Radon signals in the Elat Granite pluton, southern Arava, Israel

G. Steinitz, O. Piatibratova and U. Malik
ABSTRACT

High time resolution monitoring of radon, using alpha detectors along a 0.6 km long E-W transect in Nahal Shlomo (southern Israel) was carried out in the massive and jointed Precambrian Elat Granite. Monitoring, at a resolution of 15-minutes, is conducted in three boreholes at depths of 10, 4, and 53 meters, resulting in 3-5 year long time series. Systematic temporal variation patterns are observed, manifesting large relative signals.

Three components of variation occur in the measured signal – seasonal signals (SR), multi-day (MD) variations, and daily radon signals (DR). The SR and DR signals are periodic and the MD variation is non-periodic. Using the decomposed time series the daily levels of the components are compared at each site and among the sites. A tendency for correlation is observed between the measured radon signal and the SR and DR components, and no-correlation with the level of the MD signal. Partial fit of the components occurs among the sites.

Examining the temporal variation of the decomposed components at a site suggests an association, or even influence, between the overall level of the long-term variation of radon and the amplitude of the daily variation. The daily mean level of radon and the daily standard deviation vary periodically throughout the year. Such a coupling cannot be envisaged operating on a gas (geogas) system with radon (half-life = 3.82 days) as a trace component, but rather operating on the radon source (solid) system. The generator of the long-term (SR) variation is separate from the generator of the DR signal, but both seem to be indirectly linked.

Time offsets of hours are observed among time series of the measured signal from the sites. The lag was investigated for the measured signal and separately for the decomposed MD and DR components, using consecutive 20-day long time intervals. The resulting time series of the lag show that systematic time offsets (1-3 hours) occur, whereby the radon signal always occurs first at the easternmost site. The MD component shows a significant gradual long-term varying lag of 0-12 hours, and the DR component a significant stable 1-3 hour lag. This dissimilarity between the lag of the MD and DR components is enhanced when examining the lag of the difference between consecutive measurements. In this case of the MD signal a significant lag exists, in the range of 0.5-6 hours. In the case of DR signal a significant correlation is not obtained throughout. These differences in the statistical behavior probably point to a fundamental difference in the driving mechanism of MD and DR signals.

Diurnal (24-hours) and semidiurnal (12-hours) constituents characterize the periodic aspect of the DR component in the time series of radon. Diurnal constituents typical for gravity related phenomena are absent. The amplitudes of these constituents, calculated for consecutive 512-hour long time intervals, exhibit at all sites a similar regular temporal variation of the amplitudes of the daily cyclic constituents, clearly reflecting a seasonal pattern. The co-occurring amplitudes of the diurnal and semidiurnal constituents define an overall linear correlation with a slope in the range 0.3-0.8. This result points to a systematic and fundamental statistical property in the frequency domain of the radon time series, reflecting a specific external driving mechanism.

Correlation analysis between radon level and ambient atmospheric conditions (pressure, temperature) indicate that the latter cannot be considered as the main driving force for the observed phenomena. Analyzing the diurnal patterns of pressure and temperature in the
frequency domain, in the same manner as for radon, shows clearly that linear co-variation of diurnal and a semidiurnal component does not occur in these time series. This dissimilarity in the statistical properties of the time series corroborates the assertion that radon variation in the geogas system is not driven by the variation of pressure and temperature.

Radon signals in the geogas of the Elat granite behave as system that is driven by several geophysical processes. This proposition relies on the following:

1. The statistical properties of components within the time series and among them indicate that different processes are responsible for the periodic (SR and DR) and for the non-periodic MD variation.
2. The forcing processes are external to the local rock system and are reacting with the rock system.
3. The statistical properties in the frequency domain imply that a periodic process drives the DR with a fundamental diurnal frequency. This may also relate to the SR variation, placing both components as mirroring processes related to the rotation of the earth around itself and around the sun.
4. These processes are not influencing the radon signals through interaction with the gas phase in the pores and crevices of rock system, but are rather acting on the release of the radon from its source into the geogas. The resulting measured signal is a superposition of the different processes acting on the source of the radon in the rock system.
5. There is partial interaction between the processes, leading to non-linear effects. The most prominent interaction is the annual (seasonal) variation, which influences both the DR and the non-periodic MD signal.
6. The non-periodic MD signals can probably be associated with geophysical transients of a mechanical nature, i.e. geodynamic. This would be in line with their similarity to MD signals from the NW Dead Sea that have been correlated with seismic activity of the Dead Sea transform.

The results indicate that hitherto unrecognized dynamic processes are driving the radon signal in the Elat granite pluton, in the uppermost crustal level of the area. Radon, as a trace component in the geogas filling the permeable system in the rock, is a sensitive proxy of these processes. As far as known such results and phenomena are specific to radon. This raises the question whether they are related to the special quality of radon as being a heavy noble gas and/or to the fact that nuclear processes govern its formation and disintegration. Furthermore, so far the phenomena are observed in the natural geological environment, which raises the question as to the role and interaction of mineral lattices.

The results present new prospects for the investigation of radon phenomena in the frame of interacting geodynamic (tectonic?) and earth-sun system related geophysical processes.
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1. Introduction

The Geological Survey of Israel (GSI) started to investigate the spatial distribution of radon (222-Rn) in the late 1980's, and its temporal behavior since 1990 (Fig. 1). The activity is performed in the frame of the Israel Geodynamic Radon Project - IGRnP. Measurements are conducted in the geogas$^1$ of different rock units - Precambrian igneous and metamorphic basement rocks, Cretaceous syenite and sub-recent unconsolidated gravel. Alpha and gamma detectors, placed at depths of 1.5 to tens of meters, gather radon and ancillary information at a high time resolution (< 1 hour).

In general the understanding of the nature and the processes driving the formation of radon signals in subsurface geogas is uncertain and disputed. Establishing the geodynamic nature of the signatures and signals is based 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).

Long time series of radon collected in the frame of IGRnP display several types of signals based on the time scale of their variation. The main types recognized are multi-year, seasonal, multi-day (MD) and diurnal radon (DR) signals (Steinitz et al., 1992; Steinitz et al., 1996; Steinitz et al., 1999). These signals are assumed to be due to natural processes as they recur systematically in time and at different stations. So far descriptions of the phenomena encountered utilizing high-time resolution measurements are lacking. Furthermore, methodological guidelines for quantitative processing of such data are not established. Therefore setting a basis by describing the phenomena, the modes of processing, as well as exploratory analysis and discussion are a primary goal of this contribution.

This contribution addresses these issues by:

a. Analyzing radon signals in a limited and simple geological and environmental setting.
b. Addressing the eventual influence of environmental parameters by applying the same analytical approach used to characterize the radon signal.
c. Applying several analytical approaches in the time and space domains.
d. Setting constraints on interpretations.

Presently radon is being monitored at three arrays of stations located in a 200 km segment along the western boundary fault of the DST, in several regional arrays located along the western margin of the southern sector of the Dead Sea Rift, from the Dead Sea to the Gulf of Aqaba (Figure 1). Each array, spanning 0.5 to 20 km, consists of several monitoring sites:

1) **NW Dead Sea**
   Array of stations places 1.5m deep in unconsolidated gravel, covering a 20km sector next to main western DSR active fault trace

2) **Intraplate**
   Depth: 1.2m & 90m in massive syenite

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$^1$ geogas := gaseous phase in the unsaturated zone above the groundwater level, sometimes incorrectly referred to as “soil air” or “soil gas”.
3) Southern sector of DSR
   Array of stations covering a 20km sector in Precambrian basement rocks of
   uplifted boundary blocks of DSR
4) Gulf of Elat

The results discussed here are based on measurements at three sites (E-1, E-2, E-3) in the southern sector of the DSR array.
Figure 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 Makhtesh Ramon, 50km west of the DST
C – Southern Arava monitoring array (BGO – Bloch Geophysical Observatory)
D – Detail of Nahal Shelomo area showing the location of the boreholes on a geologic and geomorphologic background.
2. Geographic and geological setting

Radon measurement is performed in three boreholes (Table 1; Braun et al., 1977), in Nahal Shelomo located 5 km SSW of city of Elat, southern Israel. The boreholes were drilled, in the frame of a survey for subsurface liquid storage potential, into the rock face at the edge of the wadi, forming an SE-SW transect along the NW face of Nahal Shelomo (Fig. 2). The climate is arid (~50 mm/year).

![Figure 2: View northwards in Nahal Shlomo showing the geomorphologic expression of the Elat Granite. Location of site E-2 and E-3 are indicated.](image)

The country rock is a Precambrian pluton of the calc-alkaline Elat Granite located north of Nahal Shelomo and extending about 1.3×1 km. The massive to friable granite encloses small bodies of schist and gneiss and is cut by basic to acid dikes. A prominent joint system cuts the body, striking approximately N45E.

The sensors (alpha detectors) at the three sites are installed in boreholes drilled at low angles into the local rock face to depth of around 190 meters. The geological section of borehole E-3 is shown in Figure 3 (after Braun et al., 1977). Local obstacles in the holes limit access for radon sensors in the holes. Still, considerable depth (overburden) of 20-90 meters is attained due to the steep local topography (Table 2). The boreholes are devoid of casing. The air in the borehole is assumed to be in equilibrium with atmospheric air mainly via the joint system of the granite in the immediate vicinity.

<table>
<thead>
<tr>
<th>Site</th>
<th>Coordinates</th>
<th>Elevation of borehole (m above msl)</th>
<th>Inclination from horizontal</th>
<th>Direction</th>
<th>Total length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-1</td>
<td>192450/381540</td>
<td>29</td>
<td>30°</td>
<td>N49W</td>
<td>80.5</td>
</tr>
<tr>
<td>E-2</td>
<td>192352/381534</td>
<td>27</td>
<td>30°</td>
<td>N16E</td>
<td>40</td>
</tr>
<tr>
<td>E-3</td>
<td>191948/381796</td>
<td>53</td>
<td>24-30°</td>
<td>S80E</td>
<td>192.5</td>
</tr>
</tbody>
</table>

The country rock is a Precambrian pluton of the calc-alkaline Elat Granite located north of Nahal Shelomo and extending about 1.3×1 km. The massive to friable granite encloses small bodies of schist and gneiss and is cut by basic to acid dikes. A prominent joint system cuts the body, striking approximately N45E.
Table 2: Measurement conditions at monitoring sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Sensor depth along borehole (m)</th>
<th>Estimated rock overburden above sensor (m)</th>
<th>Alpha Sensor</th>
<th>Start date</th>
<th>Start (Decimal*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-1</td>
<td>(~10 m)</td>
<td>20</td>
<td>AM-910</td>
<td>11/04/2002</td>
<td>3753</td>
</tr>
<tr>
<td>E-2</td>
<td>(~4 m)</td>
<td>15-10</td>
<td>AM-910</td>
<td>19/07/2000</td>
<td>3122</td>
</tr>
<tr>
<td>E-3</td>
<td>(~55 m)</td>
<td>70-90</td>
<td>Barasol</td>
<td>7/01/2003</td>
<td>4024</td>
</tr>
</tbody>
</table>

(*) Zero day of decimal time is 1.1.1992

Figure 3: Geological cross section of borehole E-3 drilled into the Elat Granite that is crossed by sub-vertical Precambrian dikes (after Braun et al., 1977). The alpha detector is lowered to a length of close to 53m along the borehole, a depth at which the dip of the borehole changes (forming an obstruction).
Figure 4 shows the time span of data collected from boreholes E-1, E-2 and E-3.

![Figure 4](image)

**Figure 4**: Span of data collected and processed from borehole sites E-1, E-2 and E-3 in the Elat Granite pluton. Vertical bars designate data gaps.

**Atmospheric data**

The radon time series are compared with time series of atmospheric pressure and ambient temperature. Data sets utilized are from:

a. Eilat Airport, about 5 km north of sites E-1, E-2 and E-3 (for the years 2001-2003)

b. The Bloch Geophysical Observatory (Fig. 1, BGO) some 20 km north of the radon monitoring sites (2003-2005).

### 3. Methods

High time resolution Rn measurements were made using an alpha particle detector. For electronic α ray detection silicon junction detectors are installed in the systems in a special cell into which only geogas can enter. Besides α particles, the silicon junction is sensitive to heavily ionizing particles of cosmic origin, including neutrons (of minor effect in the subsurface). As the range of α particles in either air or solid matter is short (about 5 cm in air, and much less in solids) the background source must be very close to the detector in order to affect it. Thus the background of most commonly used α ray detectors is very low. This also means that the α background is almost not influenced by the by the rock/soil type in the detectors vicinity.

Detection of radon (=^{222}\text{Rn}) is performed with nuclear alpha detectors. At the sites E-1 and E-2 the alpha detector used is an Alphameter 611 (AlphaNuclear Inc., Canada), based on a 400 mm^{2} silicon junction diode, immersed in a sensing volume open to the geogas. Measurement site E-3 is performed with an alpha Barasol BT45N detector (400mm^{2} Si
diode; Algade Inc., France). In both instruments the detector is protected from the environment by a thin, aluminized Mylar anti thoron (= $^{220}$Rn) membrane. The alpha radiation impulses is recorded (as counts) every 15-minutes. The sensitivity of the instruments is 0.4-0.5 pCi/l per 1 count/15-minutes ($\sim$ 16-17 Bq/m$^3$). The timing is better than ±1 minute. Time is shown on a decimal-day scale (time since 1.1.1992). From these hourly and daily averages are calculated.

4. The measured radon signal

Large temporal variations of the radon signals are encountered at all three sites. Figure 5 presents an overview of the time-series using the daily mean radon level.

![Figure 5: Overview of the radon variation at the three borehole sites using the daily mean radon level.](image)

The statistics of the daily mean values from the three sites are presented in Table 2. The average radon levels are the lowest in the shallow level of measurement (E-2) and highest in the deepest one (E-3).

Table 3: Statistics of the radon levels at the monitoring sites based on Daily Mean levels at some 1020 mutual sampling days in the time interval of Days 4024-5050.

<table>
<thead>
<tr>
<th></th>
<th>E-1</th>
<th>E-2</th>
<th>E-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>150.5</td>
<td>90.1</td>
<td>219.1</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>98.9</td>
<td>75.7</td>
<td>159.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>11.9</td>
<td>5.1</td>
<td>21.4</td>
</tr>
<tr>
<td>Maximum</td>
<td>566.6</td>
<td>283.9</td>
<td>911.0</td>
</tr>
</tbody>
</table>
The large variation of the radon levels is superimposed on a local background level of radon. They are always significantly above the level in the atmosphere (< 1 pCi/l) as measured with the same alpha detectors (around 0-1 count/15-minutes). This background level, assumed to originate from the immediate vicinity of the sensor, varies among the sites, apparently in accordance with depth. The average, standard deviation and maximum levels show a similar pattern with the sensor depth. Several examples of the signals obtained during low radon level time intervals are given in Figure 6. From these examples it is also observed that the noise envelope of 1-hour averages is ≤10 counts/15-minutes.

Figure 6: Examples of the radon signal observed during time intervals of overall low radon levels (see text).
The patterns of frequency distribution of the daily mean level are dissimilar among the sites (Fig. 7). The shallow site E-2 depicts a distribution that differs considerably from the distributions observed at the deeper sites.

**Figure 7:** Frequency distribution patterns of the daily mean radon level
A visual inspection of the temporal variation in the radon time series from the three borehole sites allows characterizing three dominant variation types:

a. Seasonal variation – where low values occur in "winter" and high values in "summer" (Fig. 5). Such variations are known at other places, but not always.

b. Multi-Day (MD) signals, observed in Fig. 5 as sharp "spikes". Such signals are also known from other locations. Their importance lies in the fact that they have been used, at another location (NW Dead Sea), to demonstrate for the first time a statistically significant correlation between radon signals and earthquakes (Steinitz at al., 2003).

c. Daily Radon (DR) signals, which are recurring at the diurnal scale showing a cyclic behavior. The daily variation of DR signals ("peak-to-peak") is in the order of magnitude of the overall variation.

Figure 8 presents a 100-day time interval for data from E-1, E-2 and E-3. In this presentation the MD signals and DR signals are clearly observed at the three sites.

![Figure 8: 100-day time series of radon (alpha detector) from the monitoring sites.](image)

Detailed examples of 20-day long time intervals are shown in Figure 9, displaying MD and DR signals. DR signals have a symmetric spike like form with relatively flat intervals between them. On the other hand MD signals tend to have an asymmetric form with a gradually rising flank and a sharply declining flank.
The extensive and detailed time series of radon in geogas, exhibiting clear-cut and significant temporal variation patterns, are quantitatively analyzed by:

1. Decomposition of the time series according to the temporal scale of variation.
2. Investigation of basic statistical correlation parameters among sites.

**Figure 9:** Two 20-day long examples of the radon time series at the monitoring sites exhibiting the pattern and concordance of the multi-day and diurnal variation.
A fundamental feature of radon in geogas is that most of an amount at a given time vanishes from the system solely by nuclear decay (half-life of radon = 3.82 days) within a time frame in the order 20 days. This served as a basis for:

3. Investigating the temporal variation pattern of the cyclic constituents (components) of the radon signal at the different radon sites, using the FFT transform.

4. Investigating the temporal variation pattern of the cross-correlation the radon time series among radon sites. In order to substantiate a physical relation this is done in two modes:
   - on the measured signal
   - on the difference between consecutive points (looking at the derivative of the variation).

A similar approach is applied to a comparative research of further geophysical time series, possibly related. The results of this analysis will serve to map and define the geophysical reference frame for the interpretation of the phenomena.
5. Decomposition of radon signals

In order to simplify the processing the primary radon time series with measurement at a 15-minute resolution is also decimated (averaged) to two ancillary files at to 1-hour and 1-day resolution.

The measured time series are decomposed into separate time series in accordance with the observed signal type using the following scheme (Fig. 10):

1. The Daily Mean (DM) radon level is calculated from the primary readings
2. A series of smoothing experiments were performed to isolate the seasonal signal. The procedure utilized was based on visual inspection of the results. This led to a preferred two step smoothing. In the first step an intermediate time series is calculated on the 15-minute primary time series using a 61-day sliding average (4×24×61+1= 5857 points). This intermediate time series was further smoothed using a 51-day sliding average (4×24×61+1= 4897 points) to yield the smoothed seasonal trend (SR). From this seasonal trend the daily mean of the seasonal trend (SDM) is calculated.
3. The de-seasoned (residual) time series is further decomposed by a 25-hour sliding average yielding a Multi-Day (MD; smoothed) time series and a residual Daily Radon Signal (DR).

Figure 10: Decomposition scheme of the radon time series
4. The variation of the MD signal within a day allows the calculation of the Multi-Day Daily Mean (MDDM), and
5. The daily variation of the DR signal allows calculating the Daily Amplitude (DA; "peak-to-peak").

The decomposition procedure results in a set of decomposed time series per site. Supplementary decomposed high time resolution files are formed by interpolation. These data sets are stored on the GSI server using the naming convention as detailed in Table 4.

**Table 4:** Nomenclature applied to repository time series files of measured, decomposed and daily values.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Resolution (*)</th>
<th>Day</th>
<th>Hour</th>
<th>15-minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Mean</td>
<td>E-n DM.txt</td>
<td>E-n DM.txt</td>
<td>E-n DM.txt</td>
<td></td>
</tr>
<tr>
<td>Seasonal Mean</td>
<td>E-n SDM.txt</td>
<td>E-n SDM.txt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decomposed MD</td>
<td>E-n day MD.txt</td>
<td>E-n day MD.txt</td>
<td>E-n day MD.txt</td>
<td></td>
</tr>
<tr>
<td>Decomposed DR</td>
<td>E-n hour DR.txt</td>
<td>E-n hour DR.txt</td>
<td>E-n hour DR.txt</td>
<td></td>
</tr>
<tr>
<td>Peak-to-Peak</td>
<td>E-n DA.txt</td>
<td>E-n DA.txt</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* See Fig. 10; E-n refers to sites E-1, E-2 and E-3

Examples of the resulting time-series and parameters are shown below. Figure 11 shows a long-term example of the measured and decomposed time-series at site E-1.

![Figure 11: The long-term radon signal at site E-1 and its decomposed components.](image-url)
The quality of the decomposition is demonstrated in Figure 12 showing a 100-day detail of the decomposition at site E-1, and at site E-3 in Figure 13.

**Figure 12:** A 100-day detail of the decomposed radon series at E-1. All measurements in counts/15-minutes. See text.

**Figure 13:** The seasonal (SR), Multi-Day (MD) and Daily Radon signal (DR) after decomposition of the measured time series at site E-3. All measurements in counts/15-minutes. See text.
In accord with the daily levels derived for the measured (DM) and seasonal (SDM) analogous values are also derived for the decomposed multi-day (MD) and daily radon signal (DR). Figure 14 shows a 10-day segment of the MD time series and the calculated MDDM values, and Figure 15 shows, for the same 10-day time interval, the separated DR time series and Daily Amplitudes (MDDA) at two example 24-hour intervals.

**Figure 14:** A 10-day interval of the Multi-Day (MD) component and derived Multi-Day Daily Mean (MDDM) values.

**Figure 15:** The Diurnal Radon signal (DR) component in the 10-day internal shown in Fig. 14. Examples of the Daily Amplitude (DA; peak-to-peak) are indicated.
6. Results

Systematic and similar temporal variation patterns and signals in the measured signal are observed at all three sites. A visual inspection of the decomposition products at different time windows shows that the result is reasonable suggesting that the three separated components are usable components.

6.1 The daily level of radon

The time scale of the diurnal signal is short relative to the half-life of radon (3.82 days), in difference with the longer-term variation. This feature and the importance the diurnal signal suggest examining the relations among features separately for diurnal and non-diurnal ones. Based on this differentiation the time scale of a day is used as a suitable reference time unit for investigating the correlation and relation of the components. At such a scale systematic variation of the radon signal are noticed directly in the time series from the Elat pluton as well as at other locations.

The investigation at the scale of a day is pursued in the following ways, using the terminology defined in Figure 10:

a. Relation among components at each site
   - SDM and DM
   - MDDM and DM
   - MDDM and SDM
   - DA and DM
   - DA and SDM
   - DA and MDDM

b. Correlation of the following components between sites
   - DM
   - SDM
   - MDDM
   - DA
6.1.1 Relations among daily levels of the components at each site

The relations among the daily values of the measured and decomposed components of the signal for the temporal variations beyond a day are shown in Figure 16. Similar patterns are observed at each site.

**Figure 16:** Correlation diagrams showing the relations among the multi-day variation (as MDDA), the seasonal variation (as SDM) and the daily mean (DM). See text.
Using the daily average values a general tendency for correlation occurs among each of the separated seasonal (SDM) and multi-day (MDDM) signals versus the measured (DM) signal. On the other hand a lack of correlation occurs, at the scale of a day, among the separated seasonal (SDM) and multi-day variation (MDDM). The latter examines the relation between a non-periodic (MDDM) and a periodic (SDM) component in the radon signal.

The span ("intensity") of the daily variation is reflected in the daily amplitude of variation ("peak-to-peak" – DA) of the DR. The relation of the DA versus the longer-term variation is examined in Figure 17.

**Figure 17:** Correlation diagrams showing the relation of the Daily Amplitude (DA; peak-to-peak) of the DR signal versus the daily means of the long and medium term variation of the radon signal.
At all three sites the Daily Amplitude (DA) is loosely associated to the measured signal, observed as a broad correspondence pattern. The correspondence is relatively strong within the lower third of the data range and the dispersion increases at higher values, especially at site E-2. These comparable patterns at the three sites cover different fields when they are combined into a single diagram (Fig. 18). Such a distribution probably indicates that an overall relation is present between the DA and DM, but is modified by a local, site related factor.

A somewhat more pronounced and mainly more linear correspondence occurs when correlating the DA with the seasonal daily mean (SDM). In contrast it is very clear that the daily variation (DA) and the multi-day variation (MDDM) are not related. The latter examines, again, the relation between a non-periodic (MDDM) and a periodic (DA) component in the radon signal.

Figure 18: Composite diagram of the relation of Daily Amplitude (DA) to the measured Daily Mean (DM) level of radon at the three sites (see Fig. 10 for definitions).

Summarizing - the spread in the relations between components of the variation as depicted in Figs. 16-18 is related to the existence of further temporal variation within the decomposed components. This is demonstrated below.
6.1.2. Relations among components between the sites

It was shown that the measured and decomposed time series display similar temporal variation patterns. This is further investigated by looking into the correlation of the daily components between sites. The relation between the sites of the measured signal (DM) and the seasonal component (SDM) is shown in Figure 19.

**Figure 19:** Relation among sites of the Daily Mean (DM) and Smoothed Daily Mean (SDM; representing the seasonal variation) decomposed components of the variation of radon (see text).
The overall co-variation among the three time series of radon is represented in the variation patterns of the measured daily value (DM) and clearly in the seasonal values (SDM). The complex pattern of the SDM values is due to the gradual change of the fit among the compared smoothed time series. This is probably due to an incomplete decomposition of the seasonal components, yielding the observed annual loop pattern.

The relation among sites of the multi-day signal (MDDM) and the daily amplitude (DA) is shown in Figure 20. At the scale of a day a concordance is observable between the sites for both types of decomposed components.

**Figure 20:** Relation among sites of the MDDM and DA decomposed components of the variation of radon (see text).
6.1.3 Temporal variation of Daily Amplitude (DA) of the Diurnal Radon (DR) signal

In Figure 21 we plot, for each site, two time-series at a resolution of a day: the mean daily radon signal (DM) and the DR amplitude (DA). The time series of the DM radon level reflects the long-term seasonal variation and, superimposed on it as sharp spikes at this scale, the multi-day (MD) variation itself. The time series of the Daily Amplitude (DA) also shows, in all three cases, a strong seasonal variation similar to the seasonality of the MD time series.

From the patterns presented in Figure 21 it is now clearly perceived that a seasonal pattern, occurs in both time series (DM and DA), implying an association, or even influence, between the overall level of the long-term variation of the radon level and the amplitude of the short-term daily fluctuation.

![Figure 21: Time series of the Daily Mean (DM) and Daily Amplitude at the monitored sites.](image)

The issue is further examined in Figure 22 showing the temporal variation of the ratio between the DR amplitude (DA) and the mean daily (DM). This ratio ranges from 0.5 to 2 and in difference from the pattern in Figure 21 it does not show a significant long-term seasonal variation. Only the shallow site E-2 shows a somewhat disturbed pattern. These
patterns and their relations clearly demonstrate that the variability of radon within a given day (as measured by DA) follows the mean for that day (DM). This indicates that both daily mean and daily standard deviation vary periodically throughout the year.

Figure 22: Temporal variation of the ratio between the DA of the DR signal and the Daily Mean (DM). The time series of the latter reflects the seasonality.

In terms of the underlying physical processes this result is far from trivial as we are dealing with a trace component in the geogas, where the half-life of the trace component is 3.8 days. A process operating solely and directly on the gas phase that generates such a phenomenon cannot be envisaged. Therefore, having no other alternative, it must be assumed that processes releasing the radon from the rock are interacting in a fashion that leads to the observed patterns. It seems that although the generator of the long-term variation is separate from the generator of the daily cyclic signal – the two processes are indirectly linked.
6.2 Spatial time offset of radon signals

Signals of radon from regionally related sites show occasionally temporal time offsets at the scale of hours to several days. This feature, so far not described, is observed in Israel and also elsewhere (Tenerife) shows offsets. The closely spaced and geologically related set of sites from the Elat Granite serves as a good case to describe this phenomenon and isolate factors possibly influencing it.

Visual inspection of the measured and decomposed time series from the Elat granite sites shows that regular time shifts of the radon signal occur between the sites, particularly when comparing the two external sites (E-1; E-3). An example of the offsets in the case of the multi-day (MD) signal is shown in Figure 23 and for the diurnal radon signal (DR) in Figure 24. In both examples the offsets is of similar trend with the signal at E-3 lagging after the signal at E-1, i.e. occurring later in time.

Figure 23: The decomposed MD time series at E-1 and E-3 demonstrating a systematic time offset of the signal.
The time lag between sites E-1 and E-3 was investigated using the cross-correlation (CC) analysis and applying it to the measured data, to the decomposed MD time series and the DR time series with a time resolution of 15-minutes. In each case the lag among the sites was calculated for: a) the signal and, b) the difference in the signal derived from consecutive data points. The quantitative evaluation of the time lag between sites E-1 and E-3 is demonstrated, using the CC analysis, for an example data set of 20 days from sites E-1 and E-3, shown in Figure 25.

![Figure 24: The decomposed DR time series at E-1 and E-3 demonstrating a systematic time offset of the diurnal signal.](image)

The time lag between sites E-1 and E-3 was investigated using the cross-correlation (CC) analysis and applying it to the measured data, to the decomposed MD time series and the DR time series with a time resolution of 15-minutes. In each case the lag among the sites was calculated for: a) the signal and, b) the difference in the signal derived from consecutive data points. The quantitative evaluation of the time lag between sites E-1 and E-3 is demonstrated, using the CC analysis, for an example data set of 20 days from sites E-1 and E-3, shown in Figure 25.

![Figure 25: Data sets 20 days long of the time series from E-1 and E-2 used in the CC example analysis.](image)
The resulting correlation functions, where the time series of E-3 is the lagged series, are shown in Figure 26. High CC is obtained in the case of the measured signal and its components (Fig. 26-A). A similar negative lag of about 1 hour, as determined by the maxima of the correlation functions, is observed for the measured signal and the DR component (Fig. 26-B). A larger negative lag of around 4 hours is observed for the MD component (Fig. 26-B). These lags, all significant, imply that the radon signal at E-3 occurs 1 to 4 hours after the signal at E-1.

Additional insight is gained by investigating the CC relations among time series of the difference between consecutive data points (at 15-minute resolution). The resulting CC functions, for the same components, are shown in Figure 26-C and in detail in Figure 26-D. In the case of the measured signal and the decomposed MD component high correlations are obtained and a significant lag in the order of 0 (= no lag) to -1 hour is indicated. In the case of the DR a significant cross-correlation is not obtained, the maximal values being barely above the standard error. The latter result probably implies a statistical relation among the DR time series, which differs fundamentally from that among the MD time series.
The above observations on the measured values and the difference of the signal are further examined by testing the long-term behavior of these statistics as derived for the CC function. To this end the CC is calculated per consecutive 20-day time segments with an overlap of 10 days. The resulting time series of the correlation level and the lag per time segment are plotted for the measured signal (Fig. 27) and for the decomposed multi-day (MD; Fig. 28) and the diurnal radon signal (DR; Fig. 29).

Figure 27 shows the results for the measured signal for a time interval of around 900 days. During the whole time-span the lag is always negative, between –2.5 to –1 hour with an average around –1.5 hours. The correlation coefficient indicates a significant correlation throughout, relative to the low standard error (see Fig. 26; function of the large number of sampling points) for each segment.
The same analysis is applied to the decomposed MD and DR time series (Figs. 28-29). In this case the lags of the smoothed data represent the lag of the Multi-day (MD) variations (20-day segments) and the lag of the residual data reflect the lag of the DR. In the case of the MD time series the correlations are high for the measured signal as well as for the difference. In case of the DR series the correlations are high throughout for the measures signal and extremely low for difference signal (close to the standard error; compare Fig. 26-D). This difference points to a major difference in the statistical properties between the MD and DR radon signals.

Figure 28: Cross-Correlation (CC) of the decomposed MD signal (solid) and difference (dotted) among sites E-1 and E-3 (lagged). CC was calculated for time windows 20 days long with an overlap of 10 days between consecutive windows.
Figure 29: Cross-Correlation (CC) of the decomposed DR signal (solid) among sites E-1 and E-3 (lagged). The cross-correlation of the difference is not shown due to its large variation. The (low) level of correlation of the difference is shown (dotted). The CC was calculated for time windows 20 days long with an overlap of 10 days between consecutive windows.
An overview of the summary statistics of the different temporal cross-correlation patterns is given in Table 5.

**Table 5:** Statistics of the cross-correlation among the time series of radon at sites E-1 and E-3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td></td>
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<td>0.78</td>
<td>-1.62</td>
<td>0.86</td>
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<tr>
<td>Std. dev.</td>
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<td>0.07</td>
<td>25.43</td>
<td>0.16</td>
<td></td>
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<td>-1.85</td>
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<tr>
<td>Std. dev.</td>
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<td>0.11</td>
<td>0.90</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
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<td>-1.42</td>
<td>0.77</td>
<td>-3.25</td>
<td>0.11</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.35</td>
<td>0.09</td>
<td>37.67</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

The statistical parameters are presented for the components of variations (signal types), according to the measured value and the difference among following measurement points.

The CC analysis on the measured radon signal and its decomposed components from two subsurface sites 0.6 km apart shows, for a time interval of around 900 days, that:

a. A stable lag of –1 to –3 hours exists throughout for the DR component.

b. A lag for the MD component ranging from 0 or -1 hour to -8 hours, which appears to vary gradually within a time span of 100-200 days leading to a quasi-seasonal (~400 day?) variation pattern.

c. The lag of the DR component seems to override and determine the lag of the measured signal.

d. The correlation level of the lag is high, for the decomposed DR and MD signals, and for the difference time series of the MD signal. On the other hand the correlation level for the difference of the DR component is non-significant throughout.

This observation will have to be further investigated. It may be a result of the utilized decomposition that retains the analytical noise in the DR component. If this is refuted than this feature suggests a primary difference in the statistical properties among these two signal types.
6.3 The cyclic components of DR

The features of the cyclic diurnal variation in the radon time series were investigated by using the FFT. Spectra from the three sites representing different intervals, each spanning 85.33 days, at two different seasons in the annual cycle are shown in Fig. 30. Cyclic constituents are clearly observed at 1 and 2 cycles per day (diurnal = 24 hours and semidiurnal = 12 hours). Weak peaks occur also at 3 and 4 cycles/day (= 8 and 6 hours; not shown). At each of the three sites low and similar amplitudes are observed in the months December-February at 1 and 2 cycles/day. On the other hand higher values and different amplitude ratios are encountered in the June-August interval.

**Figure 30:** FFT spectra of the measured signal (15-minute sampling) at sites E-1, E-2 and E-3 for winter (left) and summer (right) intervals. The ratio between the diurnal and semi-diurnal cycle is higher in the summer.
A 24-hour cyclic variation and higher harmonics are known in various time series of earth and planetary science phenomena. Interpretation of a spectrum (periodogram) has to take into account the following caveats:

1. The estimated spectrum of a time series having strong cyclic component (frequency \( f \)) may have additional related peaks at frequencies \( 2f, 3f \ldots \) These harmonics occur in cases where the measured cyclic component is non-sinusoidal.
2. Leakage, which may occur when processing time series that are short relative to the time scale of the investigated frequency.
3. Aliasing may occur when the sampling rate is low relative to the dominant cyclic frequency.

In the case of the radon time series leakage and aliasing can be rejected as the processed time series are long and the sampling is dense relative to the diurnal scale. The issue of higher harmonics can also be discarded, specifically for the 12-hour constituent (and probably also the 8-hour signal), as it is directly observable in the data, especially in the decomposed DR time series (Fig. 31).

![Figure 31: Detail at E-3 demonstrating 24-hour and minor 12-hour components of variation in the DR signal.](image)

The long-term temporal variation of the amplitudes of the daily cyclic constituents at sites E-1, E-2 and E-2 is shown in Figure 32. The amplitudes of the cyclic constituents are derived from FFT spectra calculated per consecutive time intervals, each 512-hour (21.33 days) long, and plotted relative to the middle of each interval. The spectral maxima were located in the intervals 0.9-1.2, 1.9-2.2, 2.9-3.2 and 3.9-4.2 cycles/day.
Figure 32: The temporal variation of the daily cyclic components in the radon signal at site E-1 (top), E-2 and E-3 (bottom). See text for details.
The resulting time series exhibits in all three sites a similar regular temporal variation of the amplitudes of the constituents. The magnitude of the diurnal constituent is always equal to or larger than the semi-diurnal constituent and both clearly reflect a seasonal pattern. Noticeable is that this specific pattern is well developed even in the shallow site (E-2).

A deeper insight into the relation among the cyclic constituents is obtained by regressing the amplitudes of the diurnal and semidiurnal constituents (Fig. 33). In all three cases a distinct and significant linear correlation having a similar slope is shown.

![Figure 33: Correlation diagrams of the amplitudes of the diurnal and semi-diurnal constituents of radon variation in consecutive 512-hour long time segments. Limiting lines with slopes of 0.3 and 0.8 are shown on the composite diagram.](image)

As far as known such relations are observed for the first time. These distinct temporal relations in the diurnal cyclic radon signal must reflect a systematic driving mechanism. A discussion of their nature demands a search for similar patterns in other related geophysical time series collected with a similar resolution in the same region. To this end a comparison is made with results of similar analysis of ambient pressure and temperature data from the region, both sampled every 15-minute.
6.3.1 Atmospheric pressure and ambient temperature in the southern Arava

Pressure

Atmospheric pressure data is available for part of the monitoring interval from the Elat airport, situated 5 km to the north of the radon monitoring sites in the Elat Granite, and from the Bloch geophysical observatory (Amram) located further 15 km northward (Fig. 34). At the geophysical observatory the pressure is measured inside the tunnel, 140 meters from the entrance and separated by three doors. Pressure is recorded at the observatory every 15 minutes.

Atmospheric pressure variations equalize over large distances very quickly (actually at the speed of sound). This is demonstrated in Figure 35 where daily and hour average values are compared (common data are available for 20% of the time span). Thus the pressure time-series from the geophysical observatory are utilized for comparison with the radon time series.

![Figure 34: Pressure variation at the Bloch Geophysical Observatory, Amram, southern Arava](image)

![Figure 35: Correlation of pressure in the southern sector of the Arava at a daily and hour scale. The two locations are separated some 20 km. Common data spans 385 days.](image)
Temperature
Ambient temperature data is from the atmosphere outside the Bloch geophysical observatory (Amram), recorded every 15 minutes. Using this data allows to demonstrate the often supposed influence of an atmospheric parameter on radon in geogas.

Figure 36 shows a 20-day time window of the time series of radon from the shallow E-2 site and the atmospheric temperature at Amram, 20 km apart. An apparent co-variation is observed in the pattern of both time series, especially in the pattern of the cyclic daily variations that are dominant in both time series. Still, differences occur in the details of the patterns:

a. The diurnal temperature variations exhibit an additional (early) small peak near the daily maxima - absent in the radon time series.
b. The radon time series have daily maxima that are sharp compared with those of temperature
c. The daily minima of temperature are sharp compared with wider minima in the radon
d. Small peaks occurring in the radon daily minima are absent in the temperature time series.

The importance of the daily variation components in both time series makes the statistical analysis of the cyclic components to be a useful tool for investigating the association between such time series.
6.3.2 The diurnal cyclic signal of atmospheric pressure and temperature

The existence of diurnal cyclic variation components in the atmospheric parameters (i.e. pressure and temperature) is well-known. The main constituents are 24-hour (diurnal) and 12-hour (semidiurnal) periods. On a first appreciation the similarity of these phenomena lend as similar and related to those observed in the radon time series. In order to compare with the latter the pressure and temperature time series from the regions were subjected to the same statistical analysis, using similar 512-hour long intervals. Figure 37 and 38 portray the temporal pattern of the amplitudes of the diurnal periodic constituents of the ambient pressure and temperature in the region.

**Figure 37:** The temporal variation of the daily cyclic components of the ambient atmospheric pressure (Amram). See text for details.

The diurnal constituent of pressure (Fig. 37) shows a distinct seasonal variation which is lacking in the semi-diurnal constituent that exhibits a stable level. In winter the level of the diurnal constituent falls below that of the semidiurnal constituent.

In the case of temperature the diurnal constituent is the main constituent which is strongly affected by seasonality (Fig. 38). The semi-diurnal constituent (and further constituents) is much weaker throughout and exhibits a rudimentary seasonality.
The temporal and seasonal patterns of the diurnal constituents of radon time series differ significantly from those of pressure and temperature. Comparing the temporal characteristics of the diurnal and semi-diurnal constituents of pressure and temperature with those of radon it is clear that:

a. In the case of pressure the amplitude of the semidiurnal constituent keeps a stable level and the diurnal constituent falls below the semidiurnal one during winter time.

b. In the case of temperature the semi-diurnal constituent is always much lower than the diurnal constituent.

Using the results per 20-day intervals the ratios among the diurnal and semi-diurnal constituents are presented and compared in Figure 39.

The temporal and seasonal patterns of the diurnal constituents of radon time series differ significantly from those of pressure and temperature. Comparing the temporal characteristics of the diurnal and semi-diurnal constituents of pressure and temperature with those of radon it is clear that:

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b. In the case of temperature the semi-diurnal constituent is always much lower than the diurnal constituent.

Using the results per 20-day intervals the ratios among the diurnal and semi-diurnal constituents are presented and compared in Figure 39.

The dissimilar distribution patterns of the ratios of the semi-diurnal and diurnal constituents in the pressure and temperature time series are further compared and
enhanced versus the distribution pattern in the radon time series using the normalized amplitudes (Figure 40). Normalization of each set of amplitude values is performed by subtracting from each data point the mean of the set and dividing by its standard deviation.

The unambiguous patterns of temporal co-variation of the cyclic constituents in the three time series of radon in the subsurface of the Elat granite pluton must be reflecting a common driving mechanism. The same constituents in temperature and pressure time series display temporal patterns that are systematically different. This obvious dissimilarity in temporal patterns indicates that the atmospheric parameters cannot be considered as drivers of the systematic variations observed in the time series of radon in geogas.

The above line of interpretation is of special significance when considering the time series of radon measured at a shallow depth of only 4 meters (site E-2). If atmospheric influences are to be observed it is expected that they will be reflected first of all at this shallow level. In contrast, the statistical patterns of the diurnal cyclic constituents of variation at this shallow level are well in line with the features observed at the deeper sites (Figs. 21, 22). This is interpreted to indicate that atmospheric influence on the radon signal are insignificant even at this shallow depth.

**Figure 40:** Correlation diagrams of the normalized amplitudes of the diurnal and semi-diurnal constituents of radon and atmospheric pressure and temperature in consecutive 512-hour long time segments. Reference lines with slope of 1:1 are shown. Compare with Figures 26 and 32.
7. Discussion

7.1 Processing and interpretation of radon time series

Time series of radon collected in the subsurface environments, above and below the water table, are known from many locations. Observations originate from very different geological, geophysical and environmental scenarios. Reviewing studies in the last several decades the impression is that the phenomena are complex and probably multifaceted. Different modes of descriptive and quantitative analytical approaches have been used for the processing of the data. The result is a wide span of interpretations, including contradicting ones, as to the mechanism driving the observed radon signals. One of the consequences is that comparison between studies is difficult, which inhibits sound understanding.

Long and high-resolution time series are collected from some 20 monitoring sites in the frame of IGRnP, grouped in local arrays based on geological context. These extensive data sets enabled the formulation of a descriptive phenomenology of the basic signal types, appearing consistently within one time series as well as in time series from different locations. Based on this familiarity the first attempts of quantitative statistical data processing techniques were applied and the derived results were compared and tested with other temporal phenomena – environmental, geophysical (Steinitz et al., 1999, 2003) and physical (Steinitz et al., 2005) – in an attempt to seek plausible interpretations.

Distinctive features are observed in the radon time series from the Elat granite. The temporal variation of radon reflects processes occurring in the subsurface environment, at upper crustal levels. The displayed characteristics place them in the realm of features observed in geophysical time series from the atmosphere, hydrosphere and solid earth. The characteristics that place them in the realm of geophysical time series are:

- Systematic temporal variation patterns at the scales of hours to years;
- Related temporal variations occur at locations that are beyond the distance of lateral transfer (diffusion, mixing, advection) of radon bearing geogas;
- Different modes and time scales of signals occur, superimposed at one location.
- Periodic and non-periodic signals occur together.

The phenomena in the time series from the Elat granite are representative of phenomena occurring in other stations of the IGRnP in Israel. Thus the conclusions drawn for the phenomena in the Elat granite are essentially applicable also to other locations. The discussion of the results addresses the following set of considerations:

- Geological considerations
- Influence of atmospheric factors (pressure, temperature)
- Geophysical inferences based on the statistical analysis
- Setting a geophysical framework for the diurnal signal
7.2 Geological considerations

Radon-222 occurs as a trace component in the geogas of the Elat granite, at daily levels in the range of 5 to 500 pCi/l, always significantly above atmospheric values. No prior indication exists indicating that varying radon levels are to be expected in this relatively homogenous and massive rock body. The choice of the monitoring sites can be considered as random as it was based on boreholes drilled for an unrelated purpose.

The investigated radon system is hosted in a hard, massive, homogeneous jointed granite body, above the local water table. There is no ground to assume that the geogas at the investigated depth, composed basically of air, is subject to advection and transfer phenomena within this geological regime, beyond minor local fluctuations due to changes in above ground atmospheric conditions (mainly pressure). There is no indication for active geogas flow systems acting as a carrier gas in the dense jointed granite system. If flow occurs in this environment its velocity is certainly less than several meters per day. The considerations on the flow regime imply that the source of the radon is local, from the country rock in the vicinity of the sensor, probably near it or at a slightly lower level. Geological reasoning puts a limit to the distance: the combination of possible upward flow rate of the geogas (<10 m/day) and the half-life of radon (3.82 days) and the eventual dilution of the trace gas limits the distance to the range of 0-50 meters.

Concerning the radon in the subsurface the anticipation therefore is for uniform and mainly stable levels in the geogas. In difference with the latter the radon levels display temporal variations that are:

a. Large, systematic and recurring both in the spatial dimension and in the temporal dimension.

b. The overall variation is composed of three signal types – seasonal, multi-day (MD) and daily radon signals (DR).

c. The seasonal and DR signals are periodic in the time domain; The MD signals are of a non-periodic nature.

d. The signals have very different time scales, especially relative to the half-life of radon.

At each site a partial concordance occurs among components of the signal. The daily amplitude (DA = “peak-to-peak” variation) of the DR signal is proportional to the overall daily level as determined by the seasonal signal. On the other hand there is no correlation between the DA of the DR and the daily mean of the multi-day signal (MDDM).

A systematic time delay of the measured radon signal occurs between two subsurface locations 0.6 km apart in an east-west direction. The time delay, observed during more than 900 days is such that the signal in the western site lags behind the signal in the eastern one. This phenomenon shows separate timing patterns for the MD and the DR variation. The periodic DR signal shows a stable lag of about 1.5 hours while the MD variation shows a time lag ranging from 0.25 to 12 hours that changes gradually over long time intervals. As a lateral gas flow from east (site E-1) to west (site E-3) is excluded the different lag patterns are probably imposed on the rock system itself.

The conclusion from these observations is that several processes are involved and reflected in the generation of these phenomena in the geogas. As far as known generation of such signals with such inter-relations is not possible within the gas phase proper. Therefore the
generation must be due to processes acting on the rock system, probably on its release to the geogas medium.
The systematic long term and similar occurrence of the periodic and non-periodic radon signals in the relatively uniform Elat granite implies that the radon system varies in tandem as a system at the scale of one kilometer. Co-variation patterns of such spatial scale are also known at other locations in Israel.

7.3 The influence of atmospheric ambient pressure and temperature

The radon system in the Elat granite belongs to the large group of cases of radon in geogas in upper crustal levels investigated worldwide. In the majority of these cases small and large temporal variations of radon have been observed, often resembling atmospheric variation patterns. Furthermore, the observations originate in uppermost levels of the crust and are in contact with the ambient atmosphere. This underlies the tendency to try to compare and investigate the eventual influence of atmospheric pressure and temperature variations on radon phenomena. Such an approach is especially attractive in light of the similarity of periodic radon signals with well known atmospheric seasonal and diurnal variation patterns.

The connection of radon variation patterns with atmospheric influences was examined in many works (Clement and Wilkening, 1974; Since 2000: Finkelstein et al., 2006, Iskander et al., 2004, Muramatsu et al., 2002, Perrier et al., 2004, Richon et al., 2005, Yakovleva et al., 2003). The examination relied mostly on visual inspection and application of basic and general statistical correlation criteria on relatively short time series or longer time series with a low sampling frequency. Reviewing the literature on this issue shows that the overall conclusions are highly inconclusive, and even of a conflicting nature when trying to explain radon variations in geogas as due to atmospheric influences.

The proposition that change in ambient atmospheric pressure and temperature influence variation of radon in geogas does not conform to the following general considerations:

a) Similar variation of other trace components in geogas, and especially of similar large scale, is not observed.
b) Assuming a relationship then dissimilar correlation patterns and coefficients must be assumed to explain the very diverse radon variation patterns encountered at different locations, even over short local distances.
c) Temperatures in the subsurface, at depths of several meters in rock bodies, are stable to better than 0.5°C. This negates the influence of local site temperature variation as a driving mechanism for radon variation. On the other hand there is no straightforward process by which external (ambient) temperature variations can be propagated to drive radon variations at depth.

Negation of a causal relation between atmospheric pressure and/or ambient temperature variation and radon in geogas of the Elat Granite relies on the following:

a) The measured radon signal is composed of three distinct components, each having its specific characteristics in the time domain. As far as known it is not possible to generate such a multi-pattern through the variation of pressure and temperature.
b) Atmospheric interactions cannot produce the observed time lag between the radon signal in E-1 and E-3, and especially not the different lag patterns of the MD and DR signals.
c) DR signals constitute a significant proportion of the total variation of the measured radon signal. The different temporal variation patterns of the spectral constituents, and especially the constant ratio among the semi-diurnal and the diurnal constituents rule out ambient pressure and temperature as a driving mechanism. In addition the disordered atmospheric patterns cannot produce the ordered pattern in the radon system.

d) Hitherto statistical investigations on the relation between atmospheric parameters and radon relied generally on testing for correlation among values assumed to be independent. In contrast, the statistical tests utilized here relate to the fact that values are elements of a time series. This approach is more robust as it takes into account the fact that a measured value is dependent on the value of the previous measurement.

These criteria are at least partially independent. Refuting the influence of atmospheric pressure and temperature variations at the scale of a day probably indicates a similar conclusion for the long-term variations (MD and seasonal signals).

7.4 A geophysical framework

Extraterrestrial and terrestrial (deep earth) processes drive the active geophysical phenomena that are observed at the surface of the earth. Continuous geodynamic activity originating within the earth is as far as observed, of a non-periodic nature at the scale of this discussion. Radon time series from the Elat granite exhibit both periodic and non-periodic signals.

Extraterrestrial phenomena are reflected on Earth as periodic phenomena associated with the irradiance from the sun and the gravitational interactions. The generation of cyclic geophysical phenomena at the time scale from years to hours is associated with the motions and interactions of the celestial system consisting of the sun-earth-moon and planets.

In general, the generation of cyclic diurnal geophysical signals is attributed to the rotation of the earth, which leads to two principal effects (Wilhelm et al., 1997):

a. "Pseudo tidal" – due to the solar irradiance. This affects primarily the diurnal temperature pattern and also the atmospheric pressure.

b. Gravitational effects due to the rotation of the earth and the varying geometric relations with the celestial bodies (mainly Moon and Sun). These lead to tidal effects in the magnetosphere, atmosphere (atmospheric tide), hydrosphere (ocean tides; aquifer tide) and solid earth. The response of the solid earth to gravitational tidal forcing is termed Earth Tide, and is manifested as deformation of its surface. Earth Tide patterns vary in time and from place to place due to geographic effects as well as complex interactions between the different effects, e.g. ocean tides affecting the crust.

A complex set of earth tide periods occur in the range of the daily cycle. Important components (constituents) are concentrated around 24 hours (1 cycle/day) and 12 hours (2 cycles/day). The major contributing component is the moon, then the sun, then the elliptical motion of the moon around the earth, and also others. Table 1 lists the main tidal periods around 1 and 2 cycles/day.
### Table 6: The main tidal diurnal and semi diurnal constituents

<table>
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<tr>
<td>Large lunar elliptic</td>
<td>N2</td>
<td>12.66</td>
<td>1.8957</td>
<td>19</td>
</tr>
<tr>
<td>Principal lunar</td>
<td>M2</td>
<td>12.42</td>
<td>1.9324</td>
<td>100</td>
</tr>
<tr>
<td>Principal solar</td>
<td>S2</td>
<td>12.00</td>
<td>2.0000</td>
<td>47</td>
</tr>
<tr>
<td>Lunar-solar declinational</td>
<td>K2</td>
<td>11.97</td>
<td>2.0050</td>
<td>13</td>
</tr>
</tbody>
</table>

* The numbers 1 and 2 refer to the components with approximately 1 and 2 cycles/day.

The interaction of these with the solid earth, the hydrosphere and the atmosphere and ionosphere generates a large set of mutually interacting phenomena, resulting in partially correlated phenomena. These are observed by different measurements such as gravity, deformation of the solid earth, earth magnetism, tide, atmospheric pressure and temperature. Distinguishing between geophysical phenomena driven by gravity and those driven by irradiance processes is based, among other things, on the cyclic properties of these processes at the annual-seasonal and diurnal scale. Irradiance related effects are due to the rotation of the earth around the Sun (seasonal-annual cycle) and the rotation of the earth around itself (24-hour cycle). Gravity related effects are much more complex due mainly to the mutual interactions of the masses of the rotating earth-moon-sun. In this case a series of cyclic patterns are formed which vary as function of location on the earth.

Gravimeters and super conducting gravimeters are utilized for the direct observation of tidal effects. In addition the responses of earth systems to tidal processes are recorded in the atmosphere by pressure sensors, in the hydrosphere by tide gauges and pressure transducers, and on the solid earth by measuring offsets using strain-meters, tilt-meters etc.

One of the approaches for validating and testing a sensor system to strain is by evaluating its response to earth tides. Examples for this approach is the utilization of borehole water level measurements as strain indicators (Roeloffs, 1996) and identification of earth tide forcing in glacial drainage (Kulessa et al., 2003).

In comparison, the cyclic diurnal barometric pressure and ambient temperature are governed by components with periods of 12.00 and 24.00 hours. Thus the detection of cyclic components close to 1.93 (M2) and 0.93 (O1) cycles/day are assumed as indicative of gravity induced tidal forcing.

The periodic radon signals (SR, DR) in the Elat granite make up a significant part of the observed variation and have the following indicative characteristics:

- The radon time series contain prominent cyclic phenomena of two types: a long term seasonal-annual variation, and diurnal variations with periods of 24-, 12- and 8-hours.
- Cyclic components specific to tidal influence are absent from the spectra. This relates especially to frequencies around 1.93 (M2) and 0.93 (O1) cycles/day
Furthermore, the 24-hour and the 12-hour constituents are characterized that their amplitudes are modulated by a seasonal influence, and that the ratio of the amplitudes is stable (around 0.5) over the annual cycle.

Spectral analysis of the radon time series from Elat granite negates both atmospheric as well earth tide processes as driving mechanism for radon variation in the geogas. Still the distinct and prominent seasonal and especially the diurnal cyclic phenomena, having similarities with the recognized tide phenomena, allows suggesting to designate them as radon tides that are independently driven. It is suggested that the periodic nature of the DR and the seasonal signals are linked in some way to the rotation of the earth and its rotation around the sun, respectively. A separate process generates the MD signals.

8. Conclusions

Radon-222 occurs as a trace component in the geogas of the Elat Granite, at levels that are always significantly above atmospheric values. High time resolution monitoring in three boreholes along a 0.6 km long E-W transect was carried out in the massive and jointed Precambrian Elat Granite.

Radon signals in the geogas of the Elat granite behave as system that is driven by several geophysical processes. This proposition relies on the following:

1. The statistical properties of components within the time series and among them indicate that different processes are responsible for the periodic (SR and DR) and for the non-periodic MD variation.
2. The forcing processes are external to the local rock system and are reacting with the rock system.
3. The statistical properties in the frequency domain imply that a periodic process drives the DR with a fundamental diurnal frequency. This may also relate to the SR variation, placing both components as mirroring processes related to the rotation of the earth around itself and around the sun.
4. These processes are not influencing the radon signals through interaction with the gas phase in the pores and crevices of rock system, but are rather acting on the release of the radon from its source into the geogas. The resulting measured signal is a superposition of the different processes acting on the source of the radon in the rock system.
5. There is partial interaction between the processes, leading to non-linear effects. The most prominent interaction is the annual (seasonal) variation, which influences both the DR and the non-periodic MD signal.
6. The non-periodic MD signals can probably be associated with geophysical transients of a mechanical nature, i.e. geodynamic. This would be in line with their similarity to MD signals from the NW Dead Sea that have been correlated with seismic activity of the Dead Sea transform.

Hitherto unrecognized dynamic processes are driving the radon signal in the Elat granite pluton, in the uppermost crustal level of the area. The forcing processes are not influencing the radon signals through interaction with the gas phase in the pores and crevices of rock system, but are rather acting on the release of the radon from its source into the geogas. These processes that are external to the rock system are reacting with the rock system.
Radon, as a trace component in the geogas filling the permeable system in the rock, is a sensitive proxy of these processes.

The DR signal is driven by an external periodic process, with a fundamental diurnal frequency. This may also relate to the SR variation, placing both periodic components as mirroring processes related to the rotation of the earth around itself and the sun. The non-periodic MD signals can probably be associated with geophysical transients of a mechanical nature, i.e. geodynamic. This would be in line with their similarity to MD signals from the NW Dead Sea that have been correlated with seismic activity there.

The signal types observed in the massive Elat granite are similar to those observed in gravel (unconsolidated) along the active western fault at the NW Dead Sea sector, where a connection is demonstrated between multi-day (MD) radon flux variation and earthquakes in the Dead Sea rift. This similarity raises the possibility that radon signals in the Elat Granite reflect processes similar to those observed in the NW Dead Sea area.

As far as known such results and phenomena are specific to radon. This raises the question whether they are related to the special quality of radon as being a heavy noble gas and/or to the fact that nuclear processes govern its formation and disintegration. Furthermore, so far the phenomena are observed in the natural geological environment, which raises the question as to the role and interaction of mineral lattices.

The behavior of the radon system in the Elat granite represents a geophysical system for which the governing and driving mechanisms and parameters cannot be specified, at this stage, due to:

a. Lack of a theoretical basis for explaining the phenomena.
b. The need of results from dedicated controlled experiments.
c. Lack of comparative examples of radon time series with features of similar scale of variation and pattern do not exist at this stage.
d. Time series of other geophysical phenomena and processes that can be related are not known.

These observations and consideration raise several further questions:

1) Does the fact that radon is a very heavy noble gas is related to the issue
2) To what extent are the underlying processes related to the fact that radon is formed and disintegrates by nuclear decay.
3) What is the role of mineral lattices in the interactions with the driving forces.

Notwithstanding these limitations the results open new prospects for the investigation of radon phenomena in the frame of interacting geodynamic (tectonic?) and earth-sun system related geophysical processes.

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References


