Microbially induced clay weathering: Smectite-to-kaolinite transformation

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Abstract

Microbially induced formation and transformation of clay minerals are known to be ubiquitous in nature. This work investigated the smectite-to-kaolinite transformation by Bacillus mucilaginosus, a kind of silicate-weathering bacterium. Results showed that the microbe-smectite system doubled protein production compared with the abiotic controls and enhanced dissolved 1.6% of total Si and 0.9% of total Al from smectite after the 25 days experiment. The formation of kaolinite was verified through its distinguished d_{001}-spacing of 0.710 nm revealed by synchrotron radiation X-ray diffraction (SR-XRD) and high-resolution transmission electron microscope (HR-TEM). HR-TEM analysis indicated some mixed layers of smectite and kaolinite appeared in the form of a super-lattice structure. Moreover, the compositional and morphological changes of the solids suggested the emergence of kaolinite was associated with the formation of amorphous SiO₂ and fragmented clay particles with lower Si/Al ratio and exposed crystal edge. Based on the detection of –C=O species on the smectite surface and the decrease of pH from 8.5 to 6.5, we inferred the organic ligands secreted by Bacillus mucilaginosus complexed with cations, especially for Si, which stripped the tetrahedral sheets and promoted the kaolinization of smectite. To our knowledge, this is the first report of microbially induced smectite-to-kaolinite transformation under ambient conditions in a highly-efficient way. This work could shed light on a novel pathway of microbe-promoted weathering of smectite to kaolinite at the Earth surface conditions. Such a robust and efficient transformation from expansive smectite to non-expansive clays as kaolinite may be of great potential in enhancing oil recovery in reservoirs.

Keywords: Smectite-to-kaolinite transformation, clay minerals, Bacillus mucilaginosus, super-lattice structure, microorganism

Introduction

Clay minerals and microorganisms are two of the most essential and associative components on Earth (Dong et al. 2009; Mueller 2015; Cuadros 2017; Li et al. 2019). Microorganisms (e.g., bacteria and fungi) can facilitate the formation and transformation of clay minerals through nucleation (Konhauser et al. 1993), biomineralization (Kawano and Tomita 2001), dissolution (Banfield et al. 1999), alteration (Dudek et al. 2006), etc. In reverse, redox and decomposition of clay minerals can either provide electron energy or elemental nutrients for microbial growth (Kim et al. 2004; Cuadros 2017; Li et al. 2019).

The mutual transformations of kaolinite, smectite, and illite, which are three clay minerals with the most abundant and reactive mixed layers in the soil, have been experimentally demonstrated under different biotic and abiotic conditions (Bergaya and Lagaly 2006; Dong et al. 2009; Cuadros et al. 2017). In particular, the interconversion of 2:1 type clay minerals, i.e., smectite and illite, has been reported to occur by the catalysis of microorganisms under ambient conditions, in which the microbial redox of Fe(III)/Fe(II) pair was the key to regulate interlayer cations and final mineral phases (Manceau et al. 2000; Dong et al. 2009; Shelobolina et al. 2012; Kim et al. 2004; Zhao et al. 2017). In comparison, the transformation of 1:1 type clay minerals such as kaolinite to 2:1 type clays of smectite/illite is more difficult due to the requirement of other well-matched tetrahedral sheets. Even so, the illitization or smectitization of kaolinite has been demonstrated to occur through the simultaneous uptake of Si, Fe, and Mg, bio-reduction of Fe, and fixation of K, which requires intricate dissolution and precipitation (Andrade et al. 2014; Cuadros et al. 2017).

However, the opposite process of microbial kaolinization of smectite or illite has received less attention. In geological settings, the kaolinization of smectite is an important proxy of paleoclimate change, and kaolinite is generally a product of highly hydrolytic weathering in warm humid climates (Altschuler et al. 1963; Karathanasis and Hajek 1983; Robert and Kennett 1992; Amouric and Olives 1998; Dudek et al. 2006; Ryan and Huertas.