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Dissolution rates of subsoil limestone in a doline on the Akiyoshi-dai Plateau, Japan: An approach from a weathering experiment, hydrological observations, and electrical resistivity tomography

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ABSTRACT

This study aims at estimating the controlling factors for the denudation rates of limestone, which often forms solution dolines on karst tablelands. Our approaches include (1) electrical resistivity tomography (ERT) to reveal shallow subsurface structures and hydrological settings, (2) automated monitoring of volumetric water content in soil profiles and manual measurements of subsurface CO_2 concentrations and soil water chemistry, and (3) a field weathering experiment using limestone tablets with the micro-weight loss technique for determining current denudation rates. The field experiment and monitoring were carried out over 768 days from 2009–2011 at four sites with varying topographic and hydrological conditions along the sideslope of a doline on the Akiyoshi-dai karst plateau in SW-Japan. The installation depths of the limestone tablets were 15 cm or 50 cm below the slope surface. The soil moisture conditions varied site by site. Water-saturated conditions continued for 40–50% of the whole experimental period at 50-cm depth of upper and middle sites, while only 0–10% of the experimental period was water-saturated at the other sites. Chemical analysis revealed that the soil water was chemically unsaturated with calcite for all the sites. Spatial differences in concentrations of CO_2 in soil pore air were statistically less significant. The denudation rates of the buried limestone tablets were 17.7–21.9 mg cm^{-2} a^{-1} at the upper and middle slopes, where the soil was water-saturated for a long time after precipitation. The lowest denudation of 3.9 mg cm^{-2} a^{-1} was observed on lower slopes where soil was not capable of maintaining water at a near saturation level even after precipitation. Statistical analysis revealed that the denudation rates of the tablets were strongly controlled by the duration for which soil pores were saturated by water (the conditions defined here are degrees of water saturation greater than 97%). Electrical resistivity tomography indicated that areas with high soil moisture conditions were located at the deeper zone on the lower slopes and the bottom of the doline, where denudation would be faster.

1. Introduction

Solution dolines are among the best known karst landforms. Dissolution of limestone in shallow superficial part of karst terrain, i.e., epikarst zone (Bakalowicz, 2012), plays a major role in the development of dolines (Williams, 1983, 2008; Ford and Williams, 2007). In the epikarst zone, limestone dissolution occurs faster along joints and fissures, and subsoil karren develop below ground surface (Sauro, 2012). In the case of karst terrain with shallow soil and massive rock structure, exposed limestone between joints forms pinnacle karst on ground surface.

The spatial distribution of denudation rates is one of the basic issues in understanding the landform evolution of solution dolines. Accelerated dissolution at the doline center is a key concept in doline formation (Gams, 2000). Few studies, however, have evaluated the spatial distribution of denudation rates based on observations of hydrological processes in dolines. Zambo and Ford (1997) calculated the amount of limestone to be dissolved based on monitoring of soil temperatures, water content, concentrations of CO_2 in soil and soil water chemistry. They concluded that thicker soil above the soil–bedrock interface at the doline bottom has a 5–10 times higher solvent capacity (1.8–3.0 mg cm^{-2} a^{-1}) than soil on slopes.

Field weathering experiments that measure weight loss of rock specimens are one of the approaches to quantify spatial variations of limestone denudation rates (Trudgill, 1977; Jennings, 1981; Trudgill et al., 1994; Inkpen, 1995; Plan, 2005; Thorn et al., 2006; Matsukura

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et al., 2007; Yoshimura et al., 2009; Hattanji et al., 2014). This technique is simple as it involves installing rock specimens with a known weight and shape at field sites and measuring weight loss after a period of time. For example, the dissolution rate on lower slopes near the valley floor is much higher than that on upper slopes in limestone terrain under humid temperate conditions (Trudgill et al., 1994). A series of weathering experiments on a high mountain limestone terrain by Plan (2005) indicated that a tablet buried in a doline had a 2.6 times faster rate of weight loss than on sites on the surrounding terrain, implying the effects of high soil water content and high flow rate in the doline. Limestone tablets buried in water-saturated soil on a granitic hillslope in Northern Japan demonstrated dissolution rates 10 times faster than those in the unsaturated soil (Matsukura et al., 2007).

Denudation rates for longer time scales (>10 ka) have recently been estimated with a new approach of *in situ* cosmogenic radionuclide ^{36}Cl for limestone plateaus. Matsushi et al. (2010) estimated the formative age of a doline on the Akiyoshi-dai Plateau in Japan using concentration of *in situ* ^{36}Cl in limestone pinnacles. Their results indicated that denudation rates near the doline bottom were faster than those at upper slopes, in other words, the denudation rates increased with the increasing size of the source area. The hydrogeomorphological setting of the doline investigated by Matsushi et al. (2010), however, has not been examined in detail before. Therefore, a combined approach using techniques involving field weathering experiments and hydrogeomorphological investigations still needs to be carried out to improve our understanding on the denudation process acting in this doline.

The aim of the present study is to reveal the controlling factors determining current denudation rates of the same doline on the Akiyoshi-dai Plateau that was investigated by Matsushi et al. (2010). Our approaches include: (1) electrical resistivity tomography (ERT) for shallow subsurface structures and hydrological settings, (2) automatic monitoring of volumetric water content in soil and manual measurements of CO_2 concentrations and water chemistry in soil, and (3) a field weathering experiment using a microweight loss technique to determine current denudation rates. Here, we discuss which factors control the denudation rates of subsoil limestone to form a solution doline under these humid temperate conditions.

2. Study sites

Intensive investigations and a field experiment were conducted at a doline on a limestone plateau with an area of 130 km^2 called 'Akiyoshi-dai' in Yamaguchi Prefecture, western Japan (Figs. 1 and 2). The underlying bedrock of the plateau is Carboniferous–Permian metamorphosed accretionary limestone. The climate on the plateau is humid temperate with a mean annual air temperature of 13.6 °C and a mean annual precipitation of 1995 mm, 70% of which is concentrated from April to September. The monthly mean air temperature fluctuates from 2.8 °C (January) to 25.0 °C (August). The area was not affected by past glaciations. The majority of vegetation cover on the plateau is anthropogenic grassland (Fig. 2). Original vegetation of broad-leaved evergreen forest remains only locally. The current grassland landscape has been retained with controlled burning every winter. Examination of stable carbon isotope ^{13}C from a speleothem in a cave indicated that yearly burning had started around A.D.1600 (Kurisaki et al., 2006). Kita (1996) who summarized old literature showed that the grass was sometimes collected for stock raising, and only the flat areas of the doline bottom were used for cultivation from around the 18th century to the middle of the 20th century. Although soil erosion was not reported in Akiyoshi-dai Plateau, vegetation change may alter hydrological and ecological processes on the plateau surface. Inokura et al. (2004) measured the concentration of CO_2 in soil air on both grassland and forest repeatedly, and indicated that the concentration of CO_2 at a given temperature in forest soil was higher than that in grassland soil, although mean concentrations of CO_2 for these sites were almost same.

We investigated a near-circular doline with a diameter of ~150 m and a depth of ~17 m located on the northern part of Akiyoshi-dai Plateau (Figs. 1 and 2). Slope inclination is gentle (<20°) from upper to middle section and it exceeds 30° at the foot of lower slope. The surface of doline bottom is almost flat with a slight bulge at the center. This solution doline is never flooded being situated at an altitude of around

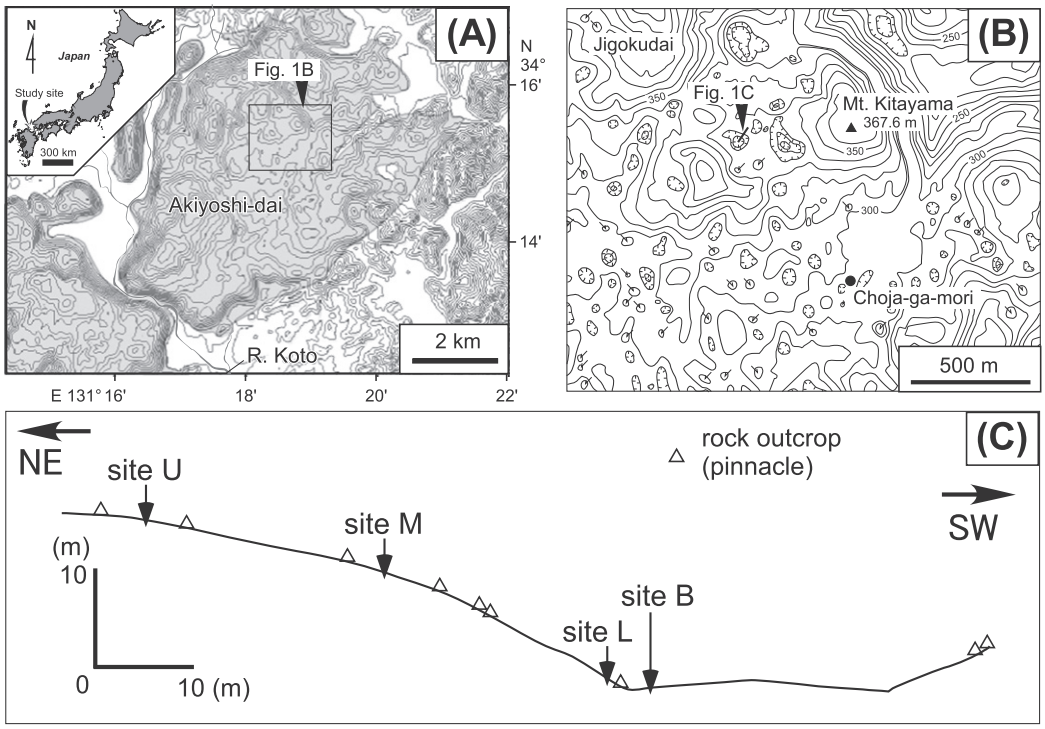

Fig. 1. Location and topography around study sites on Akiyoshi-dai Plateau. A) Location map, B) 1: 25,000 topographic map. Contour interval is 20 m for Figs. 1A and 10 m for Fig. 1B.