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Estimation of fracture porosity and permeability using radon as a tracer

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ABSTRACT

A quantitative method using the precursory radon decline as a tracer to estimate fracture porosity and permeability is presented with the help of a case study. In an undrained fractured aquifer, the in-situ volatilization of dissolved radon could cause a decline of groundwater radon precursory to an earthquake. Based on the mechanisms of in-situ radon volatilization, mathematical models have been developed to correlate the radon decline with fracture porosity and permeability in the aquifer rocks.

1. INTRODUCTION

Naturally fractured reservoirs hold large groundwater, geothermal, and hydrocarbon resources. Fracture porosity is an important formation parameter for evaluating fluid-in-place in naturally fractured reservoirs. Snow (1968) developed a method to determine fracture porosity from permeability measurements in drill holes. Other sources of information for evaluating fracture porosity and permeability include drilling history, well logging (Aguilera, 1980), well tests (Earlougher, 1977), tracer tests (Axelsson, Bjornsson and Montalvo, 2005), and production history. This paper presents a quantitative method to determine fracture porosity and permeability using radon as a tracer.

An anomalous radon decline from a background level of 791 ± 46 pCi/L to a minimum of 326 ± 9 pCi/L was observed at the well D1 in the Antung hot spring prior to the 2003 *Mw* = 6.8 Chengkung earthquake in eastern Taiwan (Kuo et al., 2006). Well D1 is completed in fractured confined aquifers of weak recharge. Under such geological conditions, the dilation of brittle rock mass and in-situ volatilization of radon could cause the anomalous declines of radon in groundwater precursory to nearby earthquakes (Kuo et al., 2006).

A mathematical model correlating the radon decline with the gas saturation, fracture porosity, and volumetric strain change in the aquifer rocks is presented in this paper. We also illustrated the application of the model to estimate fracture porosity and permeability using the radon decline precursory to the 2003 *Mw* = 6.8 Chengkung earthquake as an example.

2. RADON AND STRAIN ANOMALIES PRECURSORY TO THE 2003 *MW* = 6.8 CHENGKUNG EARTHQUAKE

To assess long term trends in radon concentrations in ground water, we began to study the Antung hot spring in eastern Taiwan about 3 km southeast of the Chihshang fault in July 2003 (Figure 1). The Chihshang fault is the most active segment of the Longitudinal Valley fault, which forms the present-day plate boundary between the Eurasian and Philippine Sea plates. The Chihshang fault (Hsu 1962) ruptured twice in 1951 during earthquakes of magnitude (M) 6.2 and (M) 7.0. A magnitude *Mw* = 6.8 earthquake occurred at 4:38 am December 10, 2003 (UT), the strongest since 1951 near the Chengkung area in eastern Taiwan.

Well D1 (Figure 1) at the Antung hot spring, located roughly 20 km north of the hypocenter of the 2003 earthquake. The radon concentration was fairly stable (780 pCi/L in average) from July 2003 to September 2003 (Figure 2). Sixty-five days before the magnitude *Mw* = 6.8 earthquake (December 10, 2003), the radon concentration of ground water started to decrease and continued to decrease for 45 days. Twenty days prior to the earthquake, the radon concentration reached a minimum value of 330 pCi/L and before starting to increase. Just before the earthquake, the radon concentration recovered to the previous background level of 780 pCi/L. The main shock also produced a sharp anomalous coseismic decrease (~300 pCi/L). After the earthquake, some irregular variations were observed, which we interpret as an indication that the strain release by the main shock was not complete and that some accumulation and release of strain continued in the region.

The geological map and cross section near Antung well D1 are shown in Figure 3. The Antung hot spring is situated in an andesitic tuffaceous sandstone block (Miocene) which is enclosed within the Paliwan Formation (Late Pliocene to Pleistocene mudstone with sandstone). The hot spring is formed nearby an eastward-dipping, high-angle reverse fault zone which contacts between the Lichi mélange and the Paliwan Formation. Some hot springs and mud volcanoes are scattered along the fault zone, indicating a Quaternary active fault. The Lichi mélange occurs as a highly deformed mudstone that is characterized by penetrative foliation visible in outcrop. The Tuluanshan Formation consists of Miocene volcanic rocks such as lava and volcanic breccia as well as tuffaceous sandstone (Chen and Wang 1996).

Well-developed minor faults and joints are common in the tuffaceous-sandstone block displaying intensively brittle deformation. It is possible that these fractures reflect deformation and disruption by the nearby faults. Ground water flows through the fault zone and is then diffused into the block along the minor fractures. The well D1 is not artesian, implying a weak recharge to a small aquifer. When the recharge rate is very slow and can be negligible, the aquifer is in undrained condition. Geological evidence suggests that the Antung hot spring at well D1 is a small low-porosity fractured aquifer in undrained conditions near an active fault.

We calculated the coseismic strain distribution due to the 2003 Chengkung earthquake based on the dislocation fault model (Okada, 1992). The calculated contractional surface strain near the Antung hot spring area is about 20 ppm (Figure 4). It implies that the coseimic strain at well D1 due to the 2003 Chengkung earthquake is about 20 ppm. We can reasonably estimate the volumetric strain at well D1 for about 5 ppm at the minimum radon concentration of 330 pCi/L. The strain behavior at well D1 precursory to the 2003 Chengkung earthquake depends on fracture porosity.

3. RADON-VOLATILIZATION AND ROCK-DILATANCY MODEL

For a fractured confined aquifer in undrained conditions, we developed a mathematical model correlating the observed decline in radon with the volumetric strain change in the crust. The model consists of two parts, i.e., the radon-volatilization model and the rock-dilatancy model. Figure 5 shows the radon-volatilization model, equation (1).

$$C_0 = C_w \left(H \times S_g + 1 \right) \tag{1}$$

where C_0 is initial radon concentration in the formation water, pCi/L; C_w is equilibrium radon concentration in the formation water, pCi/L; S_g is gas saturation, %; H is Henry's coefficient for radon, dimensionless.

Figure 6, the rock-dilatancy model, shows the variation of the volumetric strain as a function of the gas saturation with the fracture porosity as parameter. The rock-dilatancy model can also be expressed as follows.

$$de \cong \frac{S_g}{\frac{1}{\phi}} \tag{2}$$

where de is volumetric strain, dimensionless; ϕ is initial fracture porosity before rock dilatancy, fraction; S_g is gas saturation, %.

Equations (1) and (2) employ radon as a quantitative tracer to calculate strain changes associated with earthquake occurrences for a given fracture porosity. Vice versa, the radon-volatilization and rock-dilatancy models can be applied to calculate fracture porosity from the measured strain changes and radon declines associated with earthquake occurrences.

4. ESTIMATION OF FRACTURE POROSITY AND PERMEABILITY USING RADON AS A TRACER

Well D1 is situated in a fractured confined aquifer of weak recharge. Specifically, the radon concentration in groundwater decreased from a background level of 780 pCi/L to a minimum of 330 pCi/L with a volumetric strain change of about 5 ppm near well D1 precursory to the 2003 Chengkung earthquake. Based on equation (1), the radon decrease from a background level of 780 pCi/L to a minimum of 330 pCi/L required a gas saturation of 17.2 % developed in cracks in the rock. Based on equation (2), the fracture porosity at the SKE-1 well was then estimated at 0.0000291.

Snow (1968) assumed that three mutually orthogonal sets of fractures are common in nature. Snow (1968) derived the following equations to estimate the fracture porosity (ϕ) and the average aperture ($2B$) from a measured permeability (k) for a cubic arrangement of plane fractures with an average spacing (Δ).

$$\phi = 5.45\left(\frac{k}{\Delta^2}\right)^{\frac{1}{3}} \tag{3}$$

and

$$2B = \phi \frac{\Delta}{3} \tag{4}$$

Applying equations (3) and (4), we can calculate the permeability (k) at 4.09 md for well D1 with the fracture porosity of 0.0000291 by assuming an average aperture ($2B$) of 50 microns.

Figures 5 and 6 also show a graphical method to estimate fracture porosity using radon decline and crustal-strain change precursory to the 2003 Chengkung earthquake. A minimum radon fraction remaining in groundwater of 0.423 was first calculated from the record of radon decline precursory to the 2003 Chengkung earthquake. A gas saturation of 17.2 % developed in cracks in the rock was then read from the radon-volatilization curve (Figure 5). The plot of volumetric strain versus gas saturation is a straight line passing through the origin with a slope equal to fracture porosity. Figure 6 shows the straight line with a slope of 0.0000291, which is the fracture porosity at the well D1.

5. CONCLUSIONS

A quantitative method has been developed to estimate fracture porosity using the radon decline in groundwater and crustal-strain change precursory to an earthquake. The anomalous decline in groundwater radon precursory to the 2003 Chengkung earthquake has been used to estimate the fracture porosity in the aquifer rocks at 0.0000291.

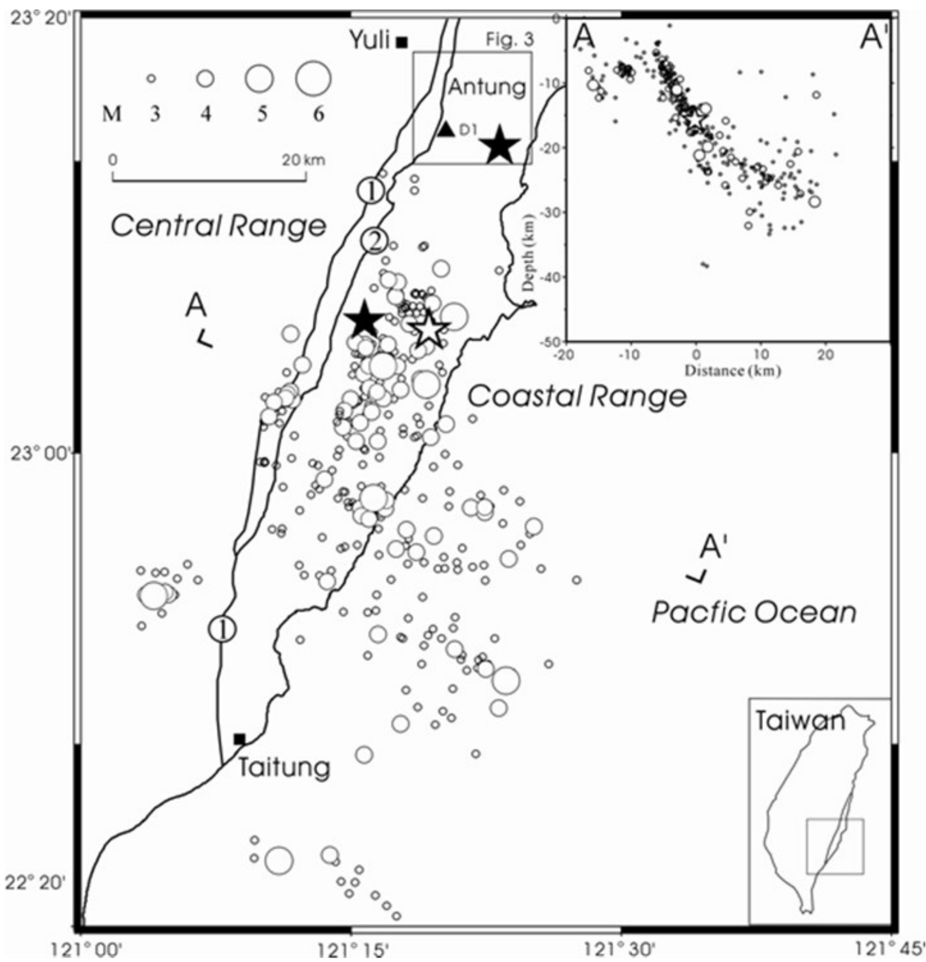

Figure 1: Map of the epicentral and hypocentral distributions of the mainshock and aftershocks of the 2003 Chengkung earthquake (adapted from Kuo et al. 2006) (open star: 2003 mainshock, open circles: 2003 aftershocks, filled stars: 1951 mainshocks, filled triangle: radon-monitoring well, ①: Chihshang, or, Longitudinal Valley Fault, ②: Yongfeng Fault).

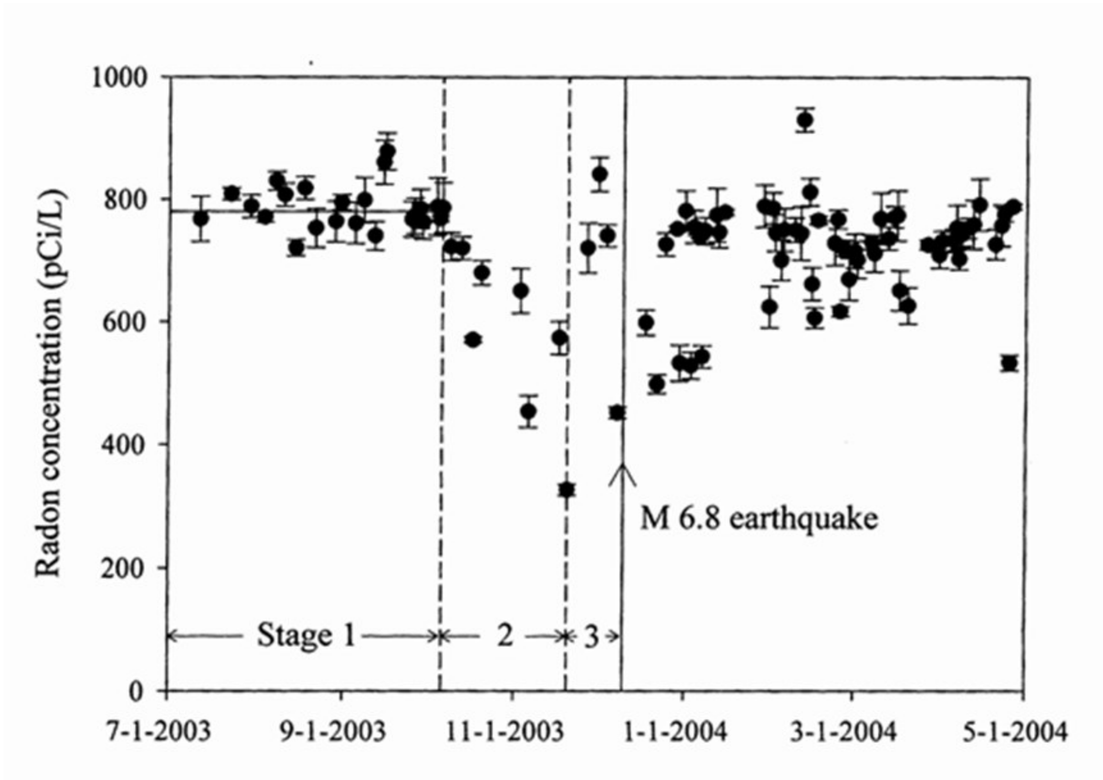

Figure 2: Radon concentration data at the monitoring well (D1) in the Antung hot spring (adapted from Kuo et al. 2006). Stage 1 is buildup of elastic strain. Stage 2 is dilatancy and development of cracks and gas saturation. Stage 3 is influx of ground water and diminishment of gas saturation.

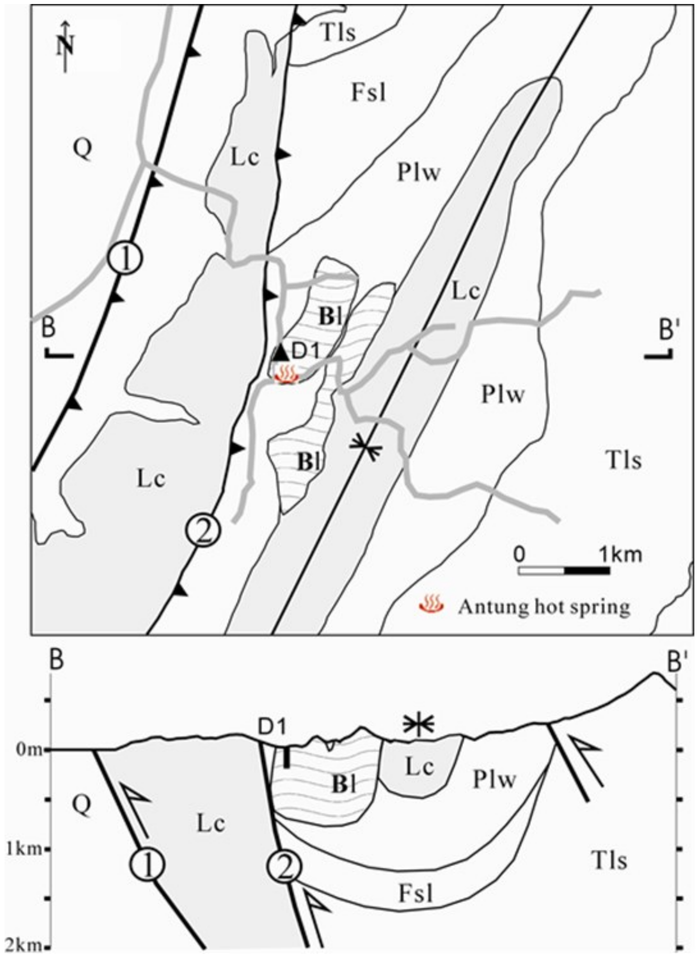

Figure 3: Geological map and cross section near the radon-monitoring well in the area of Antung hot spring (adapted from Kuo et al. 2006) (Q: Holocene deposits, Lc: Lichi mélange, Plw: Paliwan Formation, Fsl: Fanshuliao Formation, Tls: Tuluanshan Formation, Bl: tuffaceous fault block, D1: radon-monitoring well, ①: Chihshang, or, Longitudinal Valley Fault, ②: Yongfeng Fault). See Figure 1 for map location.

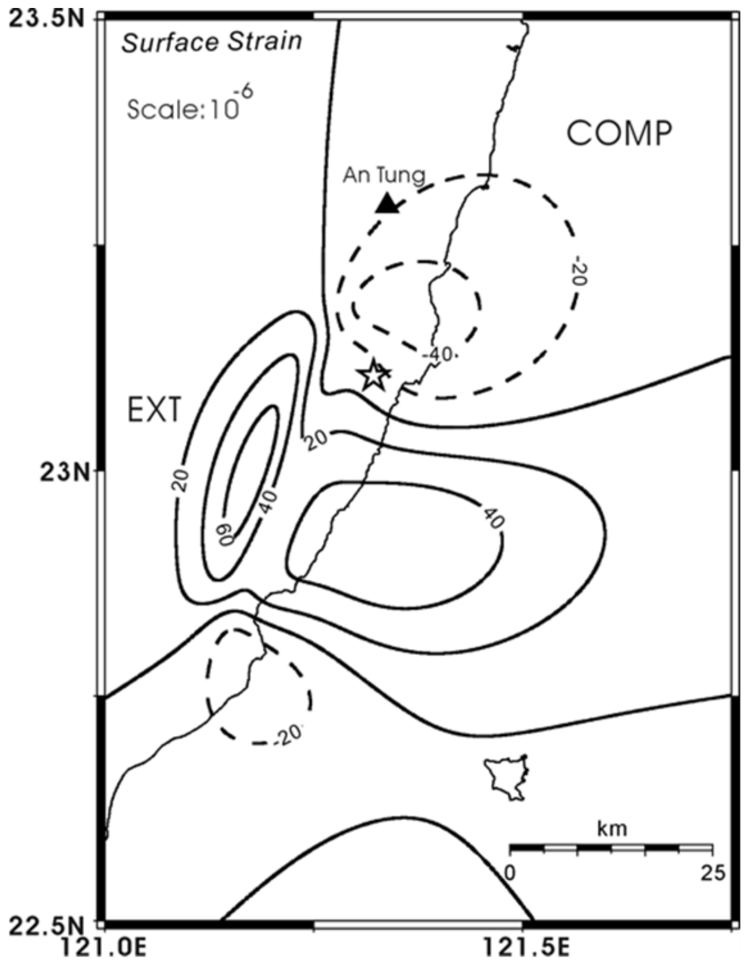

Figure 4: Distribution of coseismic surface strain (ppm) calculated based on the computer code for dislocation models by Okada (1992) (adapted from Kuo et al. 2006). Positive and negative values mean dilatation and contraction, respectively. The open star denotes the 2003 mainshock. The filled triangle denotes the radon-monitoring well (D1). EXT and COMP denote dilatation and contraction, respectively.

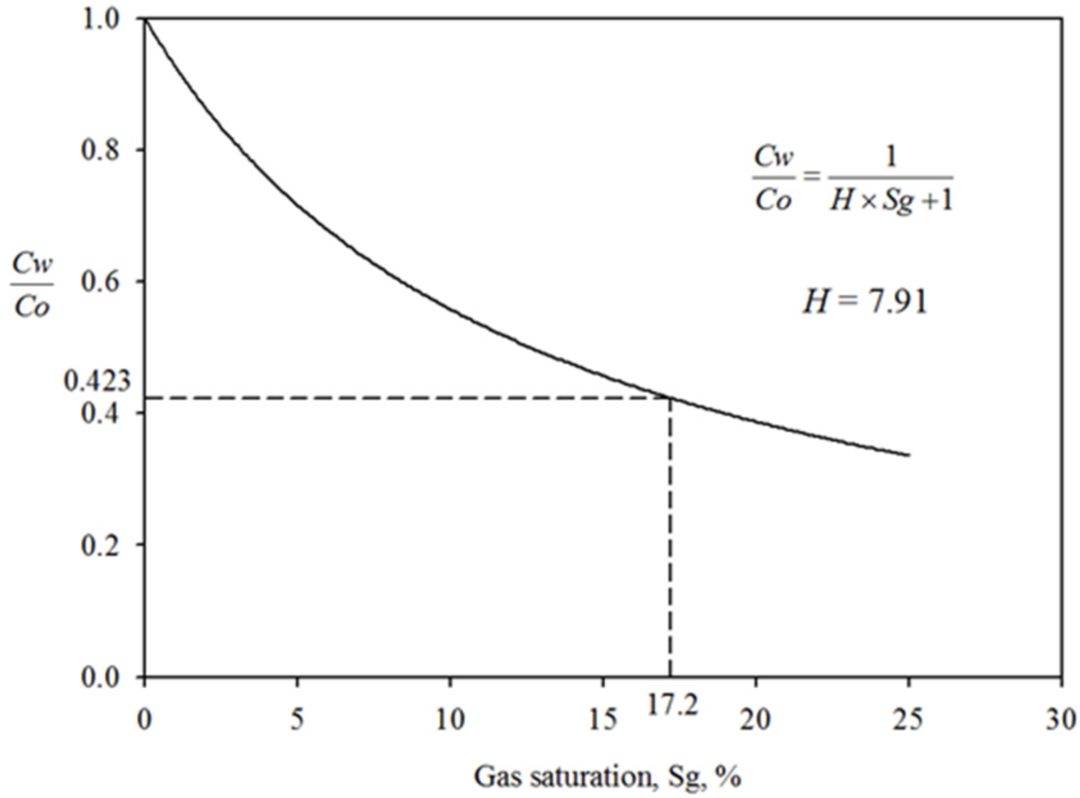

Figure 5: Variation of radon fraction remaining in groundwater with gas saturation at well D1.

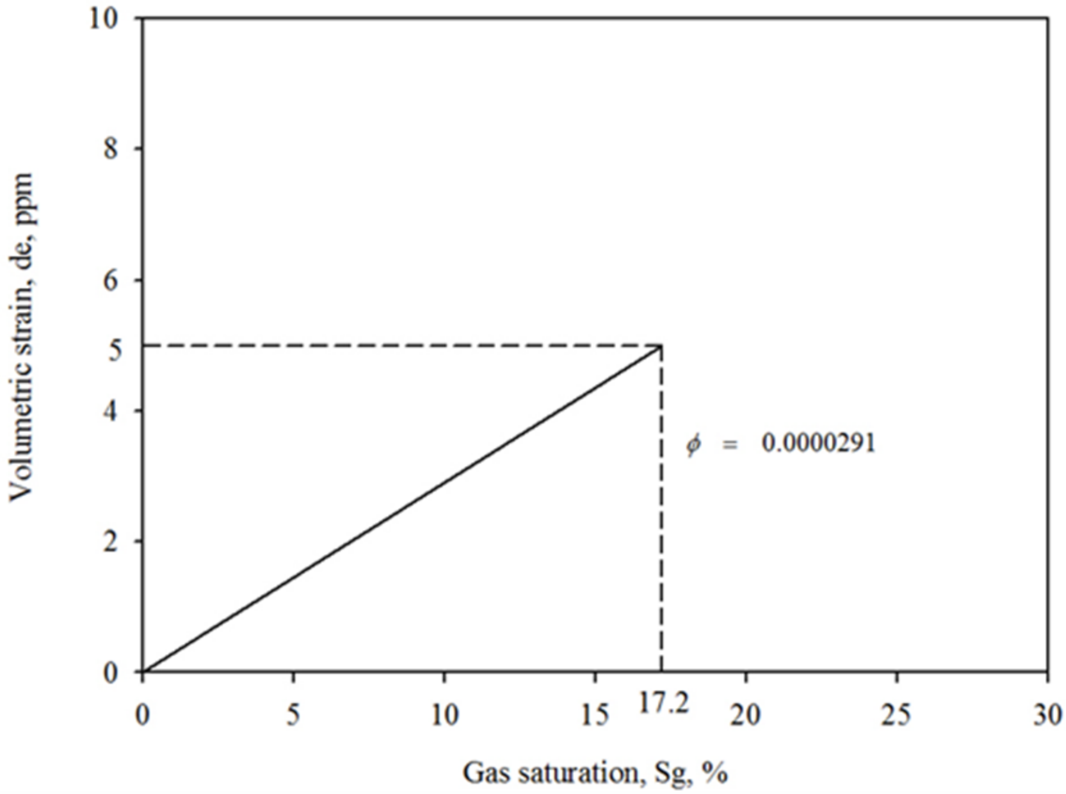

Figure 6: Variation of volumetric strain with gas saturation for fracture porosity = 0.0000291.

REFERENCES

G. Axelsson, G. Bjornsson, F. Montalvo, "Quantitative interpretation of tracer test data", Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 2005.

Aquilera, R., 1980. Naturally fractured reservoirs. Pennwell Publishing Company, OK.

Earlougher Jr., R.C., 1977. Advances in Well Test Analysis, 2nd edition. Society of Petroleum Engineers of AIME, New York.

Chen, W.S., and Y. Wang. 1996. Geology of the Coastal Range, eastern Taiwan. *Geology of Taiwan* 7.

Hsu, T.L. 1962. Recent faulting in the Longitudinal Valley of eastern Taiwan. *Mem. Geol. Soc. China* 1: 95-102.

Kuo, T, Fan, K., Kuochen, H., Chen, W., 2006. A mechanism for anomalous decline in radon precursory to an earthquake. Gr. Water 44 (5), 642-647.

Okada, Y. 1992. Internal deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America* 82, no. 2: 1018-1040.

Snow, D.T., 1968. Rock fracture spacings, openings, and porosities. J. Soil Mech. & Found. Div., ASCE 94 (1), 73-91.