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

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*

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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 earthquakes ($M_L > 3$) 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 strike-slip 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.

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.

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,

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[*] Corresponding author.
E-mail address: ccfu@earth.sinica.edu.tw (C.-C. Fu).
[1] Deceased.

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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, N_2, CO_2, and CH_4 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 CO_2 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 reverse-separation 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 strike-slip 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 sandstone-siltstone-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, N_2, CO_2, and CH_4 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

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