Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Full length Article

Spatial and temporal anomalies of soil gas in northern Taiwan and its tectonic and seismic implications



Journal of Asian Earth Sciences

Ching-Chou Fu^{a,*}, Tsanyao Frank Yang^{b,1}, Cheng-Hong Chen^b, Lou-Chuang Lee^a, Yih-Min Wu^b, Tsung-Kwei Liu^b, Vivek Walia^c, Arvind Kumar^c, Tzu-Hua Lai^d

^a Institute of Earth Sciences, Academia Sinica, Taiwan

^b Department of Geosciences, National Taiwan University, Taiwan

^c National Center for Research on Earthquake Engineering, NARL, Taiwan

^d Central Geological Survey, MOEA, Taiwan

ARTICLE INFO

Article history: Received 12 April 2016 Received in revised form 17 February 2017 Accepted 18 February 2017 Available online 22 February 2017

Keywords: Soil gas Radon Earthquake Precursor Taiwan

ABSTRACT

In this paper, we study (1) the spatial anomalies and (2) the temporal anomalies of soil gas in northern Taiwan. The spatial anomalies of soil gas are related to tectonic faults, while the temporal anomalies of soil gas are associated with pre-earthquake activities. Detailed soil gas sampling was systematically performed, and the analysis of the collected gas species shows that high helium and nitrogen concentrations appear in samples from specific sites, which coincide with the structural setting of the area studied. This analysis indicates the possibility of using these soil gases to determine fault zones in the studied area. Based on the soil gas data, a station (Tapingti) for automatic soil gas monitoring was constructed on an appropriate site at the fault zone. Some anomalous high radon concentrations at certain times can be identified from the dataset, which was generated by the continuous monitoring of soil gas for over a year. Notably, many of these anomalies were observed several hours to a few days before the earthguakes $(M_I > 3)$ that occurred in northern Taiwan. By combining the information of epicenters and fault plane solutions of these earthquakes, we find that the shallow earthquakes (<15 km) were mainly strikeslip and normal-type earthquakes, and concentrated within a distance of 30 km to the monitoring site (Group A). The deep earthquakes (>20 km) were mainly thrust-type earthquakes and distributed in greater distances (>45 km) east of the monitoring site (Group B). Such focal mechanisms of earthquakes suggest an extensional and compressional structural domain in the continental crust for Group A and Group B earthquakes, respectively. It is suggested that the pre-earthquake activities associated with the seismicity of Group B may be transmitted along the major decollement in the region below the Tapingti station, leading to the observed soil gas enhancements.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Taiwan is a young and active mountainous island formed by collision between the Philippine Sea plate and the Eurasian plate, and is thus densely faulted. The 1999 Chichi earthquake (Mw 7.6) that occurred in Central Taiwan induced faulting and remarkable surface rupture along the Chelungpu Fault, resulting in severe casualties as well as property loss. Hence, the major pursuits in disaster prevention in Taiwan are to better understand the distribution of active faults, and to assess potential earthquake hazard areas.

* Corresponding author.

Active fault zones usually have higher permeability than surrounding strata, and can therefore provide conduits for gases originating from the deep crust or mantle to migrate towards the surface. It is also common for mantle-derived gases to exhibit higher concentrations and higher flux rates due to greater strains (Trique et al., 1999; Pulinets and Dunajecka, 2007). Northern Taiwan was chosen for this study because it has been proven that it is an area where mantle-derived gases are still emanating (Lin et al., 2004; Yang et al., 2005a).

General overviews of the geochemical, structural, and seismic features in tectonically active areas have shown some evidence of correlation between soil gas anomalies and tectonic activities (Toutain et al., 1992; Ciotoli et al., 1998; Toutain and Baubron, 1999; Fu et al., 2008). For example, it has been found that blind active faults, which are usually difficult to identify at the surface,



E-mail address: ccfu@earth.sinica.edu.tw (C.-C. Fu).

¹ Deceased.

can be outlined by soil gas surveys (Fu et al., 2005; Walia et al., 2005a, 2008). Useful soil gases include noble gases, radon, and helium, which play important roles in fault delineation and earthquake precursory studies (Claesson et al., 2004; Chyi et al., 2005; Walia et al., 2005b; Yang et al., 2006; Kumar et al., 2009a; Reddy and Nagabhushanam, 2011; Fu et al., 2017).

The famous precursory anomalies in the radon concentration of groundwater have observed prior to the Izu-Oshima-kinkai earthquake in 1978 and Kobe earthquake in 1995 (Wakita et al., 1980; Igarashi et al., 1995; UNSCEAR, 2000). Changes in gas compositions have also proposed as potential precursors (Sugisaki, 1978; Sano et al., 1998). Pre-, co-, and post-seismic signals can be observed by soil gas anomalies (King, 1986; Wakita et al., 1989; Fu et al., 2008; Kumar et al., 2009b), although they are sometimes unrelated to seismic events (Heinicke et al., 1995). Some earlier investigations have revealed that these anomalies may also be affected by meteorological parameters, such as atmospheric pressure, humidity, temperature, and rainfall (Washington and Rose, 1992; Bunzl et al., 1998; Iakovleva and Ryzhakova, 2003; Fu et al., 2017). Therefore, meteorological effects are also taken into consideration when analyzing soil gas anomalies.

In a compilation of gas emissions to catalog observed earthquake precursors (Cicerone et al., 2009), only earlier works on water radon in Taiwan were mentioned (Liu et al., 1983, 1985). In recent years, there have been an increasing number of studies focusing on the use of gas measurements in Taiwan. For example, radon anomalies have been observed in soil gas and water prior to earthquakes in different areas; hence, their potential as an earthquake precursor has been mentioned or recognized (Chyi et al., 2005; Fu et al., 2008, 2009, 2017; Kumar et al., 2009a, 2009b; Kuo et al., 2006a, 2006b; Walia et al., 2009, 2010, 2013; Yang et al., 2005b).

There are three objectives in this work. First, soil gas concentrations of He, Rn, N₂, CO₂, and CH₄ that might have originated from great depths were analyzed. Geochemical data obtained from the soil gas method were compared with other geological and geophysical information on the known faults in the studied area, to see if they are useful for detecting buried faults or fractures. Second, a station equipped with a seismograph and facilities for the automatic measuring of soil Rn, Th, and CO₂ concentrations, as well as meteorological factors (atmospheric pressure, temperature, humidity, and rainfall), was installed on a geochemically sensitive site for continuous monitoring. Results of continuous monitoring on multiple parameters were used to delineate the relationship between soil gas variations and regional earthquake events. Third, data regarding relevant earthquakes were synthesized to formulate a structural configuration that can account for the proposed seismic velocity model in the context of the recent tectonics in Taiwan. The potential for using soil radon as an earthquake precursor in northern Taiwan was assessed on this basis.

2. Geological background of northern Taiwan

Tectonics of northern Taiwan is characterized by its location at the junction of two subduction sectors pertaining to the interactions between the Eurasian and the Philippine Sea plates, namely, the E-W trending Ryukyu subduction zone resulting from the Philippine Sea plate subducting northwardly beneath the Eurasian plate, and the N-S trending Manila Trench system and its extension to the island of Taiwan related to the Eurasian plate that subducts eastwardly beneath the Philippine Sea plate (Fig. 1a). Continuous convergence due to the subduction/collision of these two plates has brought the northwest-bounding Luzon Arc close to the edge of the Eurasian continent. Consequently, a NW-SE shortening in Taiwan is accommodated by a series of subparallel ENE-WSW trending reverse faults and folds developed from east to west, and many faults are boundaries for the tectonostratigraphic units of Taiwan (see the later sections). There are eight major active faults in northern Taiwan, and according to the geodetic and geological data, the fault motion changes progressively from compression to extension in northwestern and northeastern Taiwan, respectively (Hu et al., 1996). Therefore, northern Taiwan is a potential area to study variations of rare gas along active faults in relation to the earthquakes occurring in two sides of the transition zone between these two stress domains.

The target of this study is the Kuanhsi-Chutung area in northwestern Taiwan (Fig. 1b). Field geological survey, drilling core, ground resistivity, micro-earthquake, and gravity data (Lin et al., 2007) show that there are three major faults, the Tapingti Fault, the Shihmen Fault, and the Ruanciao Fault, cutting through this area in a NE-SW trend. The Tapingti Fault is a reverseseparation fault dividing the Pliocene Cholan Formation (siltstone-sandstone alternations predominant with sandstone) and the Pleistocene Yangmei Formation (sandstone-shale alternations predominant with sandstone). It is a high-angle thrust with a fault plane dipping to the east. The Shihmen Fault is a branch fault developing from the Tapingti Fault, with thrust and strikeslip components dipping to the southeast. The Ruanciao Fault is another high-angle thrust with a strike-slip component dipping to the southeast. In fact, this is also a reverse-separation fault separating the Miocene Nanchung Formation (thin sandstonesiltstone-shale alternations predominant with sandstone) from the Pliocene Cholan Formation. Exposures of both the Tapingti Fault and the Ruanciao Fault have extended to the overlying Holocene laterite and conglomerate formations, indicating that these faults may be active. However, it is rather difficult to recognize their complete surface distributions based on field and ground resistivity data. Global Position System (GPS) and precise leveling data from 1999 to 2006 revealed horizontal and vertical variations in the displacement field across faults, showing that the Tapingti Fault has less crustal deformation compared to other major faults in Taiwan (Rau et al., 2008).

3. Methodology

3.1. Principle

Gases in the air and gases derived from the deep crust and mantle have characteristic compositions that enable them to be easily distinguishable. This is an application of the fundamental basics of gas geochemistry. Soil gas compositions commonly possess the mixed characteristics of air and deep crust gases, because higher He, Rn, N₂, CO₂, and CH₄ concentrations in deeper crust often diffuse upwards to accumulate in the near-surface soil layers, and mix with air (Ciotoli et al., 1999; Tansi et al., 2005; Yuce et al., 2017). Soil gas compositions are also closely related to the porosity and composition of soils and rocks.

A basic assumption is that if the lithology of the wall rocks of a fault or fracture is essentially the same (i.e., the chemical compositions of wall rocks are similar), then the concentrations of gas species observed in the covering soil layers are greatly affected by soil types, due to the variability of porosity (Fu et al., 2005). Usually, active fault, fracture, and shear zones that cut through bedrock have higher permeability than adjacent undisturbed strata, and can thus act as channels for the upward migration of deep crust or mantle gases. These gases can then be stored in the covering soils of such tectonically active terrain, and provide information regarding the deep sources (Ciotoli et al., 1999; Baubron et al., 2002; Yang et al., 2003; Fu et al., 2005, 2008; Walia et al., 2005a, 2008). Based on this concept, the soil gas technique is commonly



Fig. 1. (a) A simplified tectonic setting sketch showing that the Philippine Sea Plate is moving towards Taiwan at a rate of 8 cm/yr. (b) The topographic map of northern Taiwan and the relative position of the study area (rectangle). Black dots indicate the soil gas measurement sites for (c) He, (d) N₂, and (e) CO₂. The contour maps of soil gas concentrations for (f) He, (g) N₂, and (h) CO₂. Red dots represent measuring sites that have soil gas concentrations greater than the threshold value. The star in (c) represents the location of the monitoring station (refer to text). Red structure lines denote the (1) Tapingti Fault, (2) Ruanciao Fault, (3) Shihmen Fault, (4) Chungchiaowo Syncline, (5) Antan Syncline, and (6) Nanhu Anticline.

adopted to explore unexposed fractures or blind faults, when these structural features are unobservable at the surface. The predominant soil type in the study area is sandy soil with high permeability; therefore, its pore space is expected to be filled with fluids and gases suitable for geochemical reconnaissance.

3.2. Sampling and analysis

With reference to the published topographic and geologic maps, sampling sites for probable faults were outlined in the Kuanhsi-Chutung area of northern Taiwan. The spatial variation survey of soil gases was carried out in a four-day period with stable meteorological conditions in August 2005. Soil gas samples were systematically collected from the 400-500 m spacing grid (Fig. 1c-h) and analyzed for He, N₂, Ar, O₂, CO₂, and CH₄. One week after the first soil gas survey, only a few sites with high helium concentration were chosen for the further analysis of soil radon. A total of 100 samples were collected with the following method described by Fu et al. (2005): soil gas sampling was conducted at depths of 80–100 cm, using a 130 cm steel probe with a 3 cm diameter. A disposable sharp awl was attached to the bottom of the steel probe to facilitate penetration into the soil with hammering, and to prevent the probe from being blocked by soil. Then, a thin solid billet was inserted into the hollow steel probe to displace the awl. A vacuum hand-pump was connected to a double-filtered (for dust and mist) rubber tube, which was then connected to the hollow steel probe to suck out the existing air before the collection of soil gases. Gas analysis was conducted within a few hours of sampling, using a leak detector (ASM100HDS, Alcatel) for helium, a radon detector (RTM 2100, SARAD), and micro gas chromatography (CP4900, Varian) for other gases (Ar, N₂, O₂, CH₄, and CO₂). The analytical limit of detection was 0.02 ppm for helium, 30 Bq/m³ for radon, and 0.05% for the other gases. The average analytical uncertainty was about 5% for most gases; however, due to low concentrations, the uncertainty for helium may be up to 10%.

3.3. Setup of continuous measurements

A sensitive site, as evidenced by the high concentration of trace gases (He and N₂, Figs. 1 and 2) was chosen for building an automatic monitoring station. In addition to the radon and carbon dioxide detectors, the station was also equipped with a strong motion accelerograph and thermo-hygro-barometer-omb rometer for the detection of earthquake intensity and the collection of local meteorological data through time (Fig. 3). The main exhaust pipe for soil gases was 2.3 m long, 10 cm in diameter, and made of polyvinyl chloride (PVC), with its lower end merging into an artificial ditch. The ditch was lined with a 50 cm gravel layer, which facilitated the collection of soil gas into our selfdesigned system and water drainage during rainy days. The water trap and electric gas cooler were used to keep a low relative humidity when gases were channeled into the detector by internal pumping. Soil gases (radon, thoron, and carbon dioxide) and meteorological data were recorded once every 15 min, and transmitted to the laboratory at the National Taiwan University via the internet.

4. Results and discussions

Our results revealed that argon and oxygen did not show significant variation in all testing spots, and cannot be used as indicator gases for tracing fault distribution. Furthermore, limited sampling sites had observable methane concentrations. Therefore, discussion here only includes the results of the major gases, nitrogen and carbon dioxide, and the trace gases, helium and radon. The



Fig. 2. Quantile-quantile plots of calculated soil gas compositions for (a) He, (b) N_2 , and (c) CO_2 . The anomaly threshold values are indicated in each panel.

concentration of these gases vary greatly in all sampling sites: N₂ ranges from 57.20 ± 3.88 to $96.75 \pm 4.50\%$; CO₂ from 0.1 to $34.81 \pm 0.46\%$; He from 4.52 ± 0.02 to 6.13 ± 0.02 ppm; and Rn from 6600 ± 300 to $32,200 \pm 1800$ Bq/m³. These gas concentrations, especially radon, are generally higher than the concentrations found in air (N₂ = 78.08\%, CO₂ = 0.036\%, He = 5.24 ppm, and Rn < 100 Bq/m³), indicating that the degree of air contamination is small. Here, we use air composition as background to identify concentration anomalies for each gas species.



Fig. 3. A sketch of the monitoring station, including the gas collection system and associated equipment.

4.1. Recognition of anomalous concentrations

Samples were collected under the same weather conditions (atmospheric temperature, humidity, and precipitation) in order to eliminate possible meteorological effects on soil gas composition. The background level of a soil gas was made by two assessments: first, threshold values were calculated using the mean values plus two standard deviations, after trimming off the anomalously high values. Accordingly, the threshold values set for He, N₂. and CO₂ were 5.41 ppm, 86.34%, and 9.17%, respectively. Second, the quantile-quantile (Q-Q) plot provides another method to distinguish different populations between background and anomalous values (Kafadar and Spiegelman, 1986; Cheng et al., 1994). The resultant threshold values for anomalous signals for He, N₂, and CO_2 were 5.42 ppm, 86.31%, and 9.03%, respectively (Fig. 2), which did not deviate significantly from the former data set. Although the first method has been used for quite some time (Baubron et al., 2002; Fu et al., 2005), in the present study we adopted values derived from the Q-Q plot method, based on a more sophisticated statistic derivation. On this basis, soil gas concentrations higher than the threshold value are depicted as red dots (Fig. 1c-e). Further, contour maps for He, N₂, and CO₂ were constructed using the SURFER technique (Fig. 1f-h).

4.2. Spatial variation of soil gases

Reconnaissance on soil gas variation in space was also used to better understand the trace of targeted fault zones. This was based on the proposition that fault zones usually exhibit a higher carrier gas flux, and thus a higher rare gas concentration (Etiope and Lombardi, 1995; Yang et al., 2003; Ciotoli et al., 2004; Fu et al., 2005; Reddy et al., 2006; Hong et al., 2010; Yuce et al., 2017). Based on the results shown in Fig. 1c–e, we first assessed if soil gas concentrations can be used as potential indicators to define faults in the studied area, by examining the relationship between the anomalies of soil gases (helium, nitrogen, and carbon dioxide) and the traces of the NE-SW trending Tapingti, Ruanciao, and Shihmen Faults, and the Kuanhsi Anticline.

By comparing the nine sampling points near the trace of the Tapingti Fault (within 100 m) with the fault lines established in the Kuanhsi-Chutung area, we found three sites with anomalous He concentrations, three with anomalous N₂ concentrations, and none with anomalous CO₂ concentrations. Out of the ten spots near the Ruanciao Fault, we found six, five, and four sites with anomalous He, N₂, and CO₂ concentrations, respectively. Out of the seven spots close to the Shihmen Fault, only one site for He, one site for N₂, and none for CO₂ have noticeable concentration anomalies. Other anomalies occur at a few sites close to the Kuanhsi Anticline. The contour maps of He (1f), N_2 (1g), and CO_2 (1h) are also shown in Fig. 1. It is of particular interest that the higher soil gas values are very close to the Ruanciao Fault trace. This is in accordance with the NE-SW enhanced permeability belt (an indication of fault) along the southeastern part of the Ruanciao Fault, which has been defined by high-frequency micro-earthquakes (Lin et al., 2007). Although not all analyzed spots along the fault show soil gas anomalies, these features indicate that a high percentage (ca. 70%) of sites with gas anomalies indeed coincides with sites with tectonic structures. We found that high radon concentrations are spatially well correlated with soil helium at the several sites that were chosen for soil radon analysis (as mentioned above), especially along the fault zone. These results are not shown in Fig. 1 due to the low sample count. Accordingly, there is potential for the use of the soil gas method to detect buried faults and/or fractures in the study area.

4.3. Soil gases sources

Some trace gases in the earth's interior (e.g., Rn and He) move by diffusion. They usually migrate to the surface from deep sources together with other gases (e.g., CO_2 , N_2 , and CH_4) known as carrier gases (Etiope and Martinelli, 2002; Yang et al., 2003; Fu et al., 2005). Since both CO_2 and N_2 are abundant in the present case,

we investigated their ability as carrier gases for Rn and He at fault zones. When the variation of He was plotted against N₂, CO₂, and CH_4 (Fig. 4a-c), a positive correlation between He and N_2 $(R^2 = 0.798)$ was found. This suggests a deep origin for these two gases, and that nitrogen could be the carrier gas for helium along fault zones. Such a phenomenon is, in fact, commonly observed in active faults in NW Taiwan (Hong et al., 2010). He is inversely and poorly correlated with both CO_2 and CH_4 ($R^2 = 0.181$ and 0.508, respectively), which may indicate an effect of dilution due to the incorporation of a large upward flux volume of deep nitrogen. It is worth noting that He concentrations were mostly lower than the air background (Fig. 4c). When taking only samples with low He concentration into consideration to examine the relationship between CH₄ and CO₂, we obtained a positive correlation $(R^2 = 0.732, Fig. 4d)$. This suggests that relatively low He concentrations in the sample may be a consequence of dilution by the dispersion of large amounts of CH₄ and CO₂ in the shallow crust (Minissale et al., 2000). However, because CH₄ only occurs as a minor component in all samples, it is difficult to confirm this hypothesis in the present study, unless more supporting evidence (e.g., isotopic data) is provided.

4.4. Temporal variation of soil gases

The anomaly zones determined are gas geochemistry-sensitive and suitable for the soil gas monitoring of earthquake precursors (Chyi et al., 2001; Fu et al., 2008; Inan et al., 2008; Woith, 2015). A sensitive site on the study area, as evidenced by high concentrations in both major and trace gases, was chosen for long-term monitoring. This locality (identified in Fig. 1c) exhibits the highest soil helium and nitrogen values in the studied area. The time series data of soil gases (radon, thoron, and carbon dioxide) and meteorological factors from 14 June 2006 to 9 September 2007 are shown in Fig. 5. We observed wide ranges of gas concentrations at soil moistures between 42.2 and 91.8% and soil temperatures from 15.3 to 28.8 °C: 33 to 20,460 Bq/m³ for radon, 32 to 9908 Bq/m³ for thoron, and 0.0 to 0.2% for carbon dioxide. Temporal variations of all the meteorological factors were small, with an average atmospheric pressure, humidity, and temperature of delta 84.9 mb, 65.4%, and 22.5 °C, respectively. The local rainfall distribution should have an insignificant influence on soil gas variation. All earthquakes were recorded by the real-time strong-motion network from the Central Weather Bureau (CWB). The strongmotion accelerograph at the station detected the intensity of each earthquake. The distribution of the relevant earthquakes that could be detected in the monitoring station is shown in Fig. 6, and the catalog of related earthquakes is listed in Table 1.

The temporal variation of soil gases shows different patterns: carbon dioxide concentrations are rather stable, but radon and thoron show some high concentration peaks in the entire spectrum through time. Precursory soil gas signals have been recognized from previous studies, which suggested that the precursory signals distinguish the background value (e.g., annual or seasonal average) from real fluctuations before an earthquake (Fu et al., 2009). In this paper, we used a residual signal processing technique to reduce the regular frequent effects for data recording. For our analysis, a residual signal of concentration dA can be determined as the difference between the observed signal intensity (soil radon concentration) and the average of several days preceding the observation day:

$$dA(t) = A(t) - RA(t) = A(t) - \langle A(t) \rangle$$
(1)

In Eq. (1), A(t) is the concentration at time t for an observed day and RA(t) is the rolling average at the same time, t, for -7 days (7 days before the observed day). The residue is plotted in the lower part of Fig. 7a and b. We can define an anomalous threshold value by using this figure when dA(t) exceeds two standard deviations, which then can be used in identifying seismic events (Fig. 7).

A comparison of soil gas data and earthquakes detected by our strong motion recorder over the monitoring period indicates that the presence of radon and thoron anomalies is quite often accompanied by seismic activity, except for twelve of twenty-five marked earthquakes (c, e, f, h, j, k, l, n, r, s, v, and u in Figs. 5 and 7). A problem with power supply caused the loss of soil gas data from 27 September to 5 October 2006, from 21 to 23 October 2006, from 3 to 9 November 2006, and from 22 to 25 March 2007. Thus, radon anomalies could not be correlated during these periods for seismic events h and j. Background radon concentrations showed high fluctuations without significant Rn peaks after February 2007, which may be related to the high frequency earthquakes that occurred during that period. This caused a blurring of the anomalous duration time in the data spectrum, especially for events n and r. Slight increases of soil gas concentrations were observed before the



Fig. 4. Variation diagrams for soil gas compositions: (a) He versus N₂, (b) He versus CO₂, (c) He versus CH₄, and (d) CH₄ versus CO₂.



Fig. 5. (a) Temporal variations of soil gas concentrations (Rn, Th, and CO₂) from 14 June 2006 to 9 September 2007. Other parameters, such as atmospheric data (pressure, humidity, and temperature), rainfall, soil gas conditions (humidity and temperature), and earthquake events, are also included.

events c, s, and v, but the residual radon concentrations did not exceed the threshold values. Therefore, only five earthquakes did not correlate with soil gas anomalies. Each radon peak was assigned to one definite earthquake from our strong motion recorder with local intensity greater than 1, and could only be correlated to some precursory anomalous peaks a few hours to a few days before the event occurred. Each precursory time was identified as illustrated in Fig. 8a, and the precursory catalog of each earthquake is listed in Table 1.

A good example is the event g (Fig. 8a) for the pre-earthquake anomalous time (Δt) and the duration time (D_t), which was about 0.7 of a day before the earthquake. Here, Δt is the time difference between the peak of the anomaly and the earthquake event, and D_t is the time duration of gas anomalies for the earthquake event. Although some events could be linked to both anomalously high radon and thoron concentrations (Fig. 5), others were only related to radon anomalies. Epicenters for the former were usually nearsurface and close to the monitoring station. Because thoron has a comparatively short half-life (55 s) and can only diffuse a short distance, increasing thoron concentrations may be a sign that the impending earthquake epicenter will be shallow (Yang et al., 2005b). Therefore, the similar peak pattern of radon and thoron may imply that the earthquake is shallow and/or great, such that the increased stress can raise the inflow rate of Rn and Th in a short time.

The mechanism for the relationship between observed radon anomalies and adjacent seismic activities is still poorly understood, although several constraints from laboratory experiments and mathematical modeling have been described (Andrews, 1977;

Dobrovolsky et al., 1979; Bolt, 1999). The elastic rebound theory is by far one of the most accepted explanations for the relationship between radon anomalies and earthquakes. According to the theory, the maximum deformation of rocks might have occurred just before an impending earthquake, and led to a large increase in crack volume due to the growth of micro-fractures (dilatancy). The dilatancy diffusion model suggests that radon anomalies are related to the growth of mechanical cracks in the dilatancy, or the change of the inflow rate of gas. During the elastic strain build-up stage, micro-cracks develop, and are filled with gas and fluid from their surroundings. Radon emanating from rock grains would be one of the gases stored in the pore space, and it migrates most likely to the near-surface by way of carrying the processes of other gases. As a result, radon concentrations can increase to certain degrees before being released by the seismic event. When the movement of a fault or an earthquake occurs, the elastic strain energy stored in the rock is released; hence, micro-fractures return to their original state (Li et al., 2006; Fielding et al., 2008; Mair and Abe, 2008). Under this circumstance, radon concentrations also return to their original level as an earthquake event becomes tranquil. The development of micro-fractures in different stages before and after an earthquake is illustrated in Fig. 8b.

4.5. The relationship between the tectonic setting and the mechanism of gas/fluid migration

Taiwan is tectonically situated in terrain resulting from the oblique collision between the Philippine Sea plate and the continental margin of the Asiatic plate, with the former plate moving about



Fig. 6. Locations of earthquake epicenters (listed in Table 1) that were detected in our monitoring station. Solid symbols indicate those that can be related to an Rn anomalous peak in the monitoring site a few hours or days before the earthquake event occurred, and open symbols indicate those for which no anomalies can be confirmed. Group A earthquakes: epicenter distance is <30 km; Group B earthquakes: epicenter distance is <30 km; Group B earthquakes: epicenter distance is between 45 and 120 km.

85 mm/year (Yu et al., 1997). The collision that followed the initial subduction of the continental lithosphere due to the opening of the South China Sea commenced at about 15 Ma (Sibuet et al., 2002). This subduction system still prevails in the southern part of Taiwan (Malavieille et al., 2002). However, the young collision has greatly disturbed the subsurface structure beneath northern Taiwan. The observation of detectable earthquakes at the monitoring site and the seismic velocity structure of northern Taiwan were used to assess the potential of using soil gas anomalies as a precursory signal.

4.5.1. Spatial variation of related earthquakes

The epicenters of 25 earthquakes (listed in Table 1) are shown in Fig. 6, and they may be related to Rn anomalies recorded in the monitoring station. Based on the distance between the epicenter and the monitoring site, two groups of earthquakes were considered. Group A includes those with an epicenter distance of <30 km, and five out of seven earthquakes in this group show anomalous signals. When event j is excluded, the success rate is about 83%. Group B includes earthquakes with epicenter distances between 45 to 120 km, and six out of eleven such earthquakes show anomalous signals (ca. 55% success rate). We also found that anomalous signals were recorded in only two (w and y) out of seven events that had epicenter distances of >120 km. These earthquakes are less relevant to this study; hence, they were not grouped, and will not be further discussed. Furthermore, if the epicenter distance is within 150 km, thirteen out of twenty-one earthquakes show anomalous signals in the recorder. When events h and i were excluded, the overall success rate was about 68%.

The seismic velocity structure (transect) across northern Taiwan along the AA' line (Fig. 6) is shown in Fig. 9. The seismic V_p structure adopted is a local earthquake tomography model developed by Wu et al. (2007), in which crustal velocities (green and light blue) reaching about a 40-km depth in the western part are clearly illustrated (Fig. 9a). This model conforms with previous propositions that the Moho boundary below the Central Range of northern Taiwan is at a depth of about 40–60 km, as shown in

Table 1

Catalog of Rn anomalies and related earthquakes occurring in Taiwan from 14 June 2006 to 9 September 2007.

No. ^a	Date	Long.	Lat.	Depth	Mag.	Int.	Distance	Δt ^b	D _t ^c
		(°E)	(°N)	(km)	(M _L)	(M _I)	(km)	(day)	(day)
a	2006/06/18 02:21	120.987	24.511	7	3.2	2	28.9	1.5	0.33
b	2006/07/07 14:35	121.154	24.976	15.5	3.6	1	27.9	0.2	0.32
с	2006/07/10 21:16	121.72	24.66	28.8	3.3	1	58	None	None
d	2006/07/22 04:56	121.649	24.183	13.8	3.9	1	78.6	3.5	0.21
e	2006/7/28 15:40	122.66	23.97	28	6.0	2	174.7	None	None
f	2006/08/28 01:11	123.03	24.836	132.1	6	2	190.1	None	None
g	2006/09/19 21:00	121.214	24.703	7	3.7	2	7	0.7	2.96
h	2006/09/30 14:49	122.439	24.507	82.7	4.9	1	132.5	Unknown ^d	Unknown
i	2006/10/10 06:01	121.163	24.58	4.9	4	2	16.2	0.6	1.25
j	2006/11/06 03:56	121.02	24.69	10.1	3.9	2	13.7	Unknown	Unknown
k	2006/12/26 20:26	120.426	21.922	41.2	7	2	320.1	None	None
1	2007/01/25 18:59	121.961	22.628	27	6.2	2	247.2	None	None
m	2007/02/05 07:10	121.68	24.47	27.8	3.8	1	60.7	5.3	5.3
n	2007/02/10 19:36	121.09	24.68	8.6	3.5	2	7.8	None	None
0	2007/2/18 23:46	122.08	24.44	17.5	4.1	1	99.3	6.7	4.42
р	2007/02/27 05:07	121.622	24.517	44	3.9	2	53	6.21	3.88
q	2007/02/28 03:57	121.723	24.033	33	4.4	2	96.3	3.4	3.4
r	2007/03/04 11:45	121.988	24.767	77.4	4.4	1	84.7	None	None
S	2007/03/08 23:37	121.896	24.557	70.4	4.7	2	77.6	None	None
t	2007/03/18 07:57	121.748	24.263	17.3	3.9	2	79.3	4.5	8.75
u	2007/05/13 01:50	121.671	24.557	44.3	4.6	2	55.9	None	None
v	2007/05/28 09:38	121.47	24.42	7.3	3.5	1	46.9	None	None
w	2007/07/23 21:40	121.649	23.703	38.4	5.8	2	124.3	17.4	29.04
х	2007/08/17 16:07	121.149	24.637	5.2	3.7	1	9.8	7.5	4.54
У	2007/09/07 01:51	122.258	24.264	62.1	6.8	3	123.2	11.5	10.46

^a The label of relevant anomalous peaks marked in Figs. 5-7.

^b The time difference between the anomalous peak and the earthquake event.

^c The duration of gas anomalies for the given earthquake event.

^d "Unknown" indicates that the relationship between the gas anomaly and the earthquake cannot be identified.

the white line in Fig. 9a (Yeh et al., 1998; Wu et al., 2006). The suture between the Central Range of the Eurasia plate and the Luzon volcanic arc of the Philippine Sea plate can be identified by a high V_p/V_s belt in Fig. 9b (yellow and orange-red color). The high V_p/V_s anomaly appears to plunge to the west, suggesting that the subduction polarity has been flipped, and that the Philippine Sea plate is underthrusting the Eurasian plate (Teng et al., 2000). This seismic zone is seismically very active due to continuous convergence, and changes in pore pressure by the Coulomb stress changes that may be attributed to near- or far-field earthquakes. It could also be caused by strain-induced changes in permeability within the preparation zone of the earthquake (Dobrovolsky et al., 1979; Upton et al., 2003).

When the fault plane solution diagrams of the studied earthquakes (Table 1) were projected on this transect (Fig. 10), the predominant patterns observed at depths less than 40 km are strikeslip and normal faults, whereas at depths greater than 40 km, strike-slip and thrust-type faults are predominant. In the crustal level (<40 km), Group A earthquakes are extensional and characterized by the lowest velocity; Group B earthquakes, including both extensional types in the shallow level and compressional types in the deep crust, vary from low to high velocities according to depth (Fig. 9). Due to the lack of focal mechanism data for events m, n, o, and v, and of soil gas data for events h and j, these events will not be further discussed.

According to the compression mechanism for releasing gases (King, 1978), the relaxation of radon at depth, which results in anomalously high concentrations in the soil, may be due to increased crustal compression before an impending earthquake. In this study, fault plane solutions of adjacent shallow earthquakes (<15 km) demonstrate that variations of soil Rn concentrations are equally sensitive in the extensional regime. This is manifested by the fact that the epicenter of earthquakes with Rn gas anomalies correlates well with low V_p (Figs. 9 and 10). In shallow layers, the low V_p values are usually associated with near-surface geologic units, such as sedimentary formations (Font et al., 2001; Wu et al.,



Fig. 7. Soil radon data from (a) 14 June to 14 October 2006, and from (b) 22 January to 9 September 2007. These two periods correspond to the marked rectangles in Fig. 5. The top trace indicates the soil Rn variation (pink line) for the current day (A(t)) and the variation (blue dashed line) averaged over -7 days of the observed day (RA(t)). Earthquake events are also shown. The bottom trace shows the residue signal $\Delta A(t)$.



Stage 1: Buildup of elastic strain

- Stage 2: Dilatancy and development of microcracks
- Stage 3: Gas emanation from gas filled pores and then migration upward to surface
- Stage 4: Elastic strain is dropped after earthquake and then the micro-cracks return to their original state
- Stage 5: Original condition
 - $\triangle t$: The time difference between the peak of anomaly and the earthquake event
 - Dt : The time duration of gas anomalies for the earthquake event

Fig. 8. Variation of radon and thoron activity in the context of earthquake and geological models.

2007), implying the existence of gas- and water-saturated or highporosity rocks. According to the V_p/V_s tomographic images for shallow crust (2–7 km) in northern Taiwan, there is a low V_p/V_s anomaly near the Kuanhsi-Chutung area (Lin et al., 2004), highlighting a potential reservoir for soil gases. Chiarabba et al. (2010) further proposed that the observed V_p/V_s before earthquakes is increased along with pore pressure and the volume of fluid-filled cracks around faults. Therefore, the existence of a shallow gas reservoir associated with active fault systems in northern Taiwan would be the major factor governing soil gas behavior before earthquake-triggered Rn relaxation.

4.5.2. The relationship between the tectonic setting and mechanism for gas release

The tectonics of arc-continent collision in Taiwan has drawn speculation about the subduction of the Philippine Sea plate versus the subduction of the Asiatic plate before collision. McIntosh et al. (2005) modeled the seismic velocity structure of the Taiwan arc-continent collision in three E-W cross-island transects. A schematic diagram drawn by these authors is depicted in Fig. 11, showing a crustal-scale cross-section along the geophysical transect in northern Taiwan (AA' in Fig. 6). This was based on the assumption of a structural style in which a detachment develops in the uppermiddle continental crust, leading to the emplacement of pre-Cenozoic metamorphic rocks in the Central Range (CR) (Suppe, 1981). When the studied earthquakes were projected on this cross-section (Fig. 11), it was found that all the Group A earth-



Fig. 9. The seismic velocity structure transecting northern Taiwan along the AA' line of Fig. 6 is derived from a local earthquake tomography model by Wu et al. (2007). (a) The V_p velocity profile; (b) the V_p/V_s ratio profile. The dots show the relocated events for M > 3 within ± 5 km of the profile. The star represents the location of the monitoring station.



Fig. 10. The focal mechanism of the projected earthquakes listed in Table 1. Note that the epicenter gets deeper towards the east.

quakes were concentrated in the upper continental crust (domain I), and the Group B earthquakes were mostly separated into the buried upper continental crust (domain II) and middle-lower continental crust (domain IV). No earthquakes with the related observable Rn anomaly in the monitoring site originated from the domain in the detached upper-middle continental crust beneath the Central Range (domain III), and only very few were from all domains of the colliding arc (domains VI to IX).



Fig. 11. A schematic diagram showing a crustal-scale cross-section along the geophysical transect (AA' in Fig. 6) based on the velocity model (McIntosh et al., 2005; Wu et al., 2007), assuming a structural style in which detachment has developed in the upper-middle continental crust. The star indicates the location of the monitoring site. Green arrows denote an extension regime, and blue arrows denote a compressional regime. Red arrows denote movement along the major decollement. WFH = Western Foothills; LV = Longitudinal Valley; HSR = Hsuehshan Range; CR = Central Range; LF = Lishan Fault. I = Upper continental crust (CC); II = Buried upper CC; III = Detached upper-middle CC; IV = Middle-lower CC; V = Continental lithospheric mantle; VI = Hoping basin; VII = Ryukyu arc basement; VIII = Philippine Sea plate crust; IX = Philippine Sea plate



Fig. 12. Variation diagrams showing the relationship between earthquake magnitude and (a), (b) epicenter distance to the monitoring site, (c) distribution of the delta time, and (d) duration of the radon anomalies. Panel (e) shows the relationship between delta time and duration of the radon anomaly. The results of Fleischer (1981) and Igarashi and Wakita (1990) are also shown by upside down triangle and triangle symbols in grey, respectively, for comparison. The solid line showing the calculated value of the maximum distance at which an earthquake of magnitude should be affect radon changes based on Fleischer (1981). Open circles indicate observations from Group A; solid circles indicate observations from Group B; grey circles indicate observations without anomalies. Fitted curves are shown as solid lines. Dashed lines indicate the 95% confidence interval of the data set.

The fitness of resolved earthquake epicenters and domains of the continent may support such a seismic velocity structure in the crustal level. Based on a GPS study, Rau et al. (2008) were able to identify two terrains with distinct deformation patterns in northern Taiwan: (1) a waning collision area in the west, and (2) a transition zone in the east. They are separated by the surface projection of the NW-trending plate boundary in northern Taiwan, and roughly correlated with the enclosed areas of the Group A and B earthquakes in Fig. 6. The waning collision area is reflected by a NW-SE internal contraction on GPS data. However, when the results of the focal mechanism are taken into consideration, they show that most Group A earthquakes are strike-slip and normal faults with earthquake epicenters shallower than 15 km, and that most Group B earthquakes are thrust faults with deeper (>20 km) hypocenters (Fig. 10). The waning collision area could have a higher permeability than other areas in northern Taiwan. allowing soil gases to cumulate before/during the shallow earthquake. An active subduction zone beneath the Eurasia plate in northern Taiwan can explain this phenomenon, with the momentum of subduction as the driving force that creates the compression and extension regimes in the deeper and shallower crusts, respectively. It is suggested that the movement along the major decollement is associated with Group B earthquakes. The preearthquake activities of Group B may have been transmitted along the major decollement to the region below the monitoring site, and there facilitated the release of soil gases, which were detected as anomalies at Tapingti station. The fold and thrust belt of the Western Foothills in northern Taiwan, where active faults prevail, is a potential area for detecting earthquakes occurring in domains of the Asiatic continent, and anomalous soil gas concentrations may be used as a precursory signal for these earthquakes.

4.5.3. The relationship between gas emission observations and seismic events

The dependent relationship between the epicenter distance to the monitoring site and the magnitude of the earthquake event was shown in Fig. 12a. The correlation for Group A earthquakes was difficult to define, as these earthquakes had epicenter distances of <30 km and small magnitudes (M_I = 3-4). The epicenter distances of Group B earthquakes were >45 km; thus, a good correlation ($R^2 = 0.66$) was obtained between these variables. The bestfit line may be used to estimate the magnitude of an earthquake with a given epicenter distance. Comparing the radon changes associated with the relation between a maximum distance and magnitude of an earthquake (Fleischer, 1981; Igarashi and Wakita, 1990). Group B earthquakes fall nearly above the calculated value of the maximum distance given by Fleischer (1981) (Fig. 12b). And, according to Dobrovolsky equation (Dobrovolsky et al., 1979), soil gas anomalies should be also observed at TPT station before all $M \ge 6$ earthquakes, which occurred within the 380 km effective preparation area. However, no significant anomalies in soil gases were observed before some large earthquakes. These indicate that, although TPT station is located inside the probable preparation zone of the earthquake, the preparation zone given by Fleischer (1981) and Dobrovolsky et al. (1979) is somewhat incompatible in this study. Therefore, we then propose that the observed radon anomalies at TPT station may be only related to earthquakes, which occurred within approximately 130 km to the monitoring site. The distance limit of sensitive zone for TPT station can be determined.

The good correlation between earthquake magnitude and delta time (Δ t) (R² = 0.63; Fig. 12c) from the Group B dataset indicates that it is possible to predict the magnitude of an impending earthquake. The moderate correlation between earthquake magnitude and duration (R² = 0.54; Fig. 12d) indicates that whole soil radon anomalies may also be affected by other parameters, such as gas reservoirs and complex geological units. The relationship between the start time of a radon anomaly to an impending earthquake (Δt) and duration of a radon anomaly (D_t) is shown in Fig. 12e. The positive relationship (R² = 0.85) suggests that a longer lasting Rn anomaly appears to reflect a longer delta time. A longer delta time and a longer duration of radon anomalies appear to be associated with a larger earthquake. In other words, a longer precursory time of a radon anomaly is related to an impending large earthquake.

5. Conclusions

The major findings of this study are listed below:

- (1) Soil gases (helium, nitrogen, and carbon dioxide) anomalies are distributed along the NE-SW trending faults in the study area, and coincide with geological traces.
- (2) Many anomalously high soil radon and thoron concentrations detected during continuous monitoring were observed several hours to a few days before earthquakes.
- (3) Based on relevant earthquakes, two types of earthquakes (Group A and Group B) can be identified. Group A earthquakes have hypocenters shallower than 15 km and are concentrated within 30 km of the monitoring station. Group B earthquakes have deeper (>20 km) hypocenters and are distributed in greater distances (>45 km) east of the monitoring site. The pre-earthquake activities of Group B may be transmitted to the region below the monitoring site along the major decollement and can facilitate the release of soil gases when squeezed; hence, soil gas anomalies could be detected at Tapingti station away from the hypocenters.
- (4) The pre-earthquake anomalous time (Δ t) ranged from 0.2 to 17.4 days, and the duration time (D_t) ranged between 0.21 and 29 days. A longer delta time and a longer duration time of a radon anomaly may be linked to a larger earthquake.

Acknowledgments

This paper is dedicated to co-author Prof. Tsanyao Frank Yang (TFY), who passed away on 12 March 2015. Born in 1961, TFY worked for many years at the Department of Geosciences, National Taiwan University (NTU), Taipei, Taiwan. His passion for research set new standards for all who worked with him. He will be greatly missed within the Earth science community. We thank Mr. B.W. Lin and D.R. Hsiao for help with sample collection and analysis. We also thank Mr. S.J. Lin and K.W. Wu for help in the maintenance of the monitoring station. This work was financially supported by the Central Geological Survey of Taiwan (TFY/5226902000-06-95-02, 104-522690400-03-01). The research is also supported by the Taiwan Earthquake Research Center (TEC) and Ministry of Science and Technology of Taiwan under grant MOST104-2119-M-001-004 and MOST 105-2116-M-052-003. The TEC contribution number for this article is 00132.

References

- Andrews, J.S., 1977. Radiogenic and inert gases in groundwater. In: Proc. 2nd Int. Symp. Water-Rock Interaction, pp. 334–342.
- 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, 69–81.
- Bolt, B.A., 1999. Earthquakes. W.H. Freeman, New York, p. 1999.
- Bunzl, K., Ruckerbauer, F., Winkler, R., 1998. Temporal and small-scale spatial variability of ²²²Rn gas in a soil with a high gravel content. Sci. Total Environ. 220, 157–166.
- Cheng, Q., Agterberg, F.P., Ballantyne, S.B., 1994. The separation of geochemical anomalies from background by fractal methods. J. Geochem. Explor. 51, 109–130.

- Chiarabba, C., De Gori, P., Boschi, F., 2010, Pore-pressure migration along a normalfault system resolved by time-repeated seismic tomography. Geology 37, 67-70.
- Chyi, L.L., Chou, C.Y., Yang, T.F., Chen, C.H., 2001. Continuous radon measurements in faults and earthquake precursor pattern recognition. Western Pacific Earth Sci. 1 (2), 43-72.
- Chyi, L.L., Quick, T.J., Yang, F.T., Chen, C.H., 2005. Soil gas radon spectra and earthquakes. Terrest., Atmosph. Oceanic Sci. 16, 763-774.
- Cicerone, R.D., Ebel, J.E., Britton, J., 2009. A systematic compilation of earthquake precursors. Tectonophysics 476, 371-396.
- Ciotoli, G., Etiope, G., Guerra, M., Lombardi, S., 1999. The detection of concealed faults in the Ofanto Basin using the correlation between soil gas fracture surveys. Tectonophysics 301, 321-332.
- Ciotoli, G., Guerra, M., Lombardi, E., Vittori, E., 1998. Soil gas survey for tracing seismogenic faults: a case study in the Fucino basin, Central Italy. J. Geophys. Res. 103, 23781-23794.
- Ciotoli, G., Lombardi, S., Morandi, S., Zarlenga, F., 2004. A multidisciplinary, statistical approach to study the relationships between helium leakage and neotectonic activity in a gas province: the Vasto basin Abruzzo-Molise (central Italy). Am. Assoc. Pet. Geol. Bull. 88, 355-372.
- Claesson, L., Skelton, A., Graham, C., Dietl, C., Morth, M., Torssander, P., Kockum, I., 2004. Hydrogeochemical changes before and after major Earthquake. Geology 32, 641-644.
- Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zone. Pure Appl. Geophys. 117, 1025-1044.
- Etiope, G., Lombardi, S., 1995. Evidence for radon transport by carrier gas through faulted clays in Italy. J. Radioanal. Nucl. Chem. 193, 291-300.
- Etiope, G., Martinelli, G., 2002. Migration of carrier and trace gases in the geosphere: an overview. Phys. Earth Planet. Inter. 129, 185-204.
- Fielding, E.J., Lundgren, P.R., Burgmann, R., Funning, G.J., 2008. Shallow fault-zone dilatancy recovery after the 2003 Bam earthquake in Iran. Nature 458, 64-68.
- Fleischer, R.L., 1981. Dislocation model for radon response to distant earthquakes. Geophys. Res. Lett. 8, 477-480.
- Font, Y., Liu, C.-S., Schnuerle, P., Lallemand, S., 2001. Constraints on backstop geometry of the southwest Ryukyu subduction based on reflection seismic data. Tectonophysics 333, 135–158.
- Fu, C.C., Yang, T.F., Walia, V., Chen, C.-H., 2005. Reconnaissance of soil gas composition over the buried fault and fracture zone in southern Taiwan. Geochem. J. 39, 427-439.
- Fu, C.C., Yang, T.F., Du, J., Walia, V., Liu, T.K., Chen, Y.G., Chen, C.-H., 2008. Variations of helium and radon concentrations in soil gases from an active fault zone in southern Taiwan. Radiat. Meas. 43, 348-352.
- Fu, C.C., Yang, T.F., Walia, V., Liu, T.K., Lin, S.J., Chen, C.-H., Hou, C.S., 2009. Variations of soil-gas composition around the active Chihshang Fault in a plate suture zone, eastern Taiwan. Radiat. Meas. 44, 940–944.
- Fu, C.C., Yang, T.F., Tsai, M.C., Lee, L.C., Liu, T.K., Walia, V., Chen, C.-H., Chang, W.Y., Kumar, A., Lai, T.H., 2017. Exploring the relationship between soil degassing and seismic activity by continuous radon monitoring in the Longitudinal Valley of eastern Taiwan. Chem. Geol. http://dx.doi.org/10.1016/j.chemgeo.2016.12.042.
- Heinicke, J., Koch, U., Martinelli, G., 1995. CO2 and radon measurements in the Vogtland area (Germany): a contribution to earthquake prediction research. Geophys. Res. Lett. 22, 771-774.
- Hong, W.L., Yang, T.F., Walia, V., Lin, S.J., Fu, C.C., Chen, Y.G., Sano, Y., Chen, C.-H., Wen, K.L., 2010. Nitrogen as the carrier gas for helium emission along an active fault in NW Taiwan. Appl. Geochem. 25, 593-601.
- Hu, J.C., Angelier, J., Lee, J.C., Chu, H.T., Byrne, D., 1996. Kinematics of convergence, deformation and stress distribution in the Taiwan collision area: 2-D finiteelement numerical modeling. Tectonophysics 255, 243–268. Iakovleva, V.S., Ryzhakova, N.K., 2003. Spatial and temporal variations of radon
- concentration in soil air. Radiat. Meas. 36, 385-388.
- Igarashi, G., Saeki, S., Takahata, N., Sumikawa, K., Tasaka, S., Sasaki, Y., Takahashi, M., Sano, Y., 1995. Ground-water radon anomaly before the Kobe earthquake in Japan. Science 269, 60-61.
- Igarashi, G., Wakita, H., 1990. Groundwater radon anomalies associated with earthquakes. Tectonophysics 180, 237-254.
- Inan, S., Akgül, T., Seyis, C., Saatçýlar, R., Baykut, S., Ergintav, S., Bas, M., 2008. Geochemical monitoring in the Marmara region (NW Turkey): a search for precursors of seismic activity. J. Geophys. Res. 113, 1–4. Kafadar, K., Spiegelman, C.H., 1986. An alternative to ordinary Q-Q plots:
- conditional Q-Q plots. Comput. Stat. Data Anal. 4 (3), 167–184.
- King, C.Y., 1978. Radon emanation on San Andreas Fault. Nature 271, 516–517.
- King, C.Y., 1986. Gas geochemistry applied to earthquake prediction: an overview. J. Geophys. Res. 91, 12269-12281.
- Kumar, A., Singh, S., Mahajan, S., Bajwa, B.S., Kalia, R., Dhar, S., 2009a. Earthquake precursory studies in Kangra valley of North West Himalayas, India, with special emphasis on radon emission. Appl. Radiat. Isot. 67, 1904-1911.
- Kumar, A., Walia, V., Singh, S., Bajwa, B.S., Mahajan, S., Dhar, S., Yang, T.F., 2009b. Earthquake precursory studies at Amritsar Punjab, India using radon measurement techniques. Int. J. Phys. Sci. 7 (42), 5669-5677.
- Kuo, T., Fan, K., Kuochen, H., Han, Y., Chu, H., Lee, Y., 2006a. Anomalous decrease in groundwater radon before the Taiwan M6.8 Chengkung earthquake. J. Environ. Radioact. 88, 101–106.
- Kuo, T., Fan, K., Kuochen, H., Chen, W., 2006b. A mechanism for anomalous decline in radon precursory to an earthquake. Ground Water 44, 642-647.

- Li, Y.G., Chen, P., Cochran, E.S., Vidale, J.E., Burdette, T., 2006. Seismic evidence for rock damage and healing on the San Andreas Fault associated with the 2004 M 6.0 Parkfield earthquake. Bull. Seismol. Soc. Am. 96, S349-S363.
- Lin, C.W., Lu, S.T., Shih, T.S., Chen, Z.Y., Lin, Y.H., 2007. Active Faults of Northern Taiwan, 2nd ed. Special Publication of Central Geological Survey, vol. 19, pp. 61-78.
- Lin, J.Y., Hsu, S.K., Sibuet, J.C., 2004. Melting features along the western Ryukyu slab edge (northeast Taiwan): tomographic evidence. J. Geophys. Res. 109, B12402. http://dx.doi.org/10.1029/2004JB003260.
- Liu, K.K., Tsai, Y.B., Yeh, Y.H., Yui, T.F., Teng, T.L., 1983. Anomalous groundwater radon changes and possible correlation with earthquakes in northern Taiwan. Eos, Transact., Am. Geophys. Union 64, 758.
- Liu, K.K., Yui, T.F., Yeh, Y.H., Tsai, Y.B., Teng, T.L., 1985. Variations of radon content in ground waters and possible correlation with seismic activities in northern Taiwan. Pure Appl. Geophys. 122, 231-244.
- Mair, K., Abe, S., 2008. 3D numerical simulations of fault gouge evolution during shear: grain size reduction and strain localization. Earth Planet. Sci. Lett. 274, 72-81
- Malavieille, J., Lallemand, S., Dominguez, S., Deschamps, A., Lu, C., Liu, C.S., Schnqrle, P., ACT scientific crew, 2002. Arc-continent collision in Taiwan: new marine observations and tectonic evolution. In: Byrne, T.B., Liu, C.S. (Eds.), Geology and Geophysics of an Arc-Continent Collision. Special Papers - Geological Society of America, vol. 358, pp. 187–211.
- McIntosh, K.D., Nakamura, Y., Wang, T.K., Shih, R.C., Chen, A., Liu, C.S., 2005. Crustalscale seismic profiles across Taiwan and the western Philippine Sea. Tectonophysics 401, 23–54.
- Minissale, A., Magro, G., Martinelli, G., Vaselli, O., Tassi, G.F., 2000. Fluid geochemical transect in the Northern Apennines (central-northern Italy): fluid genesis and migration and tectonic implications. Tectonophysics 319, 199-222.
- Pulinets, S.A., Dunajecka, M.A., 2007. Specific variations of air temperature and relative humidity around the time of Michoacan earthquake M8.1 Sept. 19, 1985 as a possible indicator of interaction between tectonic plates. Tectonophysics 431, 221–230.
- Rau, R.J., Ching, K.E., Hu, J.C., Lee, J.C., 2008. Crustal deformation and block kinematics in transition from collision to subduction: global positioning system measurements in northern Taiwan, 1995-2005. J. Geophys. Res. 113, B09404. http://dx.doi.org/10.1029/2007JB005414.
- Reddy, D.V., Nagabhushanam, P., 2011. Groundwater electrical conductivity and soil radon gas monitoring for earthquake precursory studies in Koyna, India. Appl. Geochem. 26, 731-737.
- Reddy, D.V., Sukhija, B.S., Nagabhushanam, P., Reddy, G.K., Kumar, D., Lachassagne, P., 2006. Soil gas radon emanometry: a tool for delineation of fractures for groundwater in granitic terrains. J. Hydrol. 329, 186-195.
- Sano, Y., Takahata, N., Igarashi, G., Koizumi, N., Sturchio, N.C., 1998. Helium degassing related to the Kobe earthquake. Chem. Geol. 150 (1-2), 171-179.
- Sibuet, J.C., Hsu, S.K., Le Pichon, X., Le Formal, J.P., Reed, D., Moore, G., Liu, C.S., 2002. East Asia plate tectonics since 15 Ma: constraints from the Taiwan region. Tectonophysics 344, 103–134.
- Sugisaki, R., 1978. Changing He/Ar and N₂/Ar ratios of fault air may be earthquake precursors. Nature 275, 209-211.
- Suppe, J., 1981. Mechanics of mountain building and metamorphism in Taiwan. Memoir Geol. Soc. China 4, 67-89.
- Tansi, C., Tallarico, A., Iovine, G., Folino-Gallo, M., Falcone, G., 2005. Interpretation of radon anomalies in seismotectonic and tectonicgravitational settings; the south-eastern Crati graben (northern Calabria, Italy). Tectonophysics 396, 181-193.
- Teng, L.S., Lee, C.T., Tsai, Y.B., Hsiao, L.Y., 2000. Slab breakoff as a mechanism for flipping of subduction polarity in Taiwan. Geology 28, 155–158.
- Toutain, J.P., Baubron, J.C., Le Bronec, J., Allard, P., Briole, P., Marty, B., Miele, G., Tedesco, D., Luongo, G., 1992. Continuous monitoring of distal gas emanations at Vulcano, southern Italy. Bull. Volcanol. 54, 147-155.
- Toutain, J.P., Baubron, J.C., 1999. Gas geochemistry and seismotectonics: a review. Tectonophysics 304 1–27
- Trique, M., Richon, P., Avouac, I.P., Sabroux, I.C., 1999, Radon emanation and electric potential variations associated with transient deformation near reservoir lakes. Nature 399, 137-141.
- United Nations, 2000. Sources, Effects and Risks of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 2000 Report to the General Assembly, with Scientific Annexes, vol. I. United Nations Publication, New York,
- Upton, P., Koons, P.O., Eberhart-Phillips, D., 2003. Extension and partitioning in an oblique subduction zone, New Zealand: constraints from three-dimensional numerical modeling. Tectonics 22, 1068. http://dx.doi.org/10.1029/ 2002TC001431.
- Wakita, H., Igarashi, G., Nakamura, Y., Notsu, K., 1989. Coseismic radon changes in groundwater. Geophys. Res. Lett. 16, 417-420.
- Wakita, H., Nakamura, Y., Notsu, K., Noguchi, M., Asada, T., 1980. Radon anomaly: a possible precursor of the 1978 Izu-Oshima-Kinkai earthquake. Science 207, 882.
- Walia, V., Su, T.C., Fu, C.C., Yang, T.F., 2005a. Spatial variations of radon and helium concentration in soil gas across Shan-Chiao fault, Northern Taiwan. Radiat. Meas. 40, 513-516.
- Walia, V., Virk, H.S., Yang, T.F., Mahajah, S., Walia, M., Bajwa, B.S., 2005b. Earthquake prediction studies using Radon as a precursor in N-W Himalayas, India: a case study. Terrest., Atmosph. Ocean. Sci. 16, 775-804.

- Walia, V., Mahajah, S., Kumar, A., Singh, S., Bajwa, B.S., Dhar, S., Yang, T.F., Walia, M., Bajwa, B.S., 2008. Fault delineation study using soil-gas method in Dharamsala area, NW Himalayas, India. Radiat. Meas. 43, 337–342.
- Walia, V., Lin, S.J., Hong, W.L., Fu, C.C., Yang, T.F., Wen, K.L., Chen, C.-H., 2009. Continuous temporal soil-gas composition variation for earthquake precursory studies along Hsincheng and Hsinhua faults in Taiwan. Radiat. Meas. 44, 934– 939.
- Walia, V., Lin, S.J., Fu, C.C., Yang, T.F., Hong, W.L., Wen, K.L., Chen, C.-H., 2010. Soilgas monitoring: a tool for fault delineation studies along Hsinhua Fault (Tainan), southern Taiwan. Appl. Geochem. 25, 602–607.
- Walia, V., Yang, T.F., Lin, S.J., Kumar, A., Fu, C.C., Chiu, J.M., Chang, H.H., Wen, K.L., Chen, C.-H., 2013. Temporal variation of soil gas compositions for earthquake surveillance in Taiwan. Radiat. Meas. 50, 154–159.
- Washington, J.W., Rose, A.W., 1992. Temporal variability of radon concentration in the interstitial gas of soils in Pennsylvania. J. Geophys. Res. 97, 9145–9159.
- Woith, H., 2015. Radon earthquake precursor: a short review. Europ. Phys. J.-Spec. Topics 224, 611–627. http://dx.doi.org/10.1140/epjst/e2015-02395-9.
- Wu, Y.M., Chen, Y.G., Chang, C.H., Chung, L.H., Teng, T.L., Wu, F.T., Wu, C.F., 2006. Seismogenic structure in a tectonic suture zone: with new constraints from 2006 Mw 6.1 Taitung earthquake. Geophys. Res. Lett. 33, L22305.
- Wu, Y.M., Chang, C.H., Zhao, L., Shyu, J.B.H., Chen, Y.G., Sieh, K., Avouac, J.C., 2007. Seismic tomography of Taiwan: Improved constraints from a dense network of strong motion stations. J. Geophys. Res. 112, B08312. http://dx.doi.org/10.1029/ 2007/B004983.

- Yang, T.F., Chou, C.Y., Chen, C.-H., Chyi, L.L., Jiang, J.H., 2003. Exhalation of radon and its carrier gases in SW Taiwan. Radiat. Meas. 36, 425–429.
- Yang, T.F., Lan, T.F., Lee, H.F., Fu, C.C., Chuang, P.C., Lo, C.H., Chen, C.-H., Chen, C.T.A., Lee, C.S., 2005a. Gas compositions and helium isotopic ratios of fluid samples around Kueishantao, NE offshore Taiwan and its tectonic implications. Geochem. J. 39, 469–480.
- Yang, T.F., Walia, V., Chyi, L.L., Fu, C.C., Chen, C.-H., Liu, T.K., Song, S.R., Lee, C.Y., Lee, M., 2005b. Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. Radiat. Meas. 40, 496–502.
- Yang, T.F., Fu, C.C., Walia, V., Chen, C.-H., Chyi, L.L., Liu, T.K., Song, S.R., Lee, M., Lin, C. W., Lin, C.C., 2006. Seismo-geochemical variations in SW Taiwan: multiparameter automatic gas monitoring results. Pure Appl. Geophys. 163 (4), 693– 709.
- Yeh, Y.H., Shih, R.C., Lin, C.H., Liu, C.C., Yen, H.Y., Huang, B.S., Liu, C.S., Wu, F.T., 1998. Onshore/offshore wide-angle deep seismic profiling in Taiwan. Terrest., Atmosph. Ocean. Sci. 9, 301–316.
- Yu, S.B., Chen, H.Y., Kuo, L.C., 1997. Velocity field of GPS stations in the Taiwan area. Tectonophysics 274, 41–59.
- Yuce, G., Fu, C.C., D'Alessandro, W., Gulbay, A.H., Lai, C.W., Bellomo, S., Yang, T.F., Italiano, F., Walia, V., 2017. Geochemical characteristics of soil radon and carbon dioxide within the Dead Sea Fault and Karasu Fault in the Amik Basin (Hatay), Turkey. Chem. Geol. http://dx.doi.org/10.1016/j.chemgeo.2017.01.003.