



Geofísica internacional

ISSN: 0016-7169

ISSN: 2954-436X

Universidad Nacional Autónoma de México, Instituto de Geofísica

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Geofísica internacional, vol. 61, no. 2, 2022, April-June, pp. 100-112
Universidad Nacional Autónoma de México, Instituto de Geofísica

DOI: <https://doi.org/10.22201/igeof.00167169p.2022.61.2.2197>

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ASSESSMENT OF THE TECTONIC EFFECTS ON SOIL RADON ACTIVITY ALONG THE MARGIN OF THE ARABIAN PLATE BOUNDARY IN NORTHWESTERN SYRIA

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Received: November 1, 2021; accepted: March 27, 2022; published on-line: April 1, 2022.

RESUMEN

El objetivo principal del presente estudio es evaluar el papel de la tectónica activa en el nivel de emanación de radón del suelo en dos estructuras tectónicamente activas de la Falla del Mar Muerto del Norte (NDSF, por sus siglas en inglés, al noroeste de Siria, es decir, los segmentos de falla Qastoon y Al-Harif. Las mediciones de radón se basaron básicamente en los resultados extraídos de estudios arqueosísmicos y paleosísmicos anteriores en Al-Harif, además del estudio geofísico y morfotectónico integrado en el sitio de Qastoon. Se realizaron un total de 80 mediciones de gas radón en el suelo, a una profundidad de muestreo de 75 cm; se utilizó el detector de radón AlphaGUARD PQ 2000Pro. El rango de fondo de la emisión normal de radón del suelo local se determinó en un área ubicada lejos de la influencia de las perturbaciones tectónicas. Los datos de radón obtenidos se analizaron estadísticamente y los valores medios se estandarizaron en términos de probabilidad de magnitud, lo cual mejora el proceso de comparación y facilita la separación de las variaciones normales del radón de otros valores anómalos o relacionados con la geotectónica. Los resultados generales revelaron ocurrencias notables de anomalías de radón asociadas con fallas con valores pico máximos de ~ 6 a 7 veces por encima del fondo, con una tendencia de acuerdo con los rastros previstos de rupturas de fallas en Qastoon y Al-Harif, respectivamente.

PALABRAS CLAVE: gas radón, estructuras tectónicas activas, falla norte del Mar Muerto y oeste de Siria.

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ABSTRACT

The main purpose of the present study is to assess the role of active tectonics on soil radon emanation level across two tectonically active structures of the Northern Dead Sea Fault (NDSF) northwestern Syria: namely, the Qastoon and the Al-Harif fault segments. Radon measurements were basically directed by the results drawn from earlier archaeoseismic and paleoseismic studies in Al-Harif, besides integrated geophysical and morphotectonic survey at the Qastoon site. A total of 80 soil radon gas measurements were performed at 75 cm sampling depth, using AlphaGUARD PQ 2000Pro radon detector. The background range of normal radon emission from local soil was determined in an area located far from the influence of the tectonic disturbances. The obtained radon data were statistically analyzed and the mean values were standardized in terms of magnitude probability which enhances the comparison process facilitating the separation of normal radon variations from other anomalous or geotectonic related values. The overall results revealed remarkable occurrences of fault-associated radon anomalies with maximum peak values of ~6 to 7 times above the background, trending in accordance with the predicted traces of the fault ruptures at the Qastoon and Al-Harif, respectively.

KEY WORDS: Radon gas, Active tectonic structures, Northern Dead Sea Fault, western Syria.

INTRODUCTION

The Northern Dead Sea Fault (NDSF) is widely recognized as an active tectonic structure in the eastern Mediterranean region evidenced by many large historical earthquakes (Ambraseys and Barazangi, 1989; Ambraseys and Jackson, 1998; Sbeinati *et al.*, 2005). The fault forms a major continental transform plate boundary between the Arabian plate to the east and the African plate to the west, and it accommodates their differential shift. Thus, the system has become the focus of attention for many researchers who studied its seismotectonic and geologic evolution (Barazangi *et al.*, 1993; Butler *et al.*, 1997; Brew *et al.*, 2001; Meghraui, 2015). Although the NDSF is marked by a rich historical catalogue of large earthquakes, it currently shows an apparent lack of seismicity with a prevailing status of quiescence. Moreover, analysis of recent seismic data revealed that the earthquake activity along most segments of the NDSF in western Syria is presently distinguished by producing a little number of low magnitude seismic events (Al-Hilal and Abdul-Wahed, 2018). Furthermore, Meghraoui *et al.* (2003) found evidences for ~830 years of seismic quiescence along the NDSF at Al-Harif site of Missyaf fault segment. Additionally, recent Global Positioning System (GPS) measurements along the plate boundary in NW Syria showed a fairly small relative motion between the Arabian and African plates with average geodetic velocities of ~0.6 mm/year (Alchalbi *et al.*, 2010). However, these results seem to be inconsistent with the long historical record and the consequences of field observations that bear out the activity and seismogenic potential of the concerned fault system. Thus, even though the concerned region seems nowadays to pass through a period of seismic quiescence, this temporal status is interpreted by most seismologists as a probable reflection of the slow rate of strain accumulation in a locked fault system (e.g. Alchalbi *et al.*, 2010; Kobeissi *et al.*, 2015).

From tectonic point of view, faults are described as complex structures that are generated under the actions of high stresses coupled with accumulated strains which commonly result in significant crustal deformations with massive zones of crushed and broken rocks. Hence, faults often exhibit higher permeability environment compared to the surrounding unaltered rocks. This property may turn most faulted zones into favored paths for upward migration of emanated soil gases during their

way to the Earth's surface. Among these gases, radon, a natural radioactive element constantly generated from soil and rocks is emitted to the atmosphere, particularly through weak zones such as faults (Al-Hilal and Abdul-Wahed, 2016; Mojzes Andrej *et al.*, 2017). Radon (^{222}Rn , with a half-life of 3.825 days) is a progeny nuclide of radium (^{226}Ra), which in turn is generated from the natural decay series of uranium (^{238}U). The gaseous, radioactive and inert nature of radon makes it a significant tracer which can be used to investigate some crustal activities that induce gas emission in the ground (King *et al.*, 1996; Richon *et al.*, 2010).

Radon is commonly transported within the earth's crust by two basic mechanisms, diffusion and/or convection of the gas flow (Tanner, 1964; Etiope and Martinelli, 2002). However, there are some important factors which could facilitate the migration process of radon and enhance the distance reached in the ground. Among these factors is the groundwater flow which plays a major role as driver of radon transport through permeable geologic medium, and could be brought upwards to the surface by a rising flux of some other natural gases, (e.g. CO_2 and He) which act as radon carriers via fractures and rupture zones. Accordingly, the primary goal of this work is to investigate the effects of tectonic activity on soil radon emanations across two active fault structures - the Qastoon and Al-Harif segments that are located along the NDSF in northwestern Syria.

THE STUDY AREA

The Qastoon and the Al-Harif faults represent prominent structural components of the NDSF in western Syria (Fig. 1). The Qastoon segment is located at the eastern boundary of the Ghab basin, at latitude of ($35^{\circ}.41'.30\text{N}$) and longitude of ($36^{\circ}.24'.05\text{E}$). The geological setting of the fault zone and its surroundings is characterized by thick Pliocene lacustrine sediments consisting of calcareous marls, silt, pebbles and clays alternating with repetitive sequences of sandstones and well cemented conglomerate beds at depth. The site is bordered from the north and the east by notable outcrops of Pliocene basalts along with massive deposits of chalky/clayey limestone which belong to the Middle and Upper Eocene (Devyatkin *et al.*, 1997). On the other hand, the north trending Al Harif fault segment is situated along the eastern flank of the Syrian Coastal Mountains Range, about 4 km north of the Missyaf city, at latitude of ($35^{\circ}.06'.01\text{N}$) and longitude of ($36^{\circ}.20'.05\text{E}$). The fault interacts with geologically young formations of late Pleistocene and Holocene that are composed mainly of alluvial deposits, sandy loams, clays, flood plains, coarse and fine gravels in a sandy matrix (Ponikarov, 1966).

Tectonically, the left-lateral NDSF forms a key tectonic feature in western Syria that stretches over a distance of about 150 km in parallel to the Syrian Coastal Mountains Range (Brew *et al.*, 2001). Along this distance, two major fault structures were considered important for the purpose of this study; the Qastoon and the Al Harif segments (Fig. 2). Field investigations in the study region revealed some significant geomorphic and topographic expressions which attest to the ongoing tectonic activities of the concerned fault zone. Evidences include the occurrence of recent lava flows; break in slope features; faulted young alluvial fans and the common occurrence of distinct deflected streams which indicates the role of tectonic activity in influencing the outline of drainage system (Meghraui, 2015). Besides, the formations of distinguished colluvial wedges which are commonly associated with recurrent ruptures of fault where each fault rupture creates a scarp with a sharp free face. Then, sediments that eroded from the free face is shed across the fault and filling up on the footwall of the fault due to slope failure as a result of erosion and re-deposition during successive dip

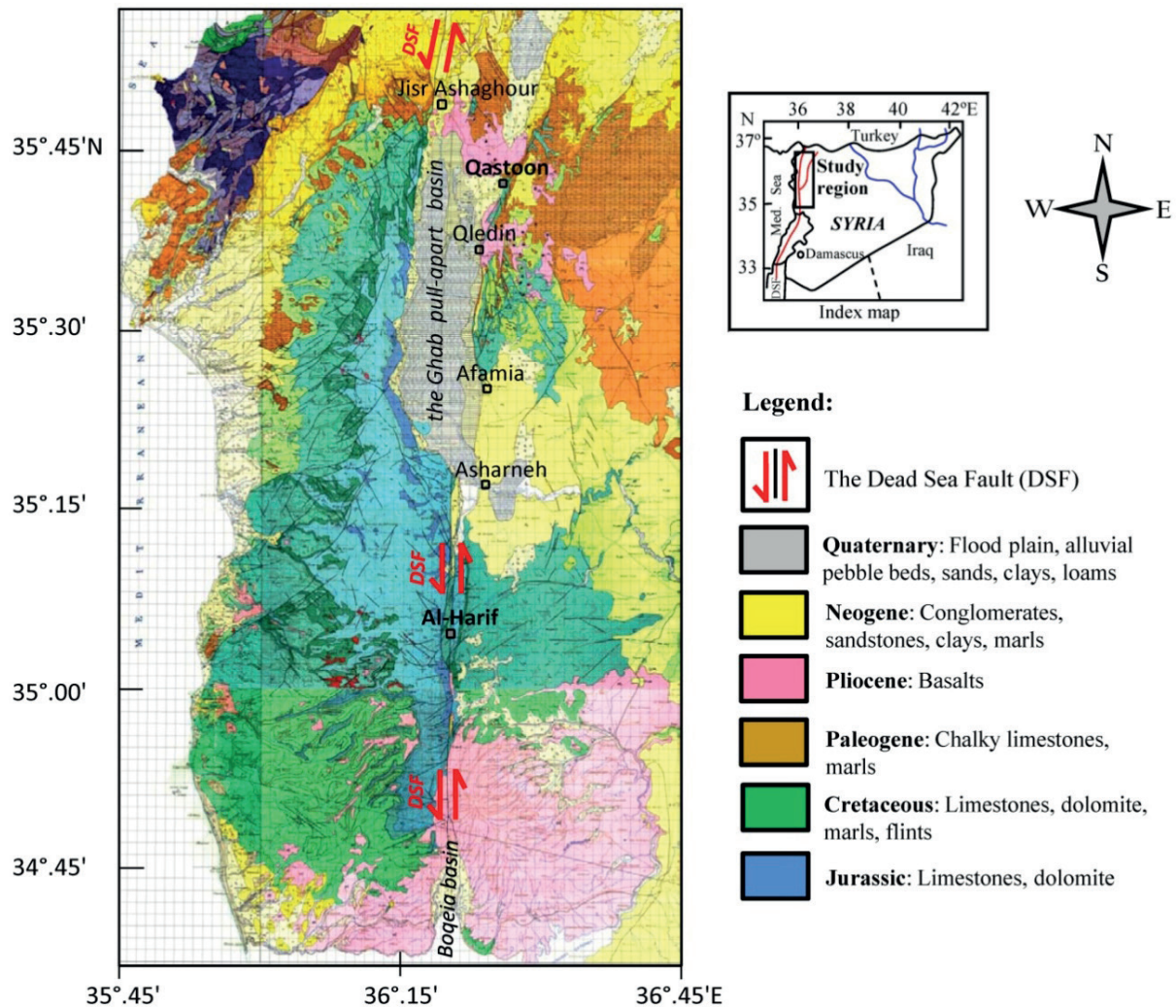


Figure 1. Geological map of western Syria showing the locations of the radon measurement sites at the Qastoon and the Al Harif faults.

slip of faulting, producing a colluvial wedge (Fig. 3). In our case, the observed colluvial wedges along the eastern Ghab fault were developed mostly due to tectonically induced gravity landslide of Pliocene-Quaternary unconsolidated sediments that are eroded from the free face of the fault scarp and accumulated at the footwall of the fault plane, producing a typical colluvial wedge, as shown in Fig. 3a, b and c. Accordingly, the interpretation of colluvial wedge stratigraphy and development may assist paleoseismologists to decode an ‘event-stratigraphy’ of past earthquakes (McCalpin, 2009).

From seismic point of view, the NDSF in western Syria and southern Turkey has been the site of several strong earthquakes ($M_s \sim 7.0$) that occurred during the last millennium (Ambraseys and Jackson, 1998; Sbeinati *et al.*, 2005; Akyuz *et al.*, 2006). The return period of large earthquakes in Syria was estimated to be about 200-350 years (Ambraseys and Barazangi, 1989). However, new evidences from palaeoseismology, archaeoseismology and historical seismicity along the NDSF in Syria revealed a seismic gap of ~ 830 years along the Missyaf fault segment (Meghraoui *et al.*, 2003). Although such temporal seismic quiescence may imply that the fault has been seismically inactive in

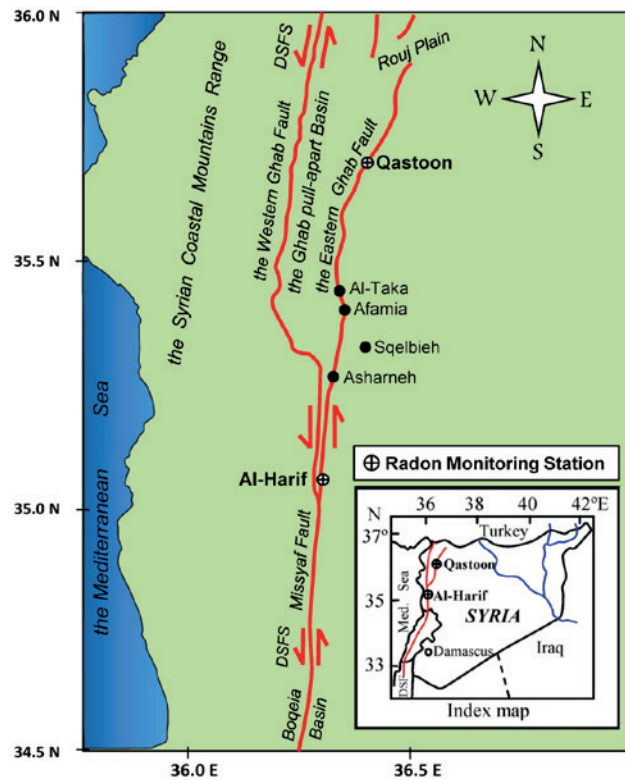


Figure 2. Tectonic map of western Syria showing the general trend of the northern Dead Sea Fault System (DSFS), including the Missyaf, Al-Harif, Qastoon and the Ghab faults.

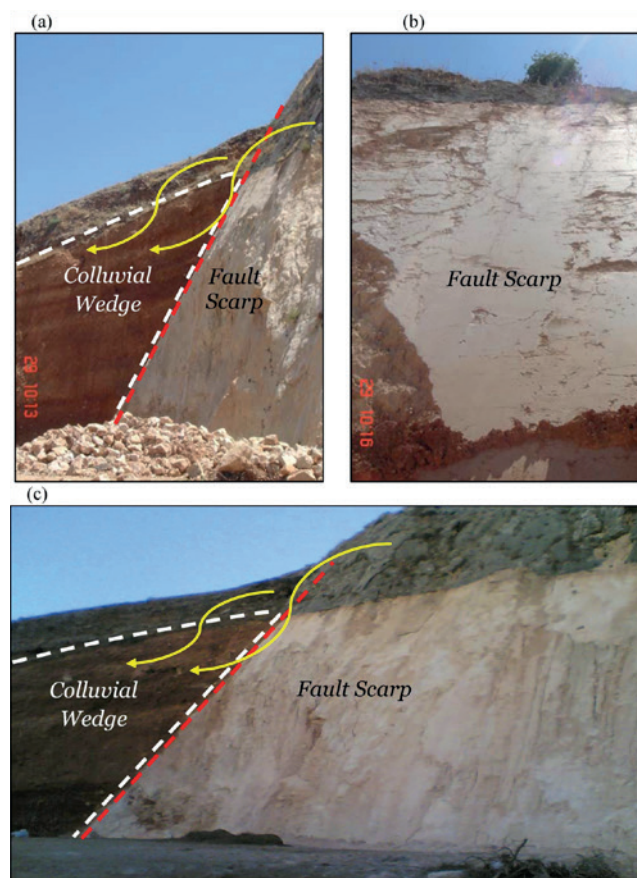


Figure 3. Field Photographs illustrating the development of typical colluvial wedges that formed along the eastern bounding fault of the Ghab pull-apart basin. The dashed red and white lines delineate the fault plane and the colluvial wedge, respectively.

the last few centuries, it might be a sign of high level of seismic hazard in the region due to a probable slow rate of interseismic strain accumulation in a locked fault (Alchalbi *et al.*, 2010). However, analysis of seismic data in Syria during the period (1995-2012) revealed that the earthquake activities in the country produce a little number of low magnitude events (Al-Hilal and Abdul-Wahed, 2018). However, Barazangi *et al.* (1993) concluded that the apparent lack of recent seismicity along the NDSF should not be interpreted as minimizing the potential hazard and risk in the region. Thus, realizing the active crustal deformation, particularly in terms of strain accumulation in the fault, and the average timing for the recurrence interval of large earthquake, are essential issues for seismic hazard assessment in the region.

RADON MEASUREMENTS

A total of eighty soil gas radon measurements carried out across the Qastoon and the Al-Harif faults, which represent two remarkable tectonic segments located along the northwestern margin of the Arabian plate in Syria (Figs. 4 & 5). The selection of these two structures for radon measurements was based on the results drawn from previous extensive field works which revealed clear evidences of current active tectonics associated with the structural evolution of the NDSF. Accordingly, the radon measurements in the Al-Harif site were oriented in the light of evidences obtained from earlier results of archaeoseismic, palaeoseismic and historical seismicity carried out in the same area (Meghraoui *et al.*, 2003). Similarly, the radon investigations at the Qastoon site were mainly guided by the outcome of previous geophysical surveys and morphotectonic mapping performed in the region by Asfahani *et al.* (2010). The ultimate conclusions of these studies attested to the ongoing tectonic activity and seismogenic potential in both the Qastoon and Al-Harif zones. In view of that, radon surveys at these two selected structures were completed using AlphaGUARD PQ2000 Pro radon monitor. In practice, radon gas is automatically drawn out into the ionization chamber of the device with a steady continuous pumping rate of 0.3L/min. For each measurement, the radon activity is sampled in 10-min intervals over a period of one hour. The system is equipped by an ionization chamber with a detection limit of 2-2000.000 Bq.m⁻³. The applied technique based on the principle that the action of tectonic stresses and shearing processes that commonly occur along the rupture zones of faults could remarkably enhance the level of radon emissions owing to increasing rock permeability of the deformed structures (Yuce *et al.*, 2017). Consequently, considerable information concerning the trend and location of the fault zone, besides understanding the nature of its tectonic activity, could be achieved through analyzing the distribution pattern of soil radon emission and defining the spatial tendency of the anomalous halos in the survey area (King *et al.*, 1996; Baubron *et al.*, 2002; Richon *et al.*, 2010; Al-Hilal and Al- Ali, 2010). The results in most of these researches revealed a clear association between the occurrence of high radon variations and the general trends of fault zones. This finding implies that the movement of radon in the ground is greatly dependent on the degree of soil permeability and the extent of fracturing in bedrocks.

DATA ANALYSIS

The set of our radon data was statistically analyzed in order to define their spatial distribution with respect to the fault trend. Such processes would assist the separation between normal radon concentrations from other anomalous or tectonic related values (Table 1). The analysis includes the estimation of minimum, maximum, mean value (x), standard deviation (SD) and the coefficient of vari-

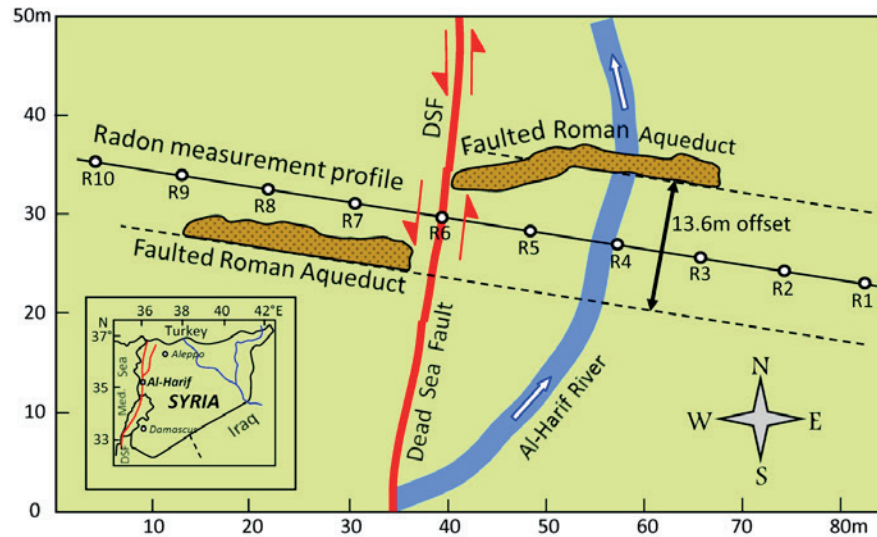


Figure 4. A sketch map of the Al-Harif site showing the trend of the Dead Sea Fault (red solid line), the radon profile (black solid line) and the location of the Al-Harif ancient aqueduct, which was faulted and displaced left-laterally by a total horizontal offset of ~13.6 m.

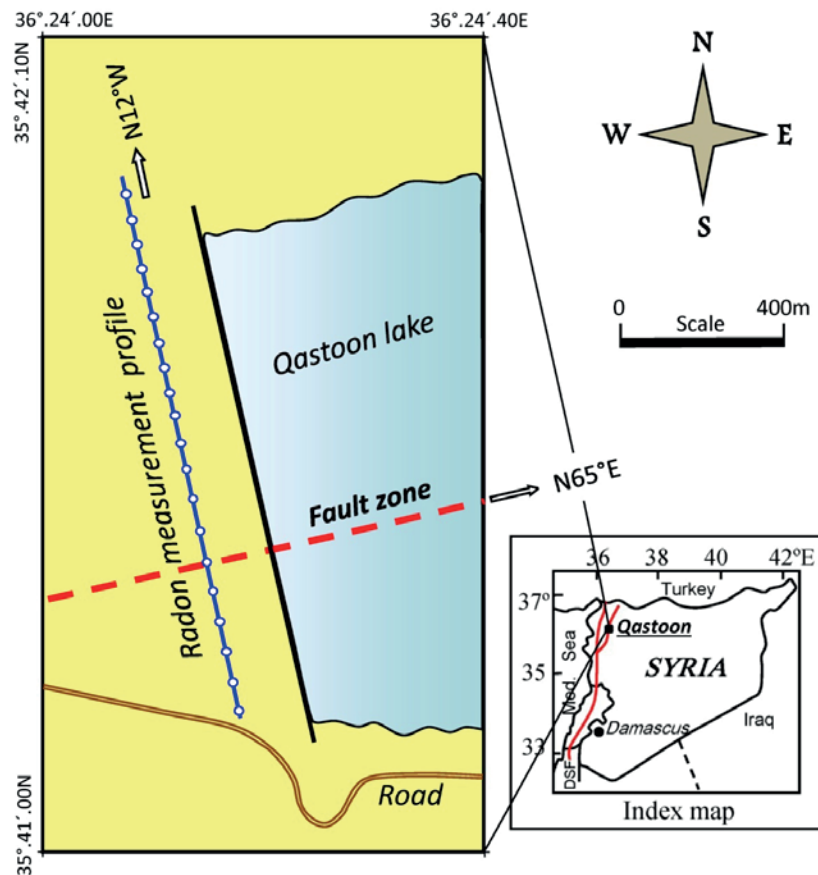


Figure 5. A sketch map of the Qastoon site illustrating the intersection of the radon profile (blue solid line) with the general trend of the Qastoon fault (red dash line).

ability (CV%), which reflects the degree of radon homogeneity in the investigated site, the higher the coefficient of variability, the lower the homogeneity of radon distribution in soil. The value of CV is generally calculated through the following formula:

$$CV\% = (SD/\bar{x}) * 100 \quad (1)$$

Additionally, in order to get a better insight into the variability of radon concentration in soil, radon data was standardized in terms of probability of magnitude, which could assist in identifying anomalous radon signals (Crockett and Holt, 2011). In general, the Standardized Radon Index (SRI) is a statistical procedure by which similar data received in various formats is converted into a common format that enhances the comparison process and helps to maximize compatibility. Accordingly, the monthly mean values of radon concentration (C_i) have been standardized (C_s) by using the following formula:

$$C_s = (C_i - \bar{x}) / SD \quad (2)$$

Where ($\bar{x}$) and (SD) are the mean value and the standard deviation, respectively.

Table 1. Results of soil radon measurement data carried out across the Qastoon and Al-Harif fault segments in northwestern Syria

	Al-Harif Fault Rn±error (Bq.m ⁻³)		The Qastoon Fault Rn±error (Bq.m ⁻³)		
	Round 1	Round 2	Round 1	Round 2	Round 3
	13570±1435	12170±1211	9740±1110	12345±1288	13300±1389
	16450±2100	16480±2110	8780±988	11734±1387	13678±1461
	16730±2170	13100±1390	14870±1890	10988±1322	11850±1390
	29622±3766	45750±6112	11488±1366	13456±1400	15300±2000
	68310±8533	62500±7355	18750±2220	12700±1406	19870±2411
	41350±5245	45940±6180	45800±6110	32891±4261	39113±4900
	46540±6645	39300±4980	40500±4960	25366±3000	36300±4767
	17800±2255	13670±1400	50280±6653	53870±7411	56100±7306
	18230±2344	15985±2210	38350±4566	33700±4110	42780±5409
	15433±2150	12811±1408	34650±4430	41258±5176	38200±4908
	-	-	23500±2975	31870±4100	31320±3980
	-	-	24500±3100	26250±3211	30840±3877
	-	-	14950±2000	24880±3005	20950±2560
	-	-	16150±2122	17450±2000	19740±2205
	-	-	13477±1730	19630±2200	18300±2100
	-	-	14334±1895	12744±1408	17677±1984
	-	-	11199±1398	13100±1590	13170±1605
	-	-	11645±1411	13644±1675	12800±1460
	-	-	10790±1302	11488±1367	12022±1400
	-	-	9320±1178	10633±1288	11920±1391
Average	28404±3664	27771±3436	21154±2670	21500±2630	23762±2925
Min	13570±1435	12170±1211	8780±988	10633±1288	11850±1389
Max	68310±8533	62500±7355	50280±6653	53870±7411	56100±7306
SD	18178	18679	13284	12036	12890
CV (%)	64	67	63	56	54

RESULTS AND DISCUSSION

According to the data listed in Table 1, it can be observed that radon concentration in the Qastoon fault varied from 8780 to 56100 Bq.m⁻³ with mean average value of 22139 Bq.m⁻³, a standard deviation of 12737 and 58% coefficient of variability. While radon concentration in the Al-Harif fault ranged between 12170 and 68310 Bq.m⁻³ with mean average value of 28087 Bq.m⁻³, a standard deviation of 18428 and 66% coefficient of variability. In order to avoid possible effects of meteorological variables on soil radon concentration, the survey was performed under comparable weather conditions during dry seasons, where air temperature varied between (35-40 °C) and (25-30 °C) for the Qastoon and Al Harif sites, respectively. Besides, the prevailing atmospheric pressure varied between (990-995 mb) and (956-960 mb) for the Qastoon and Al Harif, respectively. Further, the normal background level of soil radon activity in the study area was established in a separate stationary site that is located far from the tectonic influence of the studied faults zones. Although the average background value of local soil radon emission was set at $\sim 10000 \pm 1200$ Bq.m⁻³, the maximum radon peaks that measured above the predictable traces of the Qastoon and Al Harif fault ruptures showed much higher concentrations, exceeding 56000 and 68000 Bq.m⁻³, respectively (Figs. 6 & 7). This implies that the value of “signal-to-background ratio” indicates clear fault-associated radon anomalies with six to seven fold increases that are found in a spatial agreement with the general trends of the concerned fault zones. Such finding may verify the possibility of using radon as a reliable indicator for characterizing fault structures, and providing an insight into the significant role of local active tectonics in influencing the activity level of soil radon emissions.

As mentioned previously, the estimated rates of radon coefficient variability (CV) in the Qastoon and Al-Harif sites revealed values of 58% and 66%, respectively. Thus, it can be deduced that the common dispersal pattern of radon variations in both sites seems to be fairly high, and this may reflect low homogeneity model. Such disparity might be referred to the differences in the concentrations between zones with higher radon signals that are usually associated with the fault structures, and area with normal radon emission that are naturally emanated from the surrounding unaltered rocks. Additionally, so as to justify that the anomalously high radon values are mainly related to tectonic activities and not only derived from the decay of radium in soil, chemical analysis for ²²⁶Ra content in soil was accomplished in some samples collected from the same locations where the radon concentrations were measured. The results of the analysis revealed very low concentration of radium values ranging from 1.06 ± 0.08 to 1.14 ± 0.20 mg.kg⁻¹, with some results below the detection level (DL= 1 mg.kg⁻¹).

Furthermore, in order to display the differences between normal radon variations from other anomalous or tectonically-induced radon values, we used in this study the method of Standardized Radon Index (SRI). The principle of this technique is comparable to the Standardized Precipitation Index (SPI) used in drought modeling, where negative values indicate dry period and positive values point to wet period due to high precipitations (Crockett and Holt, 2011; Al-Hilal, 2016). According to the SRI method, the spatial correlation between the rate of soil radon emission and the geodynamic activity along the location of the fault zone has been highlighted. Thus, the comparison process of data has been enhanced, in order to show clear radon peaks that are compatible with the assumed trace of the fault ruptures as presented in Figs. 6 & 7. One significant result of this study is the occurrences of remarkable soil radon increases observed across the Al Harif fault in spatial agreement with a gap located between two pieces of a faulted ancient Roman aqueduct named locally as

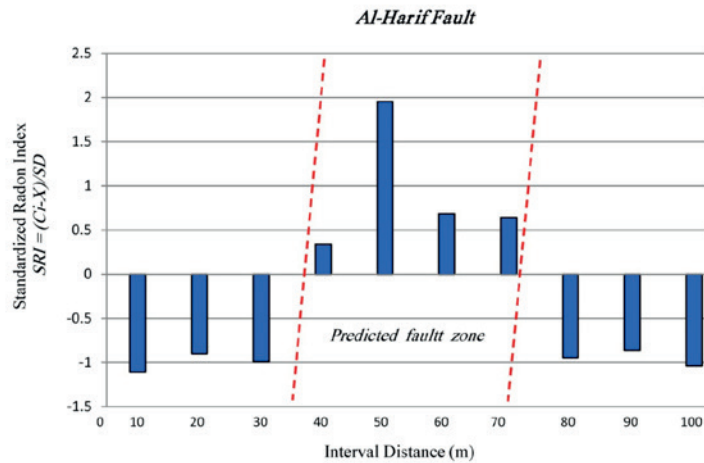


Figure 6. Standardized radon index (SRI), where anomalous radon peaks are correlated with the trace of the surface fault rupture, while negative values point to the background level.

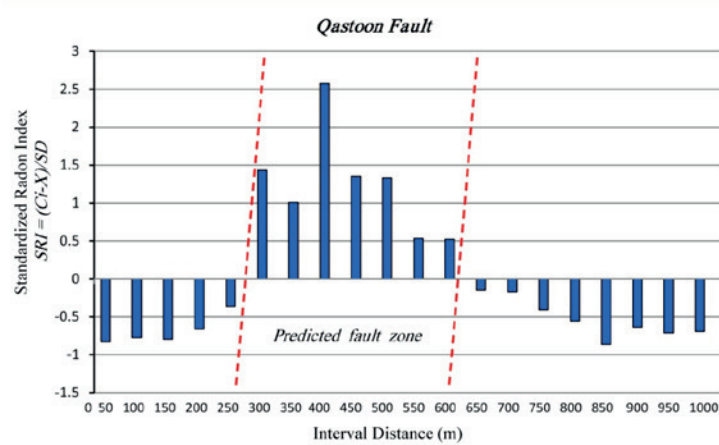


Figure 7. Standardized radon index (SRI), where anomalous radon peaks are correlated with the trace of the surface fault rupture, while negative values point to the background level.

Al-Harif aqueduct (Fig. 4). As mentioned earlier, results from archaeoseismic and palaeoseismic surveys revealed evidences that Al Harif aqueduct was fractured and repeatedly displaced left-laterally by a total horizontal offset of 13.6 ± 0.2 m due to successive displacements of three seismic events occurred along the NDSF (Meghraoui *et al.*, 2003). Additionally, field observations indicated that the displacement of the aforesaid ancient aqueduct is well correlated with clear leftward deflections of some local streams, coinciding with the fault scarp, and most likely implying recent active tectonics along this part of the NDSF. Furthermore, Asfahani *et al.*, (2010) carried out integrated geophysical and morphotectonic surveys in the Qastoon area, which is located along the eastern bounding fault of the Ghab pull-apart basin of the NDSF (Fig. 5). The overall results of their investigations led to the detection of an active tectonic structure which was developed through the ongoing active tectonic processes of the NDSF. Accordingly, it is worth to mention that these findings are very well corresponded with the results obtained from the present study which revealed clear anomalous rises of soil radon signals that occurred in agreement with the general trends of the Qastoon and Al

Harif fault lines. Therefore, it seems quite significant to shed more light on these tectonically active structures, particularly in terms of their potentiality to cause a probable seismic hazard to the study region. In other words, the consequences of our radon survey showed additional evidences of possible spatial fault-associated radon anomalies, and thereby verify the usefulness of using radon method as a reliable approach for characterizing some buried deformed structures and active faults in similar geologic environments elsewhere. In fact, the variability of soil gas radon concentration with regard to the tectonic activity of faults is basically related to the constant effects of the concentrated stress along with accumulated strains which usually result in high crustal deformations and thereby increase the degree of rocks permeability along the fault rupture zone. Such geodynamic changes will in turn enhance the mechanism of upward soil gases flow, and so increase the emanation rate of radon through the fractured bedrocks up to the ground surface.

Lastly, according to our results, and those reported in some other literatures, that the main advantages of using radon measurement technique as an important mean in some geologic and tectonic studies, can be summarized as follows: (1) the relatively low-cost and simplicity of conducting radon measurements; (2) the method is direct and the results are instantly available; (3) radon is a natural element, so this will avoid the addition of any synthetic materials to the environment. On the other hand, attention should be paid to some disadvantages that may encounter the application of radon methods, these include: (1) the variability of radon gas due its sensitivity to the ambient environmental conditions; (2) the effect of geology and the composition of the prevailing rocks at the measurement site; (3) and the relatively short half-life of radon, so it might be dispersed sometimes before reaching the ground surface. Thus, for better results and high accurate performance, it is essential to maintain the radon instrument calibrated before measurements start. Also it is recommended to carry out multiple radon samplings at the same measurement site as this would sufficiently minimize the possible occurrence of errors.

CONCLUSIONS

Systematic soil radon measurements have been performed across the Qastoon and the Al-Harif faults which represent two active tectonic segments of the northern Dead Sea Fault in northwestern Syria. The radon investigations were mainly guided by the results drawn from previous geophysical, morphotectonic, archaeoseismic and palaeoseismic surveys which were achieved in the same area and attested to the tectonic activity of the concerned fault structures. The overall results revealed the presence of a clear fault-associated radon anomaly with about six to seven fold increase of radon concentration, trending in accordance with the traces of the surface fault rupture at the Qastoon and Al-Harif, respectively. One significant result of this study is the observation of some anomalous radon increases that are remarkably corresponded with a gap located between two pieces of a faulted ancient Roman aqueduct at Al Harif site. The aqueduct was fractured and repeatedly displaced left-laterally by a total horizontal offset of 13.6 ± 0.2 m due to successive fault movements of three seismic events occurred along the Dead Sea Fault. Another point of interest is the notable occurrences of some anomalous radon emissions that are spatially consistent with the general trend of the Qastoon rupture fault zone which was detected and outlined by previous integrated geophysical and morphotectonic surveys. Ultimately, the aforesaid results could represent additional evidences regarding the possibility of using radon as a reliable and sensitive indicator for characterizing fault structures, and providing an insight into the significant role of local active tectonics in enhancing the level of soil radon emission.

ACKNOWLEDGEMENT

The author would like to express his gratitude and thanks to Professor I. Othman, Director General of the Atomic Energy Commission of Syria (AECS), for his constant encouragement. Thanks are also due to Dr. Z. Kattan, Head of the Geology Department of the AECS, for his assistance and support. I gratefully acknowledge the anonymous reviewers and the editors of the *Geofísica Internacional* for their valuable suggestions and remarks that considerably improved the quality of the paper. This work is part of a local scientific research No. AECS-G\RSS 979/2012.

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