



Soil–gas monitoring: A tool for fault delineation studies along Hsinhua Fault (Tainan), Southern Taiwan

Vivek Walia^{a,*}, Shih Jung Lin^a, Ching Chou Fu^b, Tsanyao Frank Yang^b, Wei-Li Hong^b, Kuo-Liang Wen^{a,c}, Cheng-Hong Chen^b

^a National Center for Research on Earthquake Engineering, National Applied Research Laboratories, Taipei 106, Taiwan

^b Department of Geosciences, National Taiwan University, Taipei 106, Taiwan

^c Department of Earth Sciences and Institute of Geophysics, National Central University, Jhongli 32054, Taiwan

ARTICLE INFO

Article history:

Available online 25 January 2010

ABSTRACT

Many studies have shown the soil gas method to be one of the most reliable investigation tools in the research of earthquake precursory signals and fault delineation. The present research is aimed finding the relationship between soil gas distribution and tectonic systems in the vicinity of the Hsinhua Fault zone in the Tainan area of Southern Taiwan. More than 110 samples were collected along 13 traverses to find the spatial distribution of Rn, He, CO₂ and N₂. The spatial congruence of all the gases shows that N₂ is the most probable carrier gas of He, whereas CO₂ seems to be a good carrier gas of Rn in this area. From the spatial distribution of Rn, He, CO₂ and N₂ the trace of Hsinhua Fault and neotectonic features can be identified. The spatial distribution of studied gases shows a clear anomalous trend ENE–SWS along the Hsinhua Fault.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Identifying active faults is one of the most important aspects of tectonics as seismic hazards are commonly associated with it. Faults can be described as weakened zones composed of highly fractured rock materials, gouge and fluids. Active faults are important for several reasons. Sudden displacements on active faults are the usual cause of earthquakes, and the intensity of the earthquake vibrations at a particular place is partly controlled by the distance to the fault. In addition to damage from earthquake shaking, the displacement on the fault sometimes reaches the ground surface and causes rupture and differential movement that may be as much as several meters. The Hsinhua Fault is recognized as one of the active faults in Southern Taiwan (Fig. 1). It is a right-lateral slip fault and the last movement on it occurred in 1946 accompanied by an earthquake ($M = 6.3$) (Hsu, 1971; Chang et al., 1947). It extends from coastal plain to the foothills in the Southern part of Taiwan about 10 km NE of Tainan City. Some studies have shown that this fault moved several times previous to the 1946 earthquake (Hsu, 1971; Hwang et al., 2003). The total length of the fault in the sub-surface is probably 12 km or more. The Hsinhua Fault is a back-thrust (or an upper detachment) dipping north 17° at great depth and at the high angle of 70° near the surface as shown by seismic data (Lee et al., 2000). Judging from its location, orientation and sense of slip, this structure is also likely to be an accommoda-

tion structure in the transition zone between the Kaoping and Chiayi Domains.

Active faults can provide pathways for gas leaks from the solid earth because they usually increase the permeability of soils. The spatial patterns of soil gases in faulted areas appear to be useful for identifying active tectonic structures in many cases. Recent advances in gas geochemistry have shown potential for studying both fault activity and seismic hazards (Toutain et al., 1992; Ciotoli et al., 1998; Fu et al., 2005, 2009; Walia et al., 2005a,b, 2006; Yang et al., 2005, 2006). Several gas species occur in the soil air, including those originating from atmospheric, biogenic, radiogenic and deep origins. Numbers of phenomena are known to alter the original gas concentration and a wide variation of concentrations can occur for a single gas species even in restricted areas. Studies carried out on diffuse degassing from the sub-surface have clearly shown that gases can escape towards the surface by diffusion and by advection and dispersion as they are transported by rising hot fluids and migrate along preferential pathways such as fractures and faults (Baubron et al., 2002; Yang et al., 2003). Few studies have suggested that monitoring the soil gas concentration as a function of time could be useful to forecast an impending earthquake. Information carried by rare gases like Rn and He in soils can be used for seismic fault surveillance (Chyi et al., 2005; Yang et al., 2005, 2006; Walia et al., 2006, 2007; Fu et al., 2008, 2009).

Radon is probably the most useful gas and is used frequently for fault mapping (Al-Taminmi and Abumurad, 2001; Guerra and Lombardi, 2001; Fu et al., 2005; Walia et al., 2005a) and precursory studies (Walia et al., 2005b, 2006; Yang et al., 2005, 2006). Radon

* Corresponding author. Fax: +886 2 6630 0855.

E-mail address: vivekwalia@rediffmail.com (V. Walia).

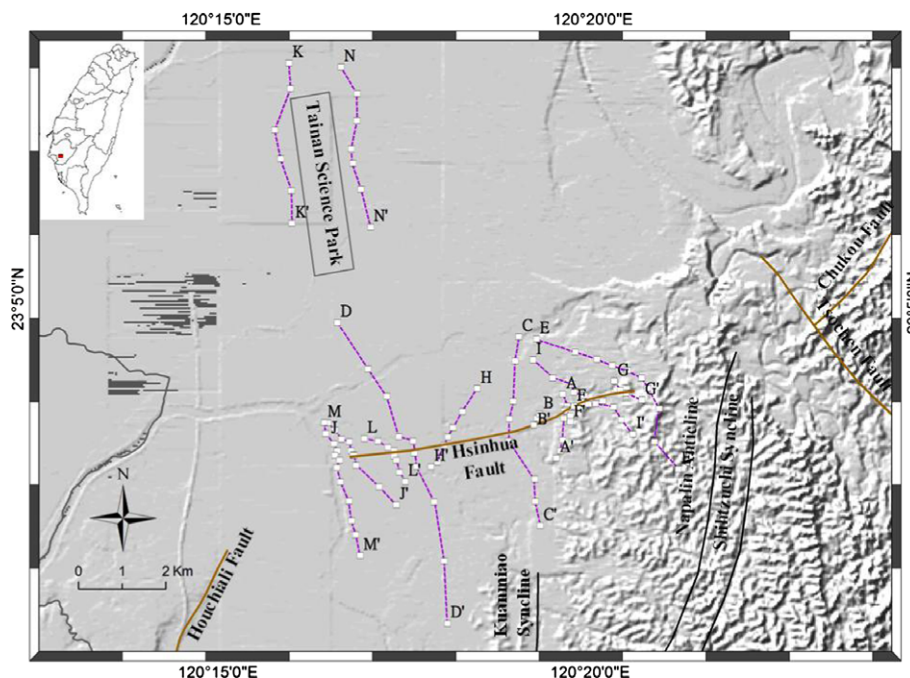


Fig. 1. Distribution of different profiles for soil–gas analysis across the Hsinhua Fault in Tainan area of Southern Taiwan. White dots represent sampling sites.

(^{222}Rn) is continuously generated from ^{226}Ra within the rock strata as an intermediate decay product of the ^{238}U radio-active series. The short half-life of ^{222}Rn ($t_{1/2} = 3.82$ d) limits its diffusion in soil, so that Rn measured at the ground surface cannot be released from a deep origin, unless there is a driving mechanism other than mere diffusion. Several models have been invoked to explain Rn migration over large distances and it has been established that Rn is transported by underground water or carrier gases, such as CO_2 , CH_4 , He or N_2 (Etiopie and Martinelli, 2002; Yang et al., 2003). Its rate of migration and its soil gas concentration are controlled by a large number of factors such as the distribution of U in the soil and bed rock, soil porosity and humidity, microcracks, granulation, surface wind, and so on.

Helium (^4He) has been commonly used as a good fault tracer as it is highly mobile, chemically inert, physically stable, highly insoluble in water, and can travel through meters of fractured overburden. Its distribution in soil gas depends on the permeability of the rocks, depth of the originating source and the influence of near-surface conditions. It migrates primarily by advection from deep accumulations toward the surface along permeable fault and fracture systems. Due to these reasons, He has a highly diffusive character with a diffusion coefficient ($1.68 \text{ cm}^2/\text{s}$) about 10 times higher than those of N_2 , O_2 and CO_2 . It diffuses at a rate much higher than Rn. Helium has a low and constant concentration of 5.239 ± 0.004 ppm in air. Due to these characteristics and the deep origin with respect to Rn, He appears to be a powerful pathfinder for crustal discontinuities, faults and fractures (Ciotoli et al., 1998; Fu et al., 2005). Recent work has observed anomalous He concentrations over faults and confirmed the presence of this gas in shallow soils as a deep fault indicator (Lombardi et al., 1996; Fu et al., 2005; Walia et al., 2005a).

Carbon dioxide is supposed to be the most abundant gas species from hydrothermal to volcanic environments. It is a well defined carrier gas for noble gases such as ^{222}Rn and ^4He which are unable to reach the surface due to low mobility and short half-life and too low a concentration, respectively. Carbon dioxide has several sources: the mantle, metamorphism of carbonate-bearing rocks, decomposition of organic material and surface biological activity

(Irwin and Barnes, 1980) and in fault zones CO_2 is a mixture of some of these sources (Fu et al., 2005). High CO_2 fluxes appear to be correlated with both high heat flux areas and limited areas with deep fracturing emitting C originating from the mantle and from decarbonation processes, with possible mixing of these two sources. Carbon dioxide discharge indicates areas with high pore pressure at depth, and is therefore used to identify potential seismic regions. Therefore it is used for fault mapping (Irwin and Barnes, 1980; Baubron et al., 1991) as well as for both seismic and volcanic monitoring (Toutain et al., 1992; Rahn et al., 1996; Lan et al., 2007). Nitrogen can also act as a good carrier for noble gases like ^{222}Rn and ^4He , and has been detected in soil and spring gases (e.g., Hong et al., 2010). Nitrogen has several sources (e.g. atmospheric, animal and industrial waste, etc.) and can be affected by various physical, chemical and biological processes. The advective movement of ^{222}Rn and ^4He must be referenced to carrier gases (viz. CO_2 , N_2) that can carry the rare gases.

In the present study interest has been focused on the distribution of ^{222}Rn , ^4He , CO_2 and N_2 concentrations in soil air to identify the scarp of the Hsinhua Fault from samples distributed in the Tainan area of Southern Taiwan. Radon and ^4He are used as tracer gases to provide a qualitative idea of fault location, whereas CO_2 and N_2 are believed to act as carriers for these gases. Further, this can be helpful for continuous geochemical monitoring of regional seismic activity and the stress built up due to collisional tectonism in Southern Taiwan.

2. Geological setting

The Southwestern Taiwan foreland is located on the Southeastern Eurasian continental margin. These rifted basins were formed during the Middle Eocene to Middle Oligocene periods in response to the NW–SE crust stretching and thinning of the Eurasian plate (Yu, 1993). In the Tainan area, the coastal plain, generally flat low-land, exposes Holocene coastal deposits. The Tainan Tableland shows a westward convex shape and an east–west asymmetry, its western part dipping gently westward, while the eastern one is

steeper. The central area shows a 2 km wide flat top. Hsieh (1972) interpreted the Tainan Tableland as an anticline above a diapir. Lee et al. (1993, 1995) considered this area as an uplifted block bounded by two normal faults, corresponding to an extensional feature of the offshore Tainan basin. In contrast, Deffontaines et al. (1997) and Lacombe et al. (1999) considered this tableland as the surface expression of a ramp anticline above a west-verging thrust, like a pop-up system. According to this interpretation, this anticline represents part of the deformation front of the Taiwan belt, farther west than the Meilin thrust. This is consistent with the offshore location of the deformation front of SW Tainan (Liu et al., 1997). So far the location of the thrust front inland of South-western Taiwan still remains uncertain.

The presence of some major tectonic elements including the Chukou Fault, the Tsochen Fault, the Napalin Anticline and the Shihzuchi Syncline in the foothills belt and the Kuanmiao Syncline and the Houchiali Fault in the Tainan Basin around the studied Hsinhua Fault are part of a Fold-and-Thrust belt that formed during the Penglai Orogeny (Fig. 1). Structures in the Tainan area show important features of the initial mountain building stage in Western Taiwan. A deeply buried basal detachment with a ramp-flat geometry existed in the constructed geological sections. Some studies suggest that the Tainan anticline is similar to the structure formed by the Hsinhua Fault (Huang et al., 2004). Both are characterized by back-thrusts and are rooted into a detachment about 5 km deep. All the structures are replaced by rift tectonic settings developed in the passive continental margin.

3. Sampling procedure

To carry out the investigations on the soil gas, a number of transverse profile surveys have been conducted across the probable locations of the Hsinhua Fault. During these surveys soil-gas samples were collected along the traverses crossing the observed structures and were analysed for Rn, He, CO₂, CH₄, Ar, O₂ and N₂.

In soils, gases are commonly sampled at depths of 0.7–1.0 m with steel probes. For this study a hollow steel probe of 3 cm diameter and 130 cm long was selected and a disposable sharp awl was attached at the bottom of the steel probe, which made the steel probe favorable for drilling into the soil and prevented soil blocking it. This steel probe was placed into the ground at a depth of about 0.8–1.0 m by pounding using a hammer and a drive-in-head. A thin solid billet (punching wire) was used to displace the tip and allowed the lower end of the probe to be in contact with the soil-surface at the required depth. A hand-pump, through a specially designed rubber tube (with two filters: one for dust and the other for mist) connected to the hollow steel probe, was used to collect gas into sample bags (Fig. 2) (Walia et al., 2005a). If the flux was good then the hand-pump could be replaced by an Alpha-pump (an automatic pump having a pumping rate of 1 L/min) to collect soil-gas in the vacuum created sample bags having a capacity of 1 L and 3 L, respectively. Before collecting the soil gas in the sample bags, the tube and the probe were flushed to get rid of the air which might be present, by pumping for about 1 min.

Sample bags used for collecting soil-gas are Tedlar standard sample bags (manufactured by SKC) which utilize a lightweight, patented single fitting of inert polypropylene that combines the hose/valve and the septum holder into one compact fitting for 1 L bags. Whereas, for 3 L bags, there are two fittings of inter polypropylene that combine the hose/valve and the septum holder which allow the sample bag to be used in closed circuit for Rn analysis.

The collected soil-gas in 1 L sample bag was analysed for ⁴He, N₂, CO₂, CH₄, Ar and O₂ using Helium detector ASM100HDS (ALCATEL) and Micro Gas Chromatography CP4900 (VARIAN), respec-

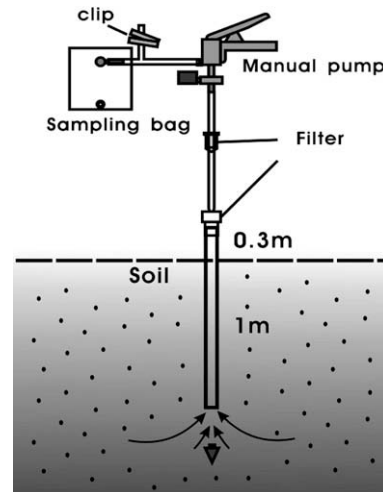


Fig. 2. Sampling scheme used for collecting soil-gas samples.

tively. The soil-gas collected in 3 L sample bag was analysed for Rn using Radon detector RTM 2100 (SARAD).

4. Results and discussion

The spatial distribution of soil gas sampling along the transverse as well as the probable fault location of the study area is illustrated in Fig. 1. The soil gas survey was performed along 13 profiles and more than 110 samples were collected for ⁴He, CO₂, N₂, CH₄, Ar, O₂, etc. (using 1 L bags) and ²²²Rn (using 3 L bags) analyses, crossing the fault system. Soil gas composition and distribution of gases in the soil atmosphere is affected by surface features such as pedological and meteorological parameters. In order to minimize the influences of these parameters sampling along each profile was performed over a short period (i.e. in a single day) and under similar (i.e. geological and meteorological) conditions.

The spatial distribution of ⁴He, ²²²Rn, CO₂ and N₂ compositions are illustrated in Fig. 3. No CH₄ was found during sample analysis and so it will not be discussed here. Oxygen and Ar did not show any distinctive variations and cannot be used as indicator gases for tracing faults in this study. However, these gases and atmospheric air are helpful to check background values of collected samples during the investigation. Along each profile one near-surface air sample was collected to make the necessary correction for atmospheric influences due to these gases.

The recorded ²²²Rn and ⁴He concentration show large spatial variation along the fault. Soil-gas ²²²Rn concentration varies from 712 to 90,974 Bq/m³ whereas the ⁴He concentration varies from 5.24 to 5.46 ppm (Table 1). The carrier gases CO₂ and N₂ show variation from 0.00% to 21.39% vol. and 75.52% to 86.48% vol., respectively (Table 1). Both ²²²Rn and ⁴He require a carrier gas/fluid to migrate towards the surface depending on the geological setting (Yang et al., 2003; Fu et al., 2008). Nitrogen has been found to be a potential carrier gas for ⁴He in many fault zones of Taiwan (Fu et al., 2008; Hong et al., 2010). Nitrogen showed very good correlation with ⁴He with a correlation coefficient of 0.75, therefore indicating that the N₂ could be the carrier gas for ⁴He in the region. In contrast, CO₂ showed very poor correlation with ⁴He having a correlation coefficient of 0.10, whereas, it showed somewhat better correlation with ²²²Rn, correlation coefficient of 0.49. Nitrogen showed very poor correlation with ²²²Rn having a correlation coefficient of 0.10. This suggests that CO₂ may be a possible candidate for the carrier gas for ²²²Rn in the area under study. Both ²²²Rn and ⁴He require a carrier gas to help in migration towards the surface.

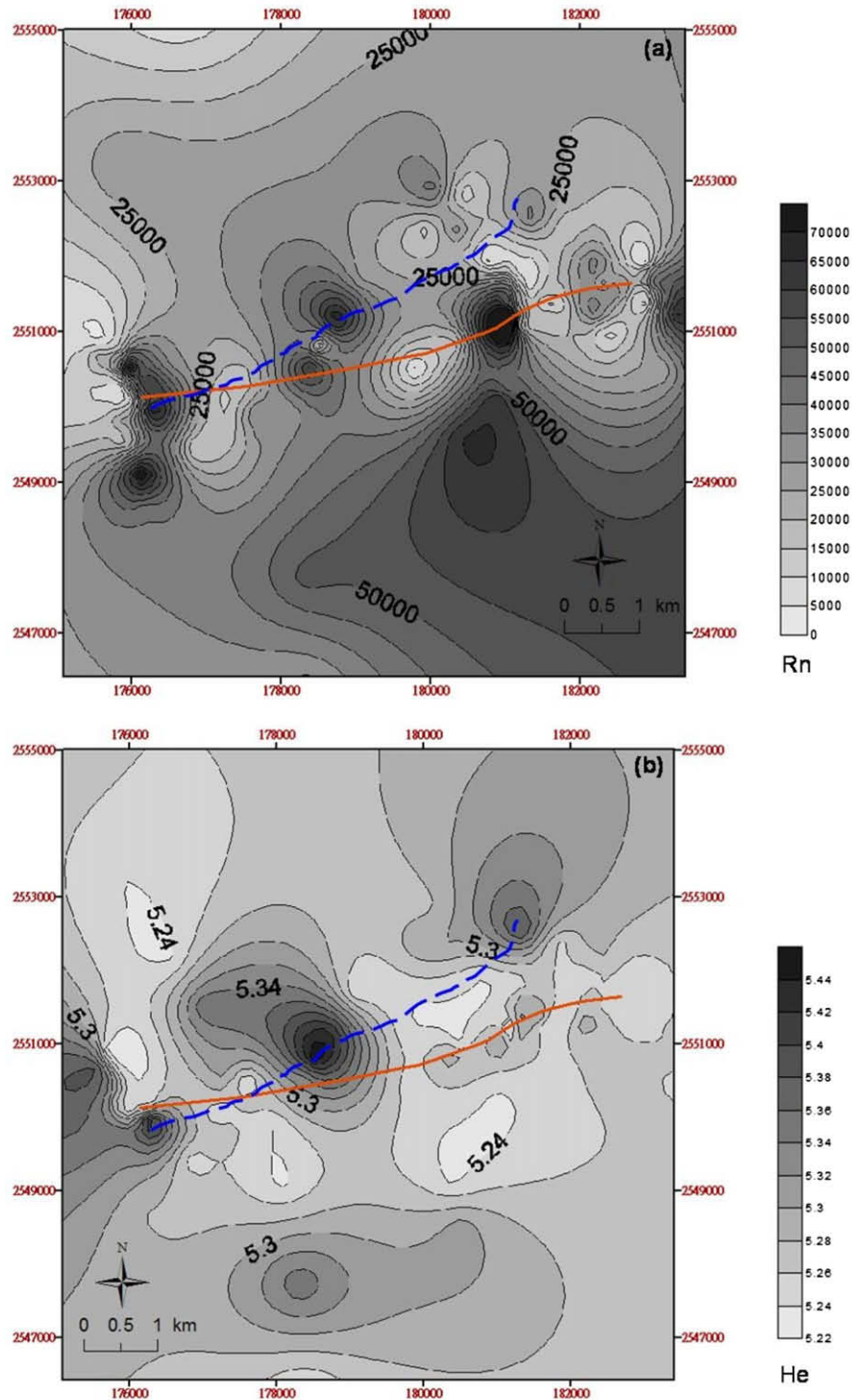


Fig. 3. Spatial distribution of soil-gases: (a) Rn (b) He (c) CO₂ and (d) N₂. The solid line represents the probable Hsinhua Fault location (reported by Central Geological Survey of Taiwan), and the long dashed line represents neotectonic features derived from this study.

However, in the investigation area their correlation with carrier gases (i.e. CO₂ and N₂) indicate there might be more than one gas source. The spatial distribution of ⁴He and CO₂ suggests that they may have different sources which rules out the possibility that CO₂ carries ⁴He. Although it is difficult to define the source of excess N₂ (severe air contamination), the excess N₂ may come from recycled air carried by underground water.

From the spatial distribution of ⁴He, ²²²Rn, CO₂ and N₂ anomalies (Fig. 3), the trace of the Hsinhua Fault can be identified in addi-

tion to neotectonic features (shown in Fig. 3 by the dashed line) almost parallel to the Hsinhua Fault. Radon and CO₂ show a clear anomalous trend ENE–SWS along the probable Hsinhua Fault location (Fig. 3a and c). Few CO₂ values show anomalies that fit well with ²²²Rn anomalies whereas poor spatial association of ⁴He with CO₂ and ²²²Rn distribution arises when contour maps are compared. All the 4 gas species used for this study show anomalous trends (indicated by the dashed line in Fig. 3) which is almost parallel to the Hsinhua Fault and crossing the Hsinhua Fault in the SW.

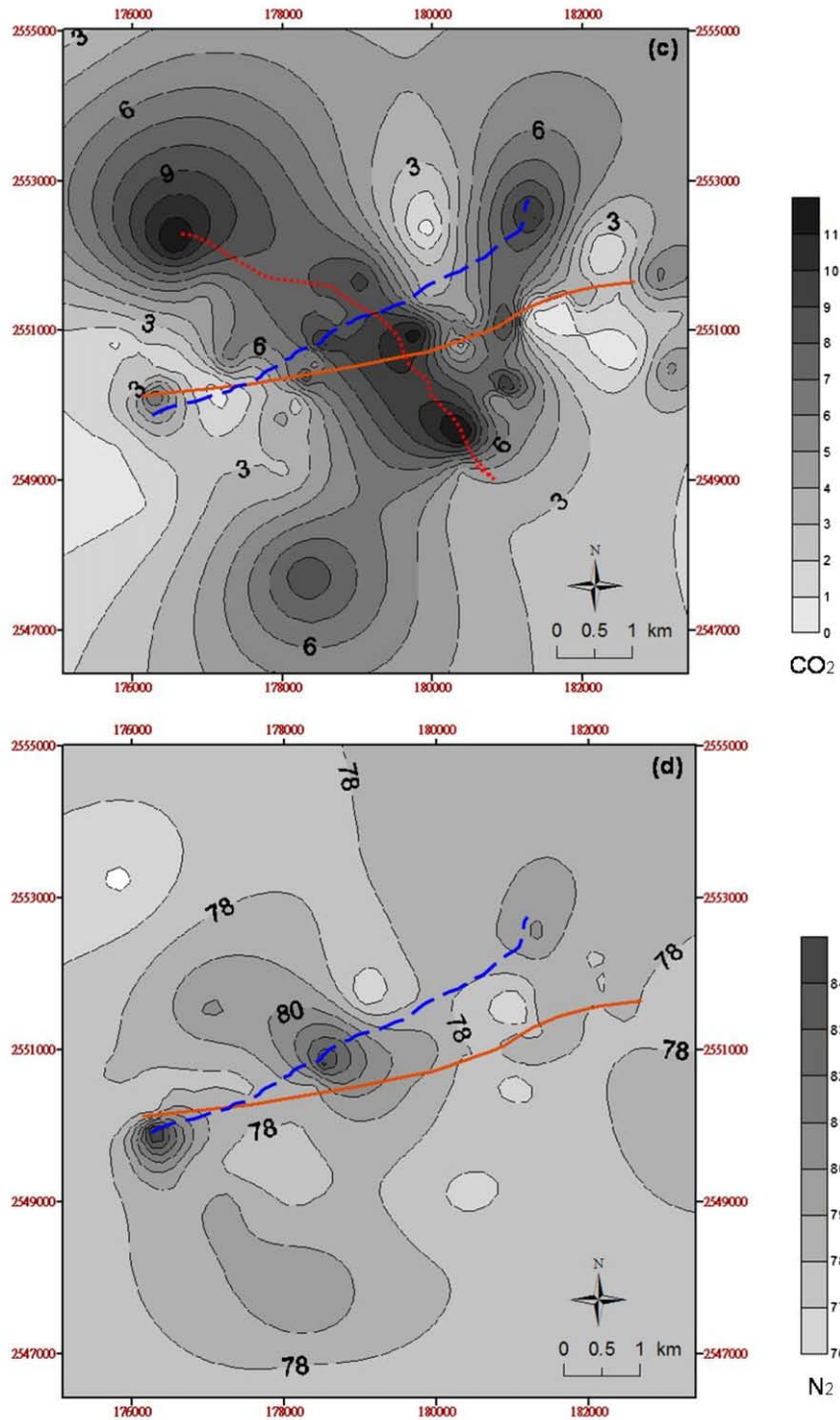


Fig. 3 (continued)

Table 1
Statistics of gas composition for the collected soil gas samples.

Gas species	Minimum	Maximum	Average	Standard deviation
^{222}Rn	712 Bq/m ³	90,974 Bq/m ³	29,460 Bq/m ³	21,097 Bq/m ³
^4He	5.24 ppm	5.46 ppm	5.27 ppm	0.05 ppm
CO ₂	0.00%	21.39%	3.34%	3.80%
N ₂	75.52%	86.48%	78.22%	1.39%

This trend in all the gas species indicates the presence of some neotectonic features. The presence of these neotectonic feature shows that the Hinshua fault is an active fault. It suggests that both ^{222}Rn and CO₂ are useful index gases for the location of faults but with different patterns. Although the highest values of ^4He concentration were not recorded along the probable fault location, the values along it were found to be higher than the identified threshold value of 5.3 ppm in the area. It can be seen that ^4He concentration shows anomalous values (i.e. 5.30 ppm or more) at about 25 points in the whole survey along all the 13 profiles. Of the 13

profiles, two profiles were on the Tainan National Science Industrial Park (TNSIP). Although the TNSIP is far from the probable location of Hsinhua Fault (Fig. 1) some points showed high values for ^{222}Rn , ^4He , N_2 and CO_2 , re-sampled after a few weeks, the same locations again showed high values of ^{222}Rn , ^4He , N_2 and CO_2 . As many as 6 cases showed values of more than 80% for N_2 . The other carrier gas CO_2 had a value of more than 10% at about 7 places.

The spatial distribution of both trace (viz. Rn^{222} and ^4He) and carrier (viz. N_2 and CO_2) gases show anomalous values in the north of the probable Hsinhua Fault location. These anomalous values in all the 4 gases are an indication of the presence of neotectonic features in the area. The absence of anomalous values along the fault location in some of the profiles may be attributed to a high water table in the region. Also, it has been noted that the values of both the carrier gases are comparatively low in the study area compared to Northern Taiwan (Walia et al., 2009; Hong et al., 2010).

5. Conclusions

From this study it can be inferred that the combined soil gas distribution of ^4He , ^{222}Rn , CO_2 , and N_2 help to identify the location of the Hsinhua Fault along with some other neotectonic features (shown by the dashed line) in the region (Fig. 3a–d). The results highlight that, analyses of two or more than two gas species give more reliable information which is clearly seen from the spatial distribution of the gas species used. Here, it is important to note that soil ^4He values may be either greater or less than atmospheric values (i.e. 5.24 ppm), and variations in anomalies of either sign can be significant in interpreting migration pathways in different environments. Further it can be concluded from this and other studies (Hong et al., 2010) that N_2 shows its strong candidature as a possible carrier gas of ^4He not only in the studied area but also in other areas of Taiwan. The spatial distribution of ^{222}Rn and CO_2 indicates that CO_2 may act as a carrier gas for ^{222}Rn in this area, as the latter cannot move long distances alone and probably has a different source to ^4He which might be shallower. Therefore, it is suggested that trace gases like ^{222}Rn and ^4He combined with carrier gases like N_2 and CO_2 in soil atmosphere may well be suitable for identifying tectonic systems.

Acknowledgments

The authors acknowledge the National Science Council of Taiwan for providing all the financial support. We are thankful to Mr. K.W. Wu for his help in sample collecting and analysis.

References

- Al-Taminmi, M.H., Abumurad, K.M., 2001. Radon anomalies along faults in North of Jordan. *Radiat. Measur.* 34, 397–400.
- 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 characterize active tectonic areas: the jaut pass example (Pyrenees, France). *Earth Planet. Sci. Lett.* 196, 69–81.
- Chang, L.S., Chow, M., Chen, P.Y., 1947. The Taiwan earthquake of December 5, 1946. *Taiwan Geol. Surv. Bull.* 1, 17–20.
- Chyi, L.L., Quick, T.J., Yang, T.F., Chen, C.-H., 2005. Soil gas radon spectra and earthquakes. *Terr. Atmos. Ocean. Sci.* 16, 763–774.
- 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.
- Deffontaines, B., Lacombe, O., Angelier, J., Chu, H.T., Mouthereau, F., Lee, C.T., Deramond, J., Lee, J.F., Yu, M.S., Liew, P.M., 1997. Quaternary transfer faulting in Taiwan foothills: evidence from a multisource approach. *Tectonophysics.* 274, 61–82.
- Etiopie, G., Martinelli, G., 2002. Migration of carrier and trace gases in the geosphere: an overview. *Phys. Earth Planet. Interiors* 129, 185–204.
- 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., Jane, D., Walia, V., Chen, Y.G., Liu, T.K., Chen, C.-H., 2008. Variations of helium and radon concentrations in soil gases from an active fault zone in Southern Taiwan. *Radiat. Measur.* 43, S348–S352.
- 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. Measur.* 44, 940–944.
- Guerra, M., Lombardi, S., 2001. Soil-gas method for tracing neotectonic faults in clay basins: the Pistocci field (Southern Italy). *Tectonophysics.* 339, 511–522.
- 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 (4), 593–601.
- Hsieh, S.H., 1972. Subsurface geology and gravity anomalies of the Tainan and Chungchou structure of the coastal plain of Southwestern Taiwan. *Petrol. Geol. Taiwan* 10, 323–338.
- Hsu, M.-T., 1971. Seismicity of Taiwan and some related problems. *Bull. Int. Inst. Seismol. Earthquake Eng.* 8, 41–160.
- Huang, S.T., Chen, Yang, K.M., Hung, J.H., Wu, J.C., Ting, H.H., Mei, W.W., Hsu, S.H., Lee, M., 2004. Deformation front development at the northeast margin of the Tainan basin, Tainan–Kaohsiung area Taiwan. *Mar. Geophys. Res.* 25, 139–156.
- Hwang, R.D., Yu, G.K., Chang, W.Y., Chang, J.P., 2003. Lateral variations of shallow shear-velocity structure in Southwestern Taiwan inferred from short-period Rayleigh waves. *Earth Planets Space* 55, 349–354.
- Irwin, W.P., Barnes, I., 1980. Tectonic relations of carbon dioxide discharges and earthquakes. *J. Geophys. Res.* 85, 3115–3121.
- Lacombe, O., Mouthereau, F., Deffontaines, B., Angelier, J.M., Chu, H.T., Lee, C.T., 1999. Geometry and quaternary kinematics of fold-and-thrust unit of Southwestern Taiwan. *Tectonics* 18, 1198–1223.
- Lan, T.F., Yang, T.F., Lee, H.F., Chen, Y.G., Chen, C.-H., Song, S.R., Tsao, S., 2007. Compositions and flux of soil gases in hydrothermal area, Northern Taiwan. *J. Volcanol. Geotherm. Res.* 15, 32–45.
- Lee, T.Y., Tang, C.H., Ting, J.S., Hsu, Y.Y., 1993. Sequence stratigraphy of the Tainan basin, offshore Southwestern Taiwan. *Petrol. Geol. Taiwan* 28, 119–158.
- Lee, T.Y., Hsu, Y.Y., Tang, C.H., 1995. Structural geometry of the deformation front between 22°N and 23°N and migration of the Penghu canyon, offshore Southwestern Taiwan arccontinent collision zone. In: *Proc. 3rd Sino-French Symp., Taipei, March 1995, ACT Symp.*, pp. 219–227.
- Lee, C.T., Chen, C.T., Chi, Y.M., Liao, C.W., Liao, C.F., Lin, C.C., 2000. Engineering Investigation of Hsinhua Fault. National Central University, 7 (in Chinese).
- Liu, C.S., Huang, I.L., Teng, L.S., 1997. Structural feature off Southwestern Taiwan. *Mar. Geol.* 137, 305–319.
- Lombardi, S., Etiopie, G., Guerra, M., Ciotoli, G., Grainger, P., Duddridge, G.A., Gera, F., Chiantore, V., Pensieri, R., Grindrod, P., Impey, M., 1996. The Refinement of Soil Gas Method Analysis as a Geological Investigative Technique. Final Report. Work Carried Out Under a Cost Sharing Contract with the European Atomic Energy Community in the framework of its 4th R & D Programme on “Management and Storage of Radioactive Waste” (1990–1994) Part A, Task 4: Disposal of Radioactive Waste. EUR 16929 EN.
- Rahn, T.A., Fessenden, J.E., Wahlen, M., 1996. Flux chamber measurements of anomalous CO_2 emission from the flanks of Mammoth Mountain California. *Geophys. Res. Lett.* 23, 1861–1864.
- 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.
- 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. Measur.* 40, 513–516.
- Walia, V., Virk, H.S., Yang, T.F., Mahajan, S., Walia, M., Bajwa, B.S., 2005b. Earthquake prediction studies using radon as a precursor in N–W Himalayas, India: a case study. *Terr. Atmos. Oceanic Sci.* 16, 775–804.
- Walia, V., Virk, H.S., Bajwa, B.S., 2006. Radon precursory signals for some earthquakes of magnitude >5 occurred in N–W Himalaya. *Pure Appl. Geophys.* 163, 711–721.
- Walia, V., Mahajan, S., Kumar, A., Singh, S., Bajwa, B.S., Dhar, S., Yang, T.F., 2007. Fault delineation study using soil-gas method in Dharamsala area, NW Himalayas India. *Radiat. Measur.* 43, S337–S342.
- Walia, V., Yang, T.F., Hong, W.L., Lin, S.J., Fu, C.C., Wen, K.L., Chen, C.-H., 2009. Geochemical variation of soil-gas composition for fault trace and earthquake precursory studies along the Hsincheng Fault in NW Taiwan. *Appl. Rad. Isotopes.* 67, 1855–1863.
- 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. Measur.* 36, 425–429.
- 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., 2005. Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. *Radiat. Measur.* 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: multi-parameter automatic gas monitoring results. *Pure Appl. Geophys.* 163, 693–709.
- Yu, H.S., 1993. Contrasting tectonic style of a foredeep with a passive margin: Southwest Taiwan and South China. *Petrol. Geol. Taiwan* 28, 97–118.