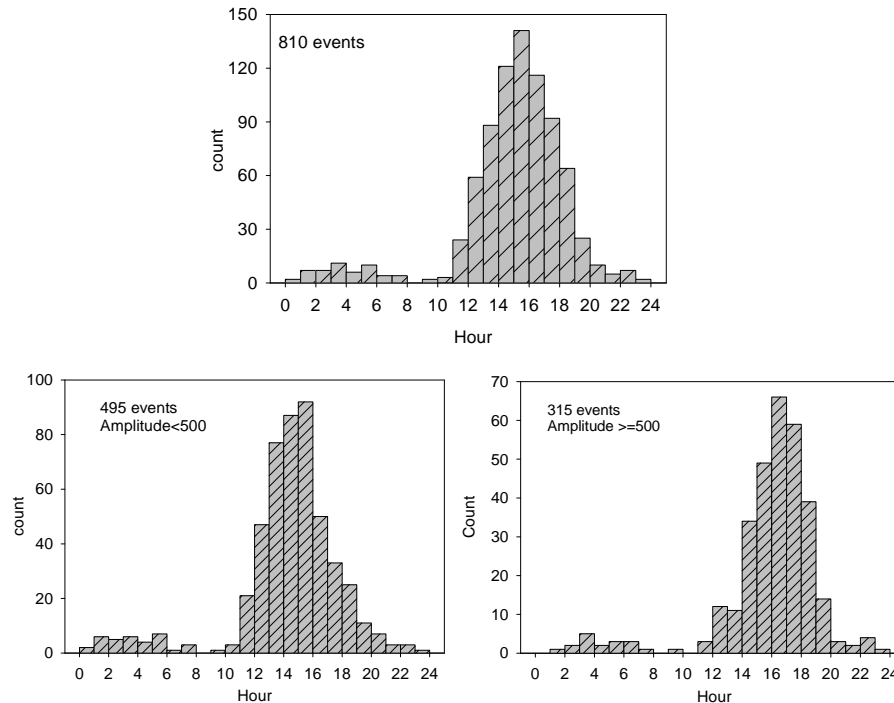
Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

Fig. 8. Distribution of peak time of SDR signals within the 24-h diurnal cycle (Top). SDR peaks tend to occur between 15 and 16 h (UT+2). The pattern is the same for SDR signals with low and high amplitudes (Bottom).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

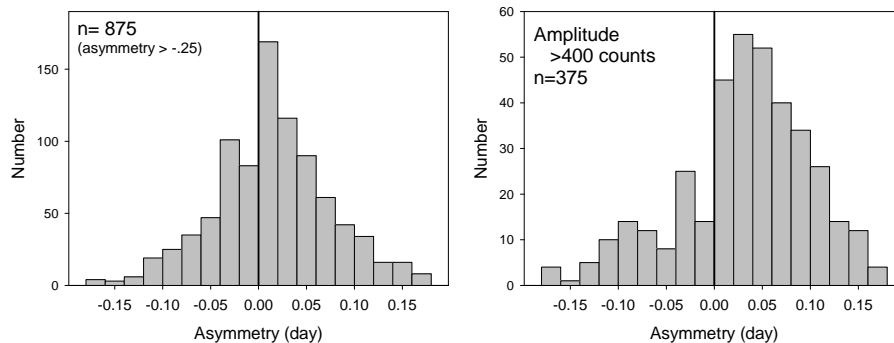


Fig. 9. Peak symmetry distribution (Left) indicating the overall faster change of the decreasing limb. The peak symmetry is calculated as the difference of width at half peak height between a decreasing flank symmetric to the rising flank and the actually decreasing flank (see Fig. 10). This incidence of asymmetry is emphasized when considering the relatively intense peaks (Right).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

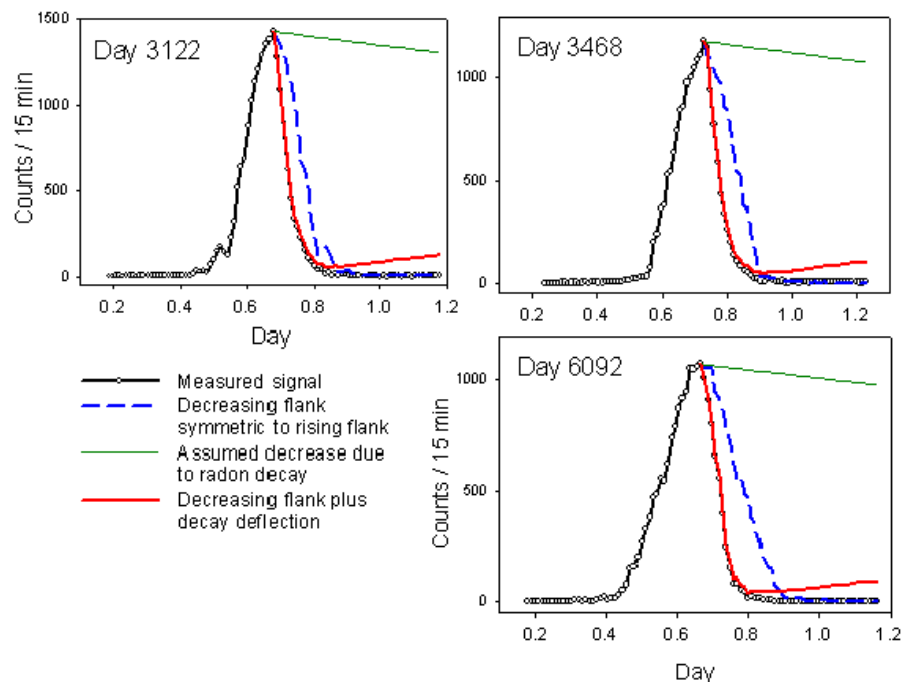


Fig. 10. Examples of intense asymmetric sub-diurnal radon (SDR) signals, having a steeper declining limb. Accounting for the radioactive decay of radon does not correct the asymmetry.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



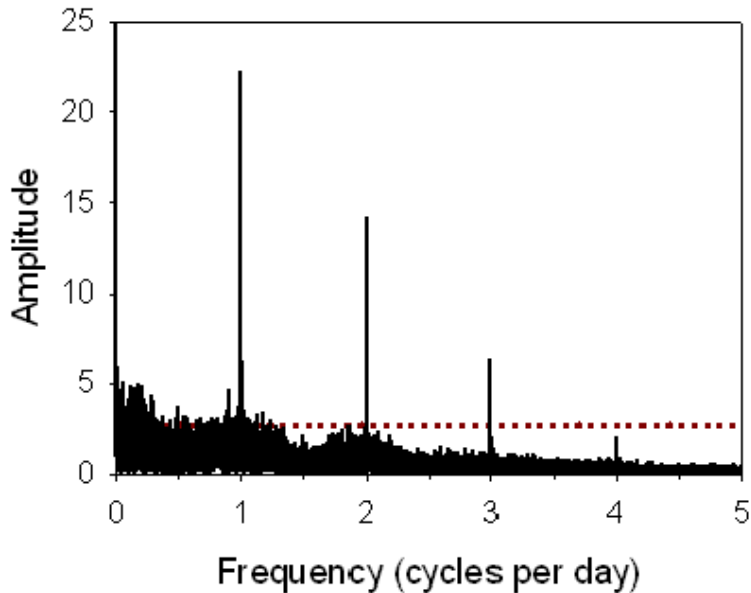


Fig. 11. FFT spectrum of a long (11-year) interval at Roded site showing frequencies of 1- , 2- and 3 cycles per day corresponding to the diurnal S1, S2 and S3 periodicities. Sampling rate is 15 min and data gaps are filled by linear interpolation.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



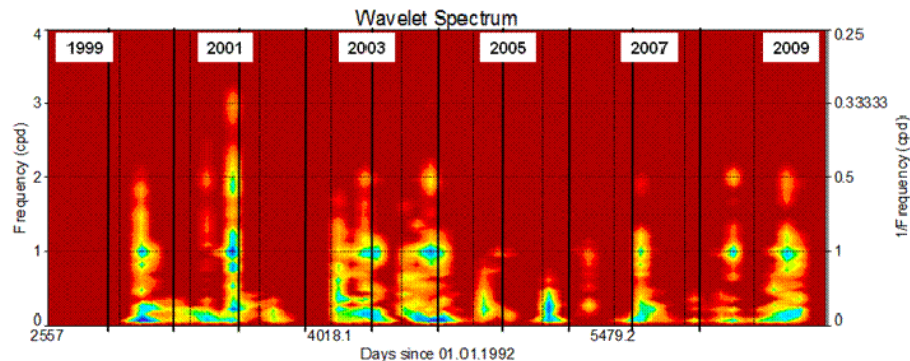
Radon signals at the Roded siteG. Steinitz and
O. Piatibratova

Fig. 12. Continuous Wavelet spectrum of 15-min data during 11 years (1999–2009, annual divisions are shown). Data gaps are filled by linear interpolation. The wavelet model used is Morlet with adjustable parameter = 20.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



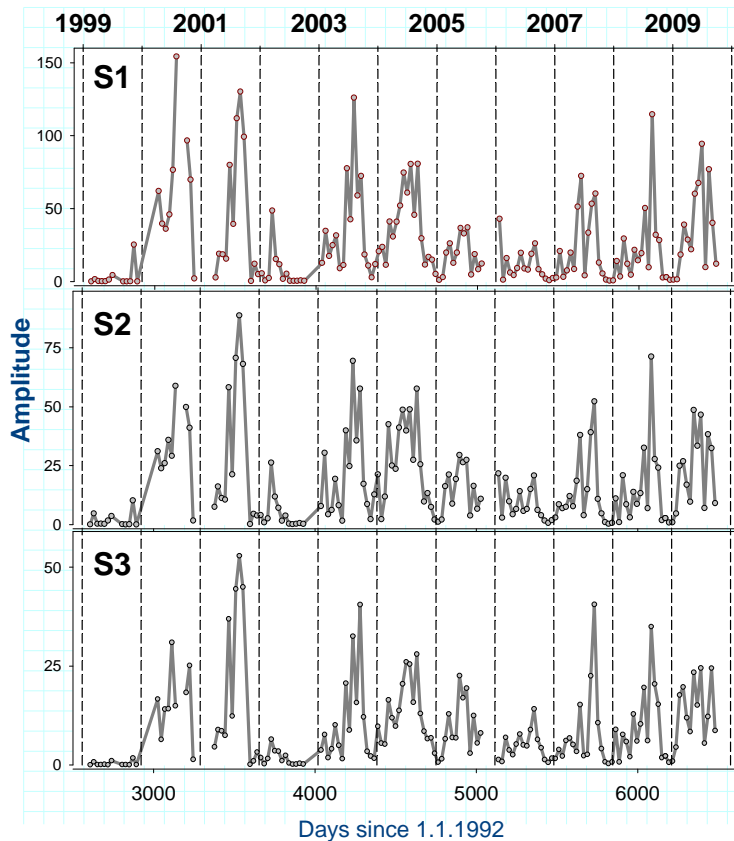


Fig. 13. The temporal variation in the radon signal of the amplitudes of the daily periodic components S1, S2 and S3, is showing: (a) concordance among the sensors of the varying amplitudes and (b) an annual modulation.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

| | |
|--------------------------|--------------|
| Title Page | |
| Abstract | Introduction |
| Conclusions | References |
| Tables | Figures |
| ◀ | ▶ |
| ◀ | ▶ |
| Back | Close |
| Full Screen / Esc | |
| Printer-friendly Version | |
| Interactive Discussion | |



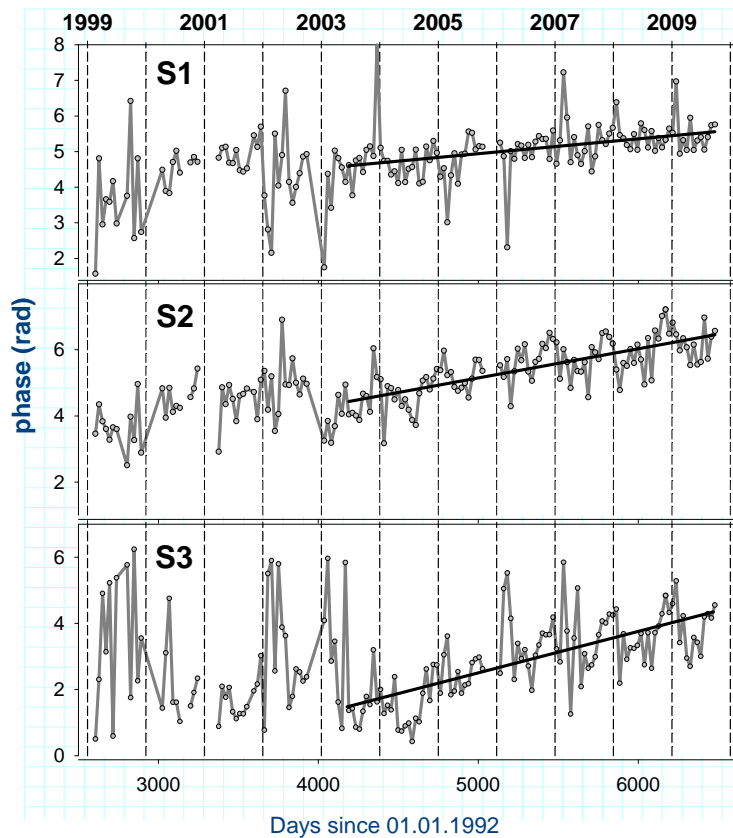


Fig. 14. The temporal variation in the radon signal of the phase of the daily periodic components S1, S2 and S3, showing a similar linear multi-year trend, clearly evident in the last seven years.

Radon signals at the Roded site

G. Steinitz and
O. Piatibratova

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

