



Measuring radon flux across active faults: Relevance of excavating and possibility of satellite discharges

Patrick Richon^{a,b,*}, Yann Klinger^c, Paul Tapponnier^c, Chen-Xia Li^d, Jerome Van Der Woerd^e, Frédéric Perrier^f

^aCEA, DAM, DIF, F-91297 Arpajon, France

^bInstitut de Physique du Globe de Paris, Équipe Géologie des Systèmes Volcaniques, 4 place Jussieu, UMR-7154 CNRS, F-75005 Paris, France

^cInstitut de Physique du Globe de Paris, Équipe de Seismotectonique, 4 place Jussieu, UMR-7154 CNRS, F-75005 Paris, France

^dInstitute of Geology, Chinese Earthquake Administration, P.O. Box 9803, 100029 Beijing, China

^eInstitut de Physique du Globe de Strasbourg, CNRS, UMR-7516, INSU, Université Louis Pasteur, Strasbourg I, 5 Rue René Descartes, F-67084 Strasbourg Cedex, France

^fInstitut de Physique du Globe de Paris, Équipe de Géomagnétisme, 4 place Jussieu, UMR-7154 CNRS et Université Paris 7 Denis-Diderot, F-75005 Paris, France

ARTICLE INFO

Article history:

Received 20 October 2008

Accepted 8 January 2010

Keywords:

Exhalation flux
Radon-222
Carbon dioxide
Faults
Earthquake
Trench

ABSTRACT

Searching for gas exhalation around major tectonic contacts raises important methodological issues such as the role of the superficial soil and the possible long distance transport. These effects have been studied on the Xidatan segment of the Kunlun Fault, Qinghai Province, China, using measurement of the radon-222 and carbon dioxide exhalation flux. A significant radon flux, reaching up to $538 \pm 33 \text{ mBq m}^{-2} \text{ s}^{-1}$ was observed in a 2–3 m deep trench excavated across the fault. On the soil surface, the radon flux varied from 7 to $38 \text{ mBq m}^{-2} \text{ s}^{-1}$, including on the fault trace, with an average value of $14.1 \pm 1.0 \text{ mBq m}^{-2} \text{ s}^{-1}$, similar to the world average. The carbon dioxide flux on the soil surface, with an average value of $12.9 \pm 3.3 \text{ g m}^{-2} \text{ day}^{-1}$, also remained similar to regular background values. It showed no systematic spatial variation up to a distance of 1 km from the fault, and no clear enhancement in the trench. However, a high carbon dioxide flux of $421 \pm 130 \text{ g m}^{-2} \text{ day}^{-1}$ was observed near subvertical fractured phyllite outcrops on a hill located about 3 km north of the fault, at the boundary of the large-scale pull-apart basin associated with the fault. This high carbon dioxide flux was associated with a high radon flux of $607 \pm 35 \text{ mBq m}^{-2} \text{ s}^{-1}$. These preliminary results indicate that, at the fault trace, it can be important to measure gas flux at the bottom of a trench to remove superficial soil layers. In addition, gas discharges need to be investigated also at some distance from the main fault, in zones where morphotectonics features support associated secondary fractures.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Radon-222 is a radioactive inert gas, with a half-life of 3.8 days, ubiquitous in natural settings as a member of the uranium-238 chain (Tanner, 1964). The radon exhalation flux at the soil surface depends on the transport properties of the medium and the concentration of its parent nucleus, radium-226. Except in the presence of uraniferous formations, the flux remains generally close to the world average of $22 \text{ mBq m}^{-2} \text{ s}^{-1}$ (Nazaroff, 1992). However, the flux can be much larger if the physical properties of the subsurface medium allow for a higher permeability to gas of the subsurface, or in the presence of a carrier gas, such as carbon dioxide, methane or water vapour, advectively driven from depth

towards the surface. A radon flux larger than $3000 \text{ mBq m}^{-2} \text{ s}^{-1}$, for instance, has been reported at several locations near hot springs in Central Nepal (Girault et al., 2009; Perrier et al., 2009). Increased radon transport to the atmosphere also leads to higher radon concentrations in the soil. Concentrations larger than $20,000 \text{ Bq m}^{-3}$, significantly larger than local background values, have been reported on volcanoes (Baubron et al., 1991; Heiligmann et al., 1997) and in tectonically active areas such as along the San Andreas Fault system in California (King et al., 1996). Mapping radon concentration and radon flux anomalies, thus, has been proposed as a way to detect hidden faults (Burton et al., 2004). A few studies also suggested that monitoring the radon concentration in the soil (Richon et al., 2007) or its exhalation to the atmosphere as a function of time could be useful in order to forecast impending earthquakes (Toutain and Baubron, 1999; Richon et al., 2003).

The pattern of radon exhalation in the vicinity of major tectonic faults remains confusing, however (Table 1). While clear anomalies

* Corresponding author. CEA, DAM, DIF, F-91297 Arpajon, France.
Tel.: +33169264000; fax: +33169267065.

E-mail address: patrick.richon@cea.fr (P. Richon).

were detected in some cases, such as the San Andreas Fault (King et al., 1996), or in the Dead Sea rift in Israel (Steinitz et al., 1992), negligible enhancement of the radon signal was reported near major faults such as the North Anatolian Fault in Turkey (Inceoz et al., 2006) and the Levant fault in Jordan (Atallah et al., 2001; Al-Bataina et al., 2005). Most of these studies, however, relied on profiles with few data points (Giammanco et al., 2009), and where more extensive studies were undertaken, for example, in California (King et al., 1996), they were discontinued. On the other hand, clear correlation of radon anomalies with Quaternary faults was reported in Italy (Tansi et al., 2005), in Germany (Kemski et al., 1992), and in France, in the Pyrenees (Baubron et al., 2002), where seismic activity and tectonic strain rates are at least one order of magnitude smaller. The correlation between radon concentration anomalies and tectonic structures, which is at present elusive but potentially promising, should thus be reexamined in a more systematic manner in active tectonic zones.

Before such comprehensive studies can be undertaken, some methodological issues need to be clarified, in particular concerning the role of the superficial soil layers. In addition, potentially interesting locations may need to be investigated away from the known fault trace. In this paper, to contribute to these methodological issues, we present preliminary results of radon-222 and carbon dioxide flux measurements along one of the major continental strike-slip faults of Asia, the Kunlun Fault (KF, Fig. 1).

2. Geological setting

The Kunlun fault is a left-lateral fault (Fig. 1) that extends roughly over a distance of about 1600 km along an east–west direction (Tapponnier et al., 2001). With a mean slip rate of about 10–12 mm per year over the last 40,000 years (Van der Woerd et al., 2000; Van der Woerd et al., 2002; Haibing et al., 2005), this fault is currently in an active cycle, with at least six earthquakes with $M \geq 7$ having successively ruptured various segments of the fault or nearby branches between 1879 and 2000 (Tapponnier and Molnar, 1977; Tapponnier et al., 2001; Klinger et al., 2005; Wen et al., 2007). In 2001, the Kokoxili earthquake, with a magnitude close to 8, ruptured a 450 km long segment of the fault, the longest strike-slip surface rupture observed so far in Asia (Klinger et al., 2005; Xu et al., 2006). Our measurements were performed at two locations

along the Xidatan segment of the KF (Fig. 1), near the eastern end of the Kokoxili rupture.

The Xidatan valley, located at an altitude of about 4200 m a.s.l., is a former pull-apart trough, floored by coalescent alluvial fans (Fig. 2). It separates metamorphic Paleozoic phyllite and arenite intruded by granites to the north from Triassic green arenite, conglomerate, phyllites and limestone to the south. The valley is almost flat, with a gentle slope to the north. The fault shortcuts the Xidatan pull-apart with a strike of about 80–90°E and its most active surface trace is marked by scarps and hectometric scale pull-apart and push-up structures in the quaternary alluvial fans (Fig. 2).

In 2004, trenches were excavated at various locations of the Xidatan segment to unearth and study evidence for paleo-earthquakes. For the aims of the present study, we selected one of these trenches (Fig. 3a and Fig. 4) in the vicinity of the Xidatan railway station (Fig. 1). This trench (4215 m a.s.l.) is 3 m wide, 20 m long, with a depth reaching 3 m in its middle section at the fault trace. Seismic fault breaks accompanied by bending of the sedimentary layers can be identified precisely in the trench. One profile of radon-222 exhalation flux was performed across the fault on the soil surface about 19 m west of the trench (Fig. 4). Radon flux measurements were also performed inside the trench, along the base of its western wall. Two profiles of carbon dioxide flux were performed near the radon profiles: one short profile, 1 m east of the trench, and one long profile, 50 m east of the trench (Fig. 4). The high water content of the sediments near the fault and in the trench, however, was a concern for gas measurements. Radon diffusion may be inhibited by water and carbon dioxide is highly soluble in water.

We thus looked for a site closer to bedrock with minimal soil covering and where geomorphology suggested a possible association with the long-term activity of the fault. A hill on the northern side of the valley, hereinafter referred to as the KA hill, was selected (Fig. 3b). The KA hill is located at the northern edge of the pull-part basin about 650 m north of the Golmud to Lhasa road, on the eastern side of the Xidatan settlement (Figs. 1 and 2). Its altitude is 4200 m a.s.l., 50 m above the road, and it shows outcrops of schistosed Paleozoic phyllites, with a dip angle of the order of 70° to the north (Fig. 3b and c). The weathered rock is covered by a thin veneer sandy soil. In contrast with the southern slopes of the valley, which are covered by snow, the northern side of the valley, and in

Table 1
Summary of radon-222 profiles performed across active faults.

Location	Fault	Sampling depth (m)	Profile length (m)	Typical number of data points	Peak radon signal (concentration or flux)	Mean background radon level	Reference
Calaveras Fault, Hollister, California	SSF	0.3	400	50	30,000 Bq m ⁻³	3000 Bq m ⁻³	(King et al., 1996)
San Andreas Fault, Point Reyes, California	SSF	0.3	150	20	30,000 Bq m ⁻³	5000 Bq m ⁻³	
Johnson Valley Fault, Landers, California	SSF	0.3	450	30	4000 Bq m ⁻³	400 Bq m ⁻³	
Dead Sea, Israel	NF	0.5	500	30	>500,000 Bq m ⁻³	26,000 Bq m ⁻³	(Steinitz et al., 1992)
Dead Sea Transform, Wadi Araba, Jordan	SSF	0.5	<50	<15	1800 Bq m ⁻³	1000 Bq m ⁻³	(Al-Bataina et al., 2005)
Dead Sea Transform, Jordan	SSF	0.5	400	<20	3000 Bq m ⁻³	<1000 Bq m ⁻³	(Atallah et al., 2001)
North Anatolian Fault, Turkey	SSF	0.5	200	<20	9800 Bq m ⁻³	6000 Bq m ⁻³	(Inceoz et al., 2006)
Shan-Chiao Fault, Taiwan	NF	0.8–1.0	2–8 km	<20	28,000 Bq m ⁻³	6000 Bq m ⁻³	(Walia et al., 2005)
Crati graben, Italy	NF	0.5–1.0	15,000	>2000	39,000 Bq m ⁻³	9100 Bq m ⁻³	(Tansi et al., 2005)
North and Northwestern Greece	NF	0.5	180	10	13,000 Bq m ⁻³	2000 Bq m ⁻³	(Ioannides et al., 2003)
Jaut Pass, Pyrenees, France	NF	1.0	1200	80	70,000 Bq m ⁻³	10,000 Bq m ⁻³	(Baubron et al., 2002)
Bad Nauheim Fault, Aachen, Germany	NF	1.0	200	<30	>1,000,100 Bq m ⁻³	30,000 Bq m ⁻³	(Israel and Björnsson, 1966)
Neuwied Basin, Rhine Graben, Germany	NF	2	125	25	140,000 Bq m ⁻³	<10,000 Bq m ⁻³	(Kemski et al., 1992)
Main Central Thrust, Nepal	TF	0.3	50	10	60,000 Bq m ⁻³	4400 Bq m ⁻³	(Perrier et al., 2009)
		Surface	50	70	5200 mBq m ⁻² s ⁻¹	20 mBq m ⁻² s ⁻¹	(Perrier et al., 2009)
		Surface	35	145	3400 mBq m ⁻² s ⁻¹	31 mBq m ⁻² s ⁻¹	(Girault et al., 2009)
Kunlun Fault, Qinghai, China (this study)	SSF	Surface	250	60	660 mBq m ⁻² s ⁻¹	20 mBq m ⁻² s ⁻¹	This study

NF, TF and SSF stands for Normal Fault, Thrust Fault and Strike-Slip Fault, respectively.

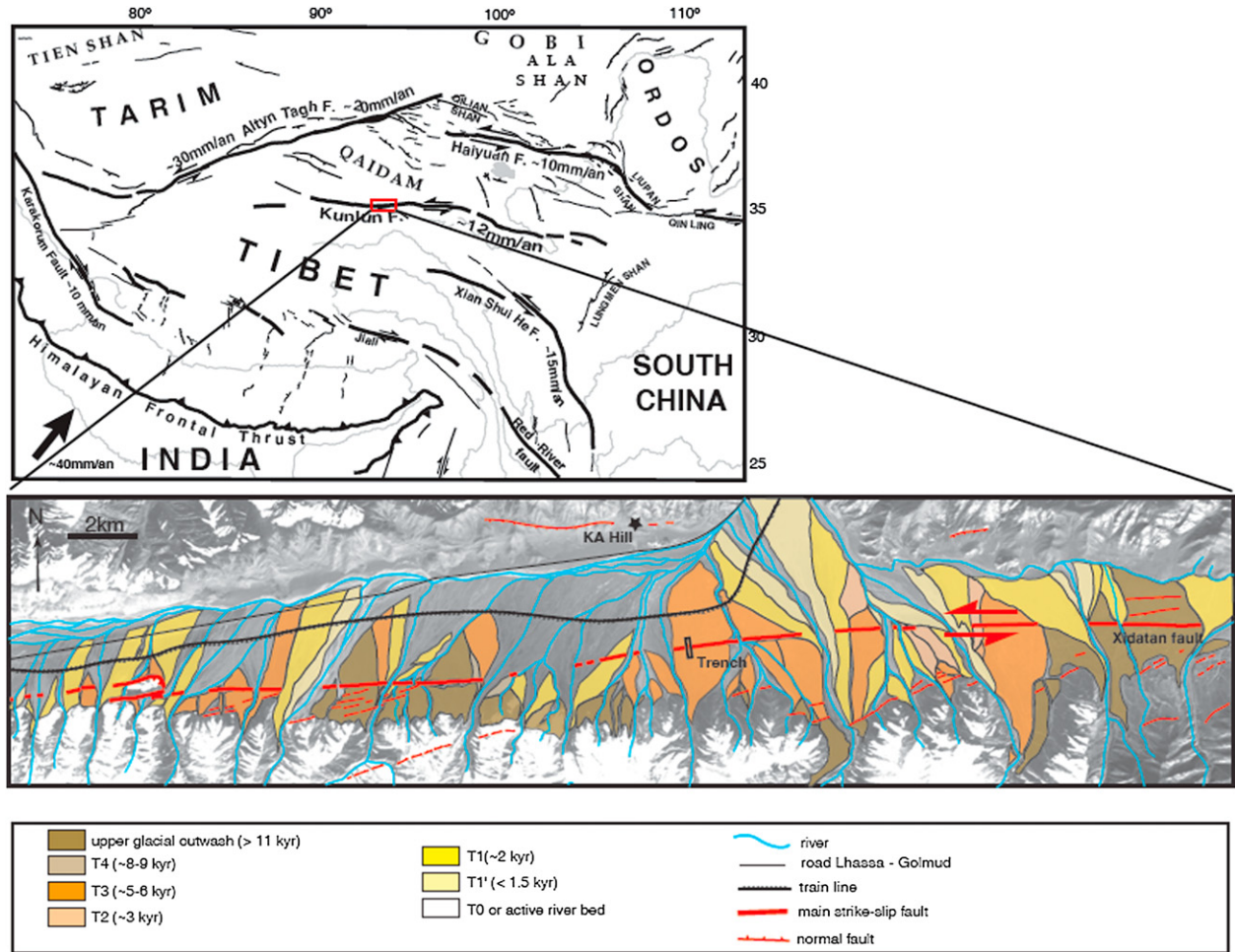


Fig. 1. Simplified geological and structural map of Xidatan trough showing locations of radon and carbon dioxide flux measurements. The trench excavated to sample the Xidatan segment of Kunlun Fault is shown as inset. The solid star indicates the location of radon and CO₂ measurements at KA Hill.

particular the KA hill, is rather dry, due to favorable sun exposition. Carbon dioxide flux measurements were performed on two parallel profiles on the summit of the KA hill, roughly following the direction of the ridge (Fig. 3a and c). At four locations, the radon flux was also measured.

3. Experimental methods

Radon exhalation was measured using the accumulation chamber method (Wilkening and Hand, 1960; Ferry et al., 2001; Ielsch et al., 2001). First, 5–10 cm of soil was scrubbed. Then an accumulation chamber of 18 L volume and 0.125 m² surface area was installed on the scrubbed area. Leakage was reduced by plastering the sides of the container with wet soil. After 1 h, the gas in the container was sampled by a Lucas scintillation flask (Lucas, 1957) with a volume of 125 mL, previously evacuated to a pressure of about 40–80 hPa. The atmospheric pressure was 620 hPa at this elevation. The radon-222 concentration in the flask was then obtained from counting photoemissions after a waiting time of 3 h, the necessary delay to achieve radioactive equilibrium between radon-222 gas and its short-lived daughters. The counting operation was performed with a CALENTM photomultiplier from Alcade. The radon exhalation flux ϕ was obtained from the measured radon concentration using (Wilkening and Hand, 1960):

$$\phi = \frac{V_{\text{acc}}}{S_{\text{acc}}} \times \frac{C_{\text{Rn}}}{T_{\text{acc}}} \quad (1)$$

where V_{acc} is the container volume, S_{acc} its base surface area, T_{acc} the accumulation time (1 h), and C_{Rn} the measured radon concentration at time T_{acc} . The point-to-point measurement error was dominated by the statistical error on the counting rate. In addition, when comparing with other experiments, a common systematic uncertainty of 5%, due to the absolute calibration of the scintillation flask, is to be added in quadrature to obtain the total error (noted as tot.)

The same scrubbing method was applied for the measurement of the carbon dioxide flux, using a smaller accumulation chamber of 5 L volume and 0.053 m² surface area. We used a smaller accumulation chamber for CO₂ flux because it was easier to scrub soil on small surface. The concentration of carbon dioxide in the container was measured using a TESTO-235TM infrared sensor whose calibration had been checked in the laboratory. The concentration of carbon dioxide was recorded manually as a function of time, with time interval of 30 s, with a maximum accumulation time varying from 10 to 20 min. The concentration $c(t)$ as a function of time was then fitted using the function:

$$c(t) = c_0 + \frac{V_{\text{acc}}}{S_{\text{acc}}} \frac{F}{\lambda_0} (1 - e^{-\lambda_0 t}), \quad (2)$$

where F was the carbon dioxide flux, c_0 a baseline concentration, and λ_0 the removal rate. The flux F was then converted into g m⁻² day⁻¹ (Lewicki et al., 2003), without applying further corrections. With this simplified method, we focused on the

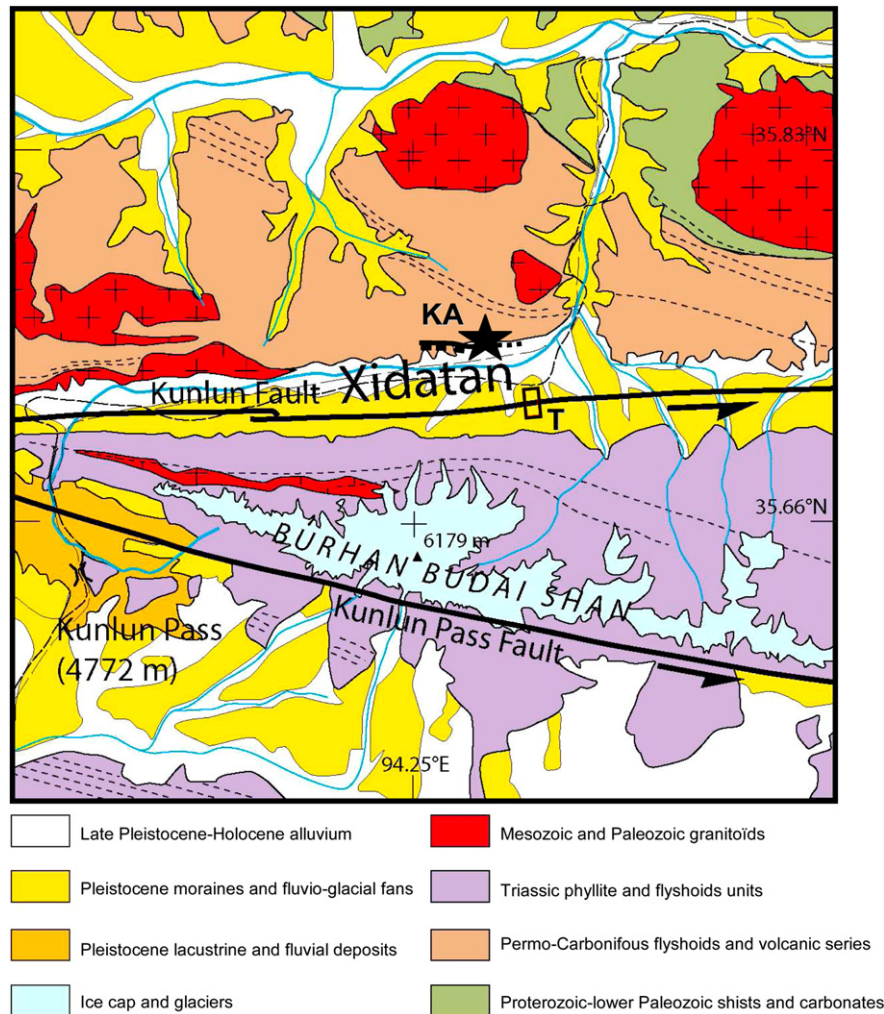


Fig. 2. Map showing the position of the trench (T) and KA hill in the Xidatan valley, China. Geological contours are taken from the 1:200,000 geological map (Geological Bureau of Qinghai Province, 1980) with white areas referring to alluvium and moraine.

search of anomalous locations. The error on the flux F was dominated here by the uncertainty on the estimation of the slope of the concentration versus time. The resulting point-to-point uncertainty varied from 15 to 25%, which was sufficient for our purpose. When comparing with other experiments, a conservative systematic uncertainty of 25% is to be added in quadrature, also noted as (tot.).

The experiment took place from 23 to 30 September 2006. An episode of limited rainfall occurred during the experiment on September 25, followed by a moderate episode of snowfall (thickness of 2 cm) from 26 to 27 September. In order to estimate the effect on soil gas flux of such atmospheric events, the CO_2 flux was repeatedly measured at different times over the duration of the experiment at different reference points. Temporal variations of the flux were observed, with a standard deviation around the mean value varying from 20 to 40%. Except in one case, such temporal fluctuations were not clearly associated with rain or snowfall but, rather, with rapid variations of atmospheric pressure and the occurrence of wind episodes.

4. Results of measurements across the fault

The results across the fault are shown in Fig. 5. Along the soil surface profile, the radon flux remained almost constant with an

average value of 14.1 ± 1.0 (tot.) $\text{mBq m}^{-2} \text{s}^{-1}$. The mean radon flux value along the segment of profile -100 m to 100 m (18.2 ± 1.1 $\text{mBq m}^{-2} \text{s}^{-1}$) was significantly higher than the mean value measured between 100 m and 200 m (11.5 ± 0.9 $\text{mBq m}^{-2} \text{s}^{-1}$). However, measurements at distances larger than 100 m along this profile were performed one day after the other measurements. Consequently, the observed systematic difference could also reflect a coherent time variation.

A much higher radon flux was observed inside the trench (Figs. 5 and 6), reaching a maximum value of 538 ± 33 (tot.) $\text{mBq m}^{-2} \text{s}^{-1}$, with 12 measurement values larger than 100 $\text{mBq m}^{-2} \text{s}^{-1}$. Such large flux values cannot be attributed to a local source because flux measurements performed on material excavated from the trench yield a value of 9.0 ± 1.5 (tot.) $\text{mBq m}^{-2} \text{s}^{-1}$.

Two properties of the measured radon flux in the trench must be noted. First, the flux was not correlated with depth in the trench. The largest value was not observed in the deepest section of the trench. The larger values of the radon flux may be associated with the vertical structures in the sediments (indicated with blue arrows in Fig. 6) seen in the northern part of the trench, possibly channeling the gas transport (Fig. 5).

The second conspicuous property of the radon flux in the trench was its time variability from day to day. While the flux

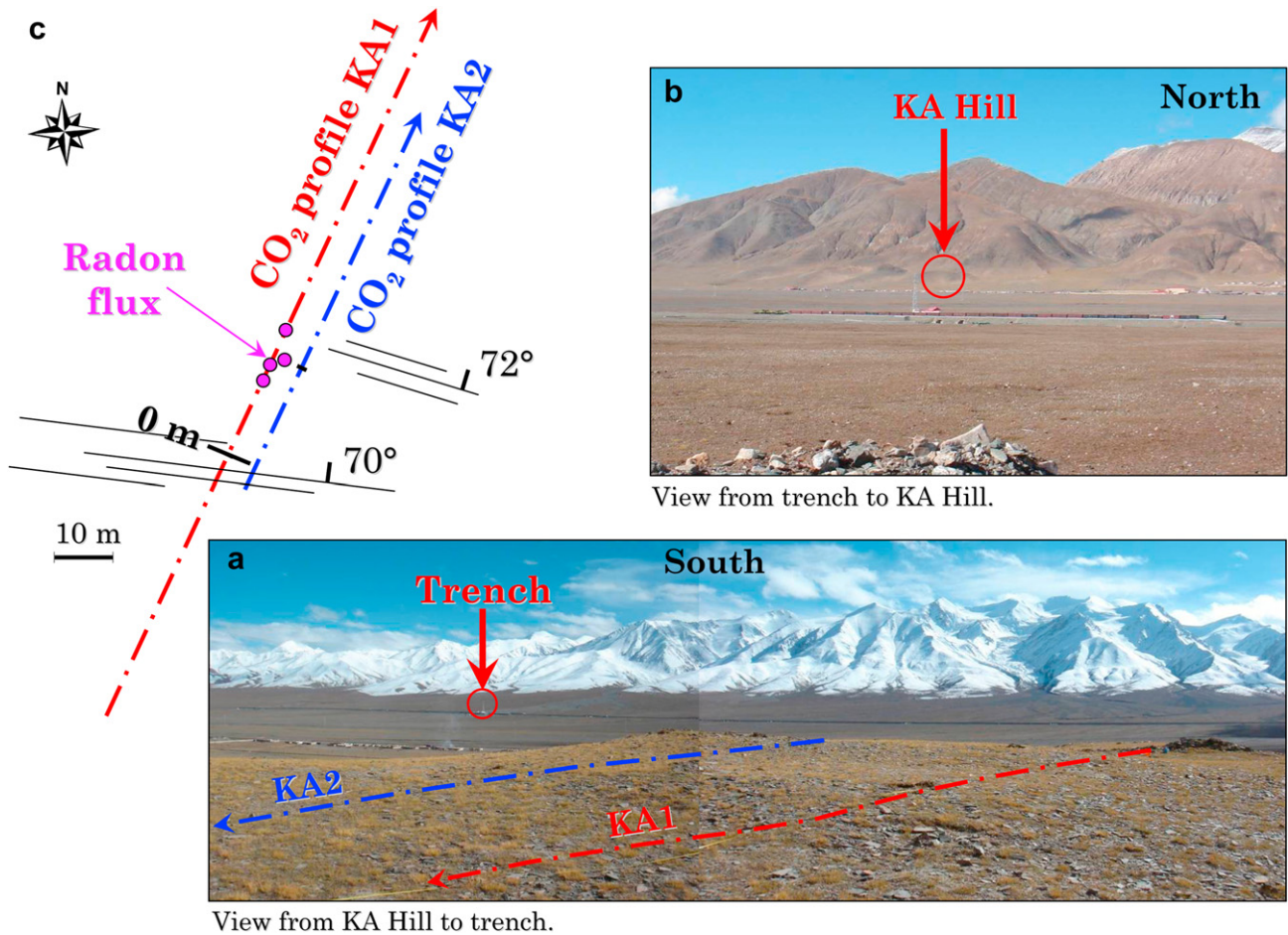


Fig. 3. Location of radon and carbon dioxide flux measurements on KA hill, at an altitude of 400 m a.s.l., 3 km north of the main trace of Kunlun Fault. (a) View of trench and southern part of the Xidatan valley from summit of KA hill. (b) View from trench, showing the KA hill. (c) Sketch of profiles performed on the KA hill.

always remained larger than the background flux measured on the soil surface, it was significantly smaller in the southern section of the trench on September 27 than on September 28. The reduction of the flux on September 27 might be attributed to slight rainfall. Alternatively, the enhancement of the flux on September 28 may be attributed to a rapid decrease of the atmospheric pressure, leading to a barometric pumping effect (Clements and Wilkening, 1974).

The long profile of carbon dioxide flux (Fig. 5), which could not be extended much north of the fault because of steady snowfall at the end of the experiment, exhibited a spatially uniform value of the carbon dioxide flux, similar to the values observed along the short profile, with an average value of 12.9 ± 3.3 (tot.) $\text{g m}^{-2} \text{day}^{-1}$. Within 1 m of the fault trace, the average carbon dioxide flux was $6.9 \pm 1.3 \text{ g m}^{-2} \text{day}^{-1}$, thus significantly smaller than the values obtained at larger distances from the fault. Inside the trench, the

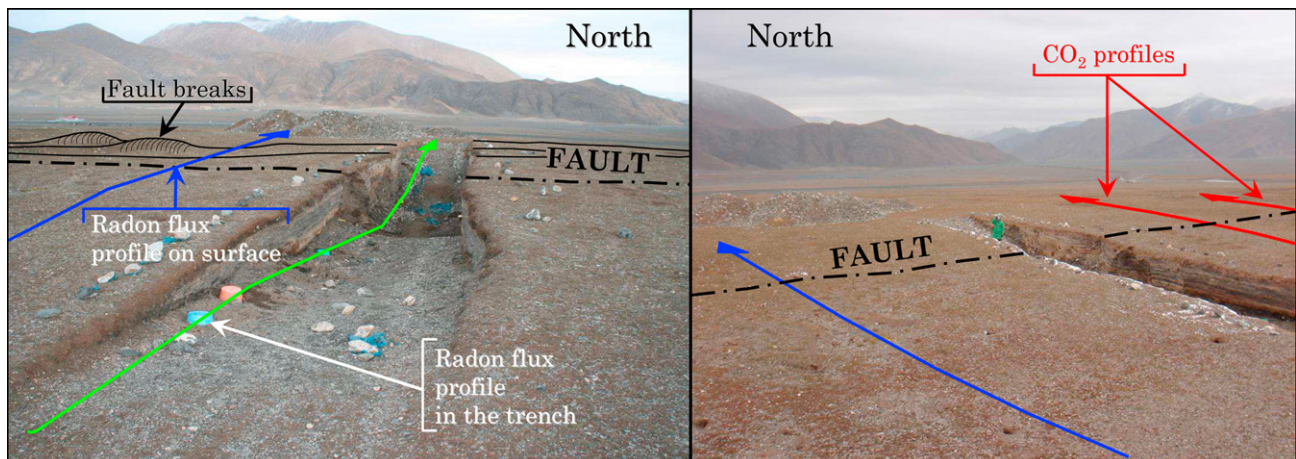


Fig. 4. Location of radon and carbon dioxide flux measurements near the trench across the surface trace of the Xidatan segment of Kunlun fault. Altitude of the surveyed area is 4215 m a.s.l.

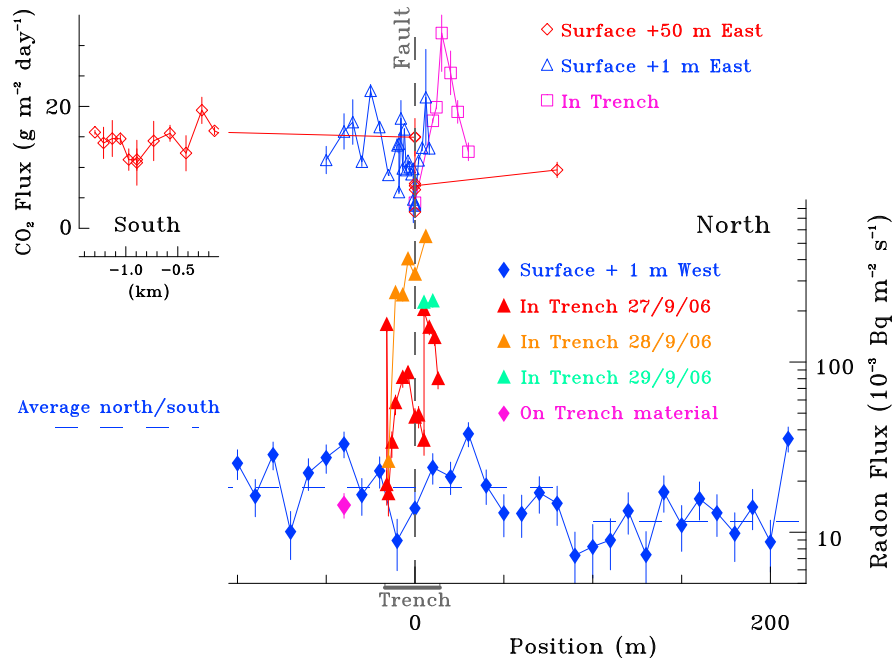


Fig. 5. Results of radon and carbon dioxide flux measurements across the trace of the Xidatan segment of Kunlun fault. Measurements performed on soil surface are compared with results at the bottom of trench. The origin of abscissas in the plots corresponds to the fault trace in the trench. Errors are point-to-point errors only, not including the common systematic uncertainty.

carbon dioxide remained at a level similar to the background value, with a mean value in the trench of 18.7 ± 3.3 (tot.) $\text{g m}^{-2} \text{day}^{-1}$, and a maximum value of 32.1 ± 6.3 $\text{g m}^{-2} \text{day}^{-1}$.

5. Results of measurements on the KA hill

On the KA hill, a significant carbon dioxide flux, larger than $80 \text{ g m}^{-2} \text{day}^{-1}$ was observed consistently on both profiles over

a distance of about 20 m. The peak values are 421 ± 130 (tot.) $\text{g m}^{-2} \text{day}^{-1}$ for the KA1 profile and 179 ± 45 (tot.) $\text{g m}^{-2} \text{day}^{-1}$ for the KA2 profile. Flux measurements were repeated eight times over a 48 h period at the maximum of KA1 profile (20 m north of origin), and values varied from $65 \pm 9 \text{ g m}^{-2} \text{day}^{-1}$, significantly larger than the background level, up to $421 \pm 77 \text{ g m}^{-2} \text{day}^{-1}$, with a mean of 187 ± 61 (tot.) $\text{g m}^{-2} \text{day}^{-1}$ (Fig. 7). Such large temporal variations suggested that advective transport was modulated by atmospheric pressure variations.

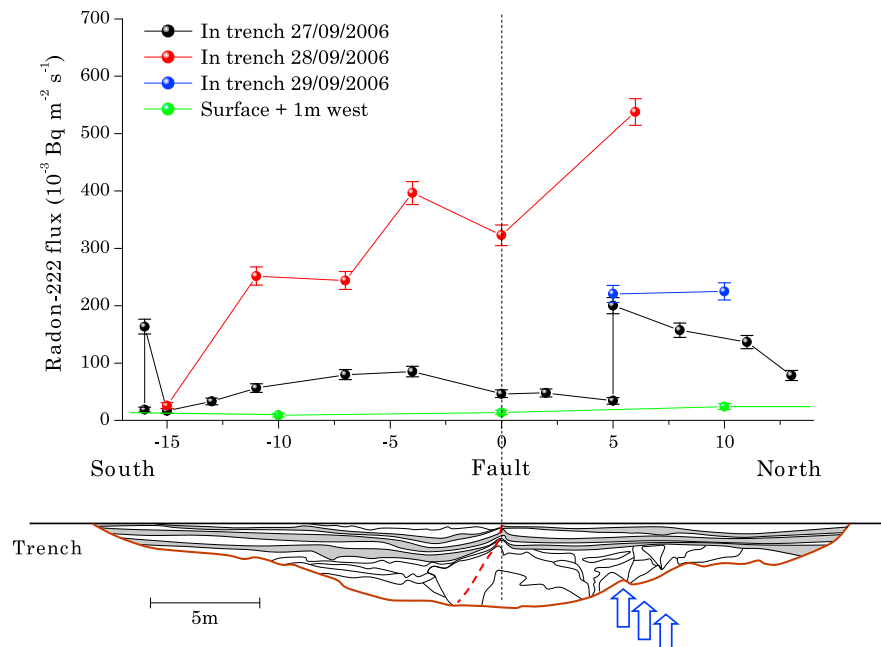


Fig. 6. Results of radon flux measurements at the bottom of the trench excavated across the Xidatan segment of the Kunlun fault. A picture of the Eastern wall of trench is shown below the data plots. Errors are point-to-point errors only, not including the common systematic uncertainty.

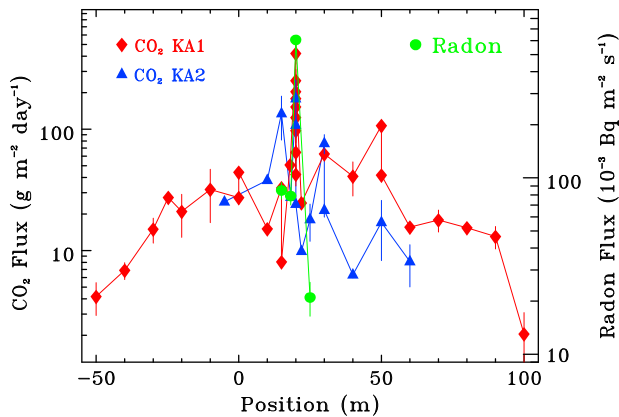


Fig. 7. Results of radon and carbon dioxide flux measurements on the KA hill at Xidatan, 3 km north of Kunlun Fault. Errors are point-to-point errors only, not including the common systematic uncertainty.

Four measurements of the radon flux were also performed on the KA hill (Fig. 3a), and the results are shown in Fig. 7. While three values were not significantly larger than the background value (average value of $62 \pm 20 \text{ mBq m}^{-2} \text{ s}^{-1}$), a large radon flux of $607 \pm 35 \text{ (tot.) mBq m}^{-2} \text{ s}^{-1}$ was observed at the point where the maximum carbon dioxide flux was observed. This large value was unambiguous, with a photomultiplier count exceeding 1000 in 3 min.

6. Discussion

The observed magnitude of the radon flux was close to the world average of $22 \text{ mBq m}^{-2} \text{ s}^{-1}$ (Nazaroff, 1992) and to annual mean values ranging from 5.9 to $59.6 \text{ mBq m}^{-2} \text{ s}^{-1}$, with an average of $24 \text{ mBq m}^{-2} \text{ s}^{-1}$, reported for soils in East Asia (Zhuo et al., 2005). An average of $37 \text{ mBq m}^{-2} \text{ s}^{-1}$ was reported for Quaternary deposits (Ielsch et al., 2001), larger than the mean value of $14.1 \pm 1.0 \text{ (tot.) mBq m}^{-2} \text{ s}^{-1}$ observed near the trench. Soil gas was also sampled at a depth of 15 cm, 1 m east of the trench, and the radon concentration, measured using a Lucas cell, was $10,800 \pm 500 \text{ Bq m}^{-3}$. Both the activity value measured and the observed mean flux were compatible with radon diffusive transport of radon in a soil having a homogeneous radium concentration of about 40 Bq kg^{-1} (Nazaroff, 1992).

Thus, the enhanced radon flux must result from advective transport from a deeper source, which might reflect enhanced gas permeability along the fault. Radon flux values larger than $100 \text{ mBq m}^{-2} \text{ s}^{-1}$ have been observed over granites and leucogranites (Ielsch et al., 2001) which are characterized by values ranging from 9 to $837 \text{ mBq m}^{-2} \text{ s}^{-1}$, with a mean of $72 \text{ mBq m}^{-2} \text{ s}^{-1}$. Our observations, thus, suggest an enhanced connectivity through the sedimentary cover to a deeper bedrock containing granites in the vicinity of the fault. The maximum value of the flux in the trench remained small compared with values larger than $3000 \text{ mBq m}^{-2} \text{ s}^{-1}$ observed near a hot spring in Central Nepal (Girault et al., 2009; Perrier et al., 2009), where massive carbon dioxide degassing occurs. Nevertheless, our results (Fig. 5) provide one of the most significant radon anomalies reported so far in association with a tectonic fault (Table 1).

The mean CO_2 flux value across the fault ($12.9 \pm 3.3 \text{ g m}^{-2} \text{ day}^{-1}$) was similar to background values reported in California (Lewicki et al., 2003), or values ranging from 5 to $20 \text{ g m}^{-2} \text{ day}^{-1}$ observed in the Kathmandu valley in Nepal (Perrier et al., 2009).

The average peak CO_2 flux observed on the KA hill was significantly larger ($187 \pm 61 \text{ g m}^{-2} \text{ day}^{-1}$), but such values of the carbon

dioxide flux remain small compared with maximum values recorded on active volcanoes and geothermal zones, which typically exceed $10,000 \text{ g m}^{-2} \text{ day}^{-1}$ on the Stromboli in Sicilia (Finizola et al., 2006), $7000 \text{ g m}^{-2} \text{ day}^{-1}$ at the Yangbajain geothermal field in Central Tibet (Chiodini et al., 1998), or $19,000 \text{ g m}^{-2} \text{ day}^{-1}$ near a hot spring in Central Nepal (Girault et al., 2009; Perrier et al., 2009). Such high values are quite exceptional, however, and lower values are more commonly observed. A mean value of $1000 \text{ g m}^{-2} \text{ day}^{-1}$, for example, was determined on the San Vicente volcano in El Salvador (Salazar et al., 2002). In the Dixie Valley geothermal field in California (Bergfeld et al., 2001), values reaching up to $570 \text{ g m}^{-2} \text{ day}^{-1}$ were only observed at a location adjacent to a fumarole. The maximum value recorded on the KA hill ($421 \pm 77 \text{ g m}^{-2} \text{ s}^{-1}$) was of the same order of magnitude.

7. Conclusion

In this paper, we show that a significant soil radon flux was measured in a trench across the KF in Xidatan. However, since no signal was observed along a parallel soil surface profile, the radon anomaly associated with the fault would have been missed without the opportunity provided by the trench. This implies that soil, especially rich in clay and with high water content, can provide an efficient barrier to the escape of radon gas to the atmosphere. This may explain why, in several instances, no significant enhancement of radon exhalation was reported across large strike-slip faults similar to the KF. To detect a signal, it may thus be necessary to sample the soil gas at a depth significantly greater than 1 m. Therefore, to assess the presence or absence of a radon anomaly, removal of a sufficient thickness of soil is mandatory, and should be performed to revisit radon profiles across major faults. It is also important to point out that it is only thanks to an excavated trench that the structure of the fault near surface can be properly observed, and that gas flux measuring points can be located. The goal, in this context, is not to locate the fault trace using gas profiles, which may or may not be possible, but to identify interesting gas discharge points when the fault structure is known.

While the high radon flux anomalies found spot on the seismic fault trace must be associated with the fault, our experiment does not preclude the existence of other radon exhalation zones in the vicinity of the fault because the trench used was only 20 m long. The Kunlun fault is a large lithospheric structure accommodating deformation at continental scale. Hence, while the active fault trace is highly localized with seismic deformation across a narrow belt at most a few tens of meters wide in the field, the damage zone associated with the long-term history of the fault may be wider than several hundred meters. More specifically, the Xidatan site trough corresponds to a left-lateral step over of the KL fault that produced local extension during an earlier fault evolution stage (Van der Woerd et al., 2000). Normal faults associated with this earlier stage are still visible, particularly near the KA Hill, which may explain the high radon flux at that location (Figs. 1 and 2).

Our preliminary data, thus, indicate that trenching is relevant, and may be sometimes compulsory, to be able to assess properly a radon flux around an active fault. In addition, it might be important to investigate secondary fracture systems, which geological or tectonic arguments can relate to the main fault. While observations made at some distance may be more difficult to relate to the fault activity, flux anomalies need to be identified and analyzed systematically. More work is needed to assess such methodological issues with the required caution before any meaningful large-scale mapping can be undertaken.

Acknowledgments

The authors thank the members of the Chinese Earthquake Administration from Beijing, Lanzhou and Golmud for assistance during fieldwork. We thank E. Pili for the fruitful discussions and support. This work was supported by funding from ANR-05-CATT-0006. This is IGP contribution 2589.

References

- Al-Batiana, B.A., Al-Taj, M.M., Atallah, M.Y., 2005. Relation between radon concentrations and morphotectonics of the Dead Sea transform in Wadi Araba, Jordan. *Radiat. Meas.* 40 (2–6), 539–543.
- Atallah, M.Y., Al-Batiana, B.A., Mustafa, H., 2001. Radon emanation along the Dead Sea transform (rift) in Jordan. *Environ. Geol.* 40, 1440–1446.
- Baubron, J.-C., Allard, P., Sabroux, J.-C., Tedesco, D., Toutain, J.-P., 1991. Soil gas emanations as precursory indicators of volcanic eruptions. *J. Geol. Soc. Lond.* 148, 571–576.
- Baubron, J.-C., Rigo, A., Toutain, J.-P., 2002. Soil gas profiles as a tool to characterise active tectonic areas: the Jaut Pass example (Pyrenees, France). *Earth Planet. Sci. Lett.* 196 (1–2), 69–81.
- Bergfeld, D., Goff, F., Janik, C.J., 2001. Elevated carbon dioxide flux at the Dixie Valley geothermal field, Nevada; relations between surface phenomena and the geothermal reservoir. *Chem. Geol.* 177 (1–2), 43–66.
- Burton, M., Neri, M., Condarelli, D., 2004. High spatial resolution radon measurements reveal hidden active faults on Mt. Etna. *Geophys. Res. Lett.* 31 (7), 1–4.
- Chiodini, G., Cioni, R., Guidi, M., Raco, B., Marini, L., 1998. Soil CO₂ flux measurements in volcanic and geothermal areas. *Appl. Geochem.* 13 (5), 543–552.
- Clements, W.E., Wilkening, M.H., 1974. Atmospheric pressure effects on ²²²Rn transport across the earth–air interface. *J. Geophys. Res.* 79, 5025–5029.
- Ferry, C., Beneito, A., Richon, P., Robe, M.C., 2001. An automatic device for measuring the effect of meteorological factors on radon-222 flux from soils in the long term. *Radiat. Prot. Dosim.* 93 (3), 271–274.
- Finizola, A., Revil, A., Rizzo, E., Piscitelli, S., Ricci, T., Morin, J., Angeletti, B., Mocochain, L., Sortino, F., 2006. Hydrogeological insights at Stromboli volcano (Italy) from geoelectrical, temperature, and CO₂ soil degassing investigations. *Geophys. Res. Lett.* 33, L17304.
- Geological Bureau of Qinghai Province, 1980. Geological map of Golmud, 1:200,000, Qinghai Province.
- Giammanco, S., Immè, G., Mangano, G., Morelli, D., Neri, M., 2009. Comparison between different methodologies for detecting radon in soil along an active fault: the case of the Pernicana fault system, Mt. Etna (Italy). *Appl. Radiat. Isot.* 67 (1), 178–185.
- Girault, F., Koirala, B.P., Perrier, F., Richon, P., Rajaure, S., 2009. Persistence of radon-222 flux during monsoon at a geothermal zone in Nepal. *J. Environ. Radioact.* 100, 955–964.
- Haibing, L., Van der Woerd, J., Tapponnier, P., Klinger, Y., Xuexiang, Q., Jingsui, Y., Yintang, Z., 2005. Slip rate on the Kunlun fault at Hongshui Gou, and recurrence time of great events comparable to the 14/11/2001, Mw ~7.9 Kokoxili earthquake. *Earth Planet. Sci. Lett.* 237, 285–299.
- Heiligmann, M., Stix, J., Williams-Jones, G., Lollar, B.S., Gustavo Garzon, V., 1997. Distal degassing of radon and carbon dioxide on Galeras volcano, Colombia. *J. Volcanol. Geoth. Res.* 77, 267–283.
- Ielsch, G., Thieblemont, D., Labeled, V., Richon, P., Tymen, G., Ferry, C., Robe, M.-C., Baubron, J.-C., Bechennec, F., 2001. Radon (²²²Rn) level variations on a regional scale: influence of the basement trace element (U, Th) geochemistry on radon exhalation rates. *J. Environ. Radioact.* 53 (1), 75–90.
- Inceoz, M., Baykara, O., Aksoy, E., Dogru, M., 2006. Measurements of soil gas radon in active fault systems: a case study along the North and East Anatolian fault systems in Turkey. *Radiat. Meas.* 41 (3), 349–353.
- Ioannides, K., Papachristodoulou, C., Stamoulis, K., Karamanis, D., Pavlides, S., Chatzipetros, A., Karakala, E., 2003. Soil gas radon: a tool for exploring active fault zones. *Appl. Radiat. Isot.* 59, 205–213.
- Israël, H., Björnsson, S., 1966. Radon (²²²Rn) and thoron (²²⁰Rn) in soil air over faults. *Zeit. Geophysik.* 33, 48–64.
- Kemski, J., Klingel, R., Schneiders, H., Siehl, A., Wiegand, J., 1992. Geological structure and geochemistry controlling radon in soil gas. *Radiat. Prot. Dosim.* 45 (1/4), 235–239.
- King, C.-Y., King, B.-S., Evans, W.C., Zhang, W., 1996. Spatial radon anomalies on active faults in California. *Appl. Geochem.* 11 (4), 497–510.
- Klinger, Y., Xu, X., Tapponnier, P., Van der Woerd, J., Lasserre, C., King, G., 2005. High-resolution satellite imagery mapping of the surface rupture and slip distribution of the Mw ~7.8, 14 November 2001 Kokoxili earthquake, Kunlun fault, northern Tibet, China. *Bull. Seism. Soc. Am.* 95 (5), 1970–1987.
- Lewicki, J.L., Evans, W.C., Hilley, G.E., Sorey, M.L., Rogie, J.D., Brantley, S.L., 2003. Shallow soil CO₂ flow along the San Andreas and Calaveras Faults. *J. Geophys. Res.* 108, 2187.
- Lucas, H.F., 1957. Improved low-level alpha-scintillation counter for radon. *Rev. Sci. Instrum.* 28 (9), 680–683.
- Nazaroff, W.W., 1992. Radon transport from soil to air. *Rev. Geophys.* 30 (2), 137–160.
- Perrier, F., Richon, P., Byrdina, S., France-Lanord, C., Rajaure, S., Koirala, B.P., Shrestha, P.L., Gautam, U.P., Tiwari, D.R., Revil, A., Bollinger, L., Contraires, S., Bureau, S., Nath Sapkota, S., 2009. A direct evidence for high carbon dioxide and radon-222 discharge in Central Nepal. *Earth Planet. Sci. Lett.* 278, 198–207.
- Richon, P., Bernard, P., Labeled, V., Sabroux, J.-C., Beneito, A., Lucius, D., Abbad, S., Robe, M.-C., 2007. Results of monitoring ²²²Rn in soil gas of the Gulf of Corinth region, Greece. *Radiat. Meas.* 42, 87–93.
- Richon, P., Sabroux, J.-C., Halbwachs, M., Vandemeulebrouck, J., Poussielgue, N., Tabbagh, J., Punongbayan, R., 2003. Radon anomaly in the soil of Taal volcano, the Philippines: a likely precursor of the M 7.1 Mindoro earthquake (1994). *Geophys. Res. Lett.* 30 (9), 1481. doi:10.1029/2003GL016902. 2003.
- Salazar, J.M.L., Perez, N.M., Hernandez, P.A., Soriano, T., Barahona, F., Olmos, R., Cartagena, R., Lopez, D.L., Lima, R.N., Melian, G., 2002. Precursory diffuse carbon dioxide degassing signature related to a 5.1 magnitude earthquake in El Salvador, Central America. *Earth Planet. Sci. Lett.* 205 (1–2), 81–89.
- Steinitz, G., Vulkan, U., Lang, B., Gillat, A., Zafir, H., 1992. Radon emanation along border faults of the rift in the Dead Sea area. *Isr. J. Earth Sci.* 41, 9–20.
- Tanner, A.B., 1964. Radon migration in the ground: a review. In: Adams, J.A.S., and Lowder, W.M., (Eds.), *Proceeding of the Natural Radiation Environment*, Chicago, Chap. 9, 161–190.
- Tansi, C., Tallarico, A., Iovine, G., Folino Gallo, M., Falcone, G., 2005. Interpretation of radon anomalies in seismotectonic and tectonic-gravitational settings: the south-eastern Crati Graben (Northern Calabria, Italy). *Tectonophysics* 396 (3–4), 181–193.
- Tapponnier, P., Molnar, P., 1977. Active faulting and tectonics in China. *J. Geophys. Res.* 82, 2905–2930.
- Tapponnier, P., Xu, Z., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., Yang, J., 2001. Oblique stepwise rise and growth of the Tibet plateau. *Science* 294 (5547), 1671–1677.
- Toutain, J.-P., Baubron, J.-C., 1999. Gas geochemistry and seismotectonics: a review. *Tectonophysics* 304 (1–2), 1–27.
- Van der Woerd, J., Ryerson, F.J., Tapponnier, P., Mériaux, A.-S., Gaudemer, Y., Meyer, B., Finkel, R.C., Caffee, M.W., Zhao, G., Xu, X., 2000. Uniform slip-rate along the Kunlun Fault: implications for seismic behaviour and large-scale tectonics. *Geophys. Res. Lett.* 27 (16), 2353–2356.
- Van der Woerd, J., Tapponnier, P., Ryerson, F.J., Mériaux, A.-S., Meyer, B., Gaudemer, Y., Finkel, R.C., Caffee, M.W., Zhao, G., Xu, Z., 2002. Uniform post-glacial slip-rate along the central 600 km of the Kunlun Fault (Tibet), from ²⁶Al, ¹⁰Be, and ¹⁴C dating of riser offsets, and climatic origin of the regional morphology. *Geophys. J. Int.* 148, 356–388.
- Walia, V., Su, T.C., Fu, C.C., Yang, T.F., 2005. Spatial variations of radon and helium concentrations in soil–gas across the Shan-Chiao fault, Northern Taiwan. *Radiat. Meas.* 40 (2–6), 513–516.
- Wen, X., Yi, G., Xu, X., 2007. Background and precursory seismicities along and surrounding the Kunlun fault before the Ms8.1, 2001, Kokoxili earthquake, China. *J. Asian Earth Sci.* 30, 63–72.
- Wilkening, M.H., Hand, J.E., 1960. Radon flux at the earth–air interface. *J. Geophys. Res.* 65 (10), 3367–3370.
- Xu, X., Yu, G., Klinger, Y., Tapponnier, P., Van der Woerd, J., 2006. Reevaluation of surface rupture parameters and faulting segmentation of the 2001 Kunlunshan earthquake (Mw 7.8), northern Tibetan Plateau, China. *J. Geophys. Res.* 111, B05316.
- Zhuo, W., Furukawa, M., Guo, Q., Shin Kim, Y., 2005. Soil radon flux and outdoor radon concentrations in East Asia. *Int. Congr. Ser.* 1276, 285–286.