Need for Seismic Hydrology Research with a Geomicrobiological Focus

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Abstract: Earthquakes cause deformation in previously stable groundwater environments, resulting in changes to the hydrogeological characteristics. The changes to hydrological processes following large-scale earthquakes have been investigated through many physicochemical studies, but understanding of the associated geomicrobiological responses remains limited. To complement the understanding of earthquakes gathered using hydrogeochemical approaches, studies on the effects of the Earth’s deep crustal fluids on microbial community structures can be applied. These studies could help establish the degree of resilience and sustainability of the underground ecosystem following an earthquake. Furthermore, investigations on changes in the microbial community structure of the Earth’s deep crustal fluids before and after an earthquake can be used to predict an earthquake. The results derived from studies that merge hydrogeochemical and geomicrobiological changes in the deep crustal fluids due to the effect of stress on rock characteristics within a fault zone can be used to correlate these factors with earthquake occurrences. In addition, an earthquake risk evaluation method may be developed based on the observable characteristics of fault-zone aquifers.

Keywords: earthquake; seismic hydrology; groundwater; hydrogeochemistry; geomicrobiology

Many studies on the reaction of the Earth’s deep crustal fluids before and after earthquakes have been conducted worldwide, including in countries with a high frequency of earthquakes. Seismic hydrology is the study of earthquake prediction by analyzing hydrogeochemical phenomena before and after earthquakes to understand the reaction mechanism of hydrological factors to earthquakes. Studies have been conducted to analyze the effects of the deep crustal fluids on the groundwater level and quality when earthquakes occur [1–3]. Inert gases were analyzed to track the inflow and movement of deep and shallow groundwater in areas where the groundwater level rises and falls in the event of an earthquake. Furthermore, many isotopes, including $^{13}$C, $^{14}$C, $^{34}$S, $^{18}$O, $^2$H, $^3$H, and $^{87}$Sr, have been studied to monitor the interaction of deep groundwater with the surrounding materials [4].

In countries located in earthquake zones, attempts have been made to evaluate the patterns of change in gases dissolved in the deep crustal fluids, changes in gas emissions, and deformation of the aquifer before and after an earthquake [5,6]. South Korea was considered earthquake-safe until just a few years ago, and the geophysical aspects of its fault zones have been well studied. However, little research on seismic hydrology has been conducted, other than minor research on the rise and fall of groundwater levels and temperatures before, during, and after earthquakes using national groundwater observation network data [7]. The 2016 Gyeongju $M_w$5.4 and 2017 Pohang $M_w$5.4 earthquakes showed that South Korea can no longer be considered an earthquake-safe zone, which has resulted in an increased interest in the fault zones. Before an earthquake occurs in a fault zone, micro-faults form as a result of interaction with the crustal fluids. Hence, gas emissions and ion movements occur, and the groundwater levels change due to the geological stresses, leading to various hydrogeological and hydrogeochemical changes in response. Therefore, the hydrogeological and hydrogeochemical changes in the Earth’s deep crustal fluids in the fault zone, and their correlations with the fault zone characteristics, need to be monitored.
and studied [6]. The groundwater level changes when the fluid in a fault zone is affected by geological stress, and it can also significantly impact the flow of deep crustal fluids and the associated hydrogeochemical characteristics. Depending on the type of rock that experiences stress, the deep fluid may flow inward, and the shallow groundwater may flow outward through cracks in rocks.

The inert gases helium, neon, and argon, which are dissolved in the Earth’s deep crustal fluids, show different isotopic ratios in the atmosphere, in the mantle, and on the surface. The value of $\frac{^{3}\text{He}}{^{4}\text{He}}$ in the atmosphere ($R_a$) is $1.382 \times 10^{-6}$, which is higher than in the crust (~0.002 $R_a$) but lower than in the mantle (~8 $R_a$). The value of $\frac{^{4}\text{He}}{^{20}\text{Ne}}$ is 0.317 in the atmosphere, 10,000 in the crust, and 10,000 in the mantle [8]. Therefore, the circulation characteristics and origin of these gases (from the atmosphere, mantle, or surface) can be determined by analyzing the dissolved gas ratios in the deep crustal fluids. When stress acts on rocks and the gases are discharged to the shallow region, changes in groundwater $\frac{^{3}\text{He}}{^{4}\text{He}}$ and $\frac{^{4}\text{He}}{\text{Ar}}$ ratios can provide general information about the characteristics and stress discharge of rocks, such as the inflow of deep fluid and the discharge of shallow groundwater [6]. Moreover, the volumetric strain of rocks can be calculated using the concentration of helium discharged from the deep crustal fluids into an aquifer after the occurrence of an earthquake. The volume ($\nu$) of helium discharged from rocks in the aquifer can be determined as [6,9–13]:

$$\nu = a \times (\frac{\Delta V}{V})^{2/3}$$

(1)

where “a” is the constant that can be determined by $k_2 \times v_0$ ($k_2$ is the constant obtained from a laboratory rock crack test, $v_0$ is the initial discharge volume of helium from the aquifer rock), and $(\Delta V/V)$ represents the volume change rate. The concentration of helium discharged from the deep crustal fluids following an earthquake can be used to determine the change in volumetric strain caused by an earthquake [6].

Furthermore, the concentrations of dissolved inert gases in the Earth’s deep crustal fluids increase according to the stress change in the rocks after an earthquake. In addition, owing to the characteristics of the bedrock in the aquifer, the concentrations of dissolved Rn and Th in the deep crustal fluids can also change. The dissolved Rn in the deep crustal fluids almost doubles after an earthquake [14]. Therefore, studies that monitor the change in the concentration of dissolved Rn in the deep crustal fluids provide important hydrogeochemical information that indicates changes in stress on the aquifer rock and can be used to indicate the possibility of an earthquake [14,15].

Many researchers have conducted earthquake studies using hydrogeochemical approaches. In addition, research on the effect of the Earth’s deep crustal fluids on the change in microbial community structure can evaluate the resilience and sustainability of the underground ecosystem after an earthquake. Furthermore, an understanding of how the groundwater microbial community structure changes in response to an earthquake can be used to predict the possibility of an earthquake. Among the related literature, there have been few studies correlating community structures of deep and shallow groundwater microbes with the age of groundwater, or correlating changes in hydrogeochemical characteristics with changes in microbial community structures [16]. Recently, there has been a gradual increase in studies that monitor changes in the ecological environment of the groundwater system in response to hydrogeochemical reactions in aquifers after an earthquake [2,17–19]. Hydrochemical data indicated changes and transitions related to immediate responses of indigenous microorganisms to an earthquake’s influence on the groundwater environment [18,19]. According to Yang and Lou [19], Flavobacterium is a representative organism that appears immediately after an earthquake. The results of microbial community studies on the groundwater environment after the Gyeongju earthquake in 2016 in South Korea revealed that the hydrochemical data changed along with the appearance of Flavobacterium [18]. Furthermore, Pseudomonas is a representative microorganism inhabiting groundwater and is a pathogenic bacterium that commonly detected in patients after an earthquake [20–23]. These pathogenic bacteria dominated and
were detected in the aquifer after the Gyeongju earthquake in 2016. It is, therefore, highly important to identify and classify microorganisms indicative of earthquake activity in areas with frequent earthquakes, and to monitor such aquifer microbe communities over a long period in addition to collecting standard hydrochemical data.

The hydrogeochemical changes that occur in the Earth’s deep crustal fluids in response to the generation of stress in a fault zone can be monitored by observing changes in microbial community structures and the inert gas isotopes dissolved in the fluid. The inert gases dissolved in the deep crustal fluids can provide important information following stress discharge after an earthquake because they are sensitive to underground pressure and temperature. The characteristics of the community structures of microorganisms inhabiting deep fluids have not yet been investigated in detail. However, metagenomic analysis of microorganisms present in deep fluids can be used to define characteristics of the microbial ecosystem community structures existing deep in the underground. In addition, important information about changes in the deep underground ecosystem before and after an earthquake, as well as information relevant to earthquake prediction can be gained by analyzing the responses of these microbial community structures to an earthquake. It is believed that using data from microbial groundwater communities together with hydrochemical data in earthquake-related studies will enable a more comprehensive understanding of seismic hydrology. Furthermore, correlating the geological characteristics of rocks in the fault areas with the changes in hydrogeochemistry [24] and the ecology of the deep crustal fluids following stress changes can aid in the development of earthquake risk assessment methods for each characteristic [18,19,24] of the fault zone aquifer.

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