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

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-

**Article info**

**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.

*Corresponding author. Fax: +886 2 6630 0855.
E-mail address: vivekwalia@rediffmail.com (V. Walia).

0883-2927/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apgeochem.2010.01.017
(222Rn) is continuously generated from 226Ra within the rock strata as an intermediate decay product of the 238U radio-active series. The short half-life of 222Rn (t1/2 = 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 CO2, CH4, He or N2 (Etiope 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 cm²/s) about 10 times higher than that of N2, O2 and CO2. 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; Walla 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 222Rn 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 CO2 is a mixture of some of these sources (Fu et al., 2005). High CO2 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 222Rn 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 222Rn and 4He must be referenced to carrier gases (viz. CO2, N2) that can carry the rare gases.

In the present study interest has been focused on the distribution of 222Rn, 4He, CO2 and N2 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 CO2 and N2 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
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, Defontaines 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 southwestern Taiwan still remains uncertain.

The presence of some major tectonic elements including the Chukou Fault, the Tsochen Fault, the Napalin Anticline and the Shihzuch 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–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), respectively. 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 transverses 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 metrological) 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.
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 addition 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.
This trend in all the gas species indicates the presence of some neotectonic features. The presence of these neotectonic features shows that the Hinshua fault is an active fault. It suggests that both $^{222}$Rn and CO$_2$ are useful index gases for the location of faults but with different patterns. Although the highest values of $^4$He 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 $^4$He 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

<table>
<thead>
<tr>
<th>Gas species</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn</td>
<td>712 Bq/m$^3$</td>
<td>90,974 Bq/m$^3$</td>
<td>29,460 Bq/m$^3$</td>
<td>21,097 Bq/m$^3$</td>
</tr>
<tr>
<td>$^4$He</td>
<td>5.24 ppm</td>
<td>5.46 ppm</td>
<td>5.27 ppm</td>
<td>0.05 ppm</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.00%</td>
<td>21.39%</td>
<td>3.34%</td>
<td>3.80%</td>
</tr>
<tr>
<td>N$_2$</td>
<td>75.52%</td>
<td>86.48%</td>
<td>78.22%</td>
<td>1.39%</td>
</tr>
</tbody>
</table>

Table 1
Statistics of gas composition for the collected soil gas samples.
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 
\(^{222}\text{Rn},^{4}\text{He},^{\text{N}2}\) and \(^{\text{CO}_2}\), re-sampled after a few weeks, the same locations again showed high values of \(^{222}\text{Rn},^{4}\text{He},^{\text{N}2}\) and \(^{\text{CO}_2}\). As many as 6 cases showed values of more than 80% for \(\text{N}2\). The other carrier gas \(^{\text{CO}_2}\) had a value of more than 10% at about 7 places.

The spatial distribution of both trace (viz. \(^{222}\text{Rn}\) and \(^{4}\text{He}\)) and carrier (viz. \(\text{N}2\) and \(^{\text{CO}_2}\)) 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 \(^{\text{He}},^{222}\text{Rn},^{\text{CO}_2}\), and \(\text{N}2\) 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 \(^{\text{He}}\) 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 \(\text{N}2\) shows its strong candidature as a possible carrier gas of \(^{\text{He}}\) not only in the studied area but also in other areas of Taiwan. The spatial distribution of \(^{222}\text{Rn}\) and \(^{\text{CO}_2}\) indicates that \(^{\text{CO}_2}\) may act as a carrier gas for \(^{222}\text{Rn}\) in this area, as the latter cannot move long distances alone and probably has a different source to \(^{\text{He}}\) which might be shallower. Therefore, it is suggested that trace gases like \(^{222}\text{Rn}\) and \(^{\text{He}}\) combined with carrier gases like \(\text{N}2\) and \(^{\text{CO}_2}\) 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


