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Field and laboratory experiments on high dissolution rates of limestone in stream flow

Tsuyoshi Hattanji [a,*], Mariko Ueda [b], Wonsuh Song [c], Nobuyuki Ishii [d], Yuichi S. Hayakawa [c], Yasuhiko Takaya [c], Yukinori Matsukura [a]

[a] Faculty of Life and Environmental Sciences, University of Tsukuba, Japan
[b] Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan
[c] Center for Spatial Information Science, The University of Tokyo, Japan
[d] College of Geoscience, University of Tsukuba, Japan

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ABSTRACT

Field and laboratory experiments were performed to examine dissolution rates of limestone in stream flow. Field experiments were conducted in three stream sites (A–C) with different lithological or hydrological settings around a limestone plateau in the Abukuma Mts., Japan. Sites A and B are allogenic streams, which flow from non-limestone sources into dolines, and site C has a karst spring source. Tablets made of limestone from the same plateau with a diameter of 3.5 cm and a thickness of 1 cm were placed in the streams for 3 years (2008–2011) where alkalinity, pH and major cation concentrations were measured periodically. The saturation indices of calcite (SIc) of stream water were -2.8 ± 0.4 at site A, -2.5 ± 0.4 at site B and -0.5 ± 0.4 at site C. Annual weight loss ratios for tablets were extremely high at site A (0.11–0.14 mg cm^{-2} d^{-1}), high at site B (0.05 mg cm^{-2} d^{-1}), and low at site C (0.005 mg cm^{-2} d^{-1}). The contrasting rates of weight loss are mainly explained by chemical conditions of stream water. In addition, laboratory experiments for dissolution of limestone tablets using a flow-through apparatus revealed that flow conditions around the limestone tablet is another important factor for dissolution in the stream environment. These results revealed that limestone dissolves at a rapid rate where water unsaturated to calcite continuously flows, such as in an allogenic stream.

1. Introduction

Limestone plateaus with many dolines develop in karst terrains, especially in humid temperate regions such as Japan. One of the most important factors related to evolution of karst landforms is the denudation rate in various environments including ground surface, unsaturated soil, saturated soil and streams. The shallow weathered bedrock zone immediately beneath the soil–bedrock interface plays an important role in limestone dissolution and evolution of karst landforms (Williams, 1983). In typical karst terrains, however, limestone also dissolves in streams flowing around the margin of the plateau where stream water or groundwater is in direct contact with limestone. For example, an ‘allogenic stream’, a stream flowing from basins underlain by non-carbonate rocks, also makes a doline or other karst features (White, 1988; Ford and Williams, 2007). The impact of allogenic streams on landform evolution has not been well studied.

There are several techniques for estimating denudation rates of karst terrains. Chemical denudation rates in karst areas were classically estimated from Ca flux, i.e. average Ca ion concentrations and annual discharge from springs (e.g. Smith and Atkinson, 1976). For the case of a doline with an allogenic stream, however, estimating the denudation rate from the Ca flux method has the following problems: (1) allogenic inputs are mixed with autogenic (on plateau) inputs during flow process in cave, and (2) caves immediately below dolines with allogenic stream are generally inaccessible.

The technique of field weathering experiments using a weight loss approach is an effective method for estimating the potential for dissolution under various environmental conditions (Trudgill, 1977; Jennings, 1981; Crabtree and Trudgill, 1985; Trudgill et al., 1994; Inkpen, 1995; Matsukura and Hirose, 1999; Urushibara-Yoshino et al., 1999; Dixon et al., 2001; Thorn et al., 2002; Plan, 2005; Thorn et al., 2006; Matsukura et al., 2007; Yoshimura et al., 2009). The method is simple: installing a rock specimen with a known weight and surface area to a field site and measuring the weight loss after a period. The method also has problems that (1) the methodology itself may impact results of weathering rates (Inkpen, 1995) and (2) the estimated denudation rate for a short-term experiment (a few years) would be affected by temporal variation. However, this method enables us to directly estimate ‘spatial variation’ of limestone dissolution rates at any site. Past weathering experiments using this technique have focused on (1) topography (Crabtree and Trudgill, 1985; Plan, 2005), (2) duration (Trudgill et al., 1994), (3) climate (Urushibara-Yoshino et al., 1999), (4) difference between limestone and other rocks (Matsukura and Hirose, 1999; Thorn et al., 2002; Plan, 2005; Thorn et al., 2006;

* Corresponding author. Tel.: +81 29 853 5687.
E-mail address: hattan@geoenv.tsukuba.ac.jp (T. Hattanji).

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Matsukura et al., 2007), and (5) dissolution in caves (Yoshimura et al., 2009). Most of these experiments were conducted on the ground surface or in soil, but they did not particularly focus on dissolution in stream flow, including allogenic stream flow.

The present study focuses on the dissolution of limestone in stream flow along a margin of a karst plateau. The aim of the present study is to determine which environmental factors are significant for the dissolution under flowing water, based on a combined approach of field and laboratory experiments using limestone tablets and chemical analysis of the contact water.

2. Field experiment

2.1. Study site

Field weathering experiments were conducted around a small karst plateau, 'Sendaihira', in the central Abukuma Mountains, Japan (Fig. 1), located in humid temperate region with humid summers and dry winters. The mean annual precipitation (1981–2010) at the nearest meteorological station 'Ono-niimachi' is 1245 mm, of which 71% falls from May to October. Mean monthly temperature ranges from −0.9 °C to 22.9 °C and the annual mean is 10.5 °C. The maximum depth of snow cover around the test sites reaches 20–30 cm in February. The vegetation around the sites is a combination of natural broad-leaved forest and planted forest of Japanese cedar, although grassland is artificially maintained around the top of the plateau. The underlying bedrock of the plateau is recrystallized massive limestone, which is in contact with shale layers at the eastern side and has a strike in the NNW–SSE direction with almost vertical dip (Ehiro et al., 1989). These sedimentary rocks are metamorphosed by Cretaceous granite, which outcrops to the southern and eastern margins. The age of these layers has not been determined precisely. An airborne LiDAR DTM with a 2 m resolution reveals that two major active dolines have developed in a valley along the lithological boundary between limestone and shale (Fig. 1C). Two headwater streams originating from eastern hillslopes underlain by shale flow into both dolines, which are also connected to the two major caves beneath the karst plateau (Marui et al., 2003).

2.2. Methods

We selected three sites of streams for field experiment (Fig. 2). Sites A and B are headwater streams flowing into the dolines, and site C is located ~30 m downstream of a karst spring (Fig. 1C). Table 1 shows hydrological and geomorphic conditions for the sites. The local channel gradient represents the average gradient for a 50-m reach around each stream site. The gradient of site A is almost twice as that of site B. Channel morphology at sites B and C is a 'pool' whereas site A is located in a 'rapid' section. Stream discharge measured with a volumetric method varied from 90 $cm^3\ s^{-1}$ (site C) to 4900 $cm^3\ s^{-1}$ (site B) at base flow stages (average of May 24, June 21, and July 21, 2008). We visually confirmed that these streams are perennial and almost constant base flows continued even in cold, snowy winter season from the start to the end of the field experiment. Although we could not make direct measurements on flow velocity due to shallowness or slowness of the flow, we have estimated the mean water flux from stream width, flow depth, and discharge at the base flow stage (Table 1). The water flux at site A is about 6.5 cm/s (depth of 2 ± 1 cm) which is slightly higher than at site B (4.5 cm/s; depth of 10 ± 3 cm), and much higher than at site C (0.3 cm/s; depth of 10 ± 3 cm).

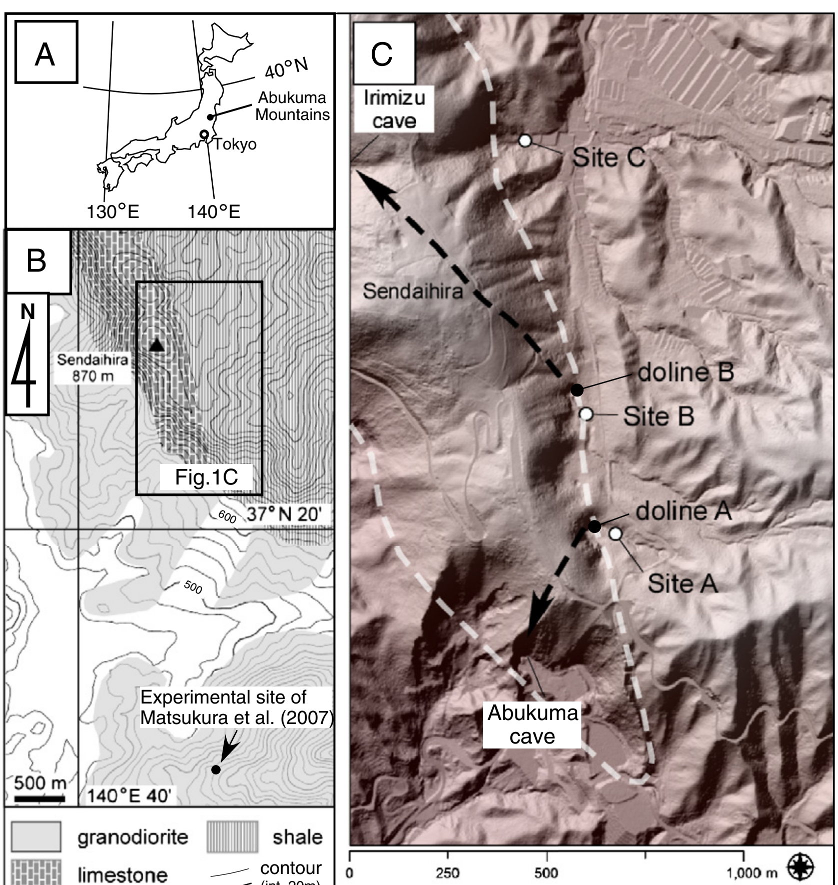

Fig. 1. Location and geologic map of the study area (A, B) and relief shading map using LiDAR DTM with a 2 m resolution around the study sites (C). Contour interval of B is 20 m. In C, the white broken line shows the margin of limestone exposure, and the broken lines with black arrows indicate the connection between dolines and caves proven by Marui et al. (2003).