HRVATSKI GEOGRAFSKI GLASNIK 86/1, 71–89 (2024.)

UDK 551.435.88(234.422.1 Velebit)
552.54(234.422.1 Velebit)
911.2:551](234.422.1 Velebit)

DOI 10.21861/HGG.2024.86.01.03

Original scientific paper
Izvorni znanstveni članak

Received / Primljeno
2024-02-19 / 19-02-2024

Accepted / Prihvaćeno
2024-05-02 / 02-05-2024

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Investigation of short-term denudation rates using the rock tablet method in Northern Velebit National Park (Croatia)

Istraživanje kratkotrajne stope denudacije metodom stijenskih pločica u NP Sjeverni Velebit (Hrvatska)

The formation of karst landscapes is the result of a series of processes, whereby rock weathering and denudation play important roles. Soluble carbonate rocks are chemically weathered (dissolved) on the surface or under soil cover resulting in the formation of different karst morphologies and controlling surface denudation. The Dinaric karst area is the type-site for numerous karst features and phenomena, but studies on carbonate weathering in this region are still scarce, especially in the mountainous regions. To better understand the formation of Dinaric karst mountainous landscapes, we studied denudation rates at the northern part of Velebit Mountain using the rock tablet method. Denudation was measured using rock tablets consisting of local lithologies and "standard rock tablets" exposed to the natural environment at the surface, but also buried in the soil. Furthermore, rock tablets were placed in three different settings (open slope, small clearing, bottom of a doline) to evaluate the local factors impacting the denudation rate. The results of this study showed that the denudation rate is highly dependent on local factors and lithology, and that local rock tablets from different lithologies should be used to determine the actual denudation rate.

Key words: denudation, rock tablet method, lithology, karst, Dinaric karst, Velebit

Formiranje krških krajolika rezultat je niza procesa, pri čemu najvažniju ulogu igraju trošenje stijena i denudacija. Topive karbonatne stijene kemijski se troše (otapaju) na površini ili ispod pokrova tla, što rezultira stvaranjem različitih krških oblika i kontrolira površinsku denudaciju. Područje dinarskog krša tipsko je mjesto za brojne krške forme i pojave, ali su istraživanja trošenja karbonatnih stijena na ovom području još uvijek oskudna, posebice u planinskim predjelima. Stoga smo s ciljem boljeg razumijevanja formiranja planinskih krajolika dinarskog krša proučavali stope denudacije na sjevernom dijelu Velebita metodom stijenskih pločica. Denudacija je mjerena korištenjem metode stijenskih pločica lokalnih litologija i „standardnih stijenskih pločica" izloženih prirodnom okolišu na površini, ali i ukopanih u tlu. Nadalje, stijenske pločice postavljene su u tri različita položaja (otvorena padina, mali proplanak, dno ponikve) da bi se procijenili lokalni čimbenici koji utječu na brzinu denudacije. Rezultati ovog istraživanja pokazali su da stope denudacije jako ovise o lokalnim čimbenicima i litologiji te da se za dobivanje stvarne stope denudacije trebaju koristiti stijenske pločice izrađene od lokalnih stijena.

Ključne riječi: denudacija, metoda stijenskih pločica, litologija, krš, Dinarski krš, Velebit

Introduction

Carbonate areas represent some of the most spectacular landscapes on Earth. Their formation is a result of a series of processes, among which rock weathering, and consequently denudation play the most important roles (e.g. Phillips, 2005; Borelli et al., 2007; Viles, 2012; Krautblatter and Moore, 2014). Although dissolution is the major process governing denudation in carbonate areas (e.g., Dreybrodt, 1988; Simms, 2004; Ford and Williams, 2007), physical weathering processes as well play an important role (Krklec et al., 2013, 2016, 2022; Emmanuel and Levenson, 2014). Thus, in order to understand the dynamics of karst landscape development it is necessary to study carbonate weathering processes and denudation rates (Bögli, 1980: Gunn, 2004; Stephenson and Finlayson, 2009; Olvmo, 2010; Hinderer et al., 2013; De Waele and Gutiérrez, 2022; Krklec et al., 2021).

Denudation rates can be quantified using different methods (Gabrovšek, 2009; Krklec et al., 2021) over various time scales. Rock tablets (e.g. Gams, 1959; Trudgill, 1975; Plan, 2005; Krklec et al., 2021), micro-erosion meters (e.g. High and Hanna, 1970; Cucchi et al., 2006; Stephenson and Finlayson, 2009; Yuan et al., 2022) or water hydrochemistry measurements (e.g. Gams, 1981; Droppa, 1985; Plan, 2005) are commonly used to quantify denudation rates on short term scales. On the other hand, measurements of the cosmogenic radionuclides concentrations (Stone et al., 1998; Matsushi et al., 2010; Xu et al., 2013; Ryb et al., 2014; Krklec et al., 2018, 2022) or measurements of differential erosion on bare-rock surfaces of known age (e.g. Bögli, 1980; Akerman, 1983; Lauritzen, 1990) are used to estimate long-term denudation rates.

Rock tablets method is one of the most commonly used methods to calculate denudation rate where rock samples are exposed to the natural environment over a period of time and the rate of denudation is calculated from the loss of mass during that period (see Krklec et al., 2021 for review). Although rock tablets are set in different environments, for example: in the air or the surface, in soil, caves or underwater (e.g. Hall, 1990; Turkington et al., 2003; Dixon et al., 2006; Covington et al., 2013;

Uvod

Karbonatna područja predstavljaju neke od najspektakularnijih krajolika na Zemlji. Njihovo formiranje rezultat je niza procesa, među kojima najvažniju ulogu ima trošenje stijena, a posljedično i denudacija (npr. Phillips, 2005; Borelli i dr., 2007; Viles, 2012; Krautblatter i Moore, 2014). Iako je otapanje glavni proces koji upravlja denudacijom u karbonatnim područjima (npr. Dreybrodt, 1988; Simms, 2004; Ford i Williams, 2007), procesi fizičkog trošenja također igraju važnu ulogu (Krklec i dr., 2013, 2016, 2022; Emmanuel i Levenson, 2014). Stoga, da bi razumjeli dinamiku razvoja krškog krajolika, potrebno je proučiti procese trošenja karbonata i stope denudacije (Bögli, 1980; Gunn, 2004; Stephenson i Finlayson, 2009; Olvmo, 2010; Hinderer i dr., 2013; De Waele i Gutiérrez, 2022; Krklec i dr., 2021).

Stope denudacije mogu se kvantificirati različitim metodama (Gabrovšek, 2009; Krklec i dr., 2021) u različitim vremenskim skalama. Stijenske pločice (npr. Gams, 1959; Trudgill, 1975; Plan, 2005; Krklec i dr., 2021), mikroerozijski metri (npr. High i Hanna, 1970; Cucchi i dr., 2006; Stephenson i Finlayson, 2009; Yuan i dr., 2022) ili mjerenja hidrokemijskih značajki vode (npr. Gams, 1981; Droppa, 1985; Plan, 2005) obično se koriste za kvantificiranje stopa denudacije na kratkoročnim vremenskim skalama. S druge strane, mjerenja koncentracija kozmogenih radionuklida (Stone i dr., 1998; Matsushi i dr., 2010; Xu i dr., 2013; Ryb i dr., 2014; Krklec i dr., 2018, 2022) ili mjerenja diferencijalne erozije na površinama izloženih stijena poznate starosti (npr. Bögli, 1980; Akerman, 1983; Lauritzen, 1990) koriste se za procjenu dugoročnih stopa denudacije.

Metoda stijenskih pločica jedna je od najčešće korištenih metoda za izračunavanje stope denudacije gdje su uzorci stijena izloženi prirodnom okolišu tijekom određenog razdoblja, a stopa denudacije izračunava se iz gubitka mase tijekom tog razdoblja (vidi Krklec i dr., 2021. za detalje). Iako su stijenske pločice postavljane u različitim okruženjima, na primjer: u zraku ili na površini zemlje, u tlu, špiljama ili pod vodom (npr. Hall, 1990; Turkington i dr., 2003; Dixon i dr., 2006; Covington i dr, Akiyama et al., 2015; Krklec et al., 2018), there is not much research done in high mountain areas. Rock tablets can be used to evaluate the potential or actual denudation rate, depending on material used (rock tablets of same or of local material) (e.g. Trudgill, 1977).

Dinaric karst is the largest continuous karst landscape in Europe (Mihevc et al., 2010) and is considered a "classical" karst landscape (Zupan Hajna, 2019). Despite being the type-site for numerous karst features and phenomena (Zupan Hajna, 2019), studies on carbonate weathering in the Dinaric region are still scarce, especially in mountainous regions (e.g. Bonacci, 1987; Mihevc et al., 2010; Krklec et al., 2013, 2018, 2022). Thus, the aim of this study was to quantify and characterize denudation rate in a location in northern part of Velebit Mountain and to investigate factors controlling it.

2013; Akiyama i dr., 2015; Krklec i dr., 2018), nema mnogo istraživanja u visokoplaninskom području. Stijenske pločice mogu se koristiti za procjenu potencijalne ili stvarne stope denudacije, ovisno o korištenom materijalu (pločice od istog ili lokalnog materijala) (npr. Trudgill, 1977).

Dinarski krš najveći je kontinuirani krški krajolik u Europi (Mihevc i sur., 2010) i smatra se „klasičnim" krškim krajolikom (Zupan Hajna, 2019). Unatoč tomu što je tipski lokalitet za brojne krške forme i pojave (Zupan Hajna, 2019), studije o trošenju karbonata u dinarskom području još uvijek su rijetke, posebice u planinskim područjima (npr. Bonacci, 1987; Mihevc i dr., 2010; Krklec i sur., 2013, 2018, 2022). Stoga je cilj ovog istraživanja kvantificirati i karakterizirati brzinu denudacije na lokaciji u sjevernom dijelu Velebita te istražiti čimbenike koji ju kontroliraju.

Regional setting

The study area is located in the northeastern part of Velebit Mountain, within Northern Velebit National Park (Fig. 1A). Velebit Mountain is a part of the Dinaric karst region, located along the Adriatic coast, build up from mostly carbonate sediments deposited from the Carboniferous to the Oligocene (Velić and Vlahović, 2009), forming a highly fractured anticline structure of Dinaric orientation (i.e. NW–SE; Prelogović, 1995). Three lithologies (Fig. 1B, 1D) are present in the study area: Middle and Upper Jurassic limestones, and Paleogene-Neogene carbonate breccia beds (i.e. Jelar breccia) (Velić and Vlahović, 2009). The soil cover of the study area is discontinuous, dominated by Calcomelanosoil type, with variable depth depending on the topographic position (Bertović et al., 1987; Martinović, 2000). Sites with more prominent topography (i.e. higher elevation) are characterised by shallow soil cover (< 30 cm), a high amount of soil skeletal components and frequent bedrock outcrops on the surface.

On the other hand, lower areas, or topographic depressions (i.e. dolines) have thicker soil cover and less soil skeletal components. Typical karst landscape dominates the study area (Bočić et al., 2019).

Geografski položaj

Područje istraživanja nalazi se na sjeveroistočnom dijelu Velebita, unutar Nacionalnog parka Sjeverni Velebit (sl. 1A). Velebit je dio dinarskog krškog područja, smješten duž jadranske obale, izgrađen uglavnom od karbonatnih sedimenata taloženih od karbona do oligocena (Velić i Vlahović, 2009) tvoreći visoko raspucanu antiklinalnu strukturu dinarske orijentacije (SZ–JI; Prelogović, 1995). Na istraživanom području prisutne su tri litologije (sl. 1B, 1D): vapnenci srednje i gornje jure i paleogensko-neogenske karbonatne breče (tj. Jelar breče) (Velić i Vlahović, 2009). Pedološki pokrov istraživanog područja je diskontinuiran, s kalkomelanosolom kao dominantnim tipom tla, te varijabilne dubine ovisno o topografskom položaju (Bertović i dr., 1987; Martinović, 2000). Lokacije s izraženijom topografijom (tj. višom nadmorskom visinom) karakterizira plići pedološki pokrov (< 30 cm), velika količina skeleta i česti izdanci stijena na površini.

S druge strane, niža područja ili topografske depresije (tj. ponikve) imaju deblji pedološki pokrov i manje skeletnih komponenti tla. Istraživanim područjem dominira tipičan krški reljef (Bočić i dr., 2019).

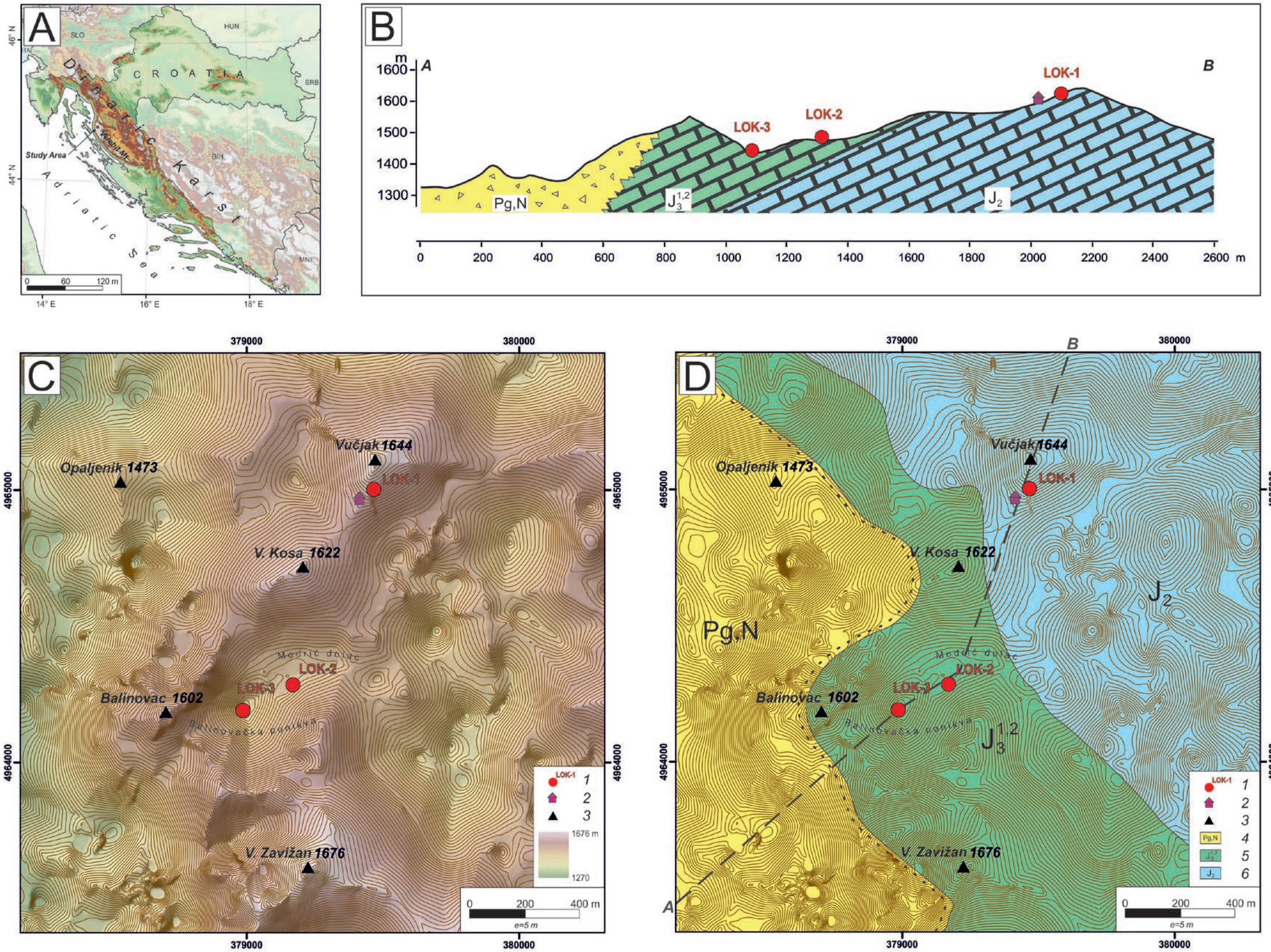

Fig. 1 Regional setting. A) Location of the study area (EU-DEM, 2016); B) Geological profile of study area (after Velić et al., 1974); C) Topographic map of the area with indicated study sites (DEM based on elevation data from DGU); D) Geological map of study area with indicated profile line and study sites. 1 - study site; 2 - Zavižan meteorological station; 3 – mountain peak; 4 - Paleogene-Neogene carbonate breccia; 5 - Upper Jurassic limestones; 6 - Middle Jurassic limestones.

Sl. 1. Geografski položaj; A) Lokacija područja istraživanja (EU-DEM, 2016); B) Geološki profil područja istraživanja (prema Velić i dr., 1974); C) Topografska karta područja istraživanja s naznačenim mjernim mjestima (DEM izrađen na temelju visinskih podataka DGU); D) Geološka karta područja istraživanja s naznačenom linijom profila i mjernim mjestima (Velić i dr., 1974). 1 – mjerno mjesto; 2 – meteorološka postaja Zavižan; 3 – vrh; 4 – paleogensko-neogenske karbonatne breče; 5 – gornjojurski vapnenci; 6 – srednjojurski vapnenci.

This research was conducted at three study sites (Fig. 1C, 2), all within 1,000 m aerial distance and 175 m altitude difference (Fig. 1C, Tab 1). The study site LOK-1 (Fig. 2A) is located on the slope below Vučjak peak, 50 meters away from Zavižan meteorological station. It is built up by thick bedded grey and grey-brown Middle Jurassic limestone sporadically interbedded by dolomite. These limestones have a high $CaCO_3$ content (up to 98%) and are often intersected by thin calcite veins, giving them a pseudo-breccia texture (Mamužić and Milan, 1973). The soil cover developed at the surface is classified as Calcomelanosoil, a well aeriated soil characterised by poor water retention.

The study site LOK-2 is located in a small clearing, around 10 meters from the bottom of Modrić doline, on its eastern side (Fig. 2B). The lithology here is dominated by Upper Jurassic grey to brown limestones with a high $CaCO_3$ content (roughly 98%). Soil cover is classified as shallow Calcocambisol (although deeper than LOK-1) with high porosity (45–65%) and characterised by poor water retention properties, but with a slightly higher humus content (when compared to LOK-1).

The study site LOK-3 is located at the bottom of Balinovac doline (i.e. Velebit botanical garden; Fig. 2C) and is built up by Paleogene-Neogene carbonate breccia, also known as Jelar beds or Velebit breccia (Velić and Vlahović, 2009). These breccia beds are composed of older (Jurassic, Cretaceous and Paleogene) carbonate fragments cemented with a microcrystalline carbonate cement, more resistant to weathering (when compared to breccia rock fragments) and often of reddish colour. The soil at this study site is classified as Calcomelanosoil but, due to thick vegetation cover (spruce forest), it has a high humus content.

The climate of the region is humid boreal, Df type according to the Köppen classification with the temperature of the coldest month below -3 °C, and the warmest month lower than 22 °C, and there is long-term snow coverage (Šegota and Filipčić, 1996). Because this area is under the influence of Vb-type of cyclones (van Bebber, 1981), it is under strong influence of moist air masses arriving from the sea, resulting in formation of abundant orographic precipitation (Šegota and Filipčić, 1996)

Ovo je istraživanje provedeno na tri mjerna mjesta (sl. 1C, 2) koja se nalaze unutar 1000 m zračne udaljenosti i 175 m visinske razlike (sl. 1C, Tab. 1). Mjerno mjesto LOK-1 (sl. 2A) nalazi se na padini ispod vrha Vučjak, 50 metara od meteorološke postaje Zavižan. Grade ga debelouslojeni sivi i sivosmeđi srednjojurski vapnenci s mjestimičnim slojevima dolomita. Ovi vapnenci imaju visok sadržaj $CaCO_3$ (do 98 %) i često su ispresijecani tankim kalcitnim žilama, što im daje teksturu pseudobreče (Mamužić i Milan, 1973). Tlo razvijeno na površini klasificirano je kao kalkomelanosol, dobro prozračeno tlo koje karakterizira slabo zadržavanje vode.

Mjerno mjesto LOK-2 nalazi se na manjem proplanku, 10-ak metara od dna Modrić doca, s njegove istočne strane (sl. 2B). Ovdje u litologiji dominiraju gornjojurski sivi do smeđi vapnenci s visokim sadržajem $CaCO_3$ (cca. 98 %). Pedološki pokrov klasificiran je kao plitki kalkokambisol (iako je dublji u usporedbi s LOK-1) s visokom poroznošću (45-65 %) i karakteriziran slabom mogućnošću zadržavanja vode, ali s malo višim sadržajem humusa (u usporedbi s LOK-1).

Mjerno mjesto LOK-3 nalazi se na dnu Balinovačke ponikve, odnosno Velebitskog botaničkog vrta (sl. 2C) i grade ga paleogensko-neogenske karbonatne breče, poznate i pod nazivom Jelar naslage ili Velebitske breče (Velić i Vlahović, 2009). Ove naslage sastavljene su od starijih (jurskih, krednih i paleogenskih) karbonatnih fragmenata cementiranih mikrokristaličnim karbonatnim vezivom, veće otpornosti na trošenje (u usporedbi s fragmentima koji grade breču) i često je crvenkaste boje. Tlo na ovom mjernom mjestu klasificirano je kao kalkomelanosol te zbog gustog vegetacijskog pokrova (šume smreke) ima visok sadržaj humusa.

Ovo područje karakterizira vlažna borealna klima, Df tipa prema Köppenovoj klasifikaciji s temperaturom najhladnijeg mjeseca nižom od -3 °C, a najtoplijeg mjeseca nižom od 22 °C te dugotrajnim snježnim pokrivačem (Šegota i Filipčić, 1996). Budući da je ovo područje pod utjecajem ciklona Vb tipa (van Bebber, 1981), pod jakim je utjecajem vlažnih zračnih masa koje dolaze s mora, što rezultira stvaranjem obilnih orografskih oborina (Šegota i Filipčić, 1996)

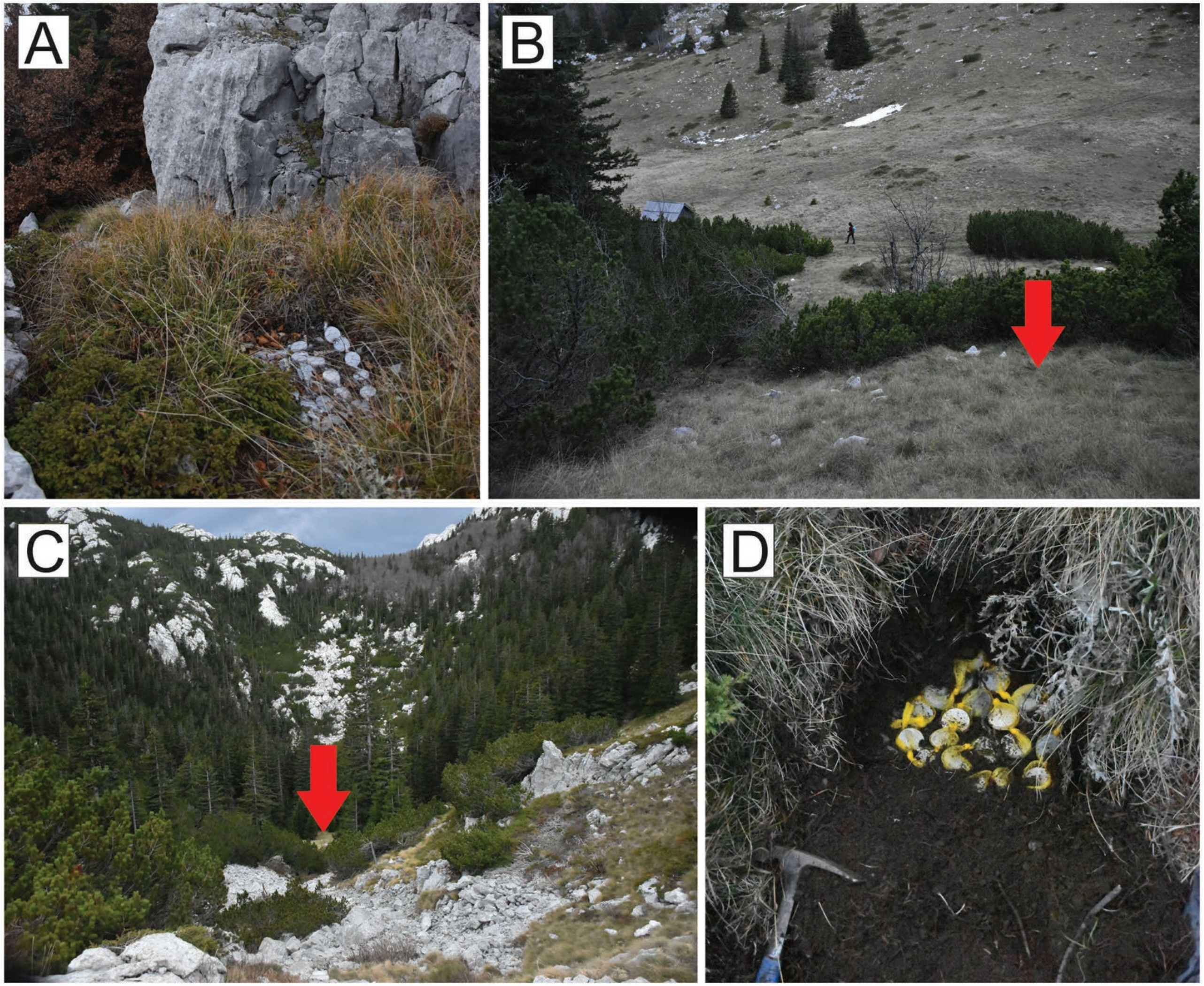

Fig. 2 Study sites in the study area (photo: Dražen Perica). Red arrows indicate the exact position of the rock tablets A) Rock tablets placed above the meteorological station Zavižan at the study site LOK-1; B) Modrić doline area with the study site LOK-2; C) Balinovac doline area with the study site LOK-3; D) Rock tablets placed in the ground at the measuring point LOK-2

Sl. 2. Mjerna mjesta na području istraživanja (foto: Dražen Perica). Crvene strelice označavaju točan položaj stijenskih pločica: A) stijenske pločice postavljene na površini iznad meteorološke postaje Zavižan, na mjernom mjestu LOK-1, B) područje Modrić doca s mjernim mjestom LOK-2, C) područje Balinovačke ponikve s mjernim mjestom LOK-3, D) stijenske pločice postavljene u tlu na mjernom mjestu LOK-2

Tab. 1 List of study sites and their coordinates and altitude (m.a.s.l.)
Tab. 1. Popis mjernih mjesta i njihove koordinate i nadmorske visine (m nm)

Study sitee / Mjerno mjesto	Location / Lokacija	Location (HTRS96/TM) / Položaj (HTRS96/TM)		m (a.s.l.) / m (nm)
		E	N	
LOK-1	Zavižan meteorological station / Meteorološka postaja Zavižan	379454	4964996	1,610.8
LOK-2	Modrić doline / Modrić dolac	379171	4964289	1,480.6
LOK-3	Balinovac doline / Balinovačka ponikva	378989	4964188	1,435.8

Tab. 2 Mean monthly temperature measured at Zavižan meteorological station during the period of 2018 to 2022. Gray shading indicates mean monthly temperatures during the study period
Tab. 2. Srednja mjesečna temperatura izmjerena na meteorološkoj postaji Zavižan u razdoblju od 2018. do 2022. (Sivo zasjenjenje označuje srednje mjesečne temperature tijekom promatranog razdoblja)

year / godina	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	average / srednjak
2018.	-1	-8	-2.2	6.6	9.3	11.1	14.4	14.8	10.8	7.2	1.8	-2.1	5.2
2019.	-6.2	-1.4	0.7	2.8	3.6	15.2	14.5	15.3	9.7	7.8	2.9	-0.8	5.3
2020.	-0.7	-0.7	-1.8	4	6.6	10.5	13.5	14.9	10.3	5.1	3.1	-1	5.3
2021.	-4.8	-1.1	-2.2	-0.2	5.8	13.9	15.2	13.4	10.1	4.3	2.3	-1.5	4.6
2022.	-2.4	-1.7	-2.1	1.6	10	14.6	15.5	14.3	9	10	1.9	0.7	6

Tab. 3 Monthly and yearly amounts of precipitation recorded at Zavižan meteorological station during the period of 2018 to 2022. Gray shading indicates mean monthly temperatures during the study period
Tab. 3. Mjesečna i godišnja količina oborine zabilježena na meteorološkoj postaji Zavižan u razdoblju od 2018. do 2022. (Sivo zasjenjenje označuje srednje mjesečne temperature tijekom promatranog razdoblja)

year / godina	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	sum / zbroj
2018	131.2	358	232.2	145	145	117	41	50.8	62.7	130	140	141	1693.6
2019	140.6	85	91.1	227	376	22.8	133.4	33.9	234	94.2	647	238	2322.4
2020	28.2	70.6	124.1	54.1	75	69.7	104.2	96.7	293	455	68.9	337	1776
2021	305.7	131	65.6	128	127	19.9	159.4	111	134	130	233	232	1776.1
2022	75	138	31.9	225	103	46	25.8	20.2	241	93.7	256	328	1583.1

and high humidity (higher than 80 %; Perica and Orešić, 1999). Furthermore, study area is characterised by the Mediterranean pluviothermic regime, where the amount of precipitation is higher in the colder part of the year, rather than in the warmer part of the year, with maxima in autumn and spring.

The local meteorological conditions are recorded at Zavižan meteorological station, located in proximity to the study area (Fig. 1C). The mean annual temperature recorded during the period from 2018 to 2022 was 5.28 °C (Tab. 2), while the average annual amount of precipitation was 1,830 mm (Tab. 3), showing a clear seasonal pattern.

The vegetation over the study area is characterized by Matgrass and Fescue grasslands (*Nardetum strictae, Festucion pungentis*) and juniper (*Pinetum*

i visoke vlažnosti zraka (više od 80 %; Perica i Orešić, 1999). Područje istraživanja karakterizira mediteranski pluviotermički režim, gdje je količina oborine veća u hladnijem nego u toplijem dijelu godine, s maksimumom u jesenskom i proljetnom razdoblju.

Lokalni meteorološki uvjeti bilježe se na meteorološkoj postaji Zavižan, koja se nalazi u blizini istraživanog područja (sl. 1C). Ovdje je srednja godišnja temperatura zabilježena u razdoblju od 2018. do 2022. godine iznosila 5,28 °C (tab. 2), dok je prosječna godišnja količina oborine iznosila 1830 mm (tab. 3) s jasnim sezonskim rasporedom.

Vegetaciju na istraživanom području karakteriziraju livade tvrdače i oštre vlasulje (*Nardetum strictae*, *Festucion pungentis*) i zajednice klekovine bora *mughi Illyricum*), submontane beech (*Aceri-Fagetum Illyricum*) and coniferous (*Piceetum croaticum subalpinum*) forests (Bertović et al., 1987; Forembacher, 1990).

Meteorological conditions during the study period

The meteorological and climate characteristics of this area are result of mixing of a warm air mass from the coastal side of Velebit Mountain with colder continental one (Penzar and Penzar, 1995; Perica and Orešić, 1999).

During the study period, the mean annual temperature was 4.7 °C, i.e. 0.9 °C higher compared to the 1971–2000 period (Zaninović, 2008). Furthermore, during the study, Zavižan meteorological station recorded 5 months with mean monthly temperatures below 0 °C (Tab. 2), 24 days with daily minimum temperatures below -10 °C and 64 days with daily maximum temperatures below 0 °C. As well, there were 149 days with daily minimum temperatures below 0 °C (i.e. days characterised by water freezing during the night and then melting during the day).

Precipitation had a seasonal character (higher amount in the colder season, Tab. 3) and during the study period the total amount of precipitation was 2,172.3 mm. During this period, 144 days had more than 0.1 mm of precipitation and 180 days had snow cover of more than 1 cm. It should be noted that due to morphology of the terrain, the amount of precipitation varies locally. Thus, during 2020 and 2021 rain gauges installed in proximity recorded a slightly higher amount of precipitation. The Zavižan 1 rain gauge installed near LOK-1 recorded 1,842.8 and 2,354.4 mm of precipitation, the Zavižan 2 – Piletin dolac rain gauge 550 m away recorded 2,225.6 and 2,523.9 mm of precipitation, and the Zavižan 3 – Budina kosa rain gauge 800 m away from LOK-3 recorded 2,334.2 and 3,178.5 mm of precipitation. Similar values were during 2020 and 2021 were also recorded in the wider area. During that period, the Rosijevo skolnište rain gauge recorded 2,576.6 and 1,783.0 mm, the Štirovača rain gauge 2,947.0 and 1,747.8 mm, and the Babrovača rain gauge 2,127.2 and 1,184.7 mm of precipitation.

krivulja (*Pinetum mughi Illyricum*), pretplaninske bukove šume (*Aceri-Fagetum Illyricum*) i pretplaninske smrekove šume (*Piceetum croaticum subalpinum*) (Bertović i sur., 1987; Forembacher, 1990).

Meteorološke značajke tijekom razdoblja mjerenja

Meteorološke i klimatske karakteristike ovog područja rezultat su miješanja tople zračne mase s primorske strane Velebita s hladnijom kontinentalnom (Penzar i Penzar, 1995; Perica i Orešić, 1999).

Tijekom istražnog razdoblja srednja godišnja temperatura iznosila je 4,7 °C, što je za 0,9 °C više u odnosu na razdoblje 1971.-2000. (Zaninović, 2008). Nadalje, tijekom istraživanja meteorološka postaja Zavižan zabilježila je 5 mjeseci sa srednjom mjesečnom temperaturom ispod 0 °C (tab. 2), 24 dana s minimalnom dnevnom temperaturom ispod -10 °C i 64 dana s maksimalnom dnevnom temperaturom ispod 0 °C. Također, tijekom promatranoga razdoblja bilo je 149 dana s minimalnim dnevnim temperaturama ispod 0 °C (tj. dana koje karakterizira smrzavanje vode tijekom noći i topljenje leda tijekom dana).

Oborine su imale sezonski karakter (viša količina u hladnijem dijelu godine, tab. 3) te je u promatranom razdoblju palo ukupno 2172,3 mm oborine. U tom razdoblju 144 dana imala su količinu oborine višu od 0,1 mm, a 180 dana snježni pokrivač deblji od 1 cm. Treba napomenuti da zbog morfologije terena količina oborine lokalno varira. Tako su tijekom 2020. i 2021. kišomjeri postavljeni u blizini zabilježili nešto višu količinu oborine. Kišomjer Zavižan 1 postavljen u blizini LOK-1 zabilježio je 1842,8 i 2354,4 mm oborine, kišomjer Zavižan 2 – Piletin dolac (udaljen 550 m) 2225,6 i 2523,9 mm oborine, dok je kišomjer Zavižan 3 – Budina kosa udaljen 800 m od LOK-3 zabilježio 2334,2 odnosno 3178,5 mm oborine. Slične vrijednosti tijekom 2020. i 2021. zabilježene su i na nešto širem području. U tom je razdoblju kišomjer Rosijevo sklonište zabilježio 2576,6 i 1783,0 mm, Štirovača 2947,0 i 1747,8 mm te Babrovača 2127,2 i 1184,7 mm oborine.

During the study period, there were 2,459.5 hours of insolation, 195 days with strong winds and 128 days with fog in the study area.

Methods

To better understand the development of karst morphology in this area and to gain insight into the rock weathering process and to quantify the denudation rate, we used the rock tablet method. This method was first introduced by Chevalier (1953) but was standardised by Gams who did a worldwide comparative study using "standard rock tablets" (1979, 1981). It has since been used in many studies (e.g. Trudgill, 1977; Matsukura and Hirose, 1999; Plan, 2005; Thorn et al., 2006; Hattanji et al., 2008; Krklec et al., 2013; 2016). In this method, denudation is calculated based on mass loss of rock samples exposed to natural environment over a period of time. Thus, we cut rock tablets out of cores from local lithologies (Middle and Upper Jurassic limestones, and Paleogene-Neogene carbonate breccia; lithology previously described in the paper) to measure actual weathering, but we also used "standard rock tablets" to measure potential weathering and allow regional comparison of results. These "standard rock tablets" are made of Upper Cretaceous (Senonian) micritic to biopelmicritic limestone from the Lipica quarry (Slovenia). These limestones consist of 97.7–98.7% $CaCO_3$ which sometimes contain shells of molluscs and plates of echinoderms (Gams, 1985).

All the rock tablets were cylindrical in shape, with those made from local lithologies having a diameter of 45.05–45.65 mm and a thickness of 6.65–17.0 mm, while the standard rock tablets had diameter of 39.92–45.99 and a thickness of 4.97–9.99 mm. Prior to exposure to natural environment rock tablets were cleaned, dried and weighed. After collection of the rock tablets from the field (after the exposure period), the same procedure was repeated. A total of 60 rock tablets (organized in 6 sets) were exposed to natural conditions for a period of approximately one year, starting on October 15th, 2020, to October 22nd, 2021. The sets of rock tablets were prepared and packed in elongated plastic bags. The rock tablets were separated from

Tijekom promatranoga razdoblja ovo je područje imalo je 2459,5 sati osunčanja, 195 dana s jakim vjetrom i 128 dana s maglom.

Metode istraživanja

Da bismo bolje razumjeli razvoj krških oblika na ovom području te dobili uvid u proces trošenja stijena i kvantificirali brzinu denudacije, upotrijebili smo metodu stijenskih pločica. Ovu je metodu prvi uveo Chevalier (1953), ali ju je standardizirao Gams koji je proveo svjetsku komparativnu studiju koristeći se „standardnim stijenskim pločicama" (1979, 1981). Poslije je ova metoda korištena u mnogim studijama (npr. Trudgill, 1977; Matsukura i Hirose, 1999; Plan, 2005; Thorn i dr., 2006; Hattanji i dr., 2008; Krklec i dr., 2013; 2016). Kod ove metode denudacija se izračunava na temelju gubitka mase uzoraka stijena izloženih prirodnom okolišu tijekom određenog razdoblja. Stoga smo izrezali stijenske pločice iz jezgri lokalnih stijena (vapnenci srednje i gornje jure te paleogensko-neogenske karbonatne breče; litologija je prethodno opisana u poglavlju 2) da bismo izmjerili stvarnu stopu trošenja stijena, ali smo također koristili „standardne stijenske pločice" za mjerenje potencijalnog trošenja koje nam mogu omogućiti regionalnu usporedbu rezultata. Te su „standardne stijenske pločice" izrađene od mikritnog do biopelmikritnog vapnenca gornje krede (senon) iz kamenoloma Lipica (Slovenija). Ti vapnenci sastoje se od 97,7 – 98,7 % $CaCO_3$, ponekad sadrže ljušture mekušaca i ploče bodljikaša (Gams, 1985).

Sve stijenske pločice bile su cilindričnog oblika, pri čemu su one izrađene od lokalnih litologija imale promjer 45,05 – 45,65 mm i debljinu 6,65 – 17,0 mm, dok su standardne stijenske pločice imale promjer 39,92 – 45,99 i debljinu 4,97 – 9,99 mm. Prije izlaganja prirodnom okolišu stijenske pločice su očišćene, osušene i izvagane. Nakon prikupljanja stijenskih pločica s terena (nakon razdoblja izlaganja) isti je postupak ponovljen. Ukupno je 60 stijenskih pločica (organiziranih u 6 setova) bilo izloženo prirodnim uvjetima u razdoblju od približno godinu dana počevši od 15. listopada 2020. do 22. listopada 2021. Setovi stijenskih pločica pripremljeni su i zatvoreni u duguljastu plastičnu mrežastu vrećicu, pločice su odvojene čvorovima, each other by knots, which allowed easy identification of the individual rock tablets. This material was selected to avoid possible interactions with the rock tablets that could affect their weathering.

The rock tablets were set at three different sites: LOK-1, LOK-2, and LOK-3. The studied sites were selected based on their geological, geomorphological, climatic, vegetational, and pedological characteristics, considering possible anthropogenic impacts (damage or loss of the material). Two sets of rock tablets were set at each site: one exposed at the surface, and the other buried in the soil. At each site, a soil pit was excavated to a depth of 20–25 cm (depending on the amount of skeletal fragments in soil), and a set of rock tablets was placed in the pit horizontally over the soil. The pit was then covered with the with the previously retrieved sediments, taking care to ensure that the surface horizon of the soil was as close as possible to the original conditions. Once, all the sediment (and original vegetation) was in place, a set of rock tablets was placed on the surface and covered with net to prevent loss of the rock tablets due to animal digging. The rock tablets were exposed to the natural environment for a period of 372 days. After the investigation period, the rock tablets retrieved from the field were carefully cleaned following the same procedure (rinsing, cleaning, drying and weighing). The weathering and denudation rate (D) was calculated for all rock tablets, using the formulas [1–5] proposed by Krklec et al. (2021), which included a limestone density of 2.688 g/cm^3 (density of standard rock tablets measured with a pycnometer).

[1] $$Absolute\ weathering = Measured\ weathering \times S_{cf}$$

[2] $$S_{cf} = f_c \times \frac{Exposed\ surface}{Rock\ volume}$$

[3] $$D = \frac{(W_1 - W_2)}{A \cdot \rho \cdot t} \cdot 10^4$$

[4] $$t = \frac{\text{Number of days of tablets exposure}}{Number\ of\ days\ per\ year}$$

[5] $$Absolute\ denudation = D \times S_{cf}$$

omogućujući jednostavnu identifikaciju svake od njih. Taj je materijal odabran da bi se izbjegle moguće interakcije sa stijenskim pločicama koje utječu na njihovo trošenje.

Stijenske pločice postavljene su na tri mjerna mjesta: LOK-1, LOK-2 i LOK-3. Lokacije istraživanja odabrane su na temelju njihovih geoloških, geomorfoloških, klimatskih, vegetacijskih i pedoloških značajki, uz vođenje računa o mogućim antropogenim utjecajima (oštećenje ili gubitak materijala). Na svako mjerno mjesto postavljena su dva seta stijenskih pločica: jedan izložen na površini, a drugi zakopan u tlo. Na svakom mjernom mjestu iskopana je jama do dubine od 20-25 cm (ovisno o količini skeleta u tlu), a set stijenskih pločica postavljen je u jamu horizontalno na tlo. Jama je zatim prekrivena prethodno izvađenim sedimentima vodeći računa da se površinski horizont tla vrati što sličnijim izvornim uvjetima. Nakon što je sav sediment (i izvorna vegetacija) bio na svom mjestu, set stijenskih pločica postavljen je na površinu i prekriven mrežom da bi se spriječio gubitak stijenskih pločica uzrokovan kopanjem životinja. Stijenske pločice bile su izložene prirodnom okolišu 372 dana. Nakon završetka razdoblja istraživanja stijenske pločice uzete s terena pažljivo su očišćene istim postupkom (ispiranje, čišćenje, sušenje i vaganje). Trošenje i stopa denudacije (D) izračunati su za sve stijenske pločice korištenjem formula [1-5] koje su predložili Krklec i dr. (2021), a koje su uključivale gustoću vapnenca od 2,688 g/cm^3 (gustoća standardnih stijenskih pločica mjerena piknometrom).

[1] $$apsolutno\ trošenje = izmjereno\ trošenje \times S_{cf}$$

[2] $$S_{cf} = f_c \times \frac{izložena\ površina}{volumen\ stijene}$$

[3] $$D = \frac{(W_1 - W_2)}{A \cdot \rho \cdot t} \cdot 10^4$$

[4] $$t = \frac{\text{broj dana izlaganja pločica}}{broj\ dana\ u\ godini}$$

[5] $$apsolutna\ denudacija = D \times S_{cf}$$

The weathering rates are given as a percentage and S_{cf} is a dimensionless unit, while the parameter f_c is expressed in mm, the exposed surface area in mm² and the rock volume in mm³. D represents denudation rate (μm/a), W_1 - W_2 is the weight difference (g) of the rock tablet after the exposure time, A is the surface of the rock tablet (cm²), ρ is the density of the rock tablet (g/cm³), t is the exposure time (years). The parameter S_{cf} is the dimensionless parameter calculated in equation 2 to correct the weathering or denudation values depending on the size of the rock tablet used. Due to the limited number of rock tablets made of Middle Jurassic limestones, and lithological properties similar to the Upper Jurassic limestones, the results for these lithologies are shown together. To account for control of inter-sample variability, weathering results from the same lithologies were averaged, taking into account differences between depths and exposure periods.

Stope trošenja izražene su u postotcima, a S_{cf} je bezdimenzionalna jedinica, dok je parametar f_c izražen u mm, izložena površina u mm², a volumen stijene u mm³. D predstavlja brzinu denudacije (μm/a), $W1$ - $W2$ je razlika u masi (g) stijenske pločice nakon razdoblja izlaganja, A je površina stijenske pločice (cm²), ρ je gustoća stijenske pločice (g/cm³), t je trajanje izlaganja (godina). Parametar S_{cf} je bezdimenzionalni parametar izračunat u jednadžbi 2 za korekciju vrijednosti trošenja ili denudacije ovisno o veličini korištene stijenske pločice. Zbog ograničenog broja stijenskih pločica izrađenih od vapnenaca srednje jure te litoloških svojstava sličnih vapnencima gornje jure rezultati ovih litologija prikazani su zajedno. Da bi se uzela u obzir kontrola varijabilnosti između uzoraka, za rezultate trošenja iz istih litologija izračunati se prosjeci, uvažavajući razlike u dubini i razdoblju izloženosti.

Results

During the study period, all rock tablets recorded weight losses (Tab. 4 and 6). After the study period, the lowest average measured weathering rate (%), when considering rock tablets of all lithologies at the surface, was recorded at LOK-1 (0.161 %), while the highest was measured at LOK-3 (0.560 %). A similar distribution of data was recorded in the soil, where the lowest average measured weathering rate was recorded at LOK-1 (0.141 %), while the highest was recorded at LOK-3 (0.530%) (Tab. 4).

When different lithologies are considered lowest average measured weathering rate on the surface was recorded in the Paleogene-Neogene carbonate breccia (0.146 %) at LOK-1, while the

Rezultati

Tijekom promatranoga razdoblja sve stijenske pločice zabilježile su gubitak težine (tab. 4 i 6). Kada se uzmu u obzir stijenske pločice svih litologija, nakon razdoblja istraživanja najniža prosječna izmjerena stopa trošenja na površini zabilježena je na LOK-1 (0,560 %), dok je najviša zabilježena na LOK-3 (0,560 %). Slična raspodjela podataka zabilježena je i u tlu, gdje je najniža prosječna izmjerena stopa trošenja zabilježena na LOK-1 (0,141 %), dok je najviša zabilježena na LOK-3 (0,530 %) (tab. 4).

Kada se uzmu u obzir različite litologije, najnižu izmjerenu prosječnu stopu trošenja na površini imale su stijenske pločice izgrađene od paleogensko-neogeneske karbonatne breče (0,146 %) na lo-

Tab. 4 Minimum, maximum and average measured weathering rate (%) when rock tablets of all lithologies are considered
Tab. 4. Minimalna, maksimalna i prosječna izmjerena stopa trošenja (%) kad se uzmu u obzir stijenske pločice svih litologija

	LOK-1		LOK-2		LOK-3	
	surface / površina	**soil** /tlo	**surface** / površina	**soil** /tlo	**surface** / površina	**soil** /tlo
minimum / minimum	0.227	0.980	0.336	0.563	0.907	0.885
maximum / maksimum	0.105	0.032	0.133	0.142	0.220	0.335
average / srednjak	0.161	0.141	0.185	0.246	0.560	0.530

Tab. 5 Average measured weathering rate (%) of the different lithologies
Tab. 5. Prosječna izmjerena stopa trošenja (%) stijenskih pločica različitih litologija

	LOK-1		LOK-2		LOK-3	
	surface / površina	**soil** /tlo	**surface** / površina	**soil** /tlo	**surface** / površina	**soil** /tlo
Jurassic limestone / Jurski vapnenac	0.149	0.034	0.160	0.188	0.502	0.433
Pg-Ng carb. breccia / Pg-Ng karb. breča	0.146	0.035	0.164	0.202	0.597	0.397
Standard rock tabletse / standardne stijenske pločice	0.180	0.301	0.221	0.325	0.599	0.693

Tab. 6 Minimum, maximum and average absolute weathering rate (%) when rock tablets of all lithologies are considered
Tab. 6. Minimalna, maksimalna i prosječna apsolutna stopa trošenja (%) kad se uzmu u obzir stijenske pločice svih litologija

	LOK-1		LOK-2		LOK-3	
	surface / površina	**soil** /tlo	**surface** / površina	**soil** /tlo	**surface** / površina	**soil** /tlo
minimum / minimum	0.098	0.128	0.168	0.235	0.423	0.418
maximum / maksimum	0.024	0.003	0.033	0.034	0.070	0.078
average / srednjak	0.053	0.018	0.062	0.084	0.185	0.180

Tab. 7 Average absolute weathering rate (%) of different lithologies
Tab. 7. Prosječna apsolutna stopa trošenja (%) stijenskih pločica različitih litologija

	LOK-1		LOK-2		LOK-3	
	surface / površina	**soil** /tlo	**surface** / površina	**soil** /tlo	**surface** / površina	**soil** /tlo
Jurassic limestone / Jurski vapnenac	0.046	0.004	0.047	0.054	0.136	0.119
Pg-Ng carb. breccia / Pg-Ng karb. breča	0.039	0.004	0.037	0.049	0.142	0.106
Standard rock tabletse / standardne stijenske pločice	0.067	0.039	0.091	0.130	0.256	0.277

Tab. 8 Denudation rate (μm/yr) when rock tablets of all lithologies are consideredd
Tab. 8. Stopa denudacije (μm/god) kada se uzmu u obzir stijenske pločice svih litologija

	LOK-1		LOK-2		LOK-3	
	surface / površina	**soil** /tlo	**surface** / površina	**soil** /tlo	**surface** / površina	**soil** /tlo
minimum / minimum	0.99108	0.03029	1.21690	1.35067	2.04485	3.19760
maximum / maksimum	2.18975	0.98033	3.00365	5.44884	8.69782	8.53886
average / srednjak	1.54888	0.13938	1.75241	2.38103	5.44018	5.13378

Tab. 9 Average denudation rate (μm/yr) of different lithologies
Tab. 9. Prosječna stopa denudacije (μm/god) stijenskih pločica različitih litologija

	LOK-1		LOK-2		LOK-3	
	surface / površina	**soil** /tlo	**surface** / površina	**soil** /tlo	**surface** / površina	**soil** /tlo
Jurassic limestone / Jurski vapnenac	1.42652	0.03257	1.48098	1.82621	4.84556	4.14130
Pg-Ng carb. breccia / Pg-Ng karb. breča	1.40932	0.03280	1.65825	1.96439	5.60321	3.85884
Standard rock tabletse / standardne stijenske pločice	1.74103	0.29948	2.07091	3.14416	5.95329	6.76373

highest rate was recorded in the standard rock tablets (0.599 %) at LOK-3. In the soil, the lowest average weathering rate of Jurassic limestone (0.034 %) was measured at LOK-1, while the highest rate of standard rock tablets (0.693 %) was recorded at LOK-3 (Tab. 5).

The results of the measured weathering rates (Tab. 4 and Tab. 5) were corrected depending on the size of the rock tablets, and the results of the absolute weathering rate (%) coincide with the results of the measured weathering rates (Tab. 6 and 7).

The highest average denudation rates calculated for all rock tablets regardless of lithology (Tab. 8) were recorded at LOK-3, while the lowest denudation rates were recorded at LOK-1. Rock tablets deployed in the soil recorded a higher denudation rate than the ones on the surface at LOK-2 site. The highest average denudation rate (6.76373 μm/yr) during the study period (Tab. 9) was calculated for standard rock tablets buried in the soil at site LOK-3, while the lowest rate (0.03257 μm/yr) was calculated for Jurassic limestone rock tablets buried in the soil at site LOK-1.

kaciji LOK-1, dok najvišu stopu bilježe standardne stijenske pločice (0,599 %) na lokaciji LOK-3. U tlu najmanju prosječnu izmjerenu stopu trošenja imali su jurski vapnenci (0,034 %) na lokaciji LOK-1, dok su najvišu stopu imale standardne stijenske pločice (0,693 %) na lokaciji LOK-3 (tab. 5).

Rezultati izmjerenih stopa trošenja (Tab. 4 i Tab. 5) korigirani su ovisno o veličini stijenskih pločica te se rezultati apsolutne stope trošenja (%) poklapaju s rezultatima izmjerenih stopa trošenja (Tab. 6 i 7).

Najviše prosječne stope denudacije izračunate za sve stijenske pločice bez obzira na litologiju (Tab. 8) zabilježene su na LOK-3, dok su najniže stope denudacije zabilježene na LOK-1. Stijenske pločice postavljene u tlu zabilježile su višu stopu denudacije od onih na površini na lokaciji LOK-2. Najviša prosječna stopa denudacije (6,76373 μm/god) tijekom razdoblja istraživanja (Tab. 9) izračunata je za standardne stijenske pločice postavljene u tlu na LOK-3, dok je najniža stopa (0,03257 μm/god) izračunata za stijenske pločice od jurskog vapnenca, postavljene u tlu na LOK-1.

Discussion

Impact of local factors on denudation rate

Although all study sites are located within 1,000 m aerial distance there are substantial differences in denudation rates between the sites. The highest average denudation rate was measured at LOK-3, both in the rock tablets exposed on the surface and those buried in the soil. The calculated denudation values for the surface exposed rock tablets at LOK-3 are 71.5% higher than those at LOK-1 and 67.8% higher than those at LOK-2. For the buried tablets, the denudation values at LOK-3 are 97.3% higher than those at LOK-1 and 53.6% higher than those at LOK-2. This difference in denudation rates can be attributed to the microclimatic characteristics of the sites, as a consequence of variations in terrain morphology.

Rasprava

Utjecaj lokalnih čimbenika na brzinu denudacije

Iako se sva mjerna mjesta nalaze unutar 1000 m zračne udaljenosti, postoje značajne razlike u stopama denudacije između njih. Najviša prosječna stopa denudacije izmjerena je na LOK-3, kako u stijenskim pločicama izloženim na površini tako i u onima postavljenima u tlu. Izračunate vrijednosti denudacije za stijenske pločice izložene na površini na LOK-3 su 71,5 % više od onih na LOK-1 i 67,8 % više od onih na LOK-2. Za stijenske pločice postavljene u tlu vrijednosti denudacije na LOK-3 su 97,3 % više od onih na LOK-1 i 53,6 % više od onih na LOK-2. Ovakva razlika u stopama denudacije može se pripisati mikroklimatskim karakteristikama lokacija kao posljedici varijacija u morfologiji terena.

The lowest average denudation rates were measured at the study site LOK-1 when all lithologies were taken into account (1.54888 μm/yr on the surface and 0.13938 μm/yr in the soil). This study site on the slope below the Vučjak peak (Fig. 1.) receives the lowest amount of precipitation, and is exposed to strong winds, as confirmed by the meteorological data (195 days during study period) and has vegetation cover of alpine juniper (*Juniperus nana*) and subalpine calcicolous tussock grasslands (*Festucion pungentis*) in the surrounding area. These strong winds deflate snow cover causing prolonged (and deeper) freezing of the ground, but also increase evapotranspiration and drying of this shallow, porous soil (Perica and Orešić, 1999) with poor water retention, slowing down the carbonate dissolution process. In addition, this site is more exposed to solar radiation compared to other study sites, which additionally influences evaporation (i.e. drying out of the soil cover). Furthermore, LOK-1 site is characterized by sparse vegetation cover compared to other study sites, resulting in a lower amount of soil organic matter that impacts the carbonate dissolution process in the soil.

The average denudation rates considering all lithologies at the study site LOK-2 were 1.75241 μm/yr for rock tablets exposed on the surface and 2.38103 μm/yr for those buried in the soil. This study site is partially protected from wind and direct sunlight and is characterised by slightly deeper soil cover (compared to LOK-1). These conditions enable longer snow accumulation, and together with a higher amount of precipitation (compared to LOK-1), lead to increased soil moisture, which enhances carbonate dissolution process of the rock tablets buried in the soil.

The highest average denudation rates, when all lithologies are considered, are recorded at the study site LOK-3 (5.44018 μm/yr on the surface, 5.13378 μm/yr in the soil). This study site located at the bottom of the Balinovac doline (i.e. in the Velebit botanical garden) is covered with spruce forests and has the highest rainfall (compared to LOK-1 and LOK-2). The terrain morphology (i.e. deep doline) leads to more humid conditions, allows a prolonged period of snow accumulation (occasionally until June) and consequently a longer period

Na mjernom mjestu LOK-1 izmjerene su najniže prosječne stope denudacije kada se uzmu u obzir sve litologije (1,54888 μm/god na površini i 0,13938 μm/god u tlu). Ovo mjerno mjesto koje se nalazi na padini ispod vrha Vučjak (sl. 1.) ima najnižu količinu oborina, a izloženo je jakim vjetrovima, što potvrđuju meteorološki podatci (195 dana s jakim vjetrom tijekom razdoblja istraživanja) i vegetacijski pokrov sastavljen od alpske kleke (*Juniperus nana*) i subalpskih vapnenačkih travnjaka (*Festucion pungentis*) koji se nalaze na ovom području. Ovi jaki vjetrovi otpuhuju snježni pokrivač uzrokujući produljeno (i dublje) smrzavanje tla, ali također povećavaju evapotranspiraciju i isušivanje ovog plitkog poroznog tla (Perica i Orešić, 1999) loših retencijskih značajki, usporavajući proces otapanja karbonata. Također, u usporedbi s drugim mjernim mjestima, ova je lokacija je više izložena osunčavanju, što dodatno utječe na evaporaciju (tj. isušivanje pokrova tla). Nadalje, u usporedbi s drugim lokacijama istraživanja LOK-1 karakterizira oskudan vegetacijski pokrov, što rezultira nižom količinom organske tvari u tlu i utječe na proces otapanja karbonata u tlu.

Prosječne stope denudacije na mjernom mjestu LOK-2, kada se uzmu u obzir sve litologije, bile su 1,75241 μm/god za stijenske pločice izložene na površini i 2,38103 μm/god za one postavljene u tlu. Ovo mjerno mjesto djelomično je zaštićeno od utjecaja vjetra i izravnog osunčavanja te ga karakterizira nešto dublji pokrov tla (u usporedbi s LOK-1). Ove značajke uzrokuju produljeno razdoblje zadržavanja snježnog pokrivača te zajedno s višom količinom oborina (u usporedbi s LOK-1) rezultira povišenom količinom vlage u tlu, čime se pospješuje proces otapanja karbonata stijenskih pločica postavljenih u tlu.

Najviše prosječne stope denudacije (kada se u obzir uzmu sve litologije) izmjerene su na mjernom mjestu LOK-3 (5,44018 μm/god na površini 5,13378 μm/god u tlu). Ovo mjerno mjesto koje se nalazi na dnu Balinovačke ponikve (tj. Velebitskog botaničkog vrta) prekriveno je šumom smreke i prima najvišu količinu oborina (u usporedbi s LOK-1 i LOK-2). Morfologija terena (duboka ponikva) rezultira vlažnijim uvjetima, omogućuje produljeno razdoblje nakupljanja snijega (povremeno do lipnja) of high soil moisture. Apart from carbonate dissolution, the slopes of Balinovac doline are modified by colluvial processes that result in thick soil cover, while the decomposition of dense vegetation leads to a high content of organic matter in the soil. Thus, the local conditions at the bottom of the Balinovac doline (high precipitation and moisture, low insolation rate, high proportion of soil organic matter) are responsible for the high denudation rates at this study site.

This spatial distribution of denudation rates (i.e. highest values at the bottom of the doline) is not surprising and was already reported by Gams (1985) and Plan (2005), who also recorded higher denudation rates in the rock tablets placed at doline bottoms. Gams (1985) data also show that the location in the doline (sunny vs. shady side) also plays an important role in rock weathering. Our results also reveal that the amount of available water for the dissolution process (i.e. precipitation and soil water content) is one of the key factors controlling denudation and landscape evolution. Similar observations were made by Akiyama et al. (2015), who used the example of a karst doline to show that the evolution of the doline depends on the spatial distribution of water-saturated zones and their temporal durability.

Lithology and rock denudation rate

To measure actual and potential weathering rates, rock tablets cut from cores of local lithologies (Jurassic limestone and Paleogene-Neogene carbonate breccia) were used, as well as “standard rock tablets” from Upper Cretaceous (Senonian) Lipica limestone. The results show that during the study period, the denudation rate measured with standard rock tablets was on average 37.4% higher than that measured with rock tablets from local lithologies at all study sites (Fig. 3).

In particular, it was 39.2% higher than for Jurassic limestone and 35.7% higher than for Paleogene-Neogene carbonate breccia. Moreover, this difference was most obvious at the study site LOK-1 (53.8 %) when all rock tablets were considered. The difference is also clear when considering the rock tablets exposed on the surface and those buried in the soil (18.4% for the tablets exposed on the surface and

i posljedično produljeno razdoblje s visokom količinom vlage u tlu. Osim procesa otapanja karbonata padine Balinovačke ponikve modificirane su koluvijalnim procesima koji rezultiraju debljim pokrovom tla, dok razgradnjom guste vegetacije dolazi do nakupljanja velike količine organske tvari u tlu. Stoga su lokalni uvjeti u dnu Balinovačke ponikve (velika količina oborina i vlage, niska insolacija, visoka količina organske tvari u tlu) odgovorni za visoke stope denudacije na ovom području istraživanja.

Ova prostorna distribucija stopa denudacije (tj. najviše vrijednosti na dnu ponikve) nije iznenađujuća. Slične rezultate zabilježili su ranije Gams (1985) i Plan (2005) koji su izmjerili više stope denudacije na dnu ponikava. Gamsovi (1985) podatci također pokazuju da položaj mjernog mjesta u ponikvi (osojna naspram prisojne strane) također igra važnu ulogu u trošenju stijena. Naši rezultati nadalje pokazuju da je količina dostupne vode (tj. oborine i sadržaj vode u tlu) za proces otapanja jedan od ključnih čimbenika koji kontroliraju denudaciju i evoluciju krajolika. Slične rezultate zabilježili su Akiyama i dr. (2015) koji su na primjeru krške ponikve pokazali da evolucija ponikve ovisi o prostornom rasporedu vodozasićenih zona i njihovoj vremenskoj trajnosti.

Litologija i stopa denudacije

Za mjerenje stvarnih i potencijalnih stopa trošenja koristili smo stijenske pločice izrezane iz jezgri lokalnih litologija (jurski vapnenac i paleogensko-neogenska karbonatna breča), ali i „standardne stijenske pločice” izrađene od gornjokrednog (senonskog) lipičkog vapnenca. Rezultati pokazuju da je tijekom razdoblja istraživanja stopa denudacije mjerena standardnim stijenskim pločicama bila u prosjeku 37,4 % viša u usporedbi s onom mjerenom korištenjem stijenskih pločica lokalnih litologija na svim mjernim mjestima (sl. 3).

Konkretno, 39,2 % viša od onih izraženih od jurskog vapnenca te 35,7 % viša od onih izrađenih od paleogensko-neogenske karbonatne breče. Također, ova je razlika bila najočitija na mjernom mjestu LOK-1 (53,8 %) kada se uzmu u obzir sve stijenske pločice. Nadalje, kada se razmatraju stijenske pločice izložene na površini i one postavljene u tlu,

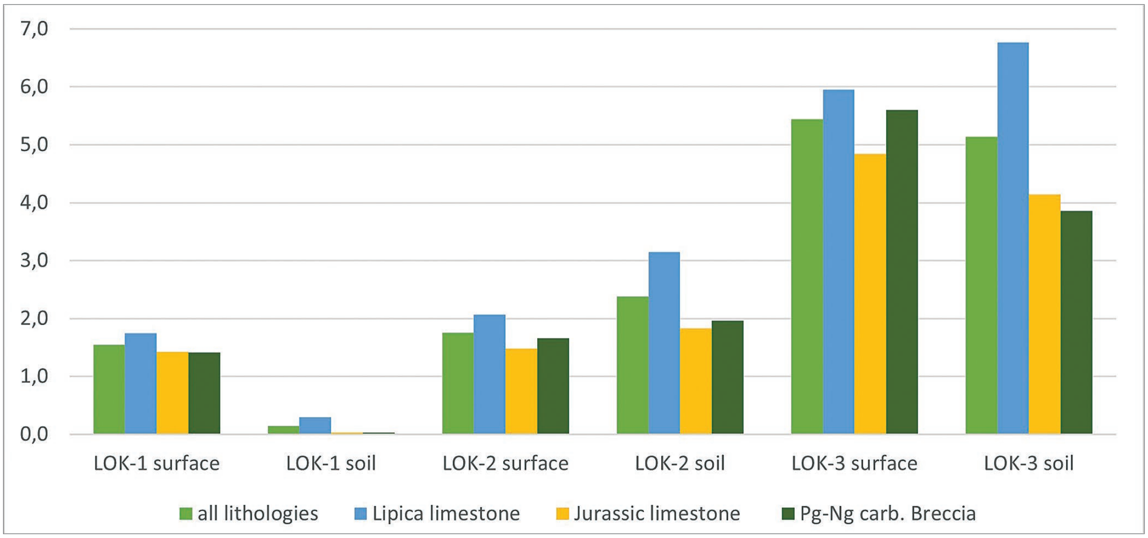

Fig. 3 Average denudation rates (μm/yr) measured at the surface and in the soil by rock tablets of different lithologies
Sl. 3. Prosječna stopa denudacije (μm/god) izmjerena na površini i u tlu korištenjem stijenskih pločica različitih litologija

56.6% for those buried in the soil). Such a discrepancy in weathering rates between local lithologies and "standard rock tablets" as a result of lithological properties of rock tablets was previously observed by other researchers (e.g. Urushibara-Yoshino et al., 1998; Day, 1984). Denudation rates strongly depend on lithology (Matsukura and Hirose, 1999; Matsukura et al., 2001, 2007; Thorn et al., 2002, 2006; Plan, 2005) due to differences in dissolution kinetics of minerals (Morse, 1983; White and Brantley, 1995), porosity, permeability and existence of discontinuities (e.g. Harrison and Hudson, 2000). Thus, although the comparison of denudation rates obtained by using standard rock tablets on a regional or even global scale is of interest for some karst studies (e.g. Gams, 1985; 1989; Zhang, 1989), the use of local lithologies clearly provides more accurate results and gives better insight into the local/regional evolution of the karst landscape.

razlika je također očita (18,4 % za pločice izložene na površini i 56,6 % za one postavljene u tlu). Sličnu nepodudarnost u stopama denudacije između lokalnih litologija i „standardnih stijenskih pločica" uslijed različitih litoloških karakteristika uočili su i drugi istraživači (npr. Urushibara-Yoshino i sur., 1998; Day, 1984). Stope denudacije snažno ovise o litologiji (Matsukura i Hirose, 1999; Matsukura i sur., 2001, 2007; Thorn i sur., 2002, 2006; Plan, 2005) zbog razlika u kinetici otapanja minerala (Morse, 1983; White i Brantley, 1995), porozitetu, propusnosti i postojanju diskontinuiteta (npr. Harrison i Hudson, 2000). Stoga, iako je usporedba stopa denudacije dobivena korištenjem standardnih stijenskih ploča regionalno ili čak širom svijeta od interesa za pojedina istraživanja (npr. Gams, 1985, 1989; Zhang, 1989), očito je da uporaba lokalnih litologija daje točnije rezultate i bolji uvid u lokalni/regionalni razvoj krškog reljefa.

Conclusions

We studied the short-term denudation rates in the northern part of the Velebit Mountain, located in the Dinaric karst region, using the rock tablet method. The results of this study show that denudation rates are strongly dependent on local factors (i.e. microclimatic characteristics, vegeta-

Zaključci

Istražili smo kratkotrajne stope denudacije metodom stijenskih pločica na sjevernom dijelu Velebita, koji se nalazi u području dinarskog krša. Rezultati ovog istraživanja pokazali su da stopa denudacije jako ovisi o lokalnim čimbenicima (tj. mikroklimatskim značajkama, vegetaciji) kao rezultatu

tion) as a result of topographical characteristics of the study area. In this study we used “standard rock tablets” to measure potential denudation and rock tablets made of local lithologies to measure actual denudation rates. During the study period, highest denudation rates were measured when using “standard rock tablets”, highlighting the necessity of using local lithologies to better understand the evolution of the local karst topography.

topografskih karakteristika područja istraživanja. U ovom smo se istraživanju za mjerenje stvarnih stopa denudacije koristili „standardnim stijenskim pločicama” za mjerenje potencijalne denudacije i stijenskim pločicama napravljenima od lokalnih litologija. Tijekom razdoblja istraživanja najveće stope denudacije izmjerene su korištenjem „standardnih stijenskih pločica”, naglašavajući nužnost korištenja lokalnih litologija za bolje razumijevanje evolucije lokalne krške topografije.

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