水力壓裂試驗過程中回流水化學演變揭示快速水–岩反應：以韓國浦項花崗閃長岩深層地熱鑽孔為例

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摘要

來自南韓浦項地熱系統的 PX-1 井在 2017 年 8 月進行花崗閃長岩層的水力壓裂試驗後，從垂直深度 4215 公尺回流的水（flowback water）監測了多種物理化學、化學及同位素參數。這些結果為混合過程、流體演化以及深層地熱系統中快速水-岩作用提供了獨特的解釋。水力壓裂試驗所注入的水是相對新鮮、具氧化性的地表水，溫度約為 29.5°C，pH 值約為 6.5。回流水中大多數溶質含量逐漸增加，其中保守性溶質如氯化物的演化趨勢符合指數「沖刷（flushing）」模型。回流水逐漸呈現鈉－氯主導的特性，pH 值接近中性（7.1），氧化還原電位為負值（約 -180 mV）。某些溶質（如鈉、鉀和矽）增加的速度超過了沖刷模型的預期，這暗示回流水從礦物水解過程中獲得了這些元素。氧與氫的穩定同位素分析顯示，最初的降水型地表水已與礦物進行了地熱氧同位素交換。回收水中氧化還原物種的演變顯示，在一個原本還原性的地熱儲層中，注入井周圍出現了逐漸氧化的區帶。回流水中矽濃度迅速增加，顯示出大量石英溶解，並指出儲層溫度可達 169°C。這為一項假設提供了合理但尚不明確的支持，即注入水所造成的石英溶解可能促使原已受應力的斷層產生位移，進而導致 2017 年 11 月浦項規模 5.5 地震的發生。

關鍵字： 地熱、浦項、水文、地球化學、壓裂、同位素

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Rapid water-rock interactions evidenced by hydrochemical evolution of flowback fluid during hydraulic stimulation of a deep geothermal borehole in granodiorite: Pohang, Korea

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ABSTRACT

Flowback water from the 4215 m deep (True Vertical Depth) PX-1 borehole, following the August 2017 hydraulic stimulation of a granodiorite geothermal reservoir in Pohang, South Korea, was monitored for a suite of physicochemical, chemical and isotopic parameters. The results provide unique insights into mixing processes, fluid evolution and rapid water-rock interaction in a deep geothermal system. Injected water for stimulation was relatively fresh, oxidising surface water, with temperature 29.5 °C and pH c. 6.5. The flowback water showed an increasing content of most solutes, with the evolution conforming to an exponential 'flushing' model for conservative solutes such as chloride. Flowback water became progressively Na–Cl dominated, with a circumneutral pH (7.1) and negative oxidation-reduction potential (c. −180 mV). Some solutes (including, Na, K and Si) increased more rapidly than a flushing model would suggest, implying that these had been acquired by the flowback water due to mineral hydrolysis. Stable isotopes of O and H indicate that initially meteoric waters have undergone geothermal oxygen isotope exchange with minerals. Evolution of redox species in recovered water suggests progressively oxidising zonation around the injection borehole in an otherwise reducing reservoir. Rapidly increasing silica concentrations in flowback water suggests extensive quartz dissolution and indicated a reservoir temperature of up to 169 °C. This lends plausible, if equivocal support to the hypothesis that quartz dissolution by injection water may have contributed to triggering movement on the pre-stressed fault associated with the November 2017 Mw 5.5 Pohang earthquake.