Comparison of Fracture Permeability Estimated from Well Tests and Radon Tracer

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ABSTRACT

Fracture permeability is often estimated from well tests. With the help of a case study, the fracture permeability estimated from well tests is compared with that estimated from radon tracer. Significant difference between the two estimated values of fracture permeability indicates the heterogeneity and range of variation in a naturally fractured reservoir. The value estimated from well tests represents the permeability of highly fractured flow path; the value estimated from radon tracer represents the average permeability of entire fractured reservoir. A quantitative means is presented in this paper to estimate fracture porosity and permeability using radon tracer.

1. Introduction

Naturally fractured reservoirs hold large groundwater, geothermal, and hydrocarbon resources. Fracture permeability is an important formation parameter for evaluating well productivity 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, well tests (Earlougher, 1977), tracer tests, and production history.

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 applied the model to estimate fracture porosity and permeability using the radon data precursory to the 2003 M_w = 6.8 Chengkung earthquake. The fracture permeability estimated from radon tracer is also compared with that estimated from well tests.

2. Estimation of fracture permeability using well tests

Well D1 (Figure 1) at the Antung hot spring is located 24 km north of the hypocenter of the 2003 earthquake. The radon concentration was fairly stable (787 ± 42 pCi/L) from July 2003 to September 2003 (Figure 2). Sixty-five days before the magnitude M_w = 6.8 earthquake (December 10, 2003), the radon concentration of ground water started to decrease and the trend continued to decrease for 45 days. Twenty days prior to the earthquake, the radon concentration reached a minimum (326 ± 9 pCi/L) before the trend started to increase. Just before the earthquake, the radon concentration recovered to the previous background level. The main shock also produced a sharp anomalous coseismic decrease.

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 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 recharge rate is very slow and can be negligible. Geological evidence suggests that the Antung hot spring at well D1 is a small low-porosity fractured aquifer in undrained conditions.

139 well tests were conducted at the well D1 in the Antung hot spring between May 1, 2007 and August 19, 2008. Jacob method (Cooper and Jacob, 1946) was used to analyze drawdown data. Figure 4 shows the estimated transmissivity versus date. The transmissivity estimated from 139 well tests is 0.035 ± 0.006 m^2/min. Given aquifer thickness of 15 m and aquifer temperature at 60 °C estimated from well logs, the calculated fracture permeability is about 2 darcy. The above value estimated from well tests represents the permeability of highly fractured flow path in the low-porosity andesite aquifer.

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. The radon-volatilization model can also be expressed as follows.

$$C_0 = C_w (H \times S_g + 1) \quad (1)$$

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.

The rock-dilatancy model can also be expressed as follows.

$$de \cong \frac{S_g}{\frac{1}{\phi}} \quad (2)$$

where de is volumetric strain, dimensionless; ϕ is facture porosity, fraction; S_g is gas saturation, %.

Equations (1) and (2) can be employed to calculate fracture porosity from the precursory radon decline and crustal strain change associated with earthquake occurrence.

4. Estimation of fracture permeability using radon tracer

An anomalous radon decline from a background level of 787 ± 42 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 M_w = 6.8 Chengkung earthquake in eastern Taiwan (Figure 2). Well D1 is completed in a fractured confined aquifer 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).

Given aquifer temperature at 60 °C, Henry's coefficient (H) for radon is 7.91. Based on equation (1), it requires a gas saturation (S_g) of 17.9 % developed in rock cracks for the above anomalous radon decline from 787 to 326 pCi/L. The calculated compression strain (de) is about 20 ppm near the Antung hot spring for the 2003 M_w = 6.8 Chengkung earthquake (Kuo et al., 2006). Given the above gas saturation (S_g) and compression strain (de), the fracture porosity (ϕ) at Well D1 can then be calculated as 0.0001117 using equation (2).

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).

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

and

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

Given the calculated fracture porosity (ϕ) of 0.0001117 for well D1 and average aperture ($2B$) of 50 microns, we can calculate the permeability (k) as 15.7 md using equations (3) and (4). The above value estimated from radon tracer represents the average permeability of entire fractured reservoir.

5. Conclusions

There is a significant difference between the above values of fracture permeability estimated from well tests and radon tracer.

(1) The fracture permeability at the well D1 in the Antung hot spring estimated from well tests is about 2 darcy. The value estimated from well tests represents the permeability of highly fractured flow path in the low-porosity andesite aquifer.

(2) The fracture permeability at the well D1 in the Antung hot spring estimated from radon tracer is about 16 md. The value estimated from radon tracer represents the average permeability of entire fractured reservoir.

REFERENCES

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

Cooper, H.H. and C. E. Jacob, 1946. A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History, *Am. Geophys. Union .Trans.*, 27, 526-534.

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

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.

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

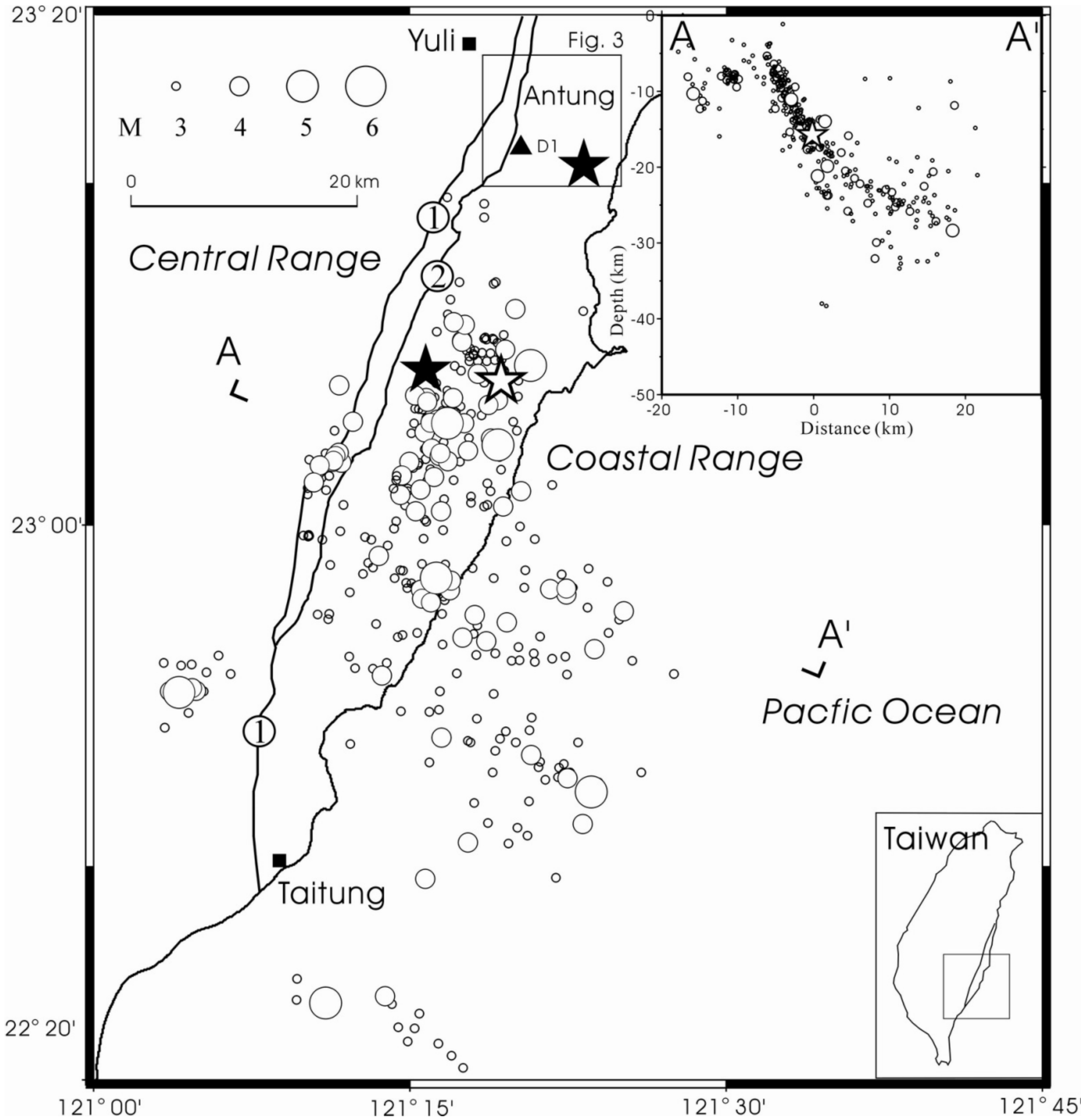

Figure 1 Map of the epicentral and hypocentral distributions of the mainshock and aftershocks of the 2003 Chengkung earthquake (adapted from Kuo et al. 2006) (open star: 2003 mainshock, open circles: 2003 aftershocks, filled stars: 1951 mainshocks, filled triangle: radon-monitoring well, ①: Chihshang,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

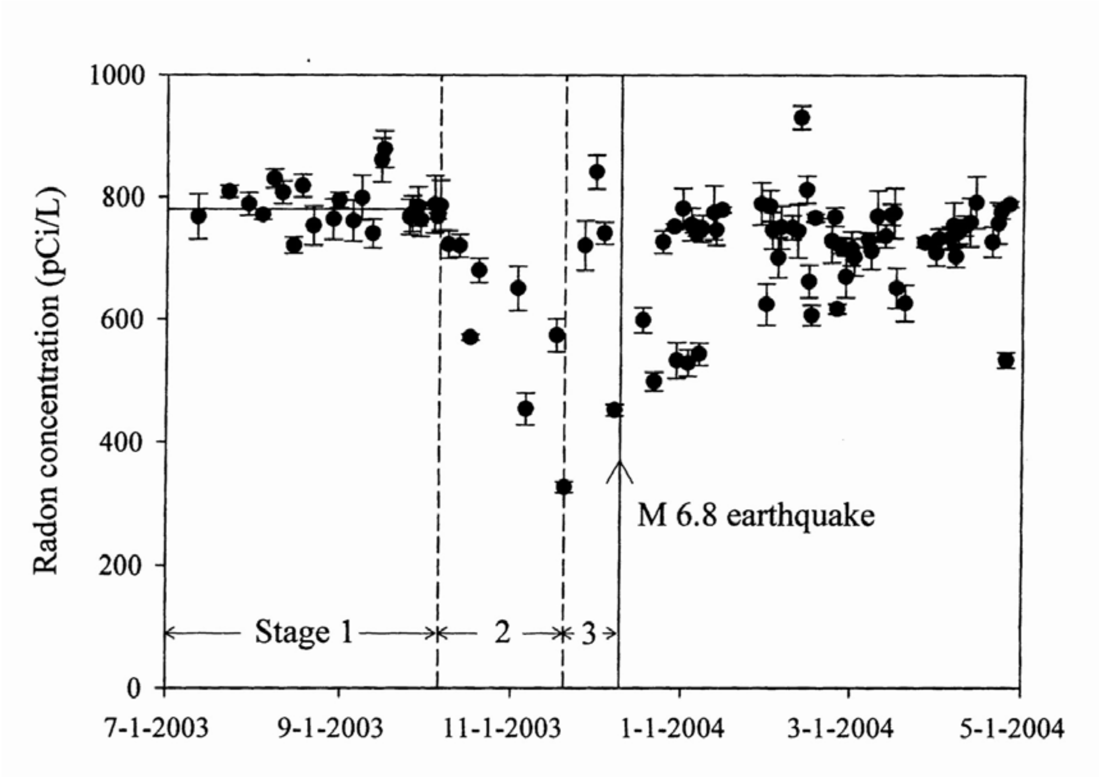

Figure 2 Radon concentration data at the monitoring well (D1) in the Antung hot spring (adapted from Kuo et al. 2006). Stage 1 is buildup of elastic strain. Stage 2 is dilatancy and development of cracks and gas saturation. Stage 3 is influx of ground water and diminishment of gas saturation.

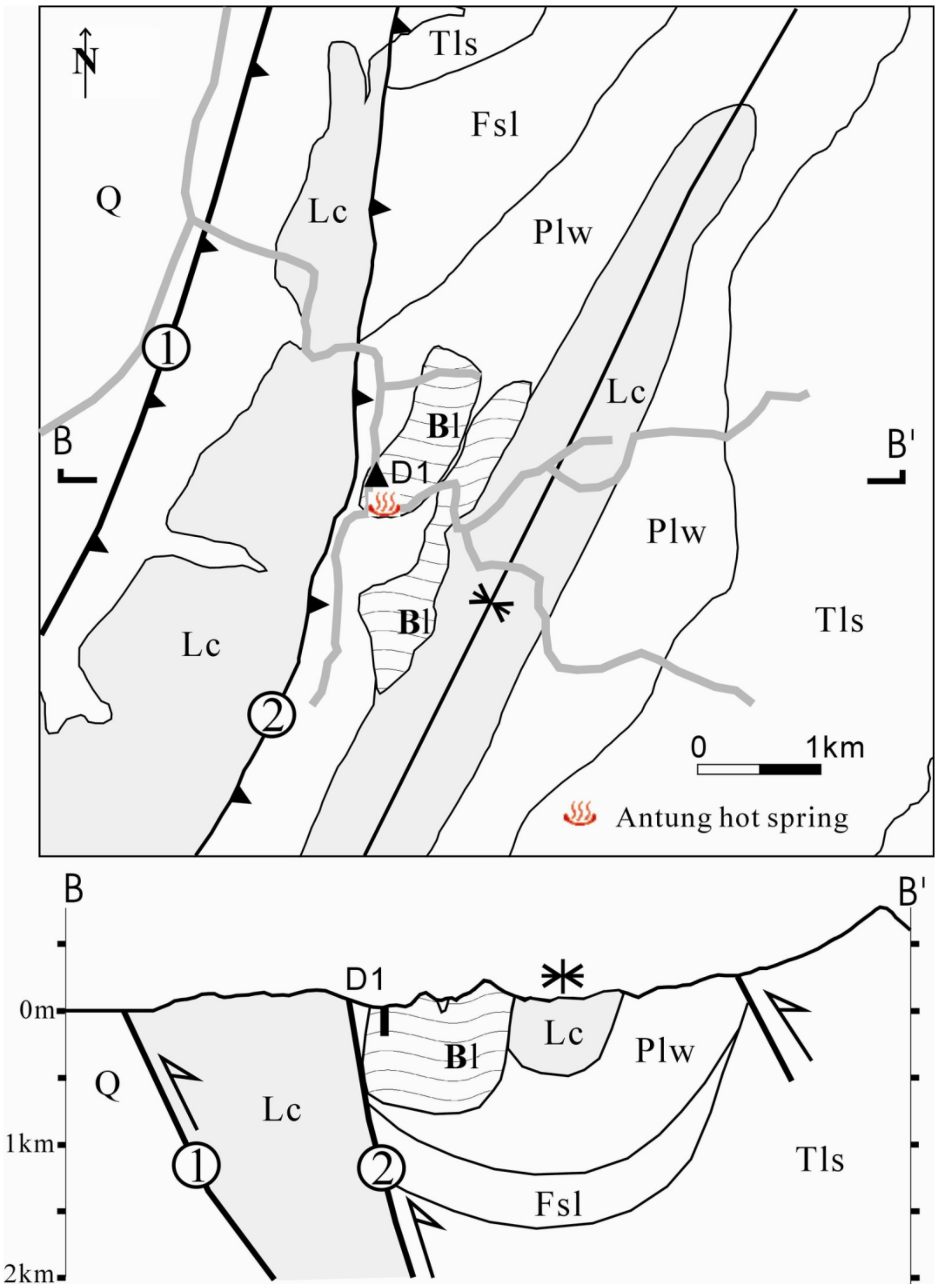

Figure 3 Geological map and cross section near the radon-monitoring well in the area of Antung hot spring (adapted from Kuo et al. 2006) (Q: Holocene deposits, Lc: Lichi mélange, Plw: Paliwan Formation, Fsl: Fanshuliao Formation, Tls: Tuluanshan Formation, Bl: tuffaceous fault block, D1: radon-monitoring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

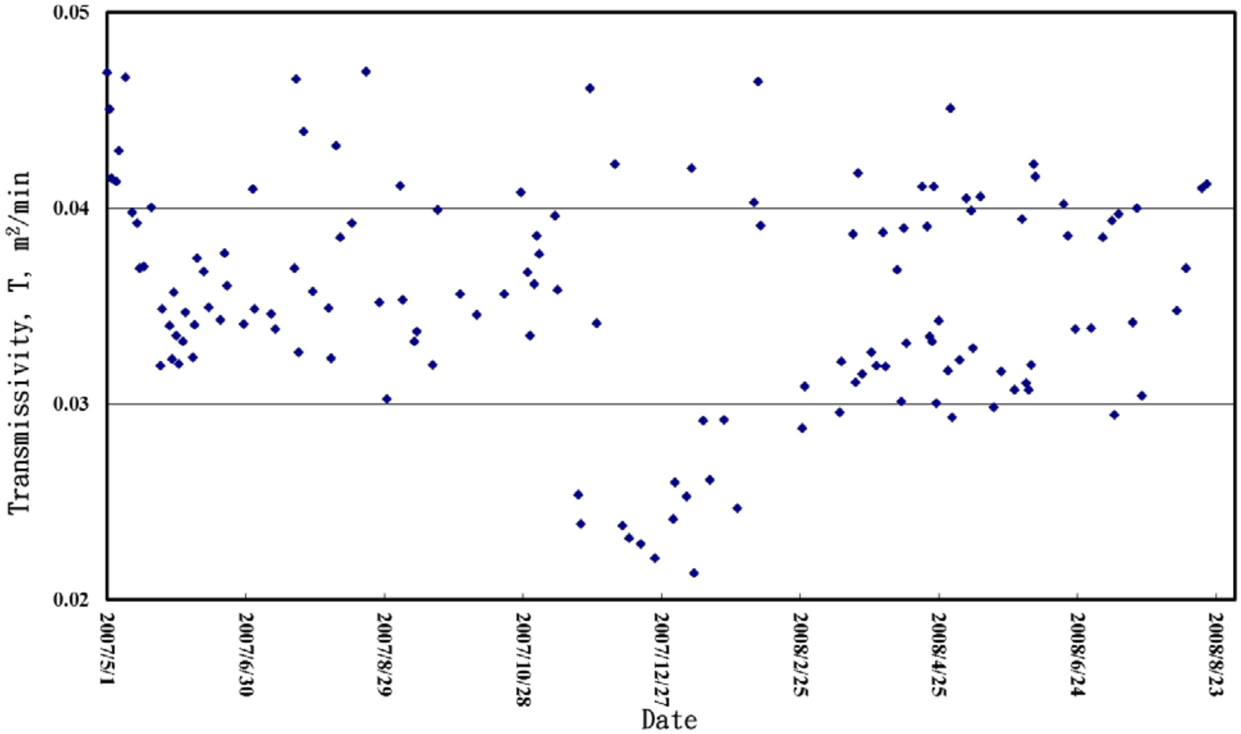

Figure 4 Transmissivity estimated from well tests at well D1 versus date