

A Statistically Significant Relation between Rn Flux and Weak Earthquakes in the Dead Sea Rift Valley

Gideon Steinitz, Ze'ev B. Begin and Naama Gazit-Yaari

The Geological Survey of Israel,

30 Malchei Israel St, Jerusalem, Israel, 95501, e-mail: steinitz@mail.gsi.gov.il

ABSTRACT

Detailed monitoring of Rn flux in gravel was carried out for a period of 8 years near the active Dead Sea rift fault. The temporal relationship between hundreds of weak earthquakes ($4.6 \geq M_L \geq 0$) and Rn flux signals was tested for time intervals related to the start time of 110 Rn flux signals. Earthquakes located within three pull-apart grabens of the Dead Sea rift valley were found to preferentially occur within the time interval of the first 3 days after the start time of 110 Rn anomalies, and the excess of earthquakes (82% relative to the expected value) is highly significant ($p=0.003$). On the other hand, a similar relationship is not found in the 2 weeks preceding or following the start time of the Rn anomalies for earthquakes occurring within the Dead Sea rift in structurally higher segments, nor out of the Dead Sea rift.

Key words: earthquakes, radon, strain, Dead Sea rift.

INTRODUCTION

A temporal association between earthquakes and anomalous Rn flux has been suggested in numerous

studies (see summary in Toutain and Baubron, 1999), with Rn anomalies either preceding earthquakes (e.g. Ulomov and Mavashev, 1971; Igarashi et al., 1995) or following them (e.g. Pinault and Baubron, 1997). These observations are indirectly supported by a study in which variations in Rn flux were demonstrated to be closely associated with transitory crustal deformations, locally induced by fast variations in the water levels of a nearby reservoir (Trique et al., 1999). Hitherto, however, a well-founded temporal correlation between earthquakes and Rn anomalies has not been presented. Here we report the results of long-term and detailed monitoring of Rn, showing, for the first time, a statistically significant relationship between earthquakes and Rn anomalies, which is in agreement with geological structure.

SETTING

This study is based on a set of 778 earthquakes ($4.6 \geq M_L \geq 0$) that occurred in the period April 1994 ~ April 2002, during the time of successful operation (2468 days) of a Rn monitoring system at the Dead Sea. The area of study is a 400×200 km rectangle, on both sides of the seismically active Dead Sea rift

(Salamon et al., 1996). In the study area (Fig. 1), the Dead Sea rift comprises three pull-apart grabens (The Dead Sea, Lake Kinneret and Hula) and two segments that are structurally higher (The Arava and the Jordan Valley segments) (Garfunkel, 1997; Friclander and Bartov, 1997; Heimann, 1990).

Rn flux was measured within the Dead Sea rift, near the NW shore of the Dead Sea, where a 20 km long and 3 km wide belt of exceptionally high Rn flux, with a very high ratio of signal to background, was identified (Steinitz et al., 1992). The high Rn flux was locally detected in springs (Mazor, 1962; Kronfeld et al., 1991), groundwater (Lang and Kafri, 1999) and especially in geo-gas within loose gravel (background level ~50 pCi/L), up to some 30 meters above the local water table (Steinitz et al., 1992, 1999). This belt is closely associated with the main western fault of the Dead Sea rift (Fig. 1B), which is active (Shapira et al., 1993; Garfunkel, 1997). A traverse perpendicular to the fault was made to measure the Rn flux at 50cm depth in the gravel; the Rn flux decreases, from ~9000 pCi/L near the fault to about 1000 pCi/L over a distance of 50m away from the fault (Steinitz et al., 1992). Detailed monitoring of ^{222}Rn was carried out with a sensor located at a distance of 5 meters from the fault trace, at a depth of 1.5m in the gravel, resulting in an almost continuous Rn time-series for 1994-2002.

The source of Rn in this area is assumed to be uranium bearing (~100 ppm) Senonian phosphates, buried at a depth of several hundred meters in the down-faulted block (Steinitz et al.,

1992). Since Rn is an ultra-trace noble gas with a diffusion distance of only several meters in air (Holford et al., 1993) and a half-life of 3.8 days, the intense variations shown by the Rn time-series recorded near the surface indicate that Rn is brought upward by a carrier gas which rises rather swiftly from depth. The combination of a geodynamically active area, a Rn-rich source and a high rate of advection enabled us to gather pertinent data on the relationship between the Rn flux and seismicity.

METHODS

The earthquake data-set

The time of occurrence and epicentral location of earthquakes in the study area (Fig. 1) were taken from the Israeli earthquake catalog, as published by the Seismological Division at the Geophysical Institute of Israel, which operates the Israel Seismic Network. The threshold of complete recording for the network is $M_L \geq 2.0$ (Shapira, 1992). We included in the data set only those earthquakes for which accuracy of location is denoted in the catalog as "High", namely less than about 4 km (comprising, in the study area, 82% of the events), while seismic events that are defined in the catalog as "possibly explosions" (5% of the events) were excluded. Also, to avoid a spurious effect of earthquake swarms on the results, we excluded earthquakes that occurred less than one day after the occurrence of an earthquake within the same tectonic segment.

The Rn monitoring setup and data-set

Detailed monitoring of ^{222}Rn has been carried out since 1994 using a

gamma-ray Rn monitoring station based on a 1.5×1.5in (2.5 cm) NaI scintillation detector, using a 10 minute integration time, recalculated for 15 minutes and averaged to 60 minutes. There are two sources for γ -ray readings: a) a constant contribution from U, K and Th in gravel rock fragments in the immediate vicinity of the sensor (<50 cm), and b) a varying contribution from ^{222}Rn in the pore geogas, mainly via the decay of ^{214}Bi . Calibration of γ -rays counts with conventional Rn flux measurements is difficult, because the actual volume and geometry of gravel geogas from which γ -rays are detected are not known. A rough calibration by simultaneous measurement with Solid State Nuclear Track Detectors indicates that 1 count per 15 minutes of the NaI sensor is approximately equivalent to 0.26 pCi/L.

Typical elevated Rn flux values are 50,000 pCi/L, while the noise level of the Rn detector system in the monitoring site (as derived from the hourly fluctuations at times of lowest Rn values) is less than 130 pCi/L. Four types of temporal variations of Rn are encountered (Fig. 2): multi-year, seasonal, diurnal and high Rn signals with a duration of several days, which are the subject of this study. In order to provide an objective determination of the start time of Rn anomalies the following procedure was followed. 1) A 25-hour running average was calculated for the Rn time-series; the times of the minima and maxima of this time-series were calculated; The times of minima are now taken as the start times of Rn signals. 2) for each start time, a "relative amplitude" was calculated as the ratio between the

running average Rn counts at the following maximum and the running average Rn counts at start time. A preliminary analysis of the data showed that only the larger Rn signals, with relative-amplitude greater than 1.9 are correlated with earthquakes. Hence, in step 3, we selected these 110 Rn signals as our data set.

APPROACH

The temporal relationship between earthquakes and Rn flux was examined for 3-day intervals relative to the start time of each of the 110 Rn anomalies. The sum of the 3-day intervals for the 110 Rn anomalies covers 330 days, which are 13.37% of the 2468 measurement days. If earthquakes and Rn anomalies are two unrelated phenomena, then the expected number of earthquakes for any 3-day interval may be calculated as 13.37% of the total number of earthquakes within the examined earthquake sub-set. The χ^2 statistic was used to determine the significance of the difference between the observed and the expected number of earthquakes. Separate tests were performed for earthquake sub-sets occurring in three different adjoining tectonic provinces within the study area (Fig. 1): a) the plate areas to the east and west of the Dead Sea rift (428 earthquakes); b) the segments between the pull-apart grabens in the Dead Sea rift valley (186 earthquakes) and c) the three pull-apart grabens (Dead Sea, Kinneret and Hula) in the Dead Sea rift valley (164 earthquakes). The Dead Sea rift valley is defined here as the area covered by flat-lying Quaternary sediments that are bordered by the Dead Sea rift fault scarps. Earthquake

epicenters as far as 270 km away from the Rn monitor have been considered.

RESULTS

The results show that earthquakes located out of the Dead Sea rift valley do not show significant clustering in the two weeks preceding and following the start time of the 110 Rn anomalies (Fig 3A; Table 1, line 6). On the other hand, earthquakes that lie within the Dead Sea rift valley significantly cluster in the 3 days following the start time of the 110 Rn anomalies (Table 1, line 1). A more detailed look at the Dead Sea rift valley shows that earthquakes occurring in the structurally higher segments of the Arava and Jordan Valley are not significantly clustered in the two weeks preceding and following the start time of the 110 Rn anomalies (Fig 3B; Table 1, line 5). Only in the Dead Sea rift pull-apart grabens earthquakes significantly cluster, and this only in the 3 days following the start time of the 110 Rn anomalies (Fig 3C; Table 1, lines 2-4).

For the three pull-apart grabens, the results show an excess of 82% relative to the expected number of earthquakes. The χ^2 value is 17.19 (Table 1, line 2), which signifies a probability of random occurrence equal to .003%. Concerned that the χ^2 distribution may not be applicable to this case, we double-checked this value by evaluating one million series of temporally random earthquakes against the 110 Rn anomalies and obtained similar results ($p=.006\%$). These results are not very sensitive to the choice of a cut-off for the time difference between successive earthquakes, aimed at avoiding the possible effect of earthquake swarms.

Even if we include in the data-set only earthquakes that occurred in the three grabens more than 5 days after a previous one, the clustering of earthquakes in the 3-day interval following the start time of the 110 Rn anomalies is significant at the level of .01%.

Of the 40 earthquakes that fall within this interval (Fig. 3C), 25 occurred in the Dead Sea, which is in accord with the proportion of the number of earthquakes in the Dead Sea segment relative to their number in the Kinneret and Hula segments (Table 1, lines 3,4).

DISCUSSION

The results just described demonstrate for the first time a statistically significant temporal relationship between earthquakes of $M_L \leq 4.6$ and Rn flux. In contrast, but in agreement with geological reasoning, earthquakes occurring out of the Dead Sea rift valley do not show a significant connection to the Rn anomalies recorded within the Dead Sea rift. It is also noteworthy that earthquakes in the Dead Sea rift valley preferentially occur after the start time of Rn anomalies and not before their onset (Fig. 3).

At our Dead Sea monitoring station, both Rn flux and atmospheric pressure were measured simultaneously. For different periods, these parameters are both positively and negatively correlated. At the scale of weeks, which is the focus of this study, cross-correlation between these parameters shows very low correlation coefficients. Spectral analysis shows that the contribution of the 12 and 24-hour periodicities is prominent for atmospheric pressure but is an order of

magnitude less for radon. Moreover, if the Rn anomalies were the result of non-tectonic factors such as weather or groundwater movement, their correlation with earthquakes in specific geological structures could not be demonstrated.

In an attempt to explain our results, we assume that plate movement along the Dead Sea Transform episodically deforms the tectonic segments within the Dead Sea rift valley. At a certain deformation level numerous locations are fractured in a manner that conforms to a model of a pre-seismic stage of distributed damage (Ben-Zion et al., 1999). Upon reaching $1-10 \times 10^{-9}$ strain, a source rock may emanate Rn (Touain and Baubron, 1999) at the NW Dead Sea, and the strain may also affect the upward transfer rate of Rn. Thus, Rn is transported by an up-flowing carrier gas, to be detected as a Rn anomaly close to the surface, several hundreds of meters above its source. As the overall deformation continues, further strain may either result in aseismic slip, or else it may increase to a level that exceeds the failure threshold somewhere within the Dead Sea rift valley, so that an earthquake occurs there within a few days after the generation of a Rn anomaly in the Dead Sea area. On the other hand, some earthquakes occur in the Dead Sea rift valley as a result of strains that are not recorded as Rn anomalies at the NW Dead Sea. These considerations may explain the fact that the statistically significant relationship between earthquakes and the 110 Rn anomalies entails only 30% of the latter.

It should be noted that while earthquakes occurring in the northern

pull-apart grabens of the Kinneret and Hula significantly correlate with Rn anomalies that are recorded in the Dead Sea pull-apart graben, earthquakes in the structurally higher Jordan valley segment, which is located between them and is closer to the Rn monitoring site, do not show a connection to these Rn anomalies (Table 1, line 6). Tectonic attributes seem to be more important in this context than proximity to the Rn monitor, but at this stage we cannot offer a mechanism that explains this observation.

Despite these difficulties we may conclude that Rn flux in the Dead Sea is significantly connected with earthquakes in the Dead Sea rift valley, and thus can be considered a sensitive indicator of changes in the local crustal stress. This has a bearing on the debate concerning the feasibility of earthquake prediction (Geler et al., 1997; Wyss, 2001). Our results indicate that Rn flux can hopefully be developed as a tool that reflects changes in regional crustal strain preceding earthquakes. In order to save precious time, the scope of such and complementary systematic monitoring should be expanded to other active geo-dynamic zones, after careful selection of appropriate locations for sensor emplacement.

ACKNOWLEDGEMENTS

We are indebted to the late U. Vulkan, to Y. Yaffe and Y. Assael for their help in the design, setting and tedious operation of the Rn monitoring stations. L. Michaeli, U. Malik and D. Kramarovski are acknowledged for their assistance in data collection and organization. Thanks are due to D.M. Steinberg and M. Ben Zvi for their

review and assistance in the statistical analysis. We thank G. Baer, Y. Bartov, Y. Harlavan, V. Lyakhovsky and N. Porat, F. Quattrocchi, M. Trique, M. Eberle and two anonymous reviewers for their valuable suggestions for improvement of the manuscript.

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