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Reconstruction of the Northeast Asian monsoon climate history for the past 400 years based on textural, carbon and oxygen isotope record of a stalagmite from Yongcheon lava tube cave, Jeju Island, Korea

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ABSTRACT

Paleoclimatic changes over the past 400 years were investigated based on textural and geochemical characteristics of the YC-2 stalagmite which grew in Yongcheon Cave (lava tube cave) on Jeju Island, Korea. The stalagmite is about 68 mm long and annual growth laminae are distinctively identified. The age of the stalagmite was mainly determined by counting annual growth laminae supplemented by other radiometric dating methods, and it is estimated that the stalagmite grew at least for *ca.* 242 years including the hiatus. This hiatus is located at about 15 mm from the base and is present in the form of one thick brown growth lamina which was formed when the stalagmite stopped to grow. Texturally, the stalagmite can be divided into two phases: Fluid inclusion-poor, compact columnar calcite (Phase A) and fluid inclusion-rich, sparse columnar calcite (Phase B). This textural division is intimately related to the spacing of growth laminae, that is, Phase A is characterized by narrower spacing of growth laminae. Phase A with narrow-spaced growth laminae indicates the slower growth rate due to lower amount of rainfall when Northeast Asian summer monsoon intensity was relatively lower. Based on high resolution carbon isotope trend, the stalagmite can be divided into three stages (Stages I, II and III). The relatively more positive carbon isotopic compositions of the Stage I ($\delta^{13}C = -3.3–0.4‰$, PDB) in the lower part indicate that it grew during the Little Ice Age (LIA) under cold and dry climate with less vegetation. The Stage II is a transitional period from cold and dry to warm and wet climate with a continuous decrease in carbon isotope values (from 0.6 to −9.6‰ in $\delta^{13}C$). This stage shows the gradual weakening of the LIA climate. Carbon isotope trend also suggests that the LIA interval was terminated near middle 1870's around Korean peninsula. Relatively low carbon isotopic compositions during Stage III ($\delta^{13}C = -11.0 \sim -8.0‰$) in the upper part should indicate that climate was changed to the warm and wet Current Warm Period. Warming since 1960 can also be recognized. Complete coincidence between textural data (internal calcite texture and growth laminae spacing) and high resolution carbon isotope compositions strongly suggests that past climate changes such as monsoonal variations in Northeast Asia have been clearly recorded in the stalagmite in Yongcheon Cave.

1. Introduction

As speleothem dating becomes more accurate and high resolution geochemical analysis is possible, paleoclimatic interpretation on the scale of a few months using stable isotope and trace element compositions of speleothems together with cave

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monitoring data has become popular (e.g., Cruz et al., 2005; Mattey et al., 2008). Especially, the amount of precipitation and air temperature was reconstructed based on stable isotope compositions of stalagmites (McDermott, 2004; Fairchild et al., 2006). Recently, high resolution oxygen isotope compositions have provided information on East Asian summer monsoon intensity variations (e.g., Wang et al., 2001; Hu et al., 2008; Zhang et al., 2008; Tan et al., 2009; Wan et al., 2011) although Pausata et al. (2011) pointed out that they may be related to the Indian summer monsoon. Carbon isotope compositions of speleothems are also known to be controlled by type of vegetation, biological activities, surface environment, and use and karstification (McDermott, 2004; Cosford et al., 2009). Recent studies showed that carbon isotope compositions of stalagmites also indicate East Asian summer monsoon intensity variations (Jo et al., 2010b, 2011, 2014).

In addition to stable isotopes, textural characteristics such as growth laminae, mineralogy, and fluid inclusions were used for paleoclimatic interpretation (e.g., Woo and Choi, 2006; Jo et al., 2010a, 2010b, 2011). Growth rate and texture of speleothems can change depending upon outside climate changes and surface conditions and therefore can provide significant paleoclimatic information (Woo et al., 2008b; Boch et al., 2011; Tan et al., 2003, 2013). Qian and Zhu (2002) reconstructed changes in amount of precipitation during the Little Ice Age (LIA) near Beijing based on changes in laminae thickness. Paulsen et al. (2003) reconstructed paleotemperature and the degree of humidity for the past 1270 years based on stable isotope compositions combined with dating results by counting growth laminae and $^{230}Th/^{234}U$ data. However, textural information linked to paleoclimate changes has been neglected compared to geochemical studies.

Most paleoclimatic studies have been carried out using speoleothems in limestone caves (e.g., McDermott, 2004; Fairchild et al., 2006). However, very few paleoclimatic data were reported from secondary speleothems in lava tube caves (e.g. Woo et al., 2004; Woo et al., 2008a). Because lava tube caves on Jeju Island are located near the surface (usually less than 10 m depth), it is expected that secondary speleothems in the caves may better record past climate changes on the surface because residence time of percolating water is very short and epikarst setting is relatively simple. Therefore, the objective of this study is to understand paleoclimatic history on Jeju Island, i.e. summer monsoon intensity variation for the past few hundred years, using textural and high resolution stable isotopic data of the stalagmite (YC-2) in Yongcheon Cave. Another concern is to characterize the demise of the Little Ice Age (LIA) near the Korean Peninsula in the Northeast Asian region.

2. Geographic and geologic setting

Korean Peninsula and Jeju Island are influenced by a typical temperate climate with clear four seasons. Also, this region is strongly controlled by Northeast Asian monsoon with warm and humid summer and cold and dry winter (Fig. 1). Meteorological data from Jeju station from 2003 to 2009 recorded that mean annual temperature is ~15.9 °C and mean annual precipitation is 1886.7 mm. Jeju Island is a volcanic island with an elliptical shape (74 km from east to west and 41 km from north to south). The island lies on the continental shelf and was formed by volcanic activities during the Quaternary. Thus, the surface of the island mostly consists of volcanic rocks such as basalt and trachyte. Yongcheon Cave is located in the northeast part of Jeju Island. It is a typical lava tube cave formed by lava flows which are between 200,000 and 300,000 years old (Hwang et al., 2005). It was reported that carbonate speleothems are being actively formed in some lava tube caves on Jeju Island (Woo et al., 2008a, 2008b) and Yongcheon Cave is one of the caves that include carbonate speleothems. The cave, about 2960 m long, was accidently discovered during drilling for an electrical pole. Various micromorphological forms and lava speleothems are present throughout the cave. Carbonate speleothems are distributed in two parts of the passage in which carbonate dune sediments are present (Fig. 1b). Carbonate sediments have been transported by wind since *ca.* 5000 BP (Ji et al., 2008). Carbonate speleothems started to grow from the supply of calcium and carbonate ions dissolved from carbonate sands by meteoric water (e.g., Woo et al., 2008b). Because of their outstanding universal values, Yongchoen and Dangcheomul caves were inscribed as a World Natural Heritage Site by UNESCO in 2007.

Yongcheon Cave provides excellent geological conditions to carry out paleoclimatic research using stalagmites compared to other natural (mostly limestone) caves because of its simple geological setting (Fig. 2). Commonly, limestone caves are overlain by thick limestone with various lithologic characters as well as with

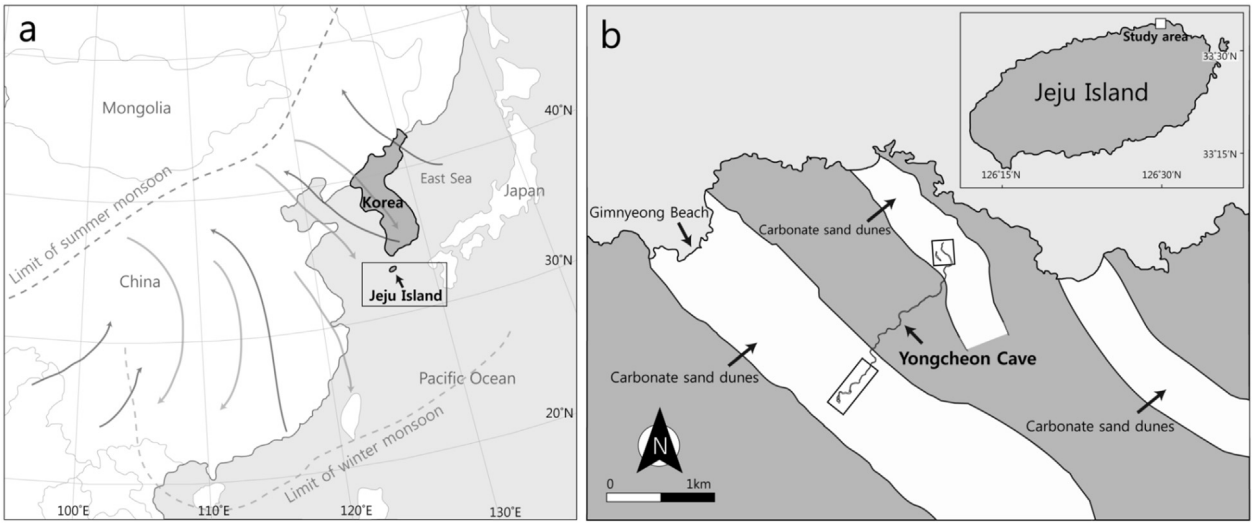

Fig. 1. a) Location of the study area (Jeju Island) in Korea. Arrows indicate generalized directions of modern summer and winter monsoonal winds. Dashed line represents the limit of the area affected by the East Asia monsoon climate system. b) Distribution of carbonate sand dunes and the location of the Yongcheon Cave. Note that sand dunes were migrated from shoreline to inland along three depressed valleys.