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Cover page: The consequences of the extreme weather event at the end of October 2018 on the road through the Dovžan Gorge along the torrential stream of Tržiška Bistrica river. Photo: Irena Mrak

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GEOLOGIJA *62/1*, 5, Ljubljana 2019
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Uvodnik

Ob letošnjem dnevu Zemlje smo na Geološkem zavodu Slovenije (GeoZS) že sedmič podelili najvišja slovenska priznanja in nagrade posameznikom in organizaciji za dosežke v geoznanosti. Medaljo Marka Vincenca Lipolda je za svoje dolgoletno delo prejel dr. Ladislav Placer, priznanje častni član GeoZS za pomembne uspehe na področju geoloških raziskav ter za uveljavitev GeoZS doma in v svetu je bilo podeljeno dr. Ljubu Žlebniku, prejemnik plakete Marka Vincenca Lipolda za vrhunske znanstveno-raziskovalne dosežke v zadnjih dveh letih je dr. Miloš Miler, priznanje častna listina Geološkega zavoda Slovenije za zasluge pri razvijanju sodelovanja z GeoZS in za pomembne prispevke pri uveljavljanju družbenega pomena raziskovalne dejavnosti pa je prejela Uprava Republike Slovenije za zaščito in reševanje.

Dogodek ob podelitvi je bil sproščen in pozitiven, prav tako nagrajenci. Z razlogom!

Doma in po svetu se povečuje zavedanje o odgovornosti te generacije in naslednjih za stanje našega planeta. Vse pomembnejše postaja tudi vprašanje dolgoročne in trajnostne oskrbe z naravnimi viri. Oči javnosti so zato uprte v nas geologe ter druge strokovnjake in raziskovalce na področjih geoznanosti. Jasno, saj bo prihodnost življenja na našem planetu odvisna od ravnanja z atmosfero, poleg tega pa tudi od trajnostnega ravnanja z geosfero, ki nam zagotavlja skoraj vse ključne naravne vire. Geoznanosti po desetletjih nekakšnega prikritega in tihega zastoja znova pridobivajo svojo veljavo. Brez poznavanja geologije danes ne gre, prav tako brez nje ni razvoja. To ve ves svet in tega se počasi začenja zavedati tudi naše ožje okolje.

Zavedanje o odgovornosti do našega planeta se povečuje, večajo pa se tudi zahteve države, državljanov in celotne družbe do naših strok. Ti zahtevajo vse več in vse bolj kakovostne odgovore na vse zahtevnejša strokovna vprašanja, kar je izredno dober, celo navdušujoč znak napredka. Svoje znanje lahko danes hitreje posredujemo v neposredno rabo, se pa žal hkrati nepričakovano ukvarjamo z vse večjim primanjkljajem na področju temeljnih znanosti, ki ga v preteklosti nismo poznali. Temeljna znanja ne zmorejo več ustrezno podpirati razvoja aplikativnega dela oziroma uporabe znanja v praksi, primanjkljaj v razvoju temeljnih znanosti pa vpliva na naše geološko delo. Ob obsedenosti s scientometrijo, z na videz objektivnim kvantitativnim vrednotenjem znanstvenega dela, so bile temeljne geoznanosti v Sloveniji odrinjene na rob, medtem ko v svetu cvetijo. Upajmo, da bo nastajajoči zakon o raziskovalni in razvojni dejavnosti uspešno ovrednotil tudi ta vprašanja ter dal geoznanosti in geoznanstvenikom veljavo, ki si jo zaslužijo.

V času pred zastojem razvoja temeljnih znanosti sta glavne raziskovalne preboje naredila letošnja prejemnika visokih priznanj, dr. Ladislav Placer in dr. Ljubo Žlebnik. Današnja generacija geologov si težko predstavlja svoje delo v Sloveniji brez temeljev, ki sta jih postavila. Najmlajši nagrajenec dr. Miloš Miler tako dokazuje, da smo tudi danes sposobni prebojnih temeljnih znanstvenih dosežkov. Konkurenca vrhunskih raziskovalcev in rezultatov je še vedno ostra, morda celo bolj kot v preteklosti, a bi lahko bila in bi morala biti še bistveno ostrejša.

Letošnje leto zaznamuje praznovanje 100-letnice Univerze v Ljubljani. Tudi visokošolsko poučevanje geologije letos praznuje stoletnico, saj se geologija v Ljubljani poučuje od ustanovitve Univerze. Geologija kot stroka torej ni od včeraj. Je ena najzgodnejših naravoslovnih znanosti in prav tista, ki je postavila temelje za naravoslovno dojemanje sveta, Zemlje in njenega razvoja, vključno z razvojem živih bitij na njej.

Pomembno je, da slovenske dosežke na področju geoznanosti prepoznavamo in jih nagrajujemo. Ne smemo pa pozabiti: geologija je univerzalna, planetarna znanost. Zanjo in za raziskovalce ni državnih meja. Naši raziskovalci se že dolgo odpirajo svetu, v obratni smeri pa nam še ne gre najbolje. Povabimo v Slovenijo raziskovalce, ki danes delujejo zunaj naših meja, in preusmerimo tok znanja. Zemlja in družba nam bosta za to hvaležni!

dr. Miloš Bavec, direktor GeoZS

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Geochemical background and threshold for 47 chemical elements in Slovenian topsoil

Geokemično ozadje in zgornja meja naravne variabilnosti 47 kemičnih elementov v zgornji plasti tal Slovenije

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Ključne besede: tla, litologija, elementi, geokemično ozadje, geokemično kartiranje, zgornja meja naravne variabilnosti, Slovenija

Abstract

Geochemical background and threshold values need to be established to identify areas with unusually high concentrations of elements. High concentrations are caused by natural or anthropogenic processes. The <2 mm fraction of 817 collected topsoil (0 – 10 cm) samples at a 5 × 5 km grid on the territory of Slovenia was analysed. Results are used here to establish the geochemical background variation and threshold values, derived statistically from the data set, in order to identify unusually high element concentrations for these elements in the soil samples. Geochemical threshold values were determined following different methods of calculation for (1) whole of Slovenia and (2) for 8 spatial units determined on the base of geological structure, lithology, relief, climate and vegetation. Medians and geochemical thresholds for whole of Slovenia were compared with data for Europe and for southern Europe separately, since large differences in the spatial distribution of many elements are observed between northern and southern Europe. Potentially toxic elements (PTEs), namely As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb, and Zn, are of particular interest. Medians of these PTE elements are all higher in Slovenia than in southern Europe. Medians of Pb and Mo are 1.5 times higher and medians of Hg and Cd are even more than 2 times higher in Slovenia. Geochemical thresholds for As, Cr, Co, Ni, Sb and Zn are of similar values in both Slovenia and southern Europe and some lower for Cu and Ni. Up to 1.5 times higher are tresholds in Slovenia for Mo and Pb and more than 2.5 times higher for Cd and Hg. These values were then compared to existing Slovenian soil guideline values for these elements.

Izvleček

Kemični elementi so v okolju, torej tudi v tleh, naravno prisotni. Povišane vsebnosti le-teh so posledica naravnih danosti ali pa jih povzročijo človekove dejavnosti. Območja povišanih koncentracij elementov so opredeljena kot območja, na katerih vsebnosti elementov presegajo vrednosti geokemičnega praga (zgornjih mej naravne variabilnosti - MNV). Na podlagi kemičnih analiz 817 vzorcev zgornje plasti tal (0–10 cm), odvzetih v mreži 5 × 5 km na območju celotne Slovenije, smo izračunali mediane (geokemično ozadje) in zgornje meje naravne variabilnosti (MNV) po več metodah za celotno Slovenijo in za 8 manjših prostorskih enot, ki smo jih določili glede na geološko zgradbo, kamninsko sestavo, relief, podnebje in rastlinstvo. Znotraj posameznih manjših prostorskih enot se izračunane MNV po različnih metodah močno razlikujejo zaradi heterogenosti enot in majhnega števila vzorcev. Mediane in zgornje meje naravne variabilnosti za celotno Slovenijo smo primerjali s podatki za celotno Evropo in še posebej južno Evropo, ker se prostorske porazdelitve elementov med južno in severno Evropo močno razlikujejo. Zanimive so vsebnosti potencialno strupenih elementov (As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Zn) in primerjava z mejnimi, opozorilnimi in kritičnimi vrednostmi za tla po slovenski zakonodaji. Mediane teh elementov so v Sloveniji višje kot v celotni Evropi in v južni Evropi. Primerjava z južno Evropo kaže, da sta mediani Pb in Mo 1,5 krat višji, mediani Cd in Hg pa celo več kot 2 krat višji v Sloveniji. V Sloveniji so MNV blizu vrednostim v južni Evropi za elemente As, Cr, Co, Ni, Sb in Zn, malo nižje za Cu in Ni, do 1,5 krat višje za elementa Mo in Pb ter več kot 2,5 krat višje za Cd in Hg.

Introduction

Chemical elements are in environment, as well as in soil, present naturally. High element concentrations in environment may be due to occurrence of mineralization, unusual rock types, such as serpentinite, black shale mudstone, etc., or may be caused by human activities (mining, metallurgy, industry, traffic, agriculture, etc.). Depending on bioavailability and stability of the material in which the chemical elements appear, their high concentration levels may present environmental risk due to element toxicity.

Anthropogenic chemical contamination is one of the most evident signals of human influence on the environment. The large amounts of industrially produced pollutants that have been introduced, over decades, into air, soil and water have caused modifications to natural elemental cycling (Gałuszka et al., 2014). Anthropogenic contamination usually leads to enrichment in many elements, particularly in industrial areas. Certain elements and their isotopes can therefore be used as geochemical indicators of anthropogenic impact. There are also secondary effects of the pollution, such as acidification, which causes increased geochemical mobility of elements in surficial deposits. Methods used in geochemistry to assess the scale of anthropogenic influence on the environment include determination of geochemical background and thresholds, calculation of enrichment and contamination factors, geoaccumulation index and pollution load index. The use of geochemical background levels to distinguish between natural and anthropogenic pollution is important (fig. 1 and 2) (Gałuszka et al., 2014).

To identify areas with unusually high (or low) concentrations of "potentially toxic elements" (PTEs), geochemical background and threshold values of these elements need to be determined.

Uvod

Kemični elementi (prvine) so v okolju, torej tudi v tleh, naravno prisotni. Njihove povišane vsebnosti v okolju so lahko posledica naravnih danosti (pojavljanje mineralizacij oziroma orudenj in kamnin z naravno visokimi vsebnostmi nekaterih elementov, kot so na primer serpentinit, črni skrilavi glinavci, itd.), ali pa jih povzročijo človekove dejavnosti (rudarstvo, metalurgija, industrija, promet, kmetijstvo, itd.). Odvisno od obstojnosti zvrsti, v katerih kemični elementi nastopajo, lahko njihove povišane vsebnosti predstavljajo okoljska tveganja zaradi biodostopnosti škodljivih elementov.

Antropogena kemična kontaminacija je eden najbolj očitnih znakov človekovega vpliva na okolje. Dolgoletno delovanje različnih industrij, prometa in drugih človekovih dejavnosti so povzročili povišanje vsebnosti nekaterih elementov v površinskih materialih (tla, sedimenti, itd.) in spremembe naravnega kroženja elementov (Gałuszka et al., 2014). Antropogeni vplivi navadno vodijo v obogatitev številnih elementov, še zlasti na industrijskih območjih. Nekateri elementi in njihovi izotopi se tako lahko uporabljajo kot geokemični indikatorji antropogenega vpliva. Poznamo tudi sekundarne učinke onesnaženja, kot je na primer zakisljevanje, ki povzroča povečano geokemično mobilnost elementov v površinskih materialih. Metode, ki jih geokemiki uporabljamo za oceno obsega antropogenega vpliva na okolje, vključujejo opredelitev ravni geokemičnega ozadja in mej naravne variacije, izračune obogatitvenih razmerij, geoakumulacijskih indeksov in indeksov onesnaženja. Še posebej pomembna je uporaba geokemičnih ravni ozadja za ločitev naravnega in antropogenega deleža onesnaženja (sl. 1 in 2) (Gałuszka et al., 2014).

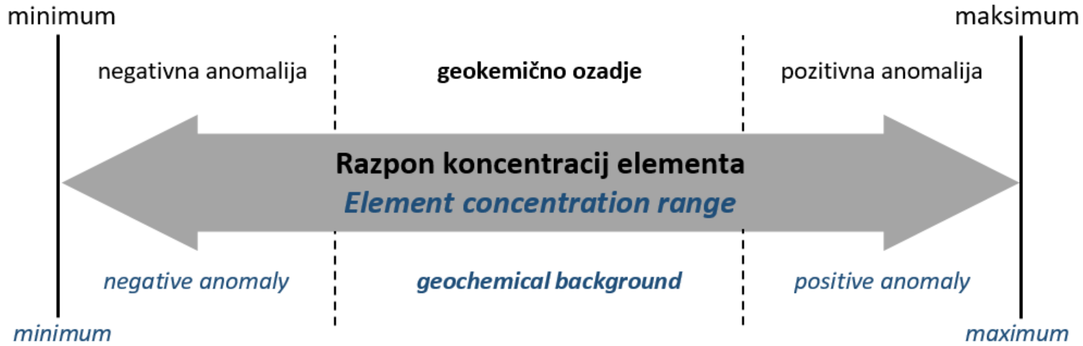

Fig. 1. Geochemical background and anomalies (after Gałuszka et al., 2014).
Sl. 1. Geokemično ozadje in anomalije (po Gałuszka et al., 2014).

Geochemical threshold values are used to identify locations with unusually high element concentrations. A lower threshold, determined in the lower part of the data distribution, is used to identify locations with unusually low element concentrations. Deficiency of certain elements in the soil can present a problem to living organisms in those environments (Reimann et al., 2018). In this work we focused solely on upper threshold and did not discuss the lower threshold.

After identification of areas with unusually high element concentrations, risk assessment must be determined in these areas. Risk assessment of soil determines whether the high element concentrations pose a threat to living organisms or the environment. It is dependent from elements, as certain elements are toxic at low concentrations and other elements are biologically essential, but harmful at higher concentration levels (Reimann et al., 2018). Proper risk assessment of soil includes comparison of determined element concentration values with effect thresholds for environmental and human health derived from (eco)toxicological data. This approach preferentially takes into account the effect of abiotic soil properties (such as mineral composition, structure and texture of the soil, water and air present in the soil) on bioavailability and toxicity of the element (examples in Smolders et al. (2009), Oorts & Schoeters (2014), Oorts et al. (2016) or Birke et al. (2016)). Proper risk assessment of certain location also requires

S pomočjo opredelitve vrednosti mej naravne variabilnosti za posamezne elemente se določa območja z nenavadno visoko (ali nizko) koncentracijo "potencialno strupenih elementov" (v nadaljevanju PTE – *potentially toxic elements*). Geokemični prag, ki je definiran kot zgornja meja naravne variabilnosti, se uporablja za določitev območij z nenavadno visoko koncentracijo elementov. Zanimiva je tudi spodnja meja naravne variabilnosti, ki je definirana v spodnjem delu porazdelitve geokemičnih podatkov in se uporablja za določitev območij z nenavadno nizko koncentracijo elementov, saj lahko tudi pomanjkanje nekaterih elementov v tleh povzroča težave živim bitjem (Reimann et al., 2018). Spodnja meja naravne variabilnosti ne sodi v vsebino tega dela, zato je v nadaljevanju ne bomo obravnavali.

Območja z nenavadno visokimi koncentracijami elementov v tleh je potrebno raziskati s posebno študijo, imenovano ocena tveganja, s katero ugotavljamo, ali te nenavadno visoke vsebnosti elementa lahko škodujejo okolju oz. živim bitjem. Nekateri elementi so namreč potencialno strupeni že v nižjih vsebnostih, drugi pa so biološko nujno potrebni, vendar njihove previsoke vsebnosti lahko škodujejo živim bitjem (Reimann et al., 2018). Pravilna ocena tveganja vključuje primerjavo izmerjenih koncentracij elementov z vrednostmi elementa, ki negativno učinkujejo na okolje in zdravje ljudi na podlagi ekotoksikoloških raziskav. Ta pristop prednostno upošteva

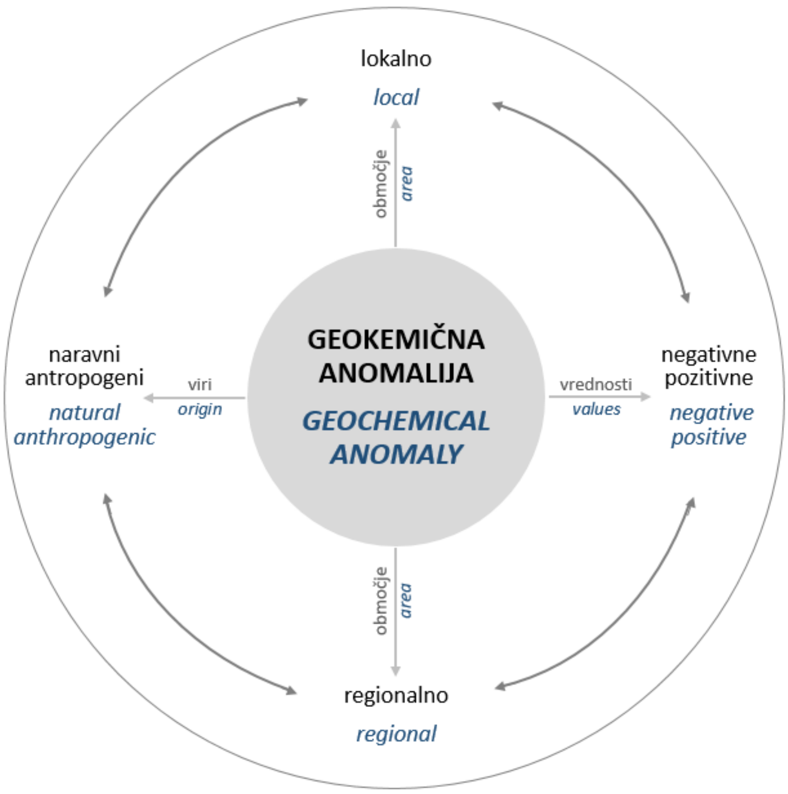

Fig. 2. Systematics of geochemical anomalies (after Gałuszka et al., 2014).

Sl. 2. Sistematika geokemičnih anomalij (po Gałuszka et al., 2014).

a substantial amount of additional data, such as bioavailability of elements, acidity (pH), grain size, cation exchange capacity and total organic carbon. Additional data must be available for each determined location with high element concentrations. Identifying geochemical (non-toxicological) threshold can simply be defined as a value above which the concentration of an element in a given data set is "unusually high". With this approach we separate locations that require attention and further analysis and studies (Reimann et al., 2018).

Unusually high element concentrations in the upper soil layer can be due to anthropogenic activities, such as urbanization, industrial activities, mining and agricultural practices. They may also be of natural origin and indicate areas with geochemically unusual rock types or areas having a high potential for the occurrence of mineral deposits (Reimann et al., 2018). The separation of these three distinct causes for high element concentrations in soil requires substantial expert knowledge about the location of possible contamination sources (cities, metal smelters, power plants, industry), climate, vegetation zones, geology, element dispersion processes, mineral deposits etc. (Reimann et al., 2018).

Materials and methods

Soil as sample material in geochemistry

Soils are an unique natural resource essential for food production and an irreplaceable component of natural ecosystems. Due to numerous environmental, economic, social and cultural functions (the multifunctionality of soils), soils are of crucial importance for life in terrestrial ecosystems (Vidic et al., 2015).

Soils represent the upper part of Earth's crust that consist of mineral particles, organic matter, water, air and living organisms (FitzPatric, 1986). They are indispensable to humanity and to maintaining a healthy natural environment.

Soil formation is a slow process. Soils form as a result of lithosphere weathering due to interactions of pedogenetic factors, which are lithological parent material, climate, relief, time and living organisms. Lithological parent material provides the original quantity of mineral material (with exception of carbonate rocks), from which soils are composed. It also influences thickness of the soil, physical, mineral and chemical attributes and further development of the soil (FitzPatrick, 1986). Climate influences soil development with solar radiation and dynamic processes in the atmosphere, which have an impact on humidity, heat

učinek abiotskih lastnosti tal (kot so mineralna sestava, tekstura in struktura tal ter voda in zrak v tleh) na biološko dostopnost (primeri v Smolders et al. (2009), Oorts & Schoeters (2014), Oorts et al. (2016) ali Birke et al. (2016)). Za določitev ocene tveganja na določenem območju so dodatno potrebni še drugi podatki o tleh, kot so biodostopni delež elementov, kislost (pH) in zrnavost tal, kationska izmenjevalna kapaciteta ter skupni organski ogljik. Tudi ti morajo biti na voljo za vsako obravnavano območje. Geokemično (ne toksikološko) zgornjo mejo naravne variabilnosti v obravnavanih tleh lahko preprosto določimo kot vrednost, nad katero je koncentracija elementa v tleh na podlagi danih podatkov "nenavadno visoka". S tako določenimi zgornjimi mejami naravne variacije izdvojimo območja tal, ki zahtevajo večjo pozornost in morda nadaljnje analize in študije (Reimann et al., 2018).

Nenavadno visoke koncentracije elementov v zgornjem sloju tal so lahko posledica antropogenih dejavnosti ali pa so naravnega izvora (Reimann et al., 2018). Za identifikacijo vzrokov visoke ravni elementov v tleh je potrebno zahtevno raziskovalno delo. Potrebno je izdelati kompleksno študijo, v kateri združujemo podatke o geoloških lastnostih (litološke značilnosti ozemlja, podatki o morebitnih orudenjih) in okoljskih značilnostih obravnavanega ozemlja, kot so npr. morebitni viri onesnaževanja (urbanizirana območja, kovinska industrija, termoelektrarne, druge vrste industrije) ter informacije o podnebju, talnih in vegetacijskih značilnostih in podobno (Reimann et al., 2018).

Materiali in metode

Tla kot vzorčni medij v geokemiji

Tla so edinstven naravni vir, ki je neposredno povezan s pridelavo hrane in splošno blaginjo, hkrati pa predstavljajo nenadomestljiv del naravnih ekosistemov. Zaradi številnih okoljskih, ekonomskih, socialnih in kulturnih funkcij so tla ključnega pomena za življenje v kopenskih ekosistemih (Vidic et al., 2015).

Tla predstavljajo zgornji del zemeljske skorje, ki ga sestavljajo mineralni delci, organska snov, voda, zrak in živi organizmi (FitzPatrick, 1986). So zelo pomembna za človeštvo in za vzdrževanje zdravega naravnega okolja.

Tvorba tal je počasen proces. Tla nastajajo ob preperevanju litosfere zaradi medsebojnega delovanja tlotvornih (pedogenetskih) dejavnikov, kot so matična podlaga, podnebje, relief, čas in organizmi. Matična podlaga zagotavlja osnovno and atmospheric deposition of particles. Organisms exchange substances and energy from lithological parent material and soils and thus directly affect soil development. The relief indirectly influences the formation of the soil by distribution of surface material and energy. Moving and retention potential of substances in the original location depend on the slope steepness. The relief also affects the thickness and humidity of the soil. Humans also have an influence on soil development, either directly by agriculture, infrastructure and urbanization or indirectly by changing relief, water regime, vegetation and pollution, which can be of point or dispersed type. Soils have a high buffering capacity which relates to stability of the soil system and the pH of the soil and to the soil retaining capacity. Thus, the content of water, mineral particles, gases as well as pollutants in the soil are regulated. However, the buffering capacity of the soil is not unlimited and therefore certain pollutants can exceed the retention or buffering capacity of the soil (FitzPatric, 1986).

Soil is a dynamic complex formation, in which biological, chemical and physical processes continuously take place. It represents a complex ecosystem that enables plant growth and biogeochemical circulation of elements. Physical processes include decomposition of rocks into smaller particles without changing their mineral and chemical composition. Physical decomposition is caused by temperature changes, frost, wind, glaciation, plant roots activity and water. Due to physical decomposition, the specific particle size increases, allowing for faster chemical decomposition. Chemical processes are dissolution, hydrolysis, hydration, oxidation or reduction, and the formation of clay and other minerals. Water, that contains dissolution of various gases and acids, plays an important role in all these processes. Most of the soil processes are of direct or indirect biological nature. Organisms are effective leaching factors in the dissolution of many elements. Due to the extremely high reproduction rate of microorganisms, their effect can be significant and can be important in the migration of elements in the soil (Siegel, 2002).

The unique characteristic of the soils is the distribution of their components and features in layers, that are dependent on the present landscape surface and that vary with depth. Migration processes of particles, chemical elements and humus substances take place due to weathering, water and organisms in the soil. Thus, soil layers are formed, which differ in morphological features: colour, density of the roots, humus

količino mineralnega gradiva (izjema je karbonatna podlaga), iz katerega sestoje tla, in vpliva na debelino, na fizikalne, mineralne in kemične lastnosti ter na nadaljnjo smer njihovega razvoja (FitzPatrick, 1986). Podnebje vpliva na razvoj s sončnim sevanjem in z dinamičnimi procesi v atmosferi, ki prenašajo vlago, toploto in vplivajo na atmosfersko odlaganje delcev. Živi svet izmenjuje z matično podlago in s tlemi snovi in energijo ter tako neposredno vpliva na razvoj tal. Relief posredno vpliva na oblikovanje tal s tem, da razporeja po površini snovi in energijo. Premeščanje ali zadrževanje snovi na prvotnem mestu je odvisno od strmine pobočja. Relief vpliva tudi na debelino in vlažnost tal. Na njihovo oblikovanje vpliva tudi človek. Neposredno z obdelovanjem, gradnjo infrastrukture in naselij, posredno pa s spreminjanjem reliefa, vodnega režima, rastlinstva in z onesnaževanjem, ki je lahko točkovno ali razpršeno. Tla imajo veliko puferno sposobnost, ki se nanaša na stabilnost talnega sistema in pH tal ter na zadrževalno sposobnost tal. Tako se uravnava vsebnost vode, mineralnih delcev, plinov kot tudi onesnaževal v tleh. Puferna sposobnost tal pa ni neomejena in zato lahko določena onesnaževala tudi presežejo zadrževalno oz. puferno sposobnost tal (FitzPatrick, 1986).

Tla so dinamična kompleksna tvorba, v kateri ves čas potekajo biološki, kemični in fizikalni procesi. Predstavljajo zapleten ekosistem, ki omogoča rast rastlin in biogeokemično kroženje elementov. Fizikalni procesi obsegajo razpadanje kamnine na manjše delce, pri čemer se njihova mineralna in kemična sestava ne spremenita. Fizikalno razpadanje povzročajo temperaturne spremembe, delovanje zmrzali, vetra, ledenikov, rastlinskih korenin in vode. Zaradi takega razpadanja se poveča specifična površina delcev, kar omogoča hitrejše kemično razpadanje. Kemični procesi so raztapljanje, hidroliza, hidratacija, oksidacija ali redukcija ter tvorba glinenih in drugih mineralov. Pri vseh teh procesih ima pomembno vlogo voda, v kateri so raztopljeni različni plini in kemične snovi. Večina talnih procesov je posredno ali neposredno biološke narave. Organizmi so učinkoviti dejavniki izluževanja in raztapljanja številnih elementov. Zaradi izredno velike razmnoževalne hitrosti mikroorganizmov je njihov skupni učinek lahko znaten in je lahko pomemben v migraciji elementov v tleh (Siegel, 2002).

Edinstvena značilnost tal je razporeditev njihovih sestavin in lastnosti v plasteh, ki so odvisne od sedanjega površja in se spreminjajo z globino. Zaradi preperevanja, delovanja vode ter organizmov v tleh potekajo procesi premeščanja delcev, content, grains, humidity and other. Individual layers are called soil horizons. They were created in the process of soil formation and interaction between the layers. They can be from few centimeters to several meters thick. Together, they form a soil profile (Siegel, 2002).

Trace elements in the soils occur in primary minerals that originate from lithological parent material, in secondary newly formed minerals, and bound to clay minerals and organic matter. In addition to geological and pedological features, soils also provide information on pollutants in the air, and are therefore a very useful and widespread sample medium.

A regional radiometric and geochemical survey was performed on the entire territory of Slovenia during the period 1990–1993 by the Geological Survey of Slovenia. Soil sampling was performed at a 5 × 5 km grid with a randomly selected starting point to ensure randomness of sampling (fig. 3) (Andjelov, 1994). In total, 817 topsoil (0–10 cm) samples were collected. The air dried samples were gently disaggregated in a ceramic mortar, sieved through a 2 mm sieve and stored. In 2012 the stored soil samples were taken out of the depot at the Geological Survey of Slovenia, pulverized in an agate mill to a fine-grain size (<0.075 mm) and submitted to chemical analysis in Bureau Veritas Mineral Laboratories at Vancouver, Canada. Samples were analysed with inductively coupled plasma (ICP) and mass spectrometry (MS) after digestion of an aliquot of 15 g sample material with aqua regia

kemičnih elementov in humusnih snovi. Tako nastanejo v tleh plasti, ki se razlikujejo po morfoloških lastnostih: barvi, prekoreninjenosti, deležu humusa, deležu skeleta, vlažnosti in drugem. Posamezne plasti imenujemo talni horizonti. Nastali so v procesu nastanka in razvoja tal v medsebojni odvisnosti. Debeli so od nekaj centimetrov do več metrov. Skupaj sestavljajo talni profil (Siegel, 2002).

Sledni elementi v tleh so vezani v obstojnih prvotnih mineralih, ki izvirajo iz matične kamnine, v drugotnih, novonastalih mineralih, ter vezani na glinene minerale in organsko snov. Ker pa poleg geoloških in pedoloških značilnosti dajejo tudi informacijo o onesnaževalih v zraku, so tla zelo uporaben in razširjen vzorčni medij.

V letih 1990–1993 je Geološki zavod Slovenije izvedel regionalno vzorčenje tal celotnega ozemlja Slovenije za potrebe izdelave karte naravne radioaktivnosti. Tla so bila sistematično vzorčena v mreži 5 × 5 km, v kateri je bila merjena tudi naravna radioaktivnost (sl. 3) (Andjelov, 1994). Skupno je bilo odvzetih 817 vzorcev zgornje plasti tal (0–10 cm), ki so bili posušeni in presejani na frakcijo <2 mm. Del vzorcev je bil arhiviran v depoju GeoZS. Leta 2012 so bili vzorci vzeti iz depoja, zmleti v ahatnem mlinčku (<0,075 mm) in posredovani v kemične analize v Bureau Veritas Mineral Laboratories (Vancouver, Kanada). Vzorci so bili analizirani z metodo induktivno vezane plazemske masne spektrometrije (ICP-MS) po razklopu z modificirano zlatotopko (15 g vzorca so raztopili v mešanici kislin HCl : HNO_3 : H_2O = 1 : 1 : 1).

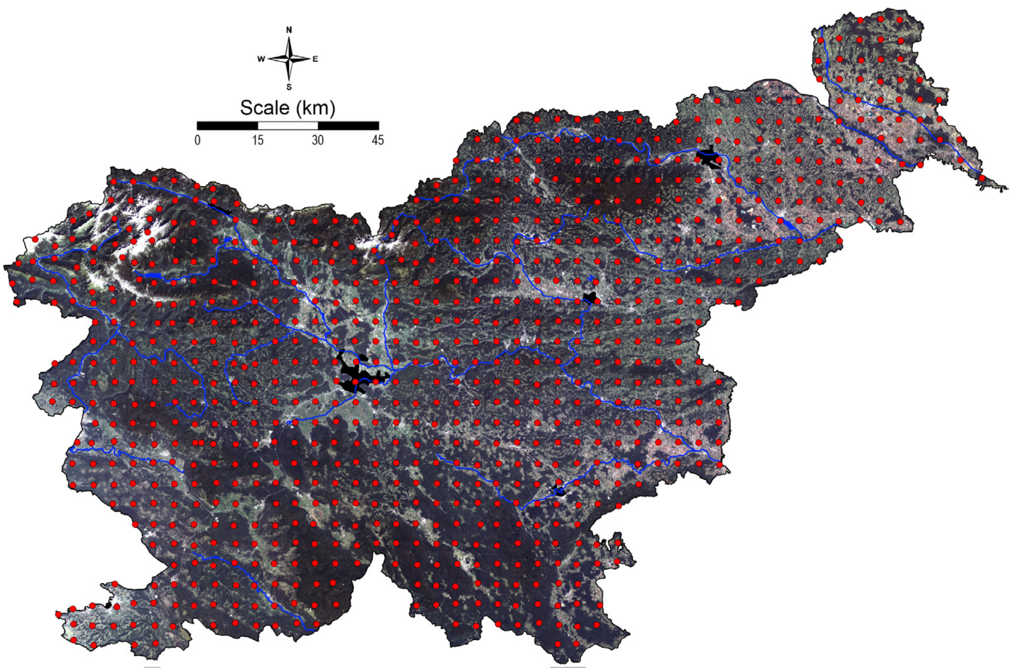

Fig. 3. Sampling locations.

Sl. 3. Prikaz vzorčnih lokacij.

(1 : 1 : 1 HCl : HNO_3 : H_2O). Concentrations of following 53 elements were determined: Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Ge, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Pd, Pt, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn, Zr.

Quality control

The quality control of analyses was assured by several methods. Aliquots of Certified Reference Materials (CRM: OREAS 43P, OREAS 44P, OREAS 45P, OREAS 45CA), and sample replicates were included randomly into the sample batches to estimate accuracy and precision of chemical analyses. Analysed concentration values of standards were compared to the certified values, as well as the repetitions of analyses of standard materials and soil samples. With this we determined the accuracy (A) and precision (P) of used analytical methods for analysed chemical elements (figs. 4 and 5). Table 1 shows the numbers

Določene so bile vsebnosti naslednjih 53 elementov: Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Ge, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Pd, Pt, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn, Zr.

Presoja kakovosti analitike

Kakovost analitike smo ocenili na podlagi rezultatov kemičnih analiz standardnih materialov (OREAS 43P, OREAS 44P, OREAS 45P, OREAS 45CA), katerih vsebnosti analiziranih elementov smo primerjali s priporočenimi vrednostmi, ter s ponovitvami analiz standardnih materialov in vzorcev tal. To je omogočilo oceno točnosti (A accuracy) in natančnosti (P precision) uporabljene analitske metode za analizirane kemične elemente (sl. 4 in 5). Naredili smo tudi pregled, v koliko vzorcih tal so vsebnosti obravnavanih kemičnih elementov pod mejo določljivosti (spodnja meja zaznavnosti) (tabela 1). Točnost (A accuracy) analitike ocenjujemo z relativno razliko med analit-

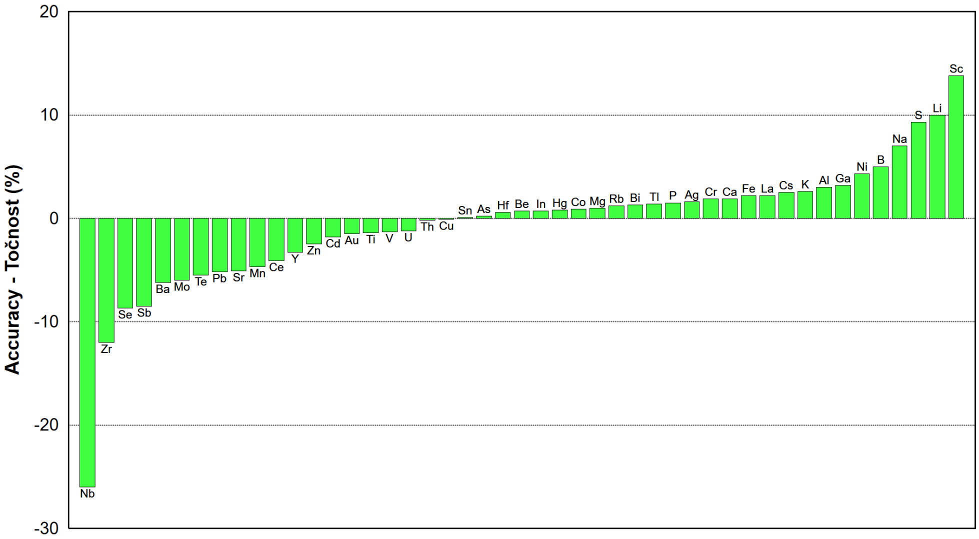

Fig. 4. Accuracy of analytical method.

Sl. 4. Točnost analitske metode.

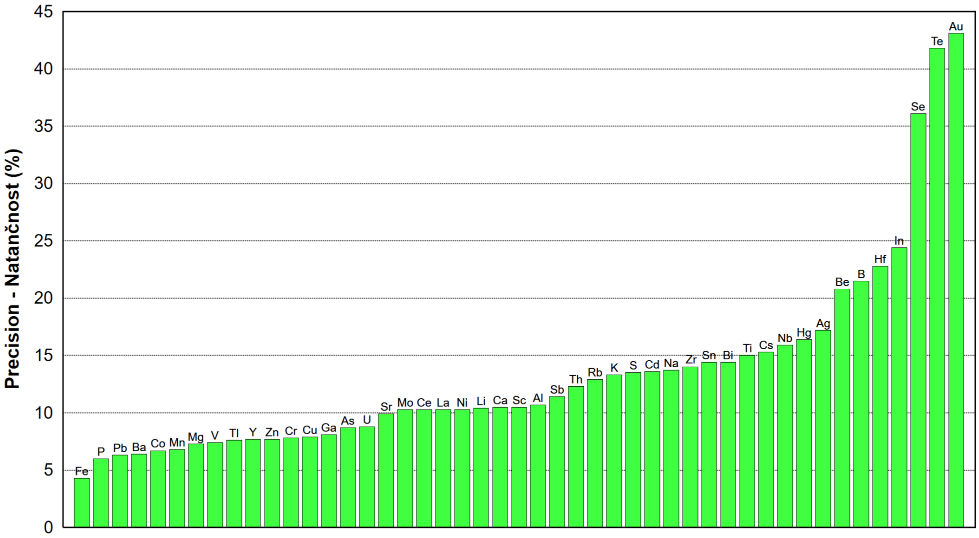

Fig. 5. Precision of analitical method.

Sl. 5. Natančnost analitske metode.

of soil samples having individual element concentrations below the lower detection limit. Accuracy (A) of analytics is evaluated as a relative difference between the analytical value of the element and its certified value. Analytical values of geological standard materials are compared with their certified values (Abbey, 1983; Reimann et al., 2009). Individual standards and their replicates were randomly distributed among the soil samples. Calculated relations between replicated values and their certified values are in fact the correction factor, by which analysed values could be divided in order to approach the certified values (Gosar, 2007).

Precision (P) of analytical methods is a measure of repeatability of determining a parameter in the same sample standard material, regardless of deviation from the certified value (Rose et al., 1979; Reimann et al., 2009).

Chemical elements Ge, Pd, Pt, Re, Ta and W were eliminated from further discussion, because their concentrations in more than 30 % of the samples were below detection limit of the analytical methods (table 1). For other chemical elements, sensitivity, accuracy (A) and precision (P) of analytical methods were satisfactory (table 1). They were included in further statistical processing.

Based on the findings described above, the following 47 chemical elements were discussed in statistical analyses: Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, Ti, Tl, U, V, Y, Zn, Zr.

Methods for determination of geochemical threshold values

In scientific literature can be found several methods for calculating the geochemical threshold which is needed for recognizing the unusually high element concentrations. We summarize a selection of the most commonly used methods.

The original and most simple approach to calculate the geochemical threshold is "Mean + 2 × standard deviations (SD)" (abr. **X2S**) of a given data set. The method was developed in exploration geochemistry to detect data outliers and to determine the threshold between geochemical background and unusually high element concentrations that can indicate areas of mineralization (Matschullat et al., 2000; Reimann & Garrett, 2005; Reimann et al., 2018). The approach has many shortcomings, among which the most important one is that the method does not consider the multimodal nature of geochemical data sets (Reimann & Filzmoser, 2000).

sko vrednostjo elementa v vzorcu in njeno priporočeno vrednostjo. Navadno primerjamo analitske vrednosti geoloških standardnih materialov z njihovimi priporočenimi vrednostmi (Abbey, 1983; Reimann et al., 2009). Posamezni standardi so bili pod laboratorijskimi številkami naključno porazdeljeni med ostale vzorce in večkrat analizirani. Izračunana razmerja med ponovitvami analiz in priporočenimi vrednostmi so pravzaprav popravni količnik, s katerim bi morali deliti analizirane vrednosti, da bi se bolje približali priporočenim vsebnostim v vzorcih (Gosar, 2007).

Natančnost (P *precision*) analitike predstavlja mero ponovljivosti določanja nekega parametra v istem vzorcu ali v standardnem materialu ne glede na odstopanje od priporočene vrednosti (Rose et al., 1979; Reimann et al., 2009).

Kemične elemente Ge, Pd, Pt, Re, Ta in W smo izločili iz nadaljnje obdelave, ker je bila njihova vsebnost v več kot 30 % vzorcev nižja od spodnje meje zaznavnosti analitike (tabela 1). Za ostale elemente smo ugotovili, da so občutljivost, točnost (A *accuracy*) in natančnost (P *precision*) analitike zadovoljivi (tabela 1), zato smo rezultate vključili v nadaljnjo statistično obdelavo.

Na podlagi zgoraj navedenih ugotovitev smo v nadaljnjih statističnih obdelavah obravnavali naslednjih 47 elementov: Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, Ti, Tl, U, V, Y, Zn, Zr.

Pregled metod za opredelitev zgornje meje naravne variabilnosti

V znanstveni literaturi najdemo več metod za določanje geokemičnih zgornjih mej naravne variabilnosti za določitev anomalno visokih vsebnosti elementov. V nadaljevanju povzemamo izbor najpogosteje uporabljenih metod.

Prvi in najpreprostejši pristop, pri katerem izračunamo zgornjo mejo naravne variabilnosti, temelji na izračunu "aritmetična sredina + 2 × standardni odklon (SD)" (okrajšano: **X2S**) za dane podatke. S tem izračunom so v preteklih geokemičnih raziskavah za iskanje mineralnih surovin računali vsebnost za definiranje meje med vsebnostmi, ki sodijo v geokemično ozadje in anomalno visokimi vsebnostmi, ki lahko nakazujejo območja mineralizacije (Matschullat et al., 2000; Reimann & Garrett, 2005; Reimann et al., 2018). Ta metoda ima več pomanjkljivosti, med katerimi je najpomembnejša neupoštevanje večmodalne narave geokemičnih podatkov (Reimann & Filzmoser, 2000).

Geokemični podatki so prostorsko variabilni, na njihove vrednosti vplivajo številni dejavniki

Table 1. Quality control of analytical method.
Tabela 1. Ocena kakovosti analitske metode.

	Unit	DL	UL	N(DL)	A (%)	P (%)
Ag	µg/kg	2	100000	817	1.6	17.2
Al	%	0.01	10	817	3.0	10.7
As	mg/kg	0.1	10000	817	0.2	8.7
Au	mg/kg	0.2	100000	797	–1.5	43.1
B	mg/kg	1	2000	631	5.0	21.5
Ba	mg/kg	0.5	10000	817	–6.2	6.4
Be	mg/kg	0.1	1000	814	0.7	20.8
Bi	mg/kg	0.02	2000	817	1.3	14.4
Ca	%	0.01	40	813	1.9	10.5
Cd	mg/kg	0.01	2000	813	–1.8	13.6
Ce	mg/kg	0.1	2000	817	–4.1	10.3
Co	mg/kg	0.1	2000	817	0.9	6.7
Cr	mg/kg	0.5	10000	817	1.9	7.8
Cs	mg/kg	0.02	2000	817	2.5	14.3
Cu	mg/kg	0.01	10000	817	–0.1	7.9
Fe	%	0.01	40	817	2.2	4.3
Ga	mg/kg	0.1	1000	817	3.2	8.1
Ge	mg/kg	0.1	100	**31**	–13.9	1.0
Hf	mg/kg	0.02	1000	658	0.6	22.8
Hg	mg/kg	0.005	50	817	0.8	16.4
In	mg/kg	0.02	1000	709	0.7	24.4
K	%	0.01	10	816	2.6	13.3
La	mg/kg	0.5	10000	817	2.2	10.3
Li	mg/kg	0.1	2000	817	10.0	10.4
Mg	%	0.01	30	817	1.0	7.3
Mn	mg/kg	1	10000	817	–4.7	6.8
Mo	mg/kg	0.01	2000	817	–6.0	10.3
Na	%	0.001	5	806	7.0	13.7
Nb	mg/kg	0.02	2000	816	–26.0	14.9
Ni	mg/kg	0.1	10000	817	4.3	10.3
P	%	0.001	5	817	1.5	6.0
Pb	mg/kg	0.01	10000	817	–5.2	6.3
Pd	µg/kg	10	100000	**10**	14.6	–
Pt	µg/kg	2	100000	**47**	3.2	6.0
Rb	mg/kg	0.1	2000	817	1.2	12.9
Re	µg/kg	1	100	**255**	1.6	18.9
S	%	0.02	5	668	9.3	13.5
Sb	mg/kg	0.02	2000	817	–8.5	11.4
Sc	mg/kg	0.1	100	817	13.8	10.5
Se	mg/kg	0.1	100	778	–8.7	36.1
Sn	mg/kg	0.1	100	817	0.1	14.4
Sr	mg/kg	0.5	10000	817	–5.1	9.9
Ta	mg/kg	0.05	2000	**0**	–	–
Te	mg/kg	0.02	1000	607	–5.5	41.8
Th	mg/kg	0.1	2000	816	–0.2	12.3
Ti	%	0.001	5	782	–1.4	15.0
Tl	mg/kg	0.02	1000	817	1.4	7.6
U	mg/kg	0.05	2000	817	–1.2	8.8
V	mg/kg	2	10000	817	–1.3	7.4
W	mg/kg	0.05	100	**335**	–38.6	10.5
Y	mg/kg	0.01	2000	817	–3.3	7.7
Zn	mg/kg	0.1	10000	817	–2.5	7.7
Zr	mg/kg	0.1	2000	800	–12.0	14.0

DL – spodnja meja detekcije analiz/lower detection limit; UL – zgornja meja detekcije analiz/upper detection limit; N(DL) – število vzorcev nad DL/number of values above DL; A (%) – točnost/accuracy; P (%) – natančnost/precision

Geochemical data have a high spatial variability, are influenced by many factors and are often imprecise due to unavoidable sampling errors, sample preparation and analytical errors. Due to these properties of geochemical data, Reimann et al. (2005) suggested to replace the earlier **X2S** approach by using "Median + 2 × median absolute deviations (abr. MAD)" (abr. **MD2MAD**), where the median is defined for a sample x_1, … …, x_n as $median_j(x_j)$. $Median_i(x_i)$ is then defined for a new data set, that is determined from absolute values obtained by subtracting the $median_j(x_j)$ from each original value in the sample. MAD is therefore determined as:

$$MAD_i(x_i) = 1.48 \times median_i|x_i - median_j(x_j)|$$

In case of normal data distribution, a constant 1.48 is added to MAD definition for approximation to standard deviation (SD) (Rousseeuw & Croux, 1993; Reimann et al., 2018). The approach **MD2MAD** is much more efficient in exposing the anomalously high element concentrations, while the approach **X2S** only determines extreme values that are not necessarily the anomalous high values. The disadvantage of the **MD2MAD** method, if applied to raw, untransformed data, is that it delivers very conservative (low) threshold values (quite often around the 90^{th} percentile), i.e., it produces a lot of sites that need to be checked (Reimann et al., 2018). The reason is that geochemical data distributions are most often strongly right-skewed, while, when using the above formula, the underlying assumption is of a symmetrical (not necessarily normal) data distribution. The correct approach to using this formula would thus be to calculate "Median + 2 × MAD" (**MD2MAD**) on the log-transformed data (e.g., using log base 10) and then to back-transform the result and use these values as threshold according to the formula (Reimann et al., 2018). Geochemical threshold is therefore determined according to formula:

Threshold (after MD2MAD approach) = $\mathbf{10^b}$

where

$$\mathbf{b} = (median_i\ (\log_{10}(x_i)) + 2 \times MAD_j\ (\log_{10}(x_j))$$

Values calculated using this approach are often comparable with the **TIF** (Tukey inner (upper) fence or upper whisker in a boxplot) method (Reimann et al., 2018). This method is based on the boxplot, an exploratory data analysis tool that depends solely on the symmetry of data dis-

in so pogosto nenatančni zaradi neizogibnih napak pri vzorčenju, pripravi vzorcev in analizah. Reimann in sodelavci (2005) so glede na naštete lastnosti geokemičnih podatkov predlagali zamenjavo prej omenjenega pristopa z izračunom "mediana + 2 × mediana absolutnih standardnih odklonov od mediane (okrajšano MAD)" (okrajšano: **MD2MAD**), kjer je mediana definirana za podatke x_1, … …, x_n kot $mediana_j(x_j)$. Nato se določi $mediana_i(x_i)$ iz novega seta podatkov, ki se ga določi kot absolutna vrednost razlike med posamezno vrednostjo novega vzorca in $mediane_j(x_j)$. MAD je tako definiran kot:

$$MAD_i(x_i) = 1{,}48 \times mediana_i|x_i - mediana_j(x_j)|$$

V primeru normalne porazdelitve podatkov je definicija MAD s konstanto 1,48 približek osnovnemu standardnemu odklonu (SD) (Rousseeuw & Croux, 1993; Reimann et al., 2018). Ta metoda veliko bolje izpostavi anomalno visoke vsebnosti. Metoda **X2S** ugotovi predvsem samo ekstremne vrednosti, ki ne predstavljajo vedno tudi anomalno visokih vsebnosti. Pomanjkljivost metode **MD-2MAD** je, da je ne smemo uporabiti na surovih, netransformiranih podatkih (Reimann et al., 2018). Pogoj za uporabo je namreč simetrična (in zlasti normalna) porazdeljenost podatkov. Če jo uporabimo za netransformirane podatke, dobimo kot rezultat zelo konzervativne (nizke) vrednosti zgornjih mej naravne variabilnosti, pogosto okoli 90. percentila. To je posledica desne asimetričnosti porazdelitve geokemičnih podatkov, ki je v geoloških materialih zelo pogosta. Obrazec za izračun predpostavlja osnovno simetrično (ne nujno normalno) porazdelitev podatkov. Zato je pravilen pristop k uporabi te metode izračun "mediana + 2 × MAD" (**MD2MAD**) s transformiranimi podatki (npr. z uporabo logaritemske transformacije) ter ponovno re-transformacijo rezultata izračuna (Reimann et al., 2018). V zadnjem primeru torej mejno vrednost za anomalno visoke vsebnosti z logaritemsko transformacijo izračunamo po obrazcu:

Zgornja meja naravne variacije
(po metodi MD2MAD) = $\mathbf{10^b}$

kjer je

$$\mathbf{b} = (mediana_i\ (\log_{10}(x_i)) + 2 \times MAD_j\ (\log_{10}(x_j))$$

Vrednosti, ki jih pridobimo s tem pristopom, so pogosto primerljive z metodo **TIF** (Tukeyeva notranja meja; ang. Tukey Inner Fence) (Reitribution. It allows the definition of a threshold for outliers even if none are present in the data set (i.e., Max < TIF), as it extrapolates from the robust inner core (25^{th} to 75^{th} percentiles) of the data structure. TIF is calculated as follows:

TIF = Q3 + 1.5 × IQR

Where Q3 stands for the 3^{rd} quartile (equivalent to the 75^{th} percentile), and IQR is the interquartile range (75^{th} – 25^{th} percentile). The multiplying factor of 1.5 in the formula is based on the assumption of a symmetrical data distribution. All values higher than TIF are therefore labeled as anomalously high values. With this approach TIF also presents a geochemical threshold value (Reimann et al., 2005). When dealing with geochemical data, which are most often right-skewed, **TIF** must be calculated on the log- (or otherwise) transformed data to achieve "symmetry". The TIF can be considered as one of the most reliable tools to calculate meaningful threshold values for any given data set (Reimann & Caritat, 2017; Reimann et al., 2018).

Reimann et al. (2005) compared methods discussed above by using normal distribution and log-normal distribution data sets. The results showed that the boxplot gives the best results when samples with anomalously high concentrations are **less than 10 %.** In case when samples with anomalously high concentrations **exceed 15 %** or even more than half of all data, only "Median + 2 × MAD" (**MD2MAD**) gives useful results (Reimann et al., 2005). Approach "Mean + 2 × standard deviation" (**X2S**) exposes only extreme values. It is only meaningful when all samples with anomalously high concentrations also represent extreme values.

Another approach, which again stems from exploration geochemistry, is to study data distributions in a cumulative probability (CP) diagram (Reimann et al., 2018). A CP diagram shows statistical distributions of data and can detect processes that cause deviation from general data distribution (Reimann et al., 2005; Reimann et al., 2018). It allows detection of samples with anomalously high element concentrations and their distance from other data. Values above threshold are most often detected as a break of the distribution in the cumulative probability diagrams.

Geochemical threshold can also be determined by using the percentile-based approach (Reimann et al., 2018). It is a simplistic method with the 90^{th}, 95^{th}, 97.5^{th} or 98^{th} percentile of a given data set defining the threshold (abr. **P90, P95, P97.5** and

mann et al., 2018). Ta metoda temelji na diagramu škatla z brki, ki omogoča določanje zgornjih mej naravne variabilnosti, tudi če med podatki ni vzorcev z anomalno visokimi vsebnostmi (torej je max < TIF). Izračuna se po sledečem obrazcu z ekstrapolacijo iz medkvartilnega razpona (25. do 75. percentil) vseh podatkov, kar predstavlja centralno "škatlo":

TIF = Q3 + 1,5 × IQR

Q3 je 3. kvartil (ekvivalent 75. percentilu) in IQR (Interquartile range) predstavlja medkvartilni razpon (75.–25. percentil). Faktor množenja 1,5 v formuli temelji na domnevi o simetrični porazdelitvi podatkov. Vse vrednosti, ki so večje od tako postavljene meje, so anomalno visoke vsebnosti. S tem pristopom TIF predstavlja mejo naravne variabilnosti (Reimann et al., 2005). Tudi **TIF** mora biti v primeru desno asimetričnih geokemičnih podatkov izračunan preko log- (ali drugače) transformiranih podatkov, da se ti približajo "simetričnosti". TIF je ena najbolj zanesljivih metod za izračun meje naravne variabilnosti za kakršnekoli podatke (Reimann & Caritat, 2017; Reimann et al., 2018).

Reimann s sodelavci (2005) je primerjal navedene metode v primeru normalne porazdelitve in logaritemsko normalne porazdelitve. Rezultati so pokazali, da diagram škatla z brki poda najboljše rezultate v primeru, da je vzorcev z anomalno visokimi vsebnostmi **manj kot 10 %**. V primeru, da je vzorcev z anomalno visokimi vsebnostmi **več kot 15 %** ali celo več kot polovica vseh podatkov, da uporabne rezultate le metoda "mediana + 2 × MAD" (**MD2MAD**) (Reimann et al., 2005). Metoda "aritmetična sredina + 2 × standardni odklon (**X2S**)" izpostavi le ekstremne vrednosti. Smiselna je le v primeru, ko vsi vzorci z anomalno visokimi vsebnostmi predstavljajo hkrati tudi ekstreme.

Za določitev vzorcev z anomalno visokimi vsebnostmi se uporablja tudi grafični prikaz porazdelitve podatkov v diagramu kumulativne verjetnosti (CP) (Reimann et al., 2018). Diagram prikazuje statistične porazdelitve podatkov, iz katerih je mogoče zaznati procese, ki povzročajo odstopanje od splošne porazdelitve podatkov (Reimann et al., 2005; Reimann et al., 2018). Omogoča določitev vzorcev z anomalno visokimi vsebnostmi ter njihovo oddaljenost od ostalih podatkov. Vrednosti nad zgornjo mejo naravne variacije se najpogosteje zazna kot prelom v porazdelitveni krivulji podatkov na teh diagramih.

P98, see also Ander et al., 2013). The 98th percentile, which identifies 2 % of all samples as upper outliers, comes closest to the original method of calculating the "mean + 2 SD" in the case of a normal distribution, which would result in 2.3 % of upper outliers. A common feature of all these statistical methods is that it will not necessarily be possible to establish a meaningful single threshold valid for the whole country, because the background varies spatially. Furthermore, there exists no valid scientific reason why 2, 5 or 10 % of the samples should be considered as "anomalous" regardless of the statistical data distribution. It will only determine the highest values in a data set that may also be anomalous. Though the method is very practical due to its simplicity and as there is no need for normal data distribution and with it, for transformations.

Zgornjo mejo naravne variabilnosti lahko določimo tudi z uporabo pristopa, ki temelji na percentilih (Reimann et al., 2018). Mejo lahko postavimo pri 90., 95., 97,5. ali 98. percentilu danih podatkov (okrajšano: **P90, P95, P97.5** ter **P98**, glej tudi Ander et al., 2013). Osemindevetdeseti percentil, ki predstavlja 2 % najvišjih vrednosti, je najbližje izvirni metodi računanja **X2S** v primeru normalne porazdelitve, ki bi v tem primeru določila 2,3 % vrednosti nad zgornjo mejo naravne variabilnosti. S tem pristopom se lahko odkrije nesmiselno visoke mejne vrednosti naravne variabilnosti na zelo velikih območjih, saj ne upoštevajo vpliva ozadja, ki se prostorsko spreminja. Prav tako ne obstaja znanstveni razlog, zakaj bi moralo biti 2, 5 ali 10 % vzorcev določenih za "anomalne". S temi metodami se najenostavneje določi le najvišje vrednosti podatkov, ki so seveda lahko tudi anomalne. Meto-

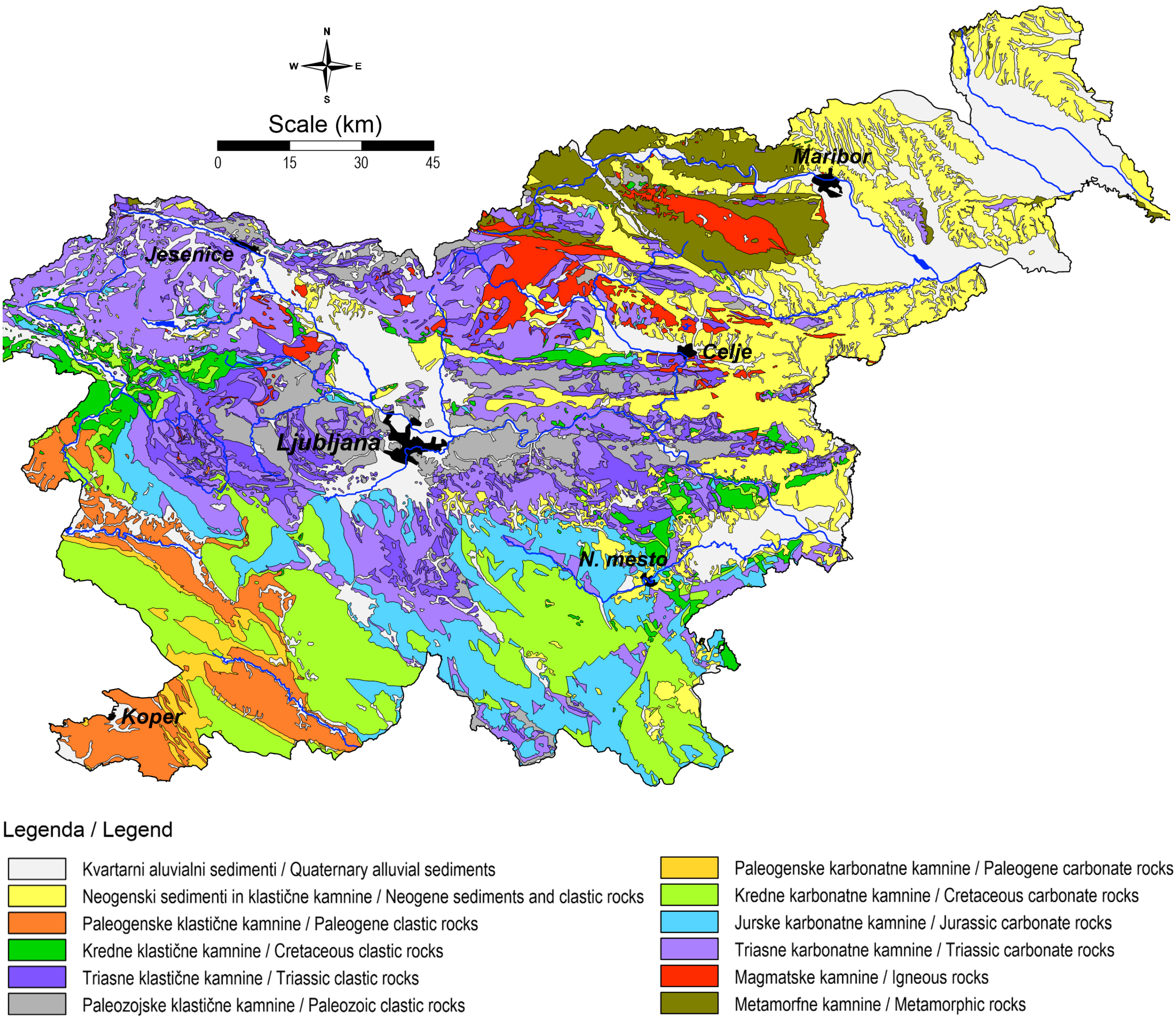

Fig. 6. Basic lithological units (after data from Bavec et al. (2016) and Novak et al. (2016)).
Sl. 6. Osnovne litološke enote (po podatkih iz Bavec et al. (2016) in Novak et al. (2016)).

In Great Britain, cumulative probability diagrams and percentiles (most frequently the 95th percentile) have been used to detect samples deviating from the "normal background deviation" and to identify a case-specific threshold (e.g. Cave et al., 2012; Johnson et al., 2012; Ander et al., 2013).

Geological and pedological settings and smaller spatial units in Slovenia

Geological diversity of Slovenia is a result of a contact between 3 larger geotectonic units in Slovenia. Most of Slovenia is composed of clastic rocks and sediments that comprise around half of Slovenian area and carbonates (limestone and dolomites), that comprise around 40 % of the area. Metamorphic rocks cover around 4 % of the area, pyroclastic rocks are less than 2 % and around 1.5 % of Slovenian area is comprised of igneous rocks (Komac, 2005, fig. 6). There are many soil types in Slovenia, as soil forming factors (lithology, relief, climate, hy-

da je vsekakor zelo praktična, ker je enostavna in ni potrebno, da so podatki normalno porazdeljeni. Zato podatkov tudi ni potrebno transformirati.

V Veliki Britaniji pogosto uporabljajo diagrame kumulativne verjetnosti in percentile (najpogosteje 95. percentil – **P95**) za ugotavljanje vzorcev, ki odstopajo od "normalne variacije v definiranem ozadju" in za določitev geokemičnega praga (zgornjih mej naravne variabilnosti) na določenem območju (npr. Cave et al., 2012; Johnson et al., 2012; Ander et al., 2013).

Geološke in pedološke značilnosti Slovenije in razmejitev na manjše prostorske enote

Slovenija leži na ozemlju stika 3 velikih geotektonskih enot in je zato geološko zelo pestra. Velik del Slovenije sestavljajo klastične kamnine in sedimenti, ki obsegajo približno polovico površine ozemlja Slovenije ter karbonati (apnenci in dolomiti), ki jih je okoli 40 %. Metamorfne kamnine obsegajo približno 4 % površine slovenskega ozemlja, piroklastičnih kamnin je manj kot 2 %, najmanj

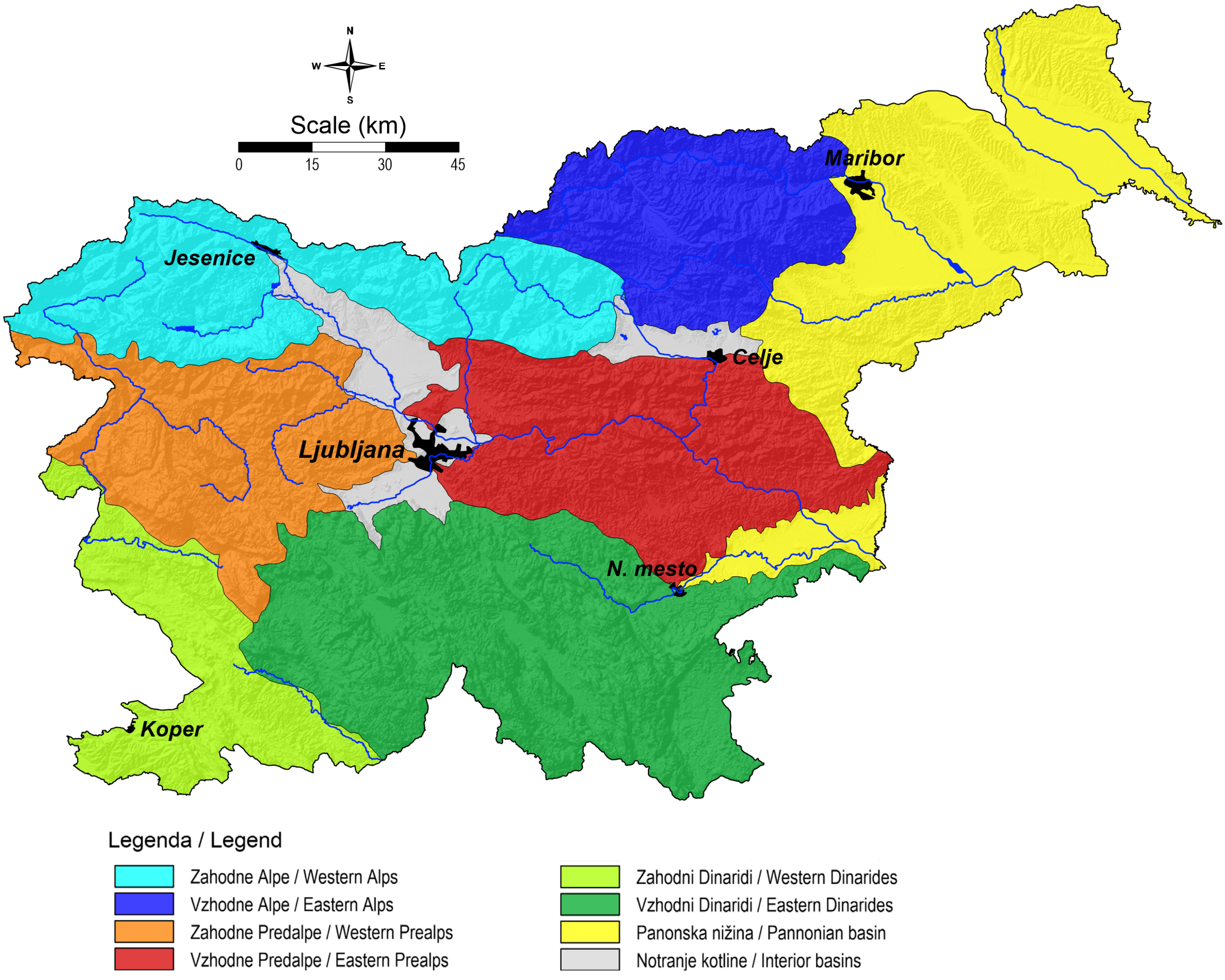

Fig. 7. Smaller spatial units in Slovenija (addapted after Poljak, 1987).
Sl. 7. Prikaz opisanih prostorskih enot v Sloveniji (prirejeno po Poljaku, 1987).

drology, vegetation, organisms and human influence) have a large spatial variability (Vidic et al., 2015). In Slovenia, lithology and relief have the greatest impact on soil formation (Vidic et al., 2015). Most of Slovenia is comprised of carbonate rocks, (including sediments and clastic rocks with carbonate clasts or cement) and soils that forms on these rocks. Lithosols and shallow rendzinas are present on steep slopes in mountain terrains. In areas with gentle slopes, brown soils on limestone and dolomite and rendzinas are present (Vidic et al., 2015). On carbonate flysch in western Slovenia and marlstones in eastern Slovenia are rendzinas and eutric brown soils. Rendzinas are also common on other clastic carbonate sediments as gravel and sand in river valleys (Vidic et al., 2015). Dystric rankers, dystric brown soils and leached soils are present on other noncarbonate clastic rocks and most of metamorphic and igneous rocks. On noncarbonate sediments in valleys of eastern Slovenia (Drava and Ptuj plains, Prekmurje), dystric soils are formed (Vidic et al., 2015).

Next, we present the spatial distribution of Slovenia, that is based on geological structure, lithology, relief, climate and vegetation acocording to suggestions from Poljak (1987). Slovenia was divided into 8 smaller spatial units (Western Alps, Eastern Alps, Western Prealps, Eastern Prealps. Western Dinarides, Eastern Dinarides, Pannonian basin and Interior basins, fig. 7), that we discuss later. Naming of spatial units is valid only for Slovenia and is not related to other units' names in Europe or in the entire Alps. Geological settings are summarized after Geology of Slovenia (Pleničar et al., 2009) and pedological settings after monograph Soils of Slovenia with soil map 1 : 250,000 (Vidic et al., 2015).

(1,5 %) pa je magmatskih kamnin (Komac, 2005, sl. 6). Ker so v Sloveniji tlotvorni dejavniki, torej matična osnova, relief, klima, vodne razmere, rastlinske združbe, dejavnost organizmov in aktivnosti človeka, močno spremenljivi in se pojavljajo v različnih kombinacijah, je tudi talna odeja zelo pestra (Vidic et al., 2015). Največji vpliv na nastajanje tal, in s tem tudi na pestrost talnih tipov v Sloveniji, imata matična podlaga in relief (Vidic et al., 2015). Za Slovenijo je najbolj značilna karbonatna podlaga (karbonatne kamnine ter sedimenti in sedimentne kamnine, ki vsebujejo karbonatna zrna ali vezivo) ter tla, ki se tam razvijajo. V visokogorskih območjih in na strmih pobočjih najdemo litosole in plitve rendzine. V nižjih predelih in na manj strmih pobočjih pa nastopajo skupaj z rendzinami tudi rjava pokarbonatna tla (Vidic et al., 2015). Na karbonatnem flišu zahodne Slovenije in laporovcih vzhodne Slovenije prevladujejo rendzine in evtrična rjava tla. Rendzine se pojavljajo tudi na drugih klastičnih karbonatnih sedimentih, kot so prodi in peski v nekaterih rečnih dolinah (Vidic et al., 2015). Na drugih nekarbonatnih klastičnih kamninah, na večini metamorfnih in magmatskih kamnin so distrični rankerji, distrična rjava tla in rjava izprana tla. V nižinah vzhodne Slovenije (Dravsko, Ptujsko polje, Prekmurje) so na nekarbonatnih sedimentih razvita distrična tla (Vidic et al., 2015).

V nadaljevanju povzemamo prostorsko razdelitev Slovenije, ki smo jo izvedli na podlagi geološke zgradbe, kamninske sestave (litologije), reliefa, podnebja in rastlinstva skladno s predlogi Poljaka (1987). Slovenijo smo razdelili na 8 manjših prostorskih enot (Zahodne Alpe, Vzhodne Alpe, Zahodne Predalpe, Vzhodne Predalpe, Zahodni Dinaridi, Vzhodni Dinaridi, Panonska nižina, Notranje kotline, sl. 7), katerih značilnosti podajamo v nadaljevanju. Prostorske enote smo določili in poimenovali samo za Slovenijo in poimenovanje nima enakega pomena kot v Evropi in celotnih Alpah. Geološke značilnosti so povzete iz monografi-

Table 2. Smaller spatial units in Slovenia and number of samples for each unit (N).
Tabela 2. Prostorske enote v Sloveniji in število pripadajočih vzorcev tal (N).

Prostorske enote – Spatial units	**N**
Zahodne Alpe (Western Alps)	99
Vzhodne Alpe (Eastern Alps)	80
Zahodne Predalpe (Western Prealps)	98
Vzhodne Predalpe (Eastern Prealps)	116
Zahodni Dinaridi (Western Dinarides)	66
Vzhodni Dinaridi (Eastern Dinarides)	163
Panonska nižina (Pannonian basin)	157
Notranje kotline (Interior basins)	38

Samples were collected at a grid of 5 × 5 km and assigned to spatial units according to their spatial distribution in Slovenia. Number of samples (N) in each spatial unit is presented in table 2.

Western Alps

Western Alps cover the area of the Julian Alps, Kamnik Savinja Alps and Karavanke Alps (Karawanks) in which are the highest peaks of Slovenia. Most of this spatial unit comprises area above the tree line, which is reflected in almost no vegetation and shallow (rendzinas) or undeveloped soils. Julian and Kamnik Savinja Alps are predominantly composed of carbonate rocks. The area developed from glacial processes and is influenced by dissolution of limestone in karstic areas. Due to lithology and dissolution of limestone, this area is also called "high or Alpine karst". The Karavanke Alps are a long mountain range along Austrian border which ends near Mežica in the east. Their lithology is diverse, with carbonate rocks, which predominate, clastic and igneous rocks.

The Julian Alps are mostly composed of limestone and dolomite (Dozet & Buser, 2009). Limestone with chert, clay marlstone and limestone with manganese nodules are also present (Buser & Dozet, 2009). Larger areas containing iron ore are in the vicinity of Pokljuka, Bohinj and Jelovica (Ogorelec et al., 2006; Pirc & Herlec, 2009). There are smaller areas of Cretaceous flysch marlstone, located in southern part of the Julian Alps (Pleničar, 2009).

The Kamnik Savinja Alps consist of mostly carbonate rocks and less clastic rocks (Dozet and Buser, 2009). Carbonate conglomerates that transit to marly clay called "sivica" are present on larger area of Smrekovec and Gornji Grad. There are Oligocene volcaniclastic rocks on Smrekovec area and other smaller areas in the Kamnik Savinja Alps (Pavšič & Horvat, 2009).

Carbonate rocks (limestones and dolomites) predominate in the Karavanke Alps. Clastic rocks are also common. Iron, lead, zinc, and antimony ores often occur at the contact of clastic rocks and carbonate rocks (Ramovš & Buser, 2009; Novak & Skaberne, 2009). Igneous rocks, limestone with chert and shales are also present in the Karavanke Alps. Also found in the Karavanke Alps are traces of manganese ore, that was mined in this area.

je Geologija Slovenije (Pleničar et al., 2009), pedološke pa po monografiji Tla Slovenije s pedološko karto v merilu 1 : 250 000 (Vidic et al., 2015).

Vzorčna mesta tal, ki so bila vzorčena v mreži 5 × 5 km, smo v skladu s prikazano prostorsko porazdelitvijo Slovenije, pripisali posameznim prostorskim enotam. V tabeli 2 je navedeno število vzorcev tal (N), odvzetih v posamezni prostorski enoti.

Zahodne Alpe

Zahodne Alpe obsegajo Julijske Alpe, Kamniško Savinjske Alpe in Karavanke, ki reliefno predstavljajo najvišje vrhove v Sloveniji. Večji del te prostorske enote obsega območja nad gozdno mejo, torej je vegetacija skromna, tla so večinoma plitva (rendzine) ali nerazvita. Območje Julijskih in Kamniško Savinjskih Alp je zgrajeno pretežno iz karbonatnih kamnin. To območje se je oblikovalo z ledeniškim delovanjem in je podvrženo recentni kraški eroziji. Zaradi litološke sestave in kraške erozije se območje Alp imenuje tudi "visoki ali alpski kras". Karavanke predstavlja dolg gorski greben, ki se vleče v ozkem pasu ob avstrijski meji do Mežice na vzhodu. Litološka sestava je pestra. Prevladujejo čiste karbonatne kamnine. Najdemo pa tudi raznovrstne klastične in magmatske kamnine.

Julijske Alpe so v večini sestavljene iz apnencev in dolomitov (Dozet & Buser, 2009). Mestoma najdemo apnence z roženci, glinene laporovce ter apnence z manganovimi gomolji (Buser & Dozet, 2009). V okolici Pokljuke – Bohinja ter Jelovice so pomembnejša orudenja železa (Ogorelec et al., 2006; Pirc & Herlec, 2009). V južnem delu Julijskih Alp so manjša območja krednega flišnega laporovca (Pleničar, 2009).

Kamniško Savinjske Alpe sestavljajo večinoma karbonatne kamnine, mestoma izdanjajo tudi klastiti (Dozet & Buser, 2009). Na širšem območju Smrekovca in Gornjega Grada ležijo karbonatni konglomerati, ki prehajajo v laporasto glino ali sivico. Na območju Smrekovca ter v manjših območjih znotraj Kamniško Savinjskih Alp najdemo oligocenske vulkanoklastične kamnine (Pavšič & Horvat, 2009).

V Karavankah prevladujejo karbonatne kamnine (apnenci in dolomiti) različnih starosti. Pogoste so tudi klastične kamnine, kjer se mestoma na njihovem stiku z apnencem pojavljajo orudenja železa, svinca, cinka in antimona (Ramovš & Buser, 2009; Novak & Skaberne, 2009). V Karavankah se mestoma pojavljajo magmatske kamnine. Ponekod najdemo apnence z roženci, skrilave glinavce in sledove manganove rude, ki so jo v preteklosti kratek čas tudi izkoriščali.

Rendzinas (profile A-C or A-R) predominates on carbonate rocks at higher altitudes and steep slopes. Rarely, brown soils (A-B-C) have formed. Dystric brown soils have formed on clastic and volcaniclastic rocks (Vidic et al., 2015).

Eastern Alps

Eastern Alps cover the area of Pohorje, a large massif that is distinctly separated from other areas.

This area is predominantly composed of igneous and metamorphic rocks. Weathering of these rocks causes forming of dystric brown soils and rankers on steeper slopes (Vidic et al., 2015). Pohorje is covered with dense vegetation with conifers, mixed forests and meadows due to fertile soils, wet climate and impermeable lithology.

Central part of the Pohorje range is composed of granodiorite batholith, that is surrounded with metamorphic rocks, of which most special are eclogite and garnet peridotite. In northern part of Pohorje there are mostly mica schists, gneisses, amphibolite and less eclogite and marble. Amphibolite that includes chlorite and epidote is found in southwestern part of Pohorje (Hinterlechner-Ravnik & Trajanova, 2009).

Phyllitic schists with quartzite, metakeratophyre, marble, graphitic slates and amphibole schists with chlorite and epidote represent the transit from lower grade metamorphic rocks to higher metamorphic grade, found west of Kobansko. Mineral garnet is more common (Hinterlechner-Ravnik & Trajanova, 2009). Miocene conglomerate with dacite tuff is present in the Ribnica-Selnica tectonic graben and on Mt. Kozjak (Pavšič & Horvat, 2009).

Quartz sandstones, conglomerates and siltstones compose western part of Eastern Alps. Dolomites, limestones, marlstones and claystone are present in smaller areas (Dozet & Buser, 2009; Buser & Dozet, 2009). In the area around Stranice and Zreče are dolomites with layers of black coal, claystone, siltstones and marlstones. In Velenje valley predominate Plio-Quaternary clastic rocks and sediments that include carbonates and pyroclastic rocks with andesite and dacite. Here are layers of lignite between clastic rocks (Markič, 2009).

Igneous rocks of Pohorje are divided into two groups: Magdalensberg series and Železna Kapla magmatic zone. Magdalensberg series passes along river Meža, via Slovenj Gradec to northwestern Pohorje and area of Remšnik. Central part of the series is composed of felsic igneous

Na karbonatnih kamninah v višjih legah z nekoliko strmejšim reliefom je prevladujoči talni tip rendzina (profil A-C ali A-R), ki le mestoma prehaja v rjava pokarbonatna tla (A-B-C). Na klastičnih in vulkanoklastičnih kamninah so distrična rjava tla (Vidic et al., 2015).

Vzhodne Alpe

Vzhodne Alpe obsegajo Pohorje, velik masiv, ki se ostro loči od sosednjih ozemelj.

Gradijo ga pretežno magmatske in metamorfne kamnine, iz katerih pri preperevanju nastajajo na strmejših delih rankerji, bolj pogosto pa distrična rjava tla (Vidic et al., 2015). Večinoma so to rodovitna tla, ki omogočajo ob obilju padavin in nepropustni geološki podlagi gost vegetacijski pokrov iglavcev, mešanega gozda in travnikov.

Na osrednjem delu grebena Pohorja je granodioritni batolit, ki ga obdajajo metamorfne kamnine. Posebnosti sta eklogit in granatov peridotit. Na severnem delu Pohorja najdemo predvsem blestnik, gnajs in amfibolit, manj je eklogita in marmorja. Amfibolit je tudi na jugozahodnem delu Pohorja, ki tu vključuje klorit in epidot (Hinterlechner-Ravnik & Trajanova, 2009).

Zahodno od Kobanskega so razvite manj metamorfozirane kamnine, ki prehajajo v močneje metamorfozirane kamnine, ki jih predstavljajo filitni skrilavci s kvarcitom, metakeratofir, marmor in grafitni skrilavec ter amfibolovi skrilavci s kloritom in epidotom. Na nekaterih območjih je zelo pogost mineral granat (Hinterlechner-Ravnik & Trajanova, 2009). Na Kozjaku ter v Ribniško-selniškem tektonskem jarku so miocenski konglomerati, ki vsebujejo tudi dacitne tufe (Pavšič & Horvat, 2009).

Na zahodnem območju Vzhodnih Alp so kremenovi peščenjaki, konglomerati in meljevci. Mestoma se pojavljajo dolomiti, apnenci, laporovci in glinavci (Dozet & Buser, 2009; Buser & Dozet, 2009). V okolici Stranic in Zreč so dolomiti s plastmi črnega premoga ter glinavci, meljevci in laporovci. V Velenjski kotlini je veliko pliokvartarnih klastitov, ki izvirajo iz podlage in jih zastopajo karbonati ter piroklastične kamnine z andezitom in dacitom, med njimi pa je prisoten lignit (Markič, 2009).

Magmatske kamnine na Pohorju izdanjajo na območju štalenskogorske serije in železnokapelske magmatske cone. Štalenskogorska serija poteka vzdolž reke Meže preko Slovenj Gradca na severozahodno Pohorje ter na območje Remšnika. Kisle magmatske kamnine sestavljajo osrednji del serije, na severnem delu serije pa so bazične magmatske kamnine (Trajanova, 2009). Železnorocks and northern part of the series is composed of mafic igneous rocks (Trajanova, 2009). Železna Kapla magmatic zone is exposed along Periadriatic lineament, passes south of Peca, via Koprivna and Črna na Koroškem and plunges beneath the sediments in the vicinity of Mt. Plešivec. Magmatic zone is mostly composed of felsic igneous rocks. Northern part of the magmatic zone is composed of syenogranitic massif and in southern part is a tonalite belt. Syenogranitic massif includes gabbro, monzogabbro, monzodiorite and monzonite (Dobnikar & Zupančič, 2009; Trajanova et al., 2009). Tonalitic belt is composed mostly of hornblende-biotite and biotite tonalite that can transit to granodiorite (Trajanova et al., 2009).

Western Prealps

Prealps have very heterogeneous lithology composed of carbonates, carbonate-clastic rocks and siliciclastic rocks (fig. 6). Lithology has an impact on erosion rate and vegetation. Western Prealps represent the area of central Slovenia, west of Ljubljana basin and comprise the Idrija-Žiri area, Tolmin area, Bača and Selška Sora area, Polhov Gradec hills, Škofja Loka hills, Poljane-Vrhnika area and Trnovski Gozd, Nanos, Hrušica and Javorniki area. Polhov Gradec-Vrhnika area is composed mainly of clastic rocks, such as quartz sandstone and quartz conglomerates (Novak & Skaberne, 2009). Sandstones, conglomerates and siltstones are found in a belt between Cerkno and Smrečje. This area is known for its copper ore and uranium deposit. Limestones, dolomites, marlstones and siltstones predominate in Polhov Gradec hills and Cerkno-Idrija area. In area around Idrija are claystone and sandstones that are rich in mercury ore (Dozet & Buser, 2009). Area between Petrovo Brdo and Železniki is composed of shale mudstones, sandstones, limestones with chert and breccias (Pleničar, 2009). Mafic igneous rocks are found in some places in Škofja Loka hills (Hinterlechner-Ravnik & Trajanova, 2009).

Trnovski gozd, Banjšice, Hrušica, Javorniki and Nanos are composed of carbonate rocks (limestones and dolomites). Bauxite loam and bauxite are present in a belt from Nanos, Hrušica to Žužemberk (Buser & Dozet, 2009).

Limestones with chert are common in the Tolmin area and Škofja Loka hills (Dozet & Buser, 2009). There are manganese deposits and iron manganese nodules between Perbla and Tolminske Ravne (Buser & Dozet, 2009). In some places in the area of Soča river valley are limestone breccias, on top of them occurs marlstone that transits

kapelska magmatska cona poteka vzdolž Periadriatskega prelomnega sistema, južno od Pece, preko Koprivne in Črne na Koroškem in tone pod sedimente v okolici Plešivca. Cono v večini sestavljajo kisle magmatske kamnine. Na severnem delu je sienogranitni masiv, na južnem pa tonalitni. V sienogranitnem masivu so prisotni gabro, monzogabro, monzodiorit in monzonit (Dobnikar & Zupančič, 2009; Trajanova et al., 2009). Tonalitni pas pa sestavlja v večini rogovačno-biotitni in biotitni tonalit, ki ponekod prehaja v granodiorit (Trajanova et al., 2009).

Zahodne Predalpe

Na sliki 6 je razvidno, da imajo Predalpe zelo heterogeno litološko zgradbo. Sestavljajo jo karbonati, karbonatno-klastične in siliciklastične kamnine. Litološka sestava močno vpliva na erozijo in vegetacijo. Zahodne Predalpe zavzemajo osrednji del Slovenije, ki leži zahodno od Ljubljanske kotline in obsegajo Idrijsko-Žirovsko ozemlje s hribovjem okoli Tolmina, ob Bači in Selški Sori, Polhograjsko hribovje, Škofjeloško hribovje, Poljansko-Vrhniško ozemlje ter Trnovski gozd, Nanos, Hrušico in Javornike. Na Polhograjsko-Vrhniškem območju najdemo klastične kamnine, predvsem kremenove peščenjake in kremenove konglomerate (Novak & Skaberne, 2009). V širokem pasu med Cerknim in Smrečjem se pojavljajo peščenjaki, konglomerati in muljevci. V tem območju je veliko rudišč bakra in uranovo rudišče. Obsežno območje Polhograjskega hribovja, Cerkljanskega in Idrijskega sestavljajo apnenci, dolomiti, laporovci in meljevci. Na Idrijskem se menjavajo glinavci in peščenjaki, ki so bogato orudeni s cinabaritom (Dozet & Buser, 2009). Na območju med Petrovim Brdom in Železniki so navzoči skrilavi glinavci, peščenjaki, apnenci z roženci in breče (Pleničar, 2009). V Škofjeloškem hribovju mestoma najdemo bazične magmatske kamnine (Hinterlechner-Ravnik & Trajanova, 2009).

Na območju Trnovskega gozda, Banjške planote, Hrušice, Javornikov ter Nanosa izdanjajo karbonatne kamnine (apnenci in dolomiti). V pasu od Nanosa in Hrušice proti Žužemberku najdemo boksitno ilovico in boksit (Buser & Dozet, 2009).

Na območju Tolmina se pojavljajo ploščati apnenci z roženci, ki jih najdemo tudi na Škofjeloškem hribovju (Dozet & Buser, 2009). Med Perblo in Tolminskimi Ravnami je veliko manganovega orudenja in železovo manganovih gomoljev (Buser & Dozet, 2009). Na območju Posočja se ponekod pojavlja apnenčeva breča, na kateri leži laporovec, ki prehaja v flišne plasti (Pleničar, 2009). Kredne into flysch (Pleničar, 2009). Cretaceous and Paleocene carbonate flysch is composed of red or grey marlstone (Drobne et al., 2009). Lacustrine sediments with predominant carbonate component are sparsely found in upper Soča river valley (Bavec & Pohar, 2009).

Eutric brown soils on flysch are found in westernmost part of Western Prealps. On carbonate rocks of western part of Western Prealps are rendzinas (profile A-C or A-R) on steeper slopes and in more favorable conditions brown soils (A-B-C). In central and eastern part of this spatial unit, clastic rocks and dystric brown soils predominate (Vidic et al., 2015).

Eastern Prealps

Eastern Prealps represent the area of the Sava Folds east of Ljubljana basin. The area consists of ridges and valleys in east–west direction. Similar as Western Prealps, this spatial unit has a very heterogeneous lithology, where clastic rocks predominate. Lithology has an impact on erosion rate and vegetation, that is mostly dense with mixed forest and arable land.

Southern part of the Sava Folds is composed of marlstone, siltstone, claystone, limestone and sandstones. There are more shale mudstones, siltstones, claystone and dolomite in northern part of the Sava Folds, and in central part, limestone and dolomite predominate. Both limestone and dolomite are also sparsely found in southern and northern part of the Sava Folds. Limestone with chert is also present in some areas (Dozet & Buser, 2009). Limestone and dolomite occur in the area of Tuhinj valley and Mirna and south from Sevnica (Buser & Dozet, 2009). Sandstones, conglomerates and siltstones are found in the Radeče area. There are also smaller copper deposits (Skaberne et al., 2009). Clastic sedimentary rocks with vein deposits of Pb, Zn, Hg, Cu, Ba and Sb are sparsely located east of Ljubljana (Novak & Skaberne, 2009).

Clastic flysch rocks can be found in Litija overthrust (Pleničar, 2009). In the area of Bohor are igneous rocks, that can be enriched with Pb and Zn (Trajanova & Grafenauer, 2009).

Northwestern part of the Sava Folds is composed of more conglomerate, followed by clay, marlstone and sandstone. Same rocks with addition of pyroclastic rocks and coal in the area from Laško to Zagorje, are found in eastern part of the Sava Folds. Coal was mined in collieries Zagorje, Trbovlje, Hrastnik, Laško and Senovo (Markič, 2007). Limestone sandstones, quartz sand and clayey marl are present in the areas

in paleocenske karbonatne fliše sestavljajo plasti rdečega ali sivega laporovca (Drobne et al., 2009). Na manjših območjih v zgornjem Posočju najdemo jezerske sedimente, v katerih prevladuje karbonatna komponenta (Bavec & Pohar, 2009).

Na skrajnem zahodnem delu Zahodnih Predalp, kjer so večinoma flišne kamnine, so prevladujoč talni tip evtrična rjava tla. V zahodnem delu, kjer je več karbonatnih kamnin, so na strmejših območjih rendzine (profil A-C ali A-R), ki ob ugodnih pogojih za razvoj tal prehajajo v rjava pokarbonatna tla (A-B-C). V centralnem in vzhodnem delu Zahodnih Predalp prevladujejo klastične kamnine, na katerih so distrična rjava tla (Vidic et al., 2015).

Vzhodne Predalpe

Vzhodne Predalpe obsegajo območje Posavskih gub vzhodno od Ljubljanske kotline, ki predstavljajo vrsto grebenov in dolin v smeri vzhod-zahod. Podobno kot Zahodne Predalpe imajo tudi Vzhodne zelo heterogeno litološko zgradbo. Območje je zgrajeno pretežno iz klastičnih kamnin. Litološka sestava močno vpliva na stopnjo erozije in vegetacijo, ki je večinoma bujna s prevladujočim mešanim gozdom in obdelanimi površinami.

V južnem delu Posavskih gub so laporovci, meljevci, glinavci, apnenci in peščenjaki. V severnem delu je več skrilavega glinavca, meljevca in dolomita, v osrednjem delu Posavskih gub pa prevladujeta apnenec in dolomit, ki se mestoma pojavljata tudi v južnem in severnem delu Posavskih gub. Ponekod se pojavlja tudi apnenec z rožencem (Dozet & Buser, 2009). Več apnenca in dolomita je tudi na območju Tuhinjske doline in Mirne ter južno od Sevnice (Buser & Dozet, 2009). Na območju Radeč izdanjajo peščenjaki, konglomerati in meljevci. Na tem območju so prisotna tudi manjša bakrova orudenja (Skaberne et al., 2009). Vzhodno od Ljubljane se mestoma pojavljajo klastične sedimentne kamnine, v katerih so žilna rudišča Pb, Zn, Hg, Cu, Ba in Sb (Novak & Skaberne, 2009).

V Litijskem narivu so flišne klastične kamnine (Pleničar, 2009). V okolici Bohorja najdemo magmatske kamnine, ki so mestoma obogatene s Pb in Zn (Trajanova & Grafenauer, 2009).

Na severozahodnem delu Posavskih gub najdemo konglomerate, ki jim sledijo glina, laporovec in peščenjak, na vzhodnem delu pa poleg teh še piroklastite ter malo premoga, ki ga več najdemo od Laškega do Zagorja. Premog so izkoriščali v premogovnikih Zagorje, Trbovlje, Hrastnik, Laško in Senovo (Markič, 2007). Na območju of Celje, Senovo and Laško synclines (Pavšič & Horvat, 2009).

Dystric brown soils and rankers predominate in southern and northern part of the Sava Folds, where there are more clastic rocks. Eutric brown soils are present on carbonate clastic rocks in eastern part of this spatial unit. Rendzinas (profile A-C or A-R) and brown soils (A-B-C) are most common on carbonate rocks in the central part of the Sava Folds (Vidic et al., 2015).

Western Dinarides

Western Dinarides are represented with wide valleys (Vipava valley, Matarsko podolje), hills and the large Karst plateau (in Slovene: Kras) that have a typical Dinaric northwest–southeast direction. Climate and vegetation are submediterranean.

Kras plateau, Čičarija and Matarsko podolje are composed mainly of limestone and dolomite with breccia with bauxite clay. In some areas, limestones include nodules and sheets of chert. Around Lipica and Sečovlje area are layers of coal (Pleničar, 2009).

Large area of Western Dinarides is covered with flysch (layers of marl, sandstone and carbonate turbidite). Red and grey marlstones are present in Vipava valley, Goriška Brda and Koper hills (Drobne et al., 2009). Flysch in Goriška Brda is of Cretaceous age (Pleničar, 2009). There is also limestone in the area of Goriška Brda (Drobne et al., 2009).

Boundary between Cretaceous and Tertiary rocks is best visible on Kras plateau between Sežana and Kozina. Rocks from the area of the boundary have increased contents of iridium, mercury and rare earth elements (Pleničar, 2009). On the boundary is also an increase in content of Ga, Sm, Zr, Co, Ni and V (Drobne et al., 2009). Limestone sparsely occurs in the area of flysch rocks.

Brown soils and rendzinas predominate on carbonate rocks (limestones and dolomites). Variation of brown soils, brown and red brown soils called also terra rossa is found on Kras plateau. Terra rossa forms on hard limestones and dolomites in submediterranean climate. Cambic horizon is brown-red to red. Organic (A) horizon is thin and poor in humus as organic matter quickly decays and mineralizes due to warm and dry climate. Contact with rocks is not straight, pockets of soil are common. Eutric brown soils predominate in the area of carbonate flysch rocks (Vipava valley, Goriška Brda and Koper hills). Dystric brown soils are present on flysch rocks in southeastern part of Western Dinarides (Vidic et al., 2015).

Celjske, Senovške in Laške sinklinale so apnenčevi peščenjaki, kremenov pesek in glinast lapor (Pavšič & Horvat, 2009).

Na južnem in severnem delu območja, kjer je več klastičnih kamnin, so distrična rjava tla in rankerji. Na karbonatnih klastičnih kamninah predvsem v vzhodnem delu Vzhodnih Predalp so evtrična rjava tla. V osrednjem delu so na karbonatnih kamninah rendzine (profil A-C ali A-R) in rjava pokarbonatna tla (A-B-C) (Vidic et al., 2015).

Zahodni Dinaridi

Zahodne Dinaride sestavljajo široke doline (Vipavska dolina, Matarsko podolje), gričevja in obsežna planota Kras, ki se raztezajo v smeri severozahod–jugovzhod. Podnebje in rastlinstvo sta submediteranska.

Na planoti Kras najdemo apnenec in dolomit ter nekaj breče z boksitno glino. Podobno je tudi v Čičariji in Matarskem podolju. Ponekod apnenec vsebuje leče in pole roženca. V okolici Lipice in v Sečovljah najdemo plasti premoga (Pleničar, 2009).

Velik del območja Zahodnih Dinaridov obsega fliš (plasti laporja, peščenjaka in karbonatnega turbidita). V Vipavski dolini, Goriških Brdih in Koprskem gričevju najdemo rdeče in sive laporovce (Drobne et al., 2009). Na območju Goriških Brd najdemo kredni fliš (Pleničar, 2009) in apnenec (Drobne et al., 2009).

Meja med krednimi in terciarnimi plastmi je najbolje vidna na Krasu med Sežano in Kozino in je zaznamovana s povišanjem iridija, kamnine vsebujejo tudi več živega srebra (Hg) in redkih zemelj (Pleničar, 2009). Na meji kreda/terciar so povišane tudi vsebnosti nekaterih drugih elementov: Ga, Sm, Zr, Co, Ni, V (Drobne et al., 2009). Mestoma se apnenec nahaja tudi na območju flišnih kamnin.

Na karbonatnih kamninah (apnenci in dolomiti) prevladujejo rjava pokarbonatna tla in rendzine. Na Krasu večkrat najdemo poseben različek rjavih pokarbonatnih tal, imenovan jerovica (terra rossa). Jerovice nastajajo na trdih apnencih in dolomitih, kjer se pojavlja submediteransko podnebje. Kambični horizont je izrazito rdeče barve. Horizont A je slabo izražen in zato slabo opazen, saj organska snov zaradi toplega in suhega podnebja hitro razpade in se mineralizira. Stik z matično podlago je izrazito neenakomeren, žepast. Na območju karbonatnih flišnih kamnin (Vipavska dolina, Goriška Brda in Koprsko gričevje) so evtrična rjava tla, na flišnih kamninah v jugovzhodnem delu Zahodnih Dinaridov pa so distrična rjava tla (Vidic et al., 2015).

Eastern Dinarides

Eastern Dinarides represent hilly karstic landscape with altitudes to 1000 meters with typical vegetation of mixed to broadleaf forests and meadows. Similar as Western Dinarides, hill ridges have a northwest–southeast direction. Bela Krajina plateau in the east represents the transition to the Pannonian basin. Limestones and dolomites predominate in this area. The area of Eastern Dinarides is also called "low or Dinaric karst". Brown soils predominate as soil type (Vidic et al., 2015).

Most of the Eastern Dinarides area is composed of limestones and dolomites and in some areas also marlstone, claystone and sandstone. Bituminous dolomite and limestone are found in the area of Cerknica lake, Logatec hills, Kočevje and Bela Krajina, where also coal can be present. Dolomite and bituminous dolomite predominate in Krim hills area, where limestone is also present. Bauxite loam and bauxite are present in a belt from Nanos, Hrušica, via Rakek, Vrhnika, Grosuplje, Krka to Žužemberk. Snežnik area is composed of limestone and breccia with bauxite clay. Area between Tržišče, Škocjan and Krško hills and Gorjanci area is comprised of clayey and marly shales with chert and limestone (Pleničar, 2009).

Marly limestone, limestone marlstone or claystone, tuffs and tuffite compose the area of Dolenjska around Mišji Dol and Primskovo (Dozet & Buser, 2009). Quartz conglomerates and quartz sandstones appear in the area around Ortnek and south of Kočevje (Novak & Skaberne, 2009). Flysch with red and grey marlstone is found in Pivka valley (Drobne et al., 2009).

Around Ilirska Bistrica is grey clay, lying on top of lignite. Coal was found south of Črnomelj and in Kočevje area. Red and brown clay spreads from Šmarje and Grosuplje via Ivančna Gorica to Trebnje and Mirna valley and in Mirna Peč and Novo mesto area. These rocks can include chert (Markič, 2009).

Most of the area of Eastern Dinarides is covered with brown soils and less rendzinas on carbonate rocks. Eutric brown soils formed on carbonate flysch rocks and dystric brown soils formed on siliciclastic rocks. The area of Bela Krajina is covered with leached soils and in some places with terra rossa, that does not form in this area any longer (Vidic et al., 2015).

Pannonian basin

Pannonian basin in Slovenia is known for its wide river valleys (Mura, Drava and Krško basin) and low hills (Goričko, Slovenske gorice and

Vzhodni Dinaridi

V Vzhodnih Dinaridih prevladuje hribovit kraški svet, ki leži na nadmorski višini do 1000 metrov, z vegetacijo mešanega do listnatega gozda s travniki. Podobno kot v Zahodnih Dinaridih se hribovja raztezajo v smeri severozahod–jugovzhod. Na vzhodu je Belokranjska planota, ki predstavlja prehod v Panonsko nižino. Ozemlje je v večini sestavljeno iz apnencev in dolomitov. Vzhodni Dinaridi se imenujejo tudi "nizki ali dinarski kras". Prevladujoči talni tip so rjava pokarbonatna tla (Vidic et al., 2015).

Apnenec in dolomit (mestoma tudi laporovec, glinavec in peščenjak) gradita večino območja Vzhodnih Dinaridov. Na območju Cerkniškega jezera, Logaške planote, Kočevskega in Bele Krajine izdanja bituminozni dolomit, ki ponekod prehaja v apnence. Pojavljajo se tudi leče premoga. V Krimskem pogorju in v njegovi okolici je apnenec, prevladujeta pa dolomit in bituminozen dolomit. V pasu Nanos, Hrušica, Rakek, Vrhnika, Grosuplje, Krka, Žužemberk sta prisotna boksitna ilovica in boksit. Območje Snežnika je zgrajeno iz apnenca in breče z boksitno glino. Na območju med Tržiščem in Škocjanom ter proti Krškem hribovju in na Gorjancih so razviti glinasti in laporasti skrilavci z rožencem in apnencem (Pleničar, 2009).

Na Dolenjskem v okolici Mišjega Dola in Primskovega so črni laporasti apnenci, apnenčevi laporovci ali glinavci, tufi in tufiti (Dozet & Buser, 2009). V okolici Ortneka in južno od Kočevja so kremenovi konglomerati in kremenovi peščenjaki (Novak & Skaberne, 2009). V Pivški kotlini izdanjajo flišne kamnine s plastmi rdečega in sivega laporovca (Drobne et al., 2009).

V okolici Ilirske Bistrice najdemo sivo glino nad lignitom. Premog so odkrili tudi južno od Črnomlja ter v okolici Kočevja. Rdeče in rjave gline se razširjajo od Šmarja in Grosupljega preko Ivančne Gorice do Trebnjega ter v Mirnski dolini in v okolici Mirne Peči in Novega mesta. Ponekod vsebujejo veliko roženca (Markič, 2009).

Na večini ozemlja Vzhodnih Dinaridov so rjava pokarbonatna tla in redkeje rendzine na karbonatnih kamninah. Na karbonatnih flišnih kamninah so evtrična rjava tla, na siliciklastičnih kamninah pa distrična rjava tla. Na območju Bele Krajine so izprana tla, najdemo pa tudi jerovice (terra rosse), ki danes na tem območju ne nastajajo več (Vidic et al., 2015)

Panonska nižina

Panonsko nižino v Sloveniji zaznamujejo široke rečne doline (Murski, Dravski in Krški bazen) in nizka hribovja (Goričko, Slovenske gorice in

Haloze with Kozjansko). River valleys are filled with gravel, sand and clay. Higher altitudes comprise clastic rocks and sediments, such as sandstone and marl. Due to the lithology, this area has a rugged terrain with intensive erosion and hydrogeological regime that is in favor to forming fertile soils, suitable for intensive agriculture.

Larger areas of Pannonian basin are composed of clastic rocks and sediments with vein quartz gravel and less chert, mica schists, diabase and andesite. Between these, lignite can be present. In some areas are coal, clay or “sivica” clay. Sandy and clayey marl, sandstone, sand, gravel and conglomerate and less limestone are present in the area of Štajerska basin and Mura basin. In Mura and Drava basin area are deposits of oil and gas (Pavšič & Horvat, 2009).

Gravel, sand and clay that originate from carbonate and metamorphic rocks from Central Alps are found in the area of Goričko, Ljutomerske and Lendavske gorice and river valleys between them. In Goričko, traces of vulcanism can also be seen. Clays can contain iron or manganese oxides and hydroxides. Most of them are found in Krško basin and Bizeljsko where they are also limonitized (Markič, 2009). Marlstones, calcarenites and other carbonate rocks, mainly limestone comprise the area in Krško basin around Čatež (Pavšič & Horvat, 2009).

Eutric brown soils formed on carbonate sediments (gravel, sand, marl and flysch) on low relief. They are more common in Krško basin. Dystric brown soils have formed on noncarbonate sediments, mostly in Drava and Mura basin. Weakly-developed soils, such as rendzinas and rankers are scarce. Alluvial soils and hypogleys formed on extensive river plains (Drava, Mura). Pseudogleys developed on hill slopes (Vidic et al., 2015).

Interior basins

Larger valleys are located within Alps, Prealps and Dinarides. The largest ones are Ljubljana-Kranj and Celje basin. They represent densely populated plains. Ljubljana-Kranj basin is filled with sediments of glacial, fluvio-glacial and lacustrine-glacial origin. Celje basin is a fertile valley filled with river sediments. In older river terraces, sediments have formed rocks (conglomerate, sandstone, tillite).

Celje basin is filled with sediments from gravel to clay. Gravel is mainly composed of carbonates, sandstone, keratophyre, diabase and chert (Markič, 2009).

Haloze s Kozjanskim). Rečne doline so zapolnjene s prodom, peskom in glino. Višji predeli so iz klastičnih kamnin in sedimentov, kot so peščenjaki in laporji. Zaradi tovrstne litološke sestave je razvit razčlenjen relief z intenzivnimi erozijskimi pojavi in hidrogeološkim režimom, ki je ugoden za nastanek rodovitnih tal, primernih za intenzivno poljedelstvo.

Večji del Panonske nižine gradijo klastične kamnine in sedimenti s prodniki žilnega kremena in manj rožence ter zelo malo blestnika, diabaza in andezita. Vmes se pojavlja tudi lignit. Mestoma se pojavljajo vložki premoga in gline ali sivice. Na območju Štajerskega bazena in Murskega bazena so peščeni in glinasti lapor, peščenjak, pesek, prod in konglomerat ter malo apnenca. Na območju Murskega in Dravskega bazena so nahajališča nafte in zemeljskega plina (Pavšič & Horvat, 2009).

Na območju Goričkega, Ljutomerskih in Lendavskih goric in v vmesnih rečnih dolinah najdemo prod, pesek in glino iz karbonatnih in metamorfnih kamnin, ki izvirajo iz Centralnih Alp. Na Goričkem so sledovi vulkanizma. Gline ponekod vsebujejo več železovih in manganovih oksidov in hidroksidov. Veliko teh kamnin najdemo tudi v Krškem bazenu in na Bizeljskem, kjer so tudi limonitizirane (Markič, 2009). V Krškem bazenu v okolici Čateža se menjavajo laporovci, kalkareniti ter druge karbonatne kamnine, predvsem apnenci (Pavšič & Horvat, 2009).

Zaradi blagega reliefa so na podlagi iz karbonatnih sedimentov (prod, pesek, lapor, fliš) razvita evtrična rjava tla, ki se pogosteje pojavljajo v Krškem bazenu, na nekarbonatnih pa distrična rjava tla predvsem v Dravskem in Murskem bazenu. Manj razvita tla, kot so rendzine in rankerji, so zelo redka. Na obsežnih ravninah ob rekah (Drava, Mura) so razvita obrečna tla in hipogleji, na pobočjih gričevij so ponekod psevdogleji (Vidic et al., 2015).

Notranje kotline

Znotraj Alp, Predalp in Dinaridov so večje kotline. Največji sta Ljubljansko-Kranjska in Celjska kotlina. Predstavljata gosto naseljeni nižini. Ljubljansko-Kranjska kotlina je zapolnjena s sedimenti ledeniškega, rečno-ledeniškega in jezersko-ledeniškega nastanka. Celjska kotlina je rodovitna dolina, ki sestoji iz rečnih sedimentov. V starejših terasah so sedimenti sprijeti v kamnine (konglomerat, peščenjak, tilit).

V Celjski kotlini najdemo sedimente velikosti od prodov do gline. Prode sestavljajo karbonati, peščenjaki, keratofir, diabaz in roženec (Markič, 2009).

Ljubljana basin is filled with gravel, sand and clay. In Bled lake and Radovljica area are carbonate sediments (silt and clay). Ljubljana moor is filled with gravels, sandy gravels and silty gravels with lacustrine and paludal sediments (Bavec & Pohar, 2009).

Juvenile soils, that formed on alluvial plains, predominate in Interior basins. In some areas, the soils are affected by streams that accumulate recent material. Brown soils formed on sediments and alluvial soils formed next to rivers. Leached soils appear in northwestern part of Ljubljana-Kranj basin. In Ljubljana moor area, topogenic peat soils have formed (Vidic et al., 2015).

Results and discussion

Table 3 shows basic statistical parameters, that were determined by parametric and nonparametric statistical methods for chemical elements Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, Ti, Tl, U, V, Y, Zn, Zr. The basic statistical parameters are mean, geometric mean, median, maximum and minimum, quartiles and percentiles (Q1 (=P25), Q2 (=P50=Md), Q3 (=P75)), skewness and kurtosis. Basic statistical parameters are shown for whole of Slovenia (table 3) and separately for smaller spatial units in appendix 1/1-8.

Box and whiskers diagrams were made for 9 major elements and for 11 trace elements (figs. 8 and 9). Box represent interquartile range (lower boundary of the box represents 1st quartile, upper boundary represents 3rd quartile) and whiskers represent Tukey inner fence (TIF). Concentration value axis scale is logarithmic.

Table 4 shows calculated geochemical threshold values (X2S, MD2MAD, TIF, P95, P97.5) for 47 chemical elements (Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, Ti, Tl, U, V, Y, Zn, Zr) for whole of Slovenia.

In appendix 2/1-8 geochemical threshold values (X2S, MD2MAD, TIF, P95, P97.5) for smaller spatial units in Slovenia are presented.

Due to nature of geochemical data, which is generally applicable for the data set in question, logarithmic data transformation is required. Skewness and kurtosis values imply that our data set does not have a normal data distribution. Therefore, we calculated geochemical thresholds using log-transformed data (labeled L). Results were afterwards back transformed.

Na območju Ljubljanske kotline so prodi, peski in glina. V Blejskem jezeru je karbonatni sediment (melj in glina), ki ga najdemo tudi v širši okolici Radovljice. Na Ljubljanskem barju so prodni, meljasti in peščeno prodni nanosi z jezerskimi in močvirskimi sedimenti (Bavec & Pohar, 2009).

V kotlinah prevladujejo mlada tla, razvita na aluvialnih ravninah, ki so mestoma še pod vplivom vodotokov, ki stalno prinašajo material. Na sedimentih so razvita rjava tla, ob rekah pa obrečna tla. V severozahodnem delu Ljubljansko-Kranjske kotline so pogosta izprana tla. Na Ljubljanskem barju so šotna tla (Vidic et al., 2015).

Rezultati in diskusija

V tabeli 3 so prikazani osnovni statistični parametri, ki smo jih določili na osnovi parametričnih in neparametričnih statističnih metod za naštete kemične elemente Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, Ti, Tl, U, V, Y, Zn, Zr. Izraženi so kot aritmetična srednja vrednost, geometrijska srednja vrednost, mediana, najmanjša in največja vrednost, kvartili oziroma percentili (Q1 (=P25), Q2 (=P50=Md), Q3 (=P75)), asimetričnost in sploščenost. Izsledki statističnih obdelav so prikazani tabelarično za celotno Slovenijo (tabela 3) in za manjše prostorske enote v prilogi 1/1-8.

Za 9 glavnih prvin in 11 slednih prvin smo izdelali diagrame škatel z brki (sl. 8 in 9), kjer škatla predstavlja medkvartilni razpon (spodnja meja je 1. kvartil, zgornja meja pa 3. kvartil), brki pa predstavljajo Tukeyevo notranjo mejo (TIF). Naj opozorimo, da je merilo osi, ki prikazuje vsebnosti elementov, logaritemsko.

V tabeli 4 navajamo izračunane vrednosti zgornje meje naravne variabilnosti (X2S, MD2MAD, TIF, P95, P97.5) za 47 elementov (Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, Ti, Tl, U, V, Y, Zn, Zr) za celotno Slovenijo.

V prilogi 2/1-8 podajamo izračunane vrednosti zgornje meje naravne variabilnosti (X2S, MD2MAD, TIF, P95, P97.5) manjših prostorskih enot v Sloveniji.

Zaradi narave porazdelitve geokemičnih podatkov, ki velja na splošno in za obravnavani set podatkov, je potrebna logaritemska transformacija podatkov. Vrednosti asimetričnosti in sploščenosti sta pokazali, da podatki nimajo normalne porazdelitve. Zato v nadaljevanju razpravljamo o mejah naravne variabilnosti, ki smo jih izračuna-

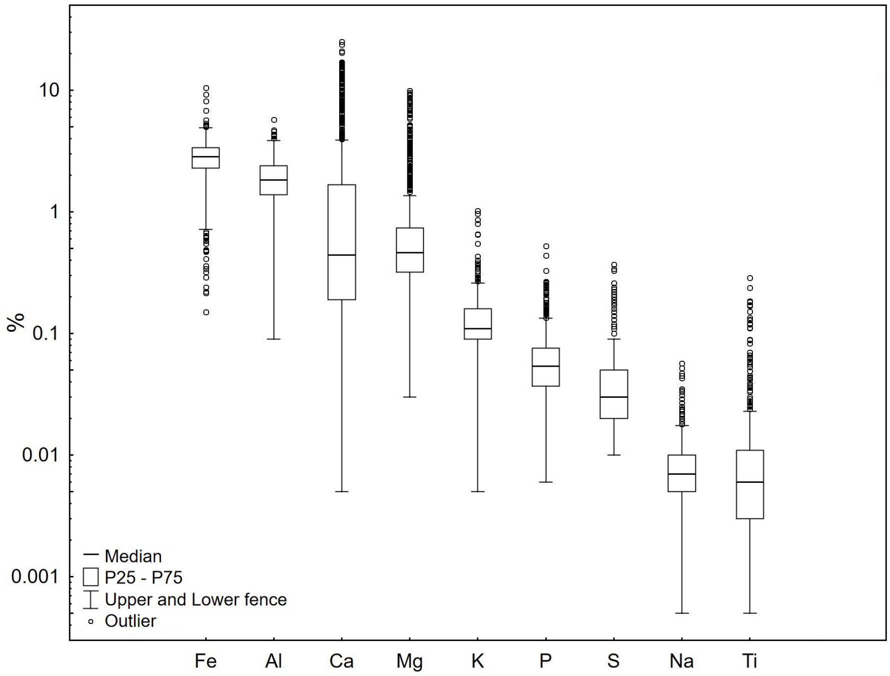

Fig. 8. Box and whiskers plot for major elements.

Sl. 8. Diagrami škatle z brki za glavne prvine.

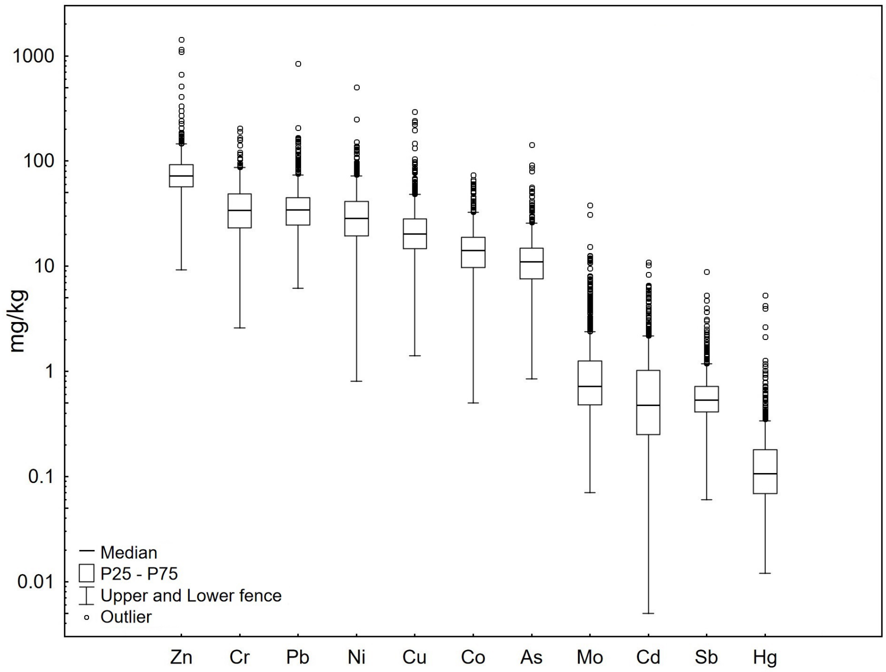

Fig. 9. Box and whiskers plot for PTEs (As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb and Zn).

Sl. 9. Diagrami škatle z brki za PTE (As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb in Zn).

In Europe, most of the element distributions clearly show the differences between the composition of the northern and southern parts of Europe. In northern Europe, influence of glaciation is obvious for most elements (Reimann et al., 2018). Reimann et al. (2018) showed soil composition data separately for northern and southern Europe, of which Slovenia is a part of. Therefore, the Slovenian soil element concentrations were compared with the soil concentrations of Europe and of southern Europe. Comparison of the element concentration in Slovenia with Europe shows that most of element concentrations are higher in Slovenia than in the whole Europe and also in the southern Europe.

li z logaritmiranimi podatki (oznaka L). Končni rezultati so antilogaritmirani.

V Evropi večina porazdelitev elementov jasno kaže razlike med sestavo severnega in južnega dela Evrope. Zelo opazen je vpliv poledenitve v severnem delu Evrope (Reimann et al., 2018). Zato je Reimann s sodelavci (2018) prikazal ločene podatke o sestavi tal za severno in južno Evropo, v katero je bila vključena tudi Slovenija. Zato naše podatke v nadaljevanju primerjamo z južno in celotno Evropo. Primerjava vsebnosti elementov v Sloveniji in južni Evropi kaže, da so vsebnosti večine elementov v Sloveniji večje kot v južni Evropi. Mediane večine elementov v Sloveniji prese-

Table 3. Basic statistical parameters for Slovenia.
Tabela 3. Osnovni statistični parametri za Slovenijo.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	78	63	62	1.0	1200	43	93	7.75	95.39	-0.17	2.95
Al	%	1.9	1.7	1.8	0.090	5.7	1.4	2.4	0.53	0.74	-1.39	4.06
As	mg/kg	13	11	11	0.85	140	7.6	15	5.67	56.73	-0.25	1.94
Au	µg/kg	2.5	1.7	1.7	0.10	110	1.1	2.7	14.62	274.70	-0.36	3.12
B	mg/kg	2.8	1.9	2.0	0.50	36	1.0	4.0	3.90	31.11	-0.07	-0.68
Ba	mg/kg	83	71	75	3.2	820	55	100	5.36	61.52	-0.89	3.52
Be	mg/kg	1.0	0.89	0.90	0.050	3.5	0.60	1.3	0.98	0.86	-0.78	2.17
Bi	mg/kg	0.36	0.32	0.33	0.020	1.3	0.24	0.43	1.28	2.53	-0.49	1.79
Ca	%	2.0	0.55	0.44	0.0050	25	0.19	1.7	2.74	8.07	0.16	-0.37
Cd	mg/kg	0.85	0.50	0.47	0.0050	11	0.25	1.0	3.86	21.40	-0.16	1.32
Ce	mg/kg	39	33	38	1.8	130	24	52	0.50	0.61	-1.22	1.88
Co	mg/kg	15	13	14	0.50	74	9.7	19	1.95	7.02	-1.12	3.34
Cr	mg/kg	38	32	34	2.6	210	23	49	2.40	11.35	-0.56	1.01
Cs	mg/kg	1.5	1.3	1.4	0.050	7.0	0.88	2.0	1.26	2.89	-0.90	1.73
Cu	mg/kg	25	21	20	1.4	300	15	28	6.14	54.76	0.07	2.41
Fe	%	2.8	2.6	2.9	0.15	10	2.3	3.4	0.85	7.03	-2.16	7.63
Ga	mg/kg	5.3	4.8	5.2	0.20	19	3.8	6.7	0.75	1.84	-1.33	3.66
Hf	mg/kg	0.071	0.047	0.050	0.010	0.37	0.020	0.10	1.44	2.38	-0.29	-0.95
Hg	mg/kg	0.17	0.12	0.11	0.012	5.3	0.069	0.18	10.38	135.24	0.84	2.09
In	mg/kg	0.039	0.033	0.040	0.010	0.25	0.030	0.050	2.31	15.37	-0.57	0.06
K	%	0.13	0.12	0.11	0.0050	1.0	0.090	0.16	4.58	34.47	0.03	3.18
La	mg/kg	18	15	17	1.0	82	11	24	1.16	4.01	-1.05	1.43
Li	mg/kg	20	17	19	0.30	150	13	24	4.27	37.31	-1.36	5.22
Mg	%	0.98	0.54	0.46	0.030	9.9	0.32	0.74	3.40	12.11	0.81	1.31
Mn	mg/kg	960	760	790	17	7200	520	1200	2.42	12.41	-0.75	2.10
Mo	mg/kg	1.4	0.84	0.72	0.070	38	0.48	1.3	7.83	92.88	0.81	1.05
Na	%	0.0079	0.0063	0.0070	0.0005	0.057	0.0050	0.010	3.03	16.49	-0.72	1.75
Nb	mg/kg	0.75	0.54	0.60	0.025	7.8	0.31	1.0	2.95	20.64	-0.44	0.05
Ni	mg/kg	34	27	29	0.80	500	20	41	6.58	90.17	-0.57	1.99
P	%	0.063	0.053	0.054	0.0060	0.52	0.037	0.076	3.57	23.20	0.01	0.82
Pb	mg/kg	40	34	34	6.2	850	25	45	13.93	294.78	0.39	2.38
Rb	mg/kg	19	17	18	0.40	94	13	23	1.79	9.53	-1.29	4.85
S	%	0.043	0.032	0.030	0.010	0.37	0.020	0.050	3.49	17.45	0.13	0.00
Sb	mg/kg	0.64	0.54	0.53	0.060	8.9	0.41	0.72	7.11	84.55	0.22	2.42
Sc	mg/kg	4.2	3.7	3.9	0.20	19	2.8	5.3	1.27	3.97	-0.86	2.11
Se	mg/kg	0.44	0.35	0.40	0.050	2.6	0.28	0.55	2.19	8.38	-0.69	1.03
Sn	mg/kg	1.3	1.1	1.1	0.10	25	0.80	1.6	11.77	215.39	0.30	2.37
Sr	mg/kg	30	16	14	1.6	940	8.5	25	7.58	76.43	0.95	1.59
Te	mg/kg	0.049	0.035	0.040	0.010	0.24	0.020	0.070	1.39	2.18	-0.14	-1.09
Th	mg/kg	4.3	3.6	4.1	0.050	17	2.7	5.7	0.59	0.91	-1.50	3.85
Ti	%	0.012	0.0057	0.0060	0.0005	0.29	0.0030	0.011	6.26	49.64	0.25	0.63
Tl	mg/kg	0.32	0.26	0.23	0.050	1.3	0.16	0.43	1.56	2.63	0.24	-0.57
U	mg/kg	1.1	0.96	1.0	0.10	10	0.70	1.4	3.69	28.00	-0.11	0.91
V	mg/kg	49	40	40	3.0	230	28	60	2.07	5.43	-0.11	0.68
Y	mg/kg	14	11	11	0.78	110	7.1	16	3.67	21.09	-0.09	0.86
Zn	mg/kg	83	72	72	9.2	1400	57	92	11.10	152.99	0.52	6.37
Zr	mg/kg	2.4	1.5	1.8	0.050	12	0.80	3.4	1.44	2.18	-0.85	0.79

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Table 4. Determined thresholds for Slovenia.
Tabela 4. Zgornje meje naravne variabilnosti za Slovenijo.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	170	210	220	230	130	190	170	300
Al	%	3.3	3.5	3.5	4.6	3.3	4.1	3.9	5.4
As	mg/kg	25	34	32	34	22	30	26	40.9
Au	µg/kg	5.8	8.1	13	9.2	3.8	6.2	5.1	10.4
B	mg/kg	8.0	9.5	8.4	11	5.0	16	8.5	32.0
Ba	mg/kg	150	200	190	220	140	180	170	250
Be	mg/kg	2.1	2.4	2.1	2.8	1.8	3.0	2.4	4.1
Bi	mg/kg	0.68	0.80	0.69	0.83	0.60	0.80	0.72	1.0
Ca	%	11	14	9.4	15	1.4	7.3	3.9	44.2
Cd	mg/kg	2.7	4.0	3.1	4.0	1.3	3.6	2.2	8.4
Ce	mg/kg	71	80	78	120	80	110	94	160
Co	mg/kg	30	38	34	47	28	39	32	50.7
Cr	mg/kg	75	89	85	110	71	100	88	150
Cs	mg/kg	3.3	3.7	3.4	5.0	3.0	4.6	3.7	7.0
Cu	mg/kg	53	68	70	69	40	54	49	75.6
Fe	%	4.3	4.5	4.8	6.5	4.4	5.0	5.0	6.0
Ga	mg/kg	9.4	10	10	14	9.3	12	11	15.7
Hf	mg/kg	0.20	0.23	0.19	0.33	0.17	0.39	0.22	1.1
Hg	mg/kg	0.44	0.66	0.82	0.54	0.24	0.41	0.35	0.76
In	mg/kg	0.070	0.090	0.083	0.11	0.070	0.094	0.080	0.11
K	%	0.25	0.32	0.31	0.32	0.20	0.28	0.27	0.38
La	mg/kg	34	39	38	57	36	51	43	76.5
Li	mg/kg	36	43	44	58	35	44	40	58.1
Mg	%	4.5	6.5	4.1	3.7	0.99	1.5	1.4	2.6
Mn	mg/kg	2200	2700	2330	3200	1800	2900	2300	4600
Mo	mg/kg	4.8	6.8	6.3	5.0	1.7	2.9	2.4	5.3
Na	%	0.018	0.021	0.020	0.026	0.016	0.020	0.018	0.028
Nb	mg/kg	1.9	2.3	2.0	3.0	1.5	3.2	2.0	5.8
Ni	mg/kg	78	94	92	110	60	87	74	130
P	%	0.13	0.18	0.15	0.17	0.11	0.15	0.13	0.22
Pb	mg/kg	82	110	110	96	64	84	75	110
Rb	mg/kg	34	39	36	47	31	39	37	51.8
S	%	0.11	0.17	0.12	0.14	0.060	0.10	0.095	0.20
Sb	mg/kg	1.4	1.7	1.7	1.6	0.97	1.2	1.2	1.7
Sc	mg/kg	7.8	9.1	8.4	11	7.5	10	9.1	13.8
Se	mg/kg	1.0	1.2	1.1	1.5	0.84	1.0	0.96	1.6
Sn	mg/kg	2.5	3.0	3.7	3.2	2.3	2.8	2.8	4.5
Sr	mg/kg	96	180	160	110	34	69	50	130
Te	mg/kg	0.13	0.15	0.13	0.20	0.13	0.31	0.15	0.46
Th	mg/kg	8.1	8.8	8.6	14	8.2	11	10	17.5
Ti	%	0.038	0.066	0.059	0.053	0.018	0.047	0.023	0.077
Tl	mg/kg	0.77	0.88	0.76	0.93	0.53	0.82	0.83	1.9
U	mg/kg	2.4	3.0	2.7	3.1	1.9	2.9	2.4	4.0
V	mg/kg	120	150	120	140	84	130	110	190
Y	mg/kg	34	45	37	43	23	36	30	55.3
Zn	mg/kg	140	170	250	190	120	150	150	190
Zr	mg/kg	6.6	7.7	6.5	13	5.4	14	7.3	29.8

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

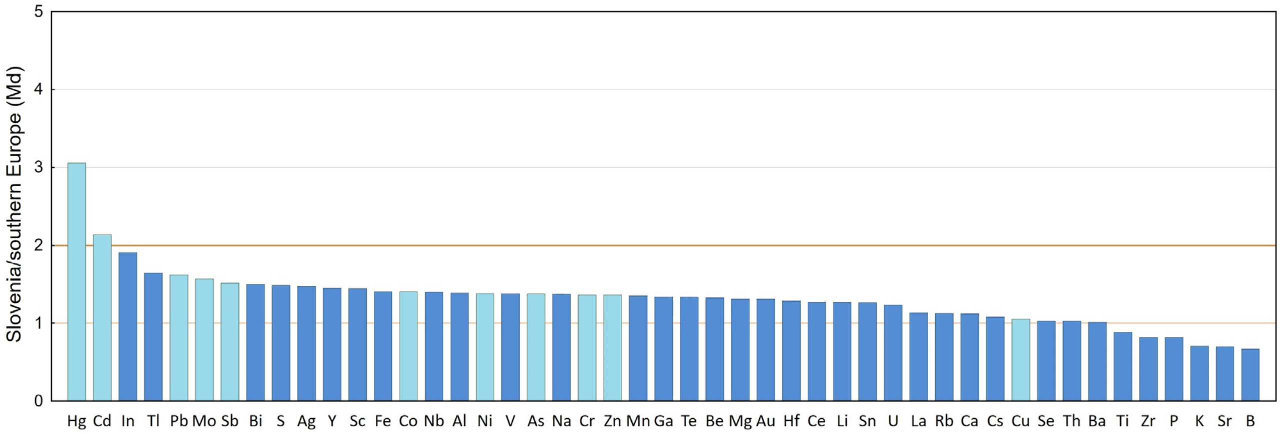

Fig. 10. Ratios of medians between Slovenia and southern Europe. Light blue colour mark PTEs, orange lines represent 1 time and 2 times higher values in Slovenia.

Sl. 10. Razmerja median med Slovenijo in južno Evropo. S svetlo modro so označeni PTE, oranžni črti predstavljata 1 krat in 2 krat višje vrednosti v Sloveniji.

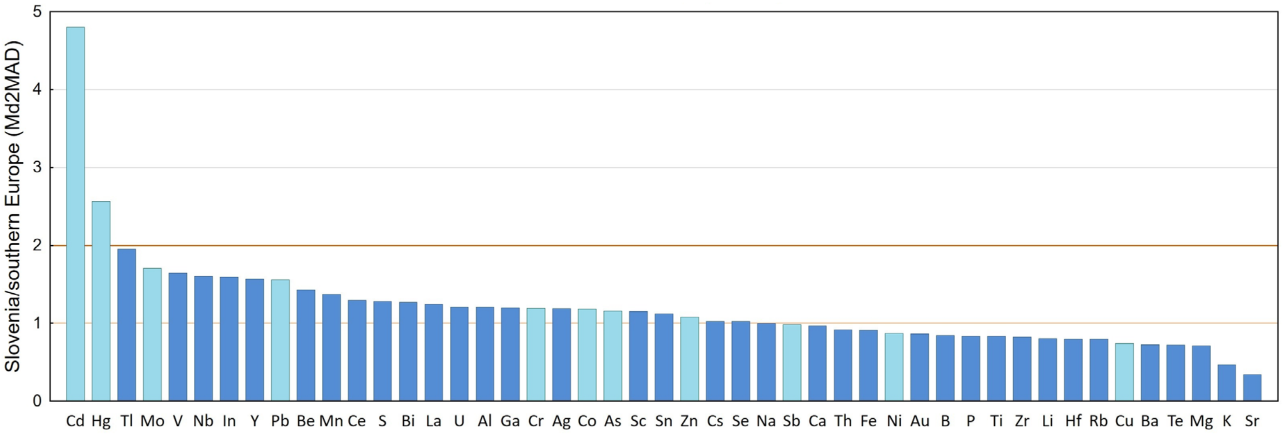

Fig. 11. Ratios of threshold (MD2MAD) between Slovenia and southern Europe. Light blue colour mark PTEs, orange lines represent 1 time and 2 times higher values in Slovenia.

Sl. 11. Razmerja zgornje meje naravne variabilnosti (MD2MAD) med Slovenijo in južno Evropo. S svetlo modro so označeni PTE, oranžni črti predstavljata 1 krat in 2 krat višje vrednosti v Sloveniji.

In Slovenia most of median element concentrations exceed median values in southern Europe (fig. 10). Mercury (Hg) and Cd medians are 2 times higher in Slovenia than in southern Europe, while the concentration of In is almost 2 times higher. Several elements (Tl, Pb, Mo, Sb, Bi, S, Ag, Y, Sc) have around 1.5 times higher median values in Slovenia. Only Ti, Zr, P, K, Sr and B have lower median concentration values in Slovenia, compared to southern Europe.

Comparison between determined MD2MAD values in Slovenia and southern Europe (fig. 11) shows that more elements in Slovenia have lower MD2MAD values than in the case of median values. MD2MAD values in southern Europe are close to Slovenian threshold values for elements Sb, Na, Se and Cs. Lead (Pb), Y, In, Nb, V and Mo have around 1.5 times higher thresholds values in Slovenia and Tl has almost 2 times higher values in Slovenia, compared to southern Europe. Com-

gajo mediane v južni Evropi (sl. 10). Živo srebro (Hg) in Cd imata v Sloveniji več kot 2 krat višje vsebnosti kot v južni Evropi, blizu 2 krat višja je tudi vsebnost In. Več elementov (Tl, Pb, Mo, Sb, Bi, S, Ag, Y, Sc) ima v Sloveniji okoli 1,5 krat višje vsebnosti mediane kot v južni Evropi. Samo Ti, Zr, P, K, Sr in B imajo nižjo mediano v Sloveniji kot v južni Evropi.

Razmerja vrednosti MD2MAD v Sloveniji in južni Evropi (sl. 11) kažejo, da ima več elementov v Sloveniji nižje vrednosti MD2MAD, kot v primeru razmerja median. Vrednosti MD2MAD so si v Sloveniji in južni Evropi blizu za elemente Sb, Na, Se in Cs. Okoli 1,5 krat so v Sloveniji višje vrednosti MD2MAD za Pb, Y, In, Nb, V in Mo. Skoraj 2 krat je v Sloveniji višja vrednost Tl. V primerjavi z južno Evropo, v Sloveniji najbolj izstopata Hg in Cd, ki imata v Sloveniji več kot 2,5 krat višje vrednosti MD2MAD.

pared to southern Europe, Hg and Cd stand out the most, with more than 2.5 times higher threshold values in Slovenia.

Most of Slovenian territory is represented by rendzinas and brown soils that have formed on carbonate rocks (Vidic et al., 2015; Zupančič et al., 2018). It took a long time for the soil to develop due to these soils forming on limestone and dolomites with 1–2 % insoluble rock residue. During soil development, the soil could also be under the influence of eolian and other deposits (Gosar, 2007). Soils on carbonate rocks often have higher concentrations of As, Bi, Co, Cr, Cu, Hg, Li, Mn, Nb, Ni, Pb, Sb, Th, U, V, Zn and Zr than Slovenian average concentration values (Gosar, 2007). Large differences in geochemical composition between soils in Slovenia and Europe can therefore be a consequence of prevailing carbonate lithology in Slovenia.

For easier understanding of medians and calculated threshold values (X2S (L), MD2MAD (L), TIF (L) and P97.5) selected elements are shown in fig. 12 to 15. Medians and geochemical threshold values are shown for smaller spatial units (left part of the graph), for whole of Slovenia and in comparison, also for southern, northern and entire Europe (right part of the graph, according to the GEMAS project, Reimann et al. (2018)). On the graph, limit value is marked with the orange dash line, warning value is marked with red dash line and critical value is marked with red full line according to Decree on limit values, alert thresholds and critical levels of dangerous substances in the soil (Official Gazette RS, 1996). Reimann et al. (2018) used 98th percentile for European data, while in Slovenia we used 97.5th percentile, as in case of an ideal normal distribution, values of X2S, MD2MAD and 97.5th percentile coincide in the same value.

Median values of individual spatial units in Slovenia are similar for elements As, Pb, Sb and Zn. In case of Co and Cr, there are higher median values in Dinarides. Higher median values for Mo are in Eastern Dinarides. Of significance are higher median values for Cu and Ni in Western Dinarides, where Ni median value exceeds the limit value (50 mg/kg) according to Official Gazette RS, 1996 (fig. 14). Large median value differences are apparent for Cd, with highest values in Western Alps, where median value also exceeds the limit value (1 mg/kg) according to Official Gazette RS, 1996 (fig. 12). Somewhat higher median values of Cd are also in Eastern Dinarides and Interior basins. Among the spatial units in Slovenia, there are large differences between median values for Hg. Mercury (Hg) median value is much higher in Western Prealps (0.270 mg/kg), compared to other spatial units (fig. 13).

V Sloveniji večji delež ozemlja predstavljajo rendzine in rjava pokarbonatna tla, ki nastajajo na karbonatnih kamninah (Vidic et al., 2015; Zupančič et al., 2018). Ker nastajajo ta tla na apnencih in dolomitih z 1–2 % netopnega ostanka kamnin, je bilo potrebno dolgo časovno obdobje, da so se tla razvila. V času razvoja tal so bila tla lahko tudi pod vplivom eolskih in drugih nanosov (Gosar, 2007). Tla na karbonatnih kamninah imajo zato pogoste višje vsebnosti As, Bi, Co, Cr, Cu, Hg, Li, Mn, Nb, Ni, Pb, Sb, Th, U, V, Zn in Zr od slovenskega povprečja (Gosar, 2007). Velike razlike med Slovenijo in Evropo so torej lahko posledica obsežnih območij karbonatnih kamnin v Sloveniji, ki pa v Evropi predstavljajo manjši delež.

Za lažje razumevanje median in izračunanih zgornjih mej naravne variabilnosti (X2S(L), MD2MAD(L), TIF(L) in P97.5) smo le-te za izbrane elemente prikazali na slikah od 12 do 15. Mediane in zgornje meje naravne variabilnosti so prikazane za prostorske enote v Sloveniji (levi del grafa), za celotno Slovenijo in primerjalno tudi za severni in južni del Evrope ter za celotno Evropo (desni del grafa, po podatkih projekta GEMAS, Reimann et al. (2018)). Na grafih smo z oranžno črtkano črto označili mejno vrednost, z rdečo prekinjeno črto opozorilno vrednost in s polno rdečo črto kritično vrednost po Uredbi o mejnih, opozorilnih in kritičnih imisijskih vrednostih nevarnih snovi v tleh (Uradni list RS, 1996). Pri podatkih o Evropi so Reimann in sodelavci (2018) uporabili vrednosti za 98. percentil, v Sloveniji pa smo uporabili 97,5. percentil. Uporabili smo ga, ker v primeru idealne normalne porazdelitve vrednosti X2S, MD2MAD in 97,5. percentil sovpadajo v isti vrednosti.

Mediane posameznih prostorskih enot v Sloveniji so si blizu za As, Pb, Sb in Zn. Pri Co in Cr opažamo višje vrednosti median v Dinaridih, pri Mo pa višje vrednosti v Vzhodnih Dinaridih. Značilnost Cu in Ni so višje vrednosti median v Zahodnih Dinaridih, kjer mediana Ni presega mejno vrednost (50 mg/kg) po Uradnem listu RS, 1996 (sl. 14). Večje razlike med medianami posameznih prostorskih enot so v primeru Cd, ki močno izstopa v Zahodnih Alpah, kjer mediana tudi presega mejno vrednost (1 mg/kg) po Uradnem listu RS, 1996 (sl. 12). Nekoliko višje vrednosti median Cd so tudi v Vzhodnih Dinaridih in Notranjih kotlinah. Med prostorskimi enotami v Sloveniji so velike razlike tudi med medianami za Hg. Mediana Hg v Zahodnih Predalpah je veliko višja (0,270 mg/kg), kot v drugih prostorskih enotah (sl. 13).

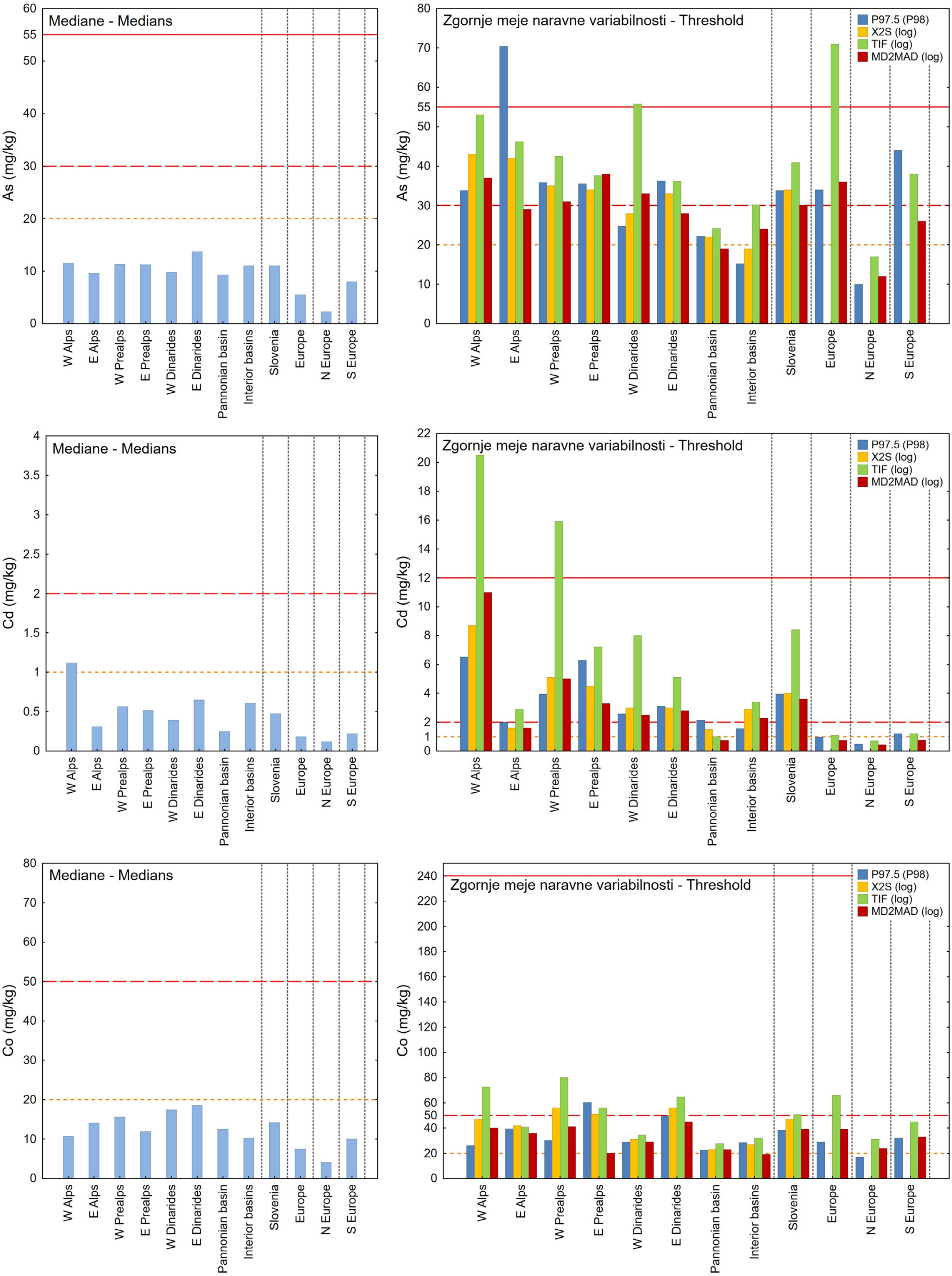

Fig. 12. Medians and thresholds calculated by different methods for arsenic (As), cadmium (Cd) and cobalt (Co). European data are after Reimann et al. (2018). Markings: orange dotted line – limit soil value, red dotted line – warning soil value, red line – critical soil value (Official Gazette RS, 1996).

Sl. 12. Prikaz median in izračunanih zgornjih mej naravne variabilnosti po izbranih metodah za arzen (As), kadmij (Cd) in kobalt (Co). Podatki za Evropo po Reimann et al. (2018). Oznake na sliki: oranžna črtkana črta – mejna vrednost, rdeča prekinjena črta – opozorilna vrednost, polna rdeča črta – kritična vrednosti (Uradni list RS, 1996).

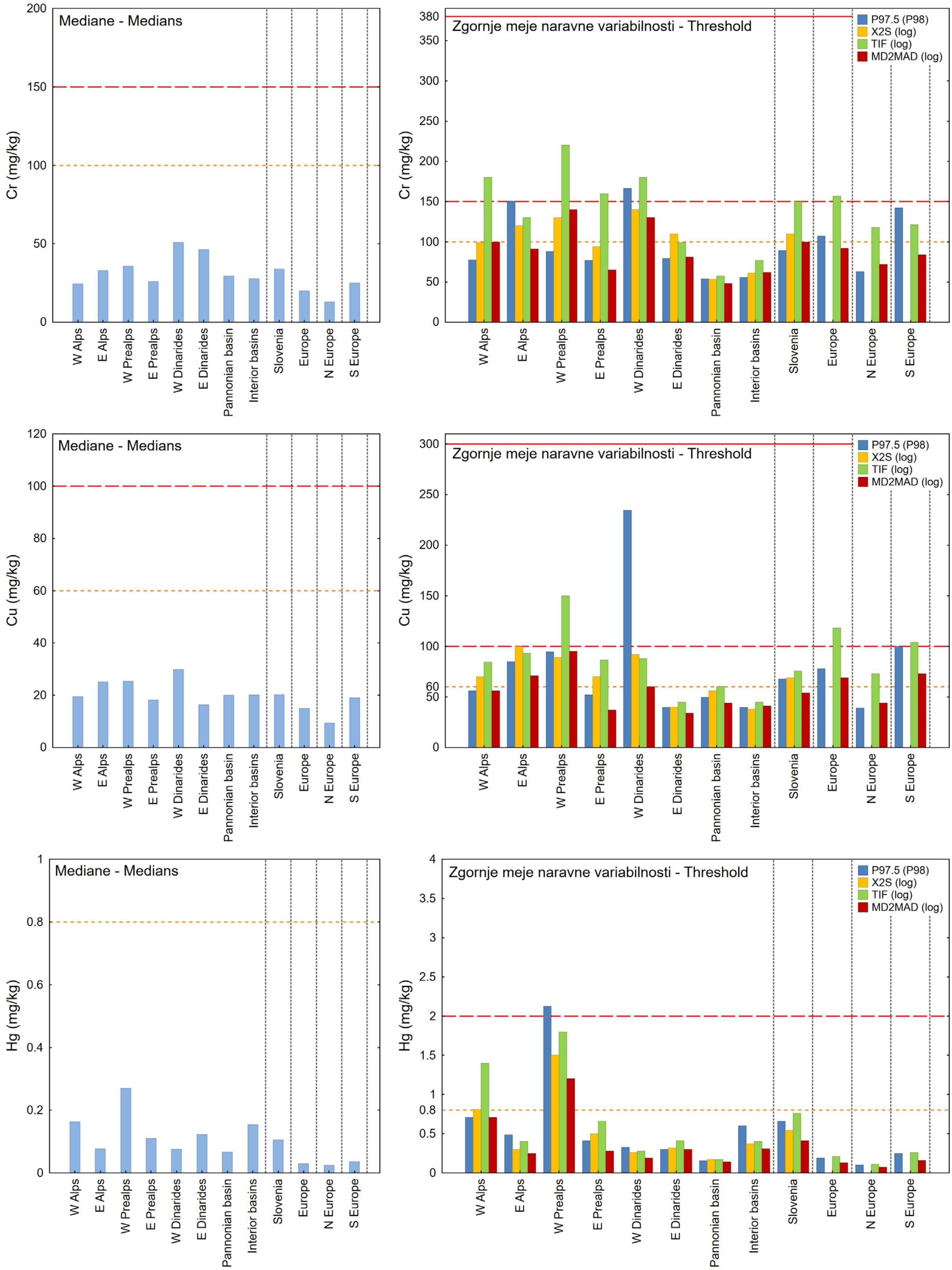

Fig. 13. Medians and thresholds calculated by different methods for chromium (Cr), copper (Cu) and mercury (Hg). European data are after Reimann et al. (2018). Markings: orange dotted line – limit soil value, red dotted line – warning soil value, red line – critical soil value (Official Gazette RS, 1996).

Sl. 13. Prikaz median in izračunanih zgornjih mej naravne variabilnosti po izbranih metodah za krom (Cr), baker (Cu) in živo srebro (Hg). Podatki za Evropo po Reimann et al. (2018). Oznake na sliki: oranžna črtkana črta – mejna vrednost, rdeča prekinjena črta – opozorilna vrednost, polna rdeča črta – kritična vrednosti (Uradni list RS, 1996).

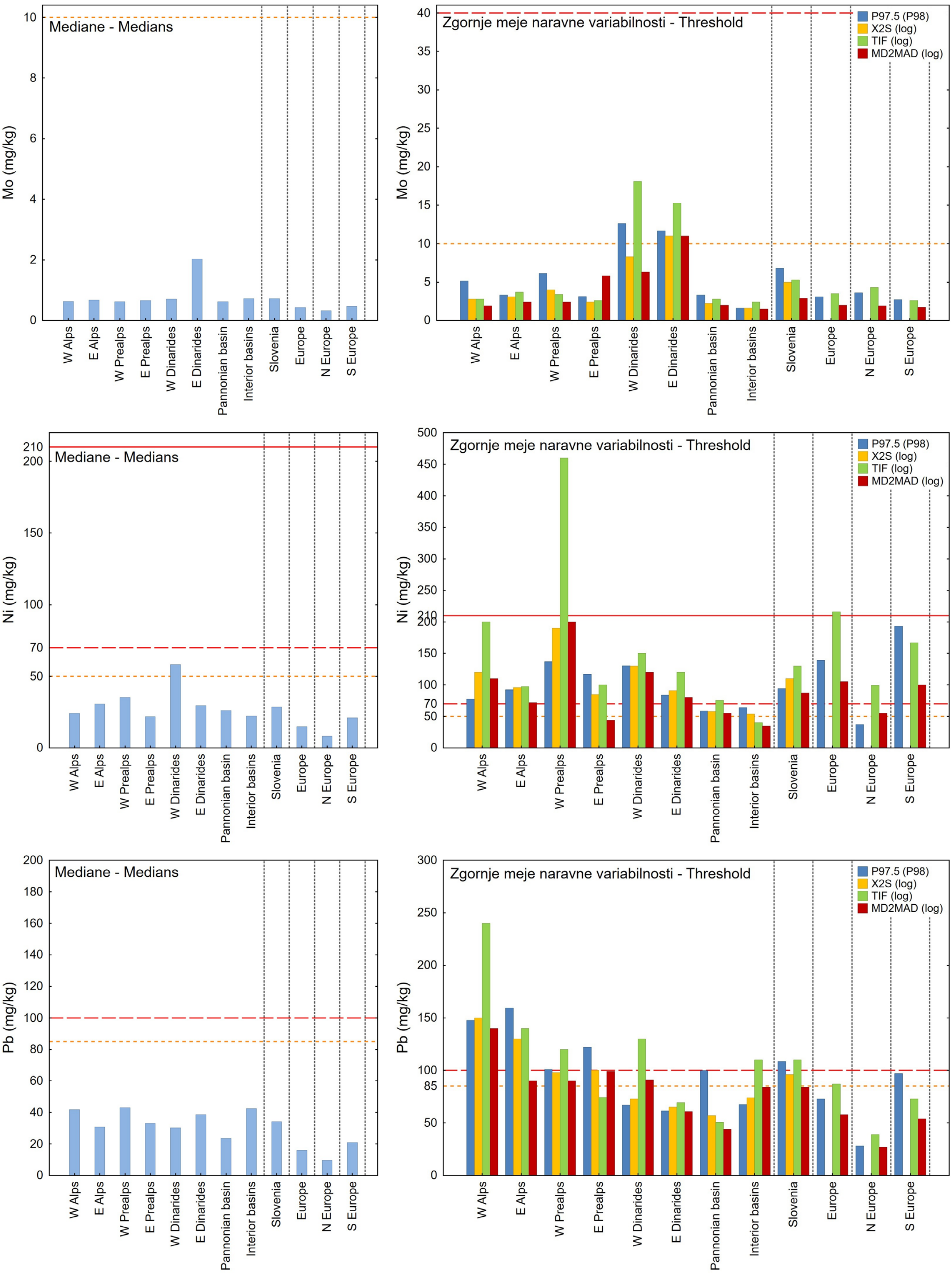

Fig. 14. Medians and thresholds calculated by different methods for molybdenum (Mo), nickel (Ni) and lead (Pb). European data are after Reimann et al. (2018). Markings: orange dotted line – limit soil value, red dotted line – warning soil value, red line – critical soil value (Official Gazette RS, 1996).

Sl. 14. Prikaz median in izračunanih zgornjih mej naravne variabilnosti po izbranih metodah za molibden (Mo), nikelj (Ni) in svinec (Pb). Podatki za Evropo po Reimann et al. (2018). Oznake na sliki: oranžna črtkana črta – mejna vrednost, rdeča prekinjena črta – opozorilna vrednost, polna rdeča črta – kritična vrednosti (Uradni list RS, 1996).

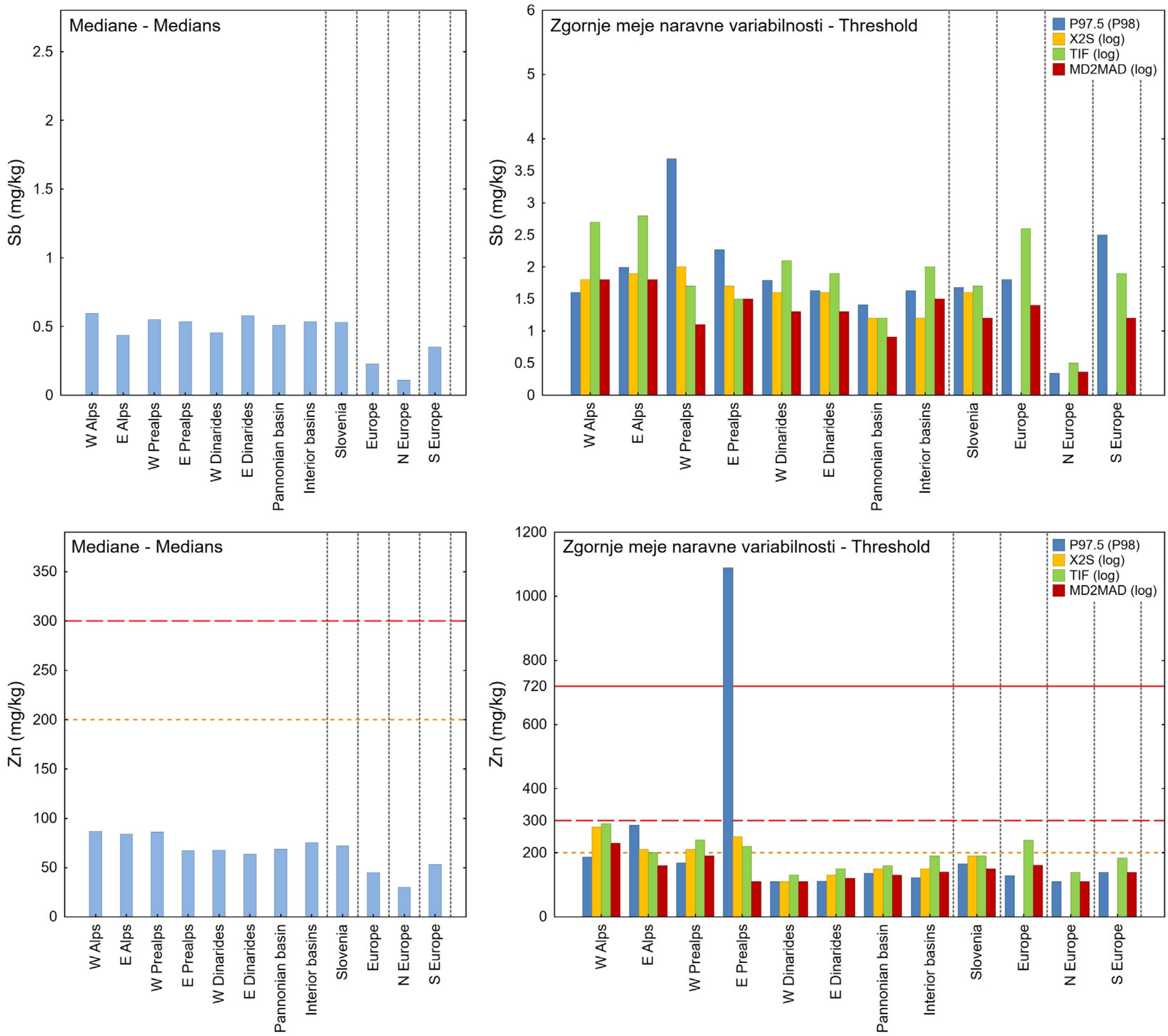

Fig. 15. Medians and thresholds calculated by different methods for antimony (Sb) and zinc (Zn). European data are after Reimann et al. (2018). Markings: orange dotted line – limit soil value, red dotted line – warning soil value, red line – critical soil value (Official Gazette RS, 1996).

Sl. 15. Prikaz median in izračunanih zgornjih mej naravne variabilnosti po izbranih metodah za antimon (Sb) in cink (Zn). Podatki za Evropo po Reimann et al. (2018). Oznake na sliki: oranžna črtkana črta – mejna vrednost, rdeča prekinjena črta – opozorilna vrednost, polna rdeča črta – kritična vrednosti (Uradni list RS, 1996).

Comparison with southern Europe shows that Cu median value in Slovenia (20 mg/kg) and southern Europe (19 mg/kg) are similar (fig. 13). Median values for As, Co, Cr, Mo, Ni, Pb, Sb and Zn are from 1.4 to 1.6 times higher in Slovenia than in southern Europe. Large differences between median values in Slovenia and southern Europe are for Cd (0.48 mg/kg in Slovenia and 0.22 mg/kg in southern Europe (Reimann et al., 2018)) and Hg (0.106 mg/kg in Slovenia (Gosar et al., 2016) and 0.036 mg/kg in southern Europe (Reimann et al., 2018)).

Calculated geochemical threshold values are similar between spatial units in Slovenia only for Sb (fig. 15). Smaller differences between spatial units are in case of As and Cr, where the thresh-

Primerjava z južno Evropo pokaže, da so si mediane Cu v Sloveniji (20 mg/kg) in južni Evropi (19 mg/kg) blizu (sl. 13). Vrednosti median As, Co, Cr, Mo, Ni, Pb, Sb in Zn so v Sloveniji od 1,4 krat do 1,6 krat višje kot v južni Evropi. Velike razlike med medianama Slovenije in južne Evrope smo ugotovili za Cd (0,48 mg/kg v Sloveniji in 0,22 mg/kg v južni Evropi (Reimann et al., 2018)) in Hg (0,106 mg/kg v Sloveniji (Gosar et al., 2016) in 0,036 mg/kg v južni Evropi (Reimann et al., 2018)).

Izračunane vrednosti zgornjih mej naravne variabilnosti so si med vsemi prostorskimi enotami v Sloveniji podobne le za Sb (sl. 15). Manjše razlike so pri As in Cr, kjer so vrednosti nižje le v Panonski nižini in Notranjih kotlinah. Nižje old values are lower only in the Pannonian basin and Interior basins. Lower geochemical threshold values in Pannonian basin and Interior basins are also for elements Co, Cu and Ni. Cobalt have lower values in Western Dinarides and Cu in Eastern Dinarides. Nickel has higher threshold values in also Western Prealps and Western Dinarides. In case of Zn, there are higher geochemical threshold values in Alps and Prealps. Large differences between spatial units are visible for Pb, where there are higher threshold values in Alps and lower values in Eastern Dinarides and Pannonian basin. Molybdenum threshold values are very high in Dinarides, compared to other spatial units. Greatest differences between spatial units are in case of Cd and Hg. Cadmium has higher geochemical threshold values in western Alps and Prealps (fig. 12) and Hg has higher values in Western Alps and highest threshold values in Western Prealps (fig. 13).

For comparison of geochemical threshold values between Slovenia and southern Europe we compared threshold values calculated using MD2MAD approach, since TIF values are very high due to wide interquartile range and percentile threshold values are too dependent on number of samples. For As, Co, Cr, Sb and Zn, MD2MAD values are similar or up to 20 % higher in Slovenia than in southern Europe. MD2MAD values for Ni and Cu are lower in Slovenia (Ni: 87 kg/kg, Cu: 54 mg/kg) than in southern Europe (Ni: 100 mg/kg, Cu: 73 mg/kg (Reimann et al. 2018)). For Mo and Pb, MD2MAD values in Slovenia are 1.5 to 1.7 times higher than in southern Europe. In Slovenia MD2MAD values for Hg are 2.6 times higher than in southern Europe, while threshold valued for Cd are 4.8 times higher than in southern Europe.

Conclusion

Slovenia was divided into smaller spatial units as homogeneous as possible. Spatial units are still very heterogeneous due to the high variability of the lithological parent material and soil type. Heterogeneity within an individual spatial unit is expressed by very different values of geochemical threshold, calculated by using different methods. Differences between calculated geochemical threshold values reflect the different concentrations of elements among spatial units and especially the high variability within individual units. Calculation of geochemical threshold using TIF method, that is based on the interquartile range (IQR), generally gives much higher values than other methods we used. This shows a high data variability between the first and third quartiles, which means a very high interquartile range (IQR).

vrednosti zgornjih mej naravne variabilnosti v Panonski nižini in Notranjih kotlinah so tudi pri Co, Cu in Ni. Kobalt ima nižje vrednosti tudi v Zahodnih Dinaridih, Cu pa v Vzhodnih Dinaridih. Ni ima višje vrednosti zgornjih mej naravne variabilnosti v Zahodnih Predalpah in Zahodnih Dinaridih. V primeru Zn so višje vrednosti zgornjih mej naravne variabilnosti v Alpah in Predalpah. Večje razlike med vrednostmi so pri Pb, kjer so višje vrednosti v Alpah ter nižje vrednosti v Vzhodnih Dinaridih in Panonski nižini. Zgornje meje naravne variabilnosti za Mo so v primerjavi z ostalimi prostorskimi enotami zelo visoke v Dinaridih. Največje razlike med prostorskimi enotami so v primeru Cd in Hg. Cd ima višje vrednosti zgornjih mej naravne variabilnosti v Zahodnih Alpah in Predalpah (sl. 12), Hg pa v Zahodnih Alpah ter najvišje v Zahodnih Predalpah (sl. 13).

Primerjavo zgornjih mej naravne variabilnosti med Slovenijo in južno Evropo smo naredili s primerjanjem vrednosti izračunanih po metodi MD2MAD, saj so vrednosti TIF zaradi velikega medkvartilnega razpona zelo visoke, vrednosti percentilov pa so zelo odvisne od števila vzorcev. Pri As, Co, Cr, Sb in Zn so si vrednosti MD2MAD podobne ali do 20 % višje kot v južni Evropi. Vrednosti MD2MAD za Ni in Cu sta nižji v Sloveniji (Ni: 87 mg/kg, Cu: 54 mg/kg) kot v južni Evropi (Ni: 100 mg/kg, Cu: 73 mg/kg (Reimann et al. 2018)). Pri Mo in Pb so vrednosti MD2MAD v Sloveniji 1,5 krat do 1,7 krat višje kot v južni Evropi. V Sloveniji so vrednosti MD2MAD za Hg 2,6 krat višje kot v južni Evropi, vrednosti za Cd pa so 4,8 krat višje v Sloveniji kot v južni Evropi.

Zaključek

Slovenijo smo poskušali razdeliti na čim bolj homogene prostorske enote, kar pa se je zaradi velike spremenljivosti v matični podlagi in talnem tipu izkazalo za praktično nemogoče. Heterogenost znotraj posameznih enot se izraža v zelo različnih vrednostih zgornjih mej naravne variabilnosti, izračunanih z različnimi metodami. V razlikah med izračunanimi zgornjimi mejami naravne variabilnosti se zrcalijo različne vsebnosti elementov po prostorskih enotah in še posebej velika spremenljivost znotraj posameznih enot. Izračun zgornje meje naravne variabilnosti z metodo TIF, ki temelji na medčetrtinskem razmiku (IQR), večinoma daje mnogo višje vrednosti kot druge uporabljene metode. V tem se kaže velika variabilnost podatkov že med prvim in tretjim kvartilom, torej zelo velik medčetrtinski razmik (IQR).

We conclude that in most cases TIF(L) values are very high, which is due to the already mentioned large interquartile range (IQR). Therefore, we focused on calculations based on methods X2S(L), MD2MAD(L) and P97.5. In case of an ideal normal distribution, all three of these methods give the same value. In smaller spatial units, calculated threshold values using methods X2S(L), MD2MAD(L) and P97.5 result in large differences. However, if we compare their values with the results that were calculated with data for whole of Slovenia, we see that they are much closer. This shows that the data set for whole Slovenia is more suitable for geostatistical analysis (larger number of samples) than data for individual spatial units. Whole Slovenia and smaller spatial units discussed in the present work are lithologically and consequently pedologically heterogeneous. More homogeneous units could be established by considering the geochemical features of the soil on a single lithology, which would be extremely demanding and time-consuming. The fragmentation of units and their number would not be appropriate.

Geochemical maps are suitable for showing spatial variability of chemical elements in the soil and for identifying areas with higher element concentrations. Geochemical maps are multilayer maps that are formed by connecting geochemical analyses and geographic-information systems. With geochemical maps, we identify spatial connections, for example, between higher element concentrations in soil and geogenic sources (lithological parent material) or anthropogenic sources (industry, traffic). At the Geological Survey of Slovenia, we

Ugotavljamo, da so vrednosti TIF(L) v večini primerov zelo visoke, kar je posledica že prej omenjenega velikega medčetrtinskega razmika (IQR). Zato smo se osredotočili na izračune po metodah X2S(L), MD2MAD(L) in P97.5. V primeru idealne normalne porazdelitve vse 3 omenjene metode dajo podobne vrednosti. V manjših prostorskih enotah so razlike med izračunanimi vrednostmi po metodah X2S(L), MD2MAD(L) in P97.5 večinoma velike. Če pa primerjamo te vrednosti z rezultati, ki so bili izračunani s podatki za celotno Slovenijo, vidimo, da so si le-te precej bliže. To kaže, da je set podatkov za celo Slovenijo primernejši za geostatistično obravnavo (večje število vzorcev) kot podatki po posameznih prostorskih enotah. Slovenija je namreč litološko in posledično še zlasti pedološko močno heterogena tudi v manjših prostorskih enotah. Bolj homogene enote bi morda lahko vzpostavili na podlagi geokemičnih lastnosti tal na enotni litološki podlagi, kar bi bilo izjemno zahtevno in zamudno. Razdrobljenost enot in njihovo število pa bi bila neustrezno velika.

Za pregled prostorske variabilnosti kemičnih elementov v tleh Slovenije in za identifikacijo območij s povišanimi vsebnostmi so zelo primerne tudi geokemične karte. Geokemične karte spadajo med večslojne zemljevide, ki jih tvorimo s povezovanjem geokemičnih analiz in geografsko-informacijskim sistemom v celoto. Z njimi ugotavljamo prostorske povezave, npr. med povišanimi koncentracijami elementov v tleh in geogenimi viri (matična kamninska podlaga) ali antropogenimi viri (industrija, promet). Na Geološkem zavodu Slovenije smo v preteklih

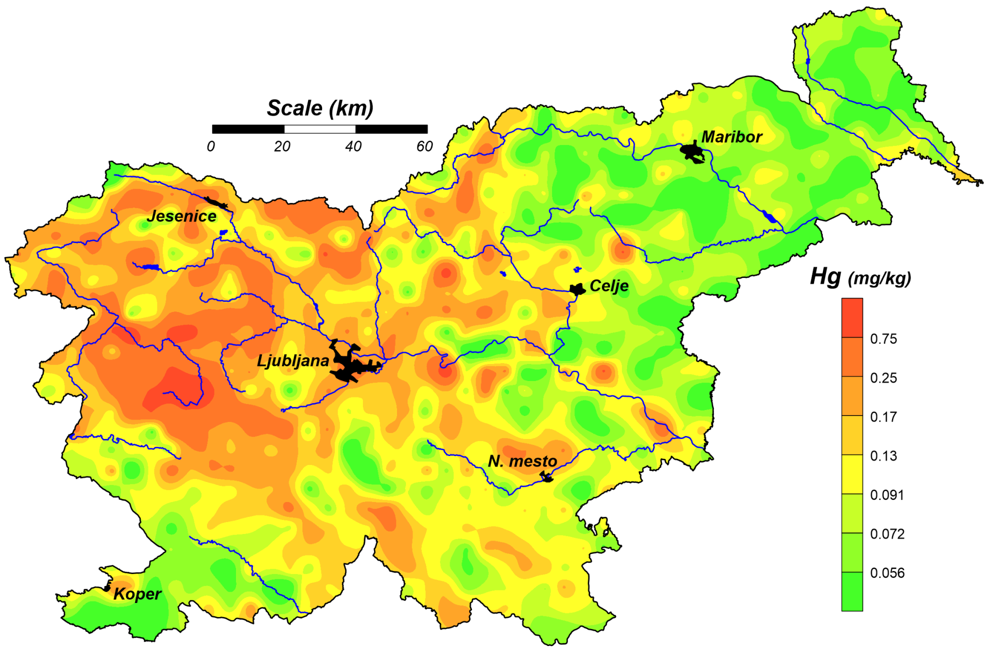

Fig. 16. Geochemical map of spatial mercury (Hg) distribution in Slovenian soil (after Gosar et al., 2016).

Sl. 16. Geokemična karta porazdelitve živega srebra (Hg) v tleh Slovenije (po Gosar et al., 2016) have produced a number of geochemical maps at different scales and participated in the preparing of geochemical atlases of Europe (Reimann et al., 2014; Salminen et al., 2005). We studied mercury concentrations in the Slovenian soil and published a geochemical map of mercury distribution in Slovenian soil (fig. 16) (Gosar et al., 2016). In the continuation of the presented work, it would be useful to create geochemical maps for 47 elements based on data set presented in this paper.

letih izdelali kar nekaj geokemičnih kart različnih meril in sodelovali pri izdelavi geokemičnih atlasov Evrope (Reimann et al., 2014; Salminen et al., 2005). Raziskovali smo vsebnosti živega srebra v tleh Slovenije in izdelali karto porazdelitve živega srebra v tleh Slovenije (sl. 16) (Gosar et al., 2016). V nadaljevanju predstavljenega dela bi bilo koristno na podlagi predstavljenih podatkov izdelati karte porazdelitev vseh obravnavanih elementov.

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We dedicate this paper to our teacher Emeritus Professor Dr. Simon Pirc and hope that he continues to monitor and evaluate the work of his students still for a long time.

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Appendix 1/1. Basic statistical parameters for Western Alps.
Priloga 1/1. Osnovni statistični parametri za Zahodne Alpe.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	84	70	67	12	410	51	110	2.43	11.34	−0.39	0.79
Al	%	1.8	1.4	1.7	0.090	4.6	0.99	2.5	0.31	−0.45	−1.27	1.46
As	mg/kg	13	11	12	0.85	80	7.2	16	3.51	19.21	−0.64	2.10
Au	µg/kg	1.9	1.2	1.3	0.10	34	0.70	2.3	8.04	73.47	−0.46	1.43
B	mg/kg	4.1	2.9	3.0	0.50	19	2.0	5.0	1.83	4.01	−0.39	−0.20
Ba	mg/kg	61	48	63	3.2	200	32	80	0.76	1.48	−1.21	1.32
Be	mg/kg	1.0	0.80	0.80	0.050	3.0	0.60	1.4	0.82	0.30	−1.04	1.52
Bi	mg/kg	0.43	0.38	0.39	0.050	1.1	0.29	0.56	0.96	1.12	−0.74	1.65
Ca	%	4.1	1.4	1.6	0.020	25	0.35	7.0	1.83	3.46	−0.23	−0.90
Cd	mg/kg	1.8	1.1	1.1	0.11	10	0.52	2.3	1.93	4.14	−0.00	−0.68
Ce	mg/kg	30	22	28	1.8	81	13	43	0.49	−0.69	−0.84	0.10
Co	mg/kg	11	8.5	11	0.50	32	5.3	15	0.58	0.17	−1.13	1.05
Cr	mg/kg	30	24	24	2.7	86	15	40	0.97	0.25	−0.40	−0.12
Cs	mg/kg	1.3	0.95	1.1	0.050	5.6	0.53	1.9	1.29	2.62	−0.93	0.88
Cu	mg/kg	22	18	19	1.4	86	13	28	1.72	5.02	−0.91	2.01
Fe	%	2.4	1.9	2.6	0.15	5.3	1.4	3.3	−0.25	−0.74	−1.44	1.43
Ga	mg/kg	4.6	3.6	4.4	0.20	14	2.3	6.3	0.57	0.22	−1.11	1.07
Hf	mg/kg	0.084	0.062	0.070	0.010	0.31	0.035	0.11	1.51	2.50	−0.34	−0.26
Hg	mg/kg	0.25	0.18	0.16	0.022	2.6	0.11	0.31	5.91	45.33	0.29	0.95
In	mg/kg	0.044	0.038	0.040	0.010	0.11	0.030	0.060	0.26	0.30	−1.12	0.60
K	%	0.12	0.098	0.11	0.0050	0.40	0.070	0.15	1.35	2.70	−1.09	3.35
La	mg/kg	15	10	11	1.0	62	5.7	20	1.31	1.85	−0.51	−0.18
Li	mg/kg	15	11	15	0.30	41	6.6	21	0.48	−0.09	−1.31	1.89
Mg	%	1.6	0.76	0.57	0.030	9.3	0.33	2.3	1.87	2.64	0.45	−0.31
Mn	mg/kg	910	650	770	31	5700	400	1300	2.78	14.40	−0.74	0.74
Mo	mg/kg	0.90	0.64	0.63	0.070	6.4	0.41	0.89	3.51	12.71	0.96	2.40
Na	%	0.0083	0.0068	0.0070	0.0010	0.052	0.0050	0.010	4.02	20.73	0.32	1.78
Nb	mg/kg	0.67	0.45	0.45	0.040	3.2	0.22	0.79	1.75	3.13	−0.14	−0.35
Ni	mg/kg	27	19	24	0.80	79	12	36	0.94	0.61	−0.98	0.97
P	%	0.079	0.062	0.056	0.011	0.33	0.043	0.095	1.90	3.60	0.14	0.14
Pb	mg/kg	53	44	42	8.5	150	30	70	1.20	0.94	−0.12	−0.17
Rb	mg/kg	14	11	13	0.40	49	7.6	19	0.91	2.03	−1.30	2.39
S	%	0.069	0.046	0.050	0.010	0.34	0.030	0.090	1.86	3.45	−0.02	−0.55
Sb	mg/kg	0.68	0.57	0.59	0.070	3.1	0.42	0.89	2.53	11.05	−0.32	1.33
Sc	mg/kg	3.8	2.9	3.4	0.20	12	1.8	5.3	0.91	0.47	−0.76	0.45
Se	mg/kg	0.59	0.46	0.40	0.050	2.5	0.30	0.80	1.97	4.99	−0.19	0.48
Sn	mg/kg	1.4	1.2	1.3	0.10	3.7	0.90	1.8	0.89	0.59	−0.98	2.12
Sr	mg/kg	25	18	18	2.8	97	9.5	35	1.49	1.90	0.08	−0.75
Te	mg/kg	0.060	0.040	0.050	0.010	0.23	0.015	0.090	1.27	1.07	−0.14	−1.11
Th	mg/kg	2.8	1.9	2.4	0.050	9.9	1.1	3.9	1.15	0.94	−0.87	1.19
Ti	%	0.011	0.0039	0.0030	0.0005	0.19	0.0020	0.0070	4.81	24.50	0.90	1.82
Tl	mg/kg	0.36	0.30	0.31	0.060	1.1	0.18	0.53	0.92	0.46	−0.20	−0.74
U	mg/kg	0.75	0.67	0.70	0.10	1.9	0.50	1.0	1.00	0.98	−0.53	1.33
V	mg/kg	37	30	39	3.0	150	21	48	1.51	6.23	−0.91	0.77
Y	mg/kg	16	10	9.7	0.78	100	6.3	19	2.44	7.54	−0.17	0.10
Zn	mg/kg	94	80	87	9.2	510	62	110	3.62	23.28	−1.05	2.85
Zr	mg/kg	2.4	1.8	2.0	0.20	8.9	1.0	3.2	1.52	2.38	−0.35	−0.03

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/2. Basic statistical parameters for Eastern Alps.
Priloga 1/2. Osnovni statistični parametri za Vzhodne Alpe.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	90	61	60	1.0	580	37	120	2.85	11.44	–0.90	3.58
Al	%	2.2	2.1	2.2	0.34	5.7	1.7	2.7	0.77	2.80	–1.23	3.31
As	mg/kg	12	7.5	7.2	1.6	140	4.6	12	5.05	29.90	0.73	1.35
Au	µg/kg	3.1	1.4	1.3	0.10	58	0.95	2.5	6.04	40.84	0.12	1.78
B	mg/kg	2.3	1.6	2.0	0.50	9.5	0.50	3.0	1.62	2.99	0.03	–1.19
Ba	mg/kg	91	78	78	14	310	59	110	1.68	3.68	–0.41	1.12
Be	mg/kg	0.92	0.84	0.90	0.20	2.2	0.70	1.1	0.93	1.83	–0.84	2.00
Bi	mg/kg	0.30	0.26	0.27	0.020	1.3	0.19	0.38	2.28	9.18	–0.96	3.48
Ca	%	1.1	0.29	0.23	0.020	17	0.12	0.52	4.41	20.27	0.70	0.71
Cd	mg/kg	0.44	0.31	0.31	0.040	2.2	0.17	0.54	2.44	6.56	0.21	0.06
Ce	mg/kg	34	31	33	5.4	65	25	44	0.13	–0.60	–1.17	1.69
Co	mg/kg	15	13	14	2.1	55	9.6	17	1.81	4.93	–0.53	1.14
Cr	mg/kg	40	32	33	6.3	210	23	46	3.05	12.13	0.02	0.72
Cs	mg/kg	2.0	1.7	1.8	0.34	7.0	0.96	2.6	1.23	2.19	–0.30	–0.36
Cu	mg/kg	30	23	25	1.7	220	17	33	4.59	29.73	–0.58	2.13
Fe	%	3.4	3.1	3.3	0.41	10	2.7	3.9	1.92	8.13	–1.47	6.17
Ga	mg/kg	6.7	6.1	6.5	0.90	19	4.8	8.1	1.16	2.96	–0.97	2.70
Hf	mg/kg	0.025	0.017	0.010	0.010	0.19	0.010	0.030	3.13	11.99	1.31	0.72
Hg	mg/kg	0.10	0.080	0.078	0.012	0.67	0.056	0.12	4.29	21.39	0.31	2.22
In	mg/kg	0.037	0.031	0.030	0.010	0.15	0.025	0.040	2.41	9.30	–0.23	0.66
K	%	0.19	0.16	0.16	0.040	1.0	0.11	0.21	3.45	13.80	0.49	1.50
La	mg/kg	16	14	16	2.1	30	11	20	0.04	–0.59	–1.27	2.00
Li	mg/kg	27	23	25	3.6	130	19	33	3.10	16.70	–0.74	1.85
Mg	%	1.2	0.81	0.69	0.090	9.3	0.53	1.1	4.05	16.87	1.04	2.97
Mn	mg/kg	720	620	630	150	2800	460	840	2.39	7.41	0.16	0.68
Mo	mg/kg	0.93	0.69	0.68	0.13	7.9	0.50	1.1	4.76	29.94	0.08	0.87
Na	%	0.014	0.011	0.012	0.0010	0.057	0.0070	0.018	1.78	4.64	–0.79	1.12
Nb	mg/kg	1.1	0.67	0.73	0.060	7.8	0.31	1.3	2.85	11.80	–0.15	–0.34
Ni	mg/kg	32	27	31	3.7	130	20	38	2.22	8.74	–0.86	1.43
P	%	0.072	0.065	0.063	0.028	0.19	0.049	0.085	1.45	2.44	0.25	–0.22
Pb	mg/kg	41	32	31	6.2	170	23	47	2.29	5.44	0.24	0.41
Rb	mg/kg	23	19	19	5.1	94	14	25	2.19	6.30	0.16	0.48
S	%	0.031	0.025	0.030	0.010	0.090	0.010	0.040	0.85	0.61	–0.27	–1.14
Sb	mg/kg	0.59	0.44	0.44	0.070	4.7	0.27	0.69	4.51	27.48	0.22	0.83
Sc	mg/kg	4.6	3.9	4.0	0.70	19	2.7	5.7	2.24	8.18	–0.08	0.61
Se	mg/kg	0.40	0.32	0.35	0.050	1.2	0.20	0.50	1.02	1.02	–0.85	0.67
Sn	mg/kg	1.4	0.94	0.90	0.20	25	0.70	1.3	8.05	68.54	1.68	8.02
Sr	mg/kg	22	14	13	3.2	390	8.8	24	7.95	67.75	0.92	3.17
Te	mg/kg	0.030	0.023	0.022	0.010	0.090	0.010	0.040	0.93	0.18	0.10	–1.46
Th	mg/kg	3.9	3.2	3.6	0.40	9.2	2.4	5.5	0.37	–0.56	–1.18	1.23
Ti	%	0.041	0.016	0.016	0.0020	0.29	0.0040	0.058	2.25	5.65	0.12	–1.21
Tl	mg/kg	0.23	0.21	0.21	0.060	0.64	0.16	0.30	1.24	2.29	–0.25	0.06
U	mg/kg	1.2	1.0	0.90	0.10	5.0	0.70	1.5	2.26	5.64	0.07	1.42
V	mg/kg	51	43	39	6.0	190	30	59	2.29	5.70	0.31	1.75
Y	mg/kg	9.0	7.8	8.3	2.4	33	5.5	11	1.79	5.41	–0.00	–0.12
Zn	mg/kg	95	85	84	17	410	68	110	3.25	13.66	0.34	3.24
Zr	mg/kg	0.75	0.41	0.50	0.050	4.7	0.20	0.97	2.43	7.10	–0.24	–0.59

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/3. Basic statistical parameters for Western Prealps.
Priloga 1/3. Osnovni statistični parametri za Zahodne Predalpe.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	91	78	83	11	570	57	110	4.47	30.62	–0.21	1.89
Al	%	2.0	1.8	1.9	0.41	3.9	1.5	2.5	0.10	–0.68	–0.90	0.67
As	mg/kg	13	11	11	1.1	52	8.0	16	2.23	7.79	–0.64	2.21
Au	µg/kg	2.6	1.9	2.0	0.10	17	1.4	2.7	3.47	16.32	–0.60	2.84
B	mg/kg	2.9	2.2	2.0	0.50	9.0	1.0	4.0	0.81	0.23	–0.52	–0.65
Ba	mg/kg	78	67	71	9.1	230	50	100	1.02	1.50	–0.69	0.98
Be	mg/kg	1.1	0.89	1.0	0.050	3.5	0.70	1.5	0.90	1.23	–1.44	3.54
Bi	mg/kg	0.47	0.43	0.45	0.16	1.1	0.32	0.57	0.81	0.42	–0.21	–0.31
Ca	%	1.5	0.51	0.52	0.020	13	0.20	1.3	2.70	7.46	–0.12	–0.33
Cd	mg/kg	0.94	0.59	0.56	0.0050	4.6	0.28	1.4	1.85	3.82	–0.86	2.82
Ce	mg/kg	36	29	32	2.4	110	19	48	0.78	0.72	–0.88	0.69
Co	mg/kg	15	12	16	0.50	36	8.2	20	0.20	–0.36	–1.81	4.71
Cr	mg/kg	37	29	36	2.6	120	19	51	0.84	1.35	–0.91	0.56
Cs	mg/kg	1.5	1.2	1.4	0.060	4.1	0.74	2.1	0.61	–0.22	–0.93	1.40
Cu	mg/kg	30	24	25	3.4	100	15	37	1.62	3.04	–0.12	0.02
Fe	%	2.9	2.7	2.9	0.24	4.9	2.5	3.5	–0.55	0.38	–2.60	9.95
Ga	mg/kg	5.1	4.6	5.0	1.2	9.5	3.8	6.6	0.08	–0.72	–0.76	–0.09
Hf	mg/kg	0.091	0.069	0.080	0.010	0.36	0.050	0.12	1.51	3.03	–0.69	0.41
Hg	mg/kg	0.44	0.28	0.27	0.046	5.3	0.16	0.42	5.32	31.96	0.76	1.60
In	mg/kg	0.044	0.039	0.040	0.010	0.11	0.030	0.050	0.73	1.20	–0.99	1.23
K	%	0.13	0.12	0.12	0.040	0.29	0.090	0.16	0.87	0.49	–0.20	–0.04
La	mg/kg	17	13	15	1.1	82	7.8	22	2.26	7.36	–0.49	0.20
Li	mg/kg	23	19	20	1.0	69	14	29	1.16	1.54	–1.25	3.08
Mg	%	0.87	0.51	0.45	0.030	8.0	0.33	0.75	3.55	13.44	0.36	1.51
Mn	mg/kg	1200	850	1000	17	7200	560	1500	3.22	18.68	–1.59	4.62
Mo	mg/kg	1.1	0.68	0.62	0.10	12	0.39	0.93	4.03	20.29	0.91	1.41
Na	%	0.0061	0.0050	0.0060	0.0010	0.017	0.0030	0.0080	0.97	0.77	–0.47	–0.19
Nb	mg/kg	0.65	0.42	0.44	0.040	2.8	0.20	0.97	1.30	1.24	–0.15	–0.70
Ni	mg/kg	42	30	35	1.4	250	15	58	2.44	10.20	–0.64	0.67
P	%	0.072	0.059	0.064	0.0090	0.22	0.039	0.098	1.24	1.76	–0.48	0.22
Pb	mg/kg	46	42	43	14	110	32	54	1.21	1.81	–0.04	0.06
Rb	mg/kg	18	16	16	4.1	39	13	23	0.65	0.04	–0.53	0.42
S	%	0.048	0.040	0.040	0.010	0.17	0.030	0.060	1.67	4.98	–0.54	0.17
Sb	mg/kg	0.80	0.61	0.55	0.21	8.9	0.45	0.76	5.84	39.54	1.78	5.26
Sc	mg/kg	4.2	3.6	4.2	0.50	13	2.8	5.3	0.82	2.10	–0.92	1.00
Se	mg/kg	0.55	0.48	0.50	0.10	1.5	0.30	0.70	1.12	0.88	–0.08	–0.29
Sn	mg/kg	1.5	1.3	1.3	0.37	5.6	0.80	2.0	1.76	5.10	0.13	–0.49
Sr	mg/kg	19	12	12	1.6	230	7.4	22	5.63	41.28	0.34	0.75
Te	mg/kg	0.063	0.047	0.060	0.010	0.20	0.030	0.080	0.94	0.74	–0.59	–0.60
Th	mg/kg	3.9	3.5	3.5	0.60	8.8	2.6	4.9	0.72	–0.02	–0.63	0.92
Ti	%	0.0042	0.0027	0.0030	0.0005	0.026	0.0010	0.0060	2.23	6.56	–0.11	–0.67
Tl	mg/kg	0.33	0.28	0.25	0.080	1.1	0.18	0.45	1.33	1.44	0.28	–0.68
U	mg/kg	1.0	0.81	0.75	0.20	5.2	0.50	1.3	2.29	7.89	0.18	–0.25
V	mg/kg	46	37	41	6.0	160	24	57	1.52	2.95	–0.43	0.02
Y	mg/kg	17	11	13	1.0	110	6.4	19	3.67	15.31	–0.20	0.74
Zn	mg/kg	88	80	86	11	190	64	110	0.46	0.02	–1.11	2.63
Zr	mg/kg	2.7	2.1	2.1	0.30	11	1.3	3.6	1.63	2.95	–0.18	–0.14

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/4. Basic statistical parameters for Eastern Prealps.
Priloga 1/4. Osnovni statistični parametri za Vzhodne Predalpe.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	71	55	55	15	1000	42	73	8.00	74.60	1.01	4.13
Al	%	1.6	1.4	1.6	0.26	3.5	1.1	1.9	0.66	0.31	-0.80	1.42
As	mg/kg	13	11	11	2.0	50	8.4	15	2.23	7.75	-0.51	1.24
Au	µg/kg	2.4	1.7	1.6	0.20	41	1.2	2.5	8.42	80.99	0.59	3.78
B	mg/kg	2.9	1.9	2.0	0.50	18	1.0	4.0	2.10	5.75	0.12	-0.94
Ba	mg/kg	88	70	70	17	820	47	100	5.73	44.76	0.49	1.43
Be	mg/kg	0.93	0.79	0.70	0.20	2.6	0.60	1.2	1.27	1.04	0.12	-0.42
Bi	mg/kg	0.31	0.29	0.30	0.090	0.75	0.23	0.39	0.72	1.06	-0.57	0.36
Ca	%	2.4	0.48	0.36	0.0050	17	0.15	2.4	1.99	2.91	0.04	-0.65
Cd	mg/kg	0.96	0.53	0.52	0.030	11	0.28	1.0	4.20	22.35	0.09	0.27
Ce	mg/kg	35	30	33	5.3	93	23	46	0.67	0.59	-0.87	0.42
Co	mg/kg	16	12	12	2.3	74	8.0	17	2.32	6.21	0.06	0.26
Cr	mg/kg	33	27	26	5.7	210	16	40	3.43	20.96	0.12	-0.08
Cs	mg/kg	1.4	1.2	1.4	0.14	5.2	0.79	2.0	1.12	2.23	-0.75	0.52
Cu	mg/kg	24	19	18	3.9	300	13	28	7.07	59.93	0.43	2.43
Fe	%	2.6	2.4	2.5	0.47	4.8	2.1	3.2	0.07	-0.30	-1.23	1.99
Ga	mg/kg	4.4	3.9	4.1	0.60	10	2.9	5.5	0.67	-0.04	-0.69	0.76
Hf	mg/kg	0.064	0.047	0.050	0.010	0.30	0.030	0.090	1.73	4.29	-0.31	-0.45
Hg	mg/kg	0.17	0.12	0.11	0.015	3.9	0.076	0.18	9.36	94.46	0.91	4.35
In	mg/kg	0.038	0.030	0.030	0.010	0.25	0.020	0.050	3.98	21.25	0.11	0.50
K	%	0.13	0.11	0.11	0.040	0.65	0.080	0.15	3.39	15.22	0.84	1.52
La	mg/kg	17	14	15	2.1	46	10	22	0.74	0.36	-0.83	0.59
Li	mg/kg	17	15	16	2.6	64	11	20	1.73	5.20	-0.52	0.87
Mg	%	1.2	0.47	0.38	0.040	9.9	0.22	0.73	2.71	6.54	0.83	0.41
Mn	mg/kg	940	680	720	54	3300	410	1100	1.50	1.67	-0.28	0.02
Mo	mg/kg	0.83	0.65	0.65	0.095	6.0	0.46	0.93	3.88	20.29	0.21	1.64
Na	%	0.0082	0.0065	0.0070	0.0005	0.043	0.0050	0.011	2.50	11.91	-1.01	2.62
Nb	mg/kg	0.53	0.40	0.45	0.025	1.7	0.26	0.71	1.21	1.51	-0.77	0.74
Ni	mg/kg	30	22	22	4.7	500	15	32	8.50	82.15	0.87	3.59
P	%	0.064	0.050	0.050	0.010	0.52	0.033	0.075	4.67	30.84	0.40	1.07
Pb	mg/kg	43	33	33	6.2	850	27	40	9.70	99.95	1.22	9.13
Rb	mg/kg	16	14	15	3.1	37	11	21	0.59	-0.14	-0.59	0.06
S	%	0.036	0.029	0.030	0.010	0.20	0.020	0.040	2.76	13.75	-0.18	-0.31
Sb	mg/kg	0.63	0.53	0.54	0.13	4.0	0.40	0.68	3.84	19.80	0.32	1.71
Sc	mg/kg	3.8	3.3	3.1	1.0	12	2.3	4.4	1.58	2.43	0.33	-0.12
Se	mg/kg	0.36	0.29	0.30	0.050	0.90	0.20	0.50	0.45	-0.55	-0.90	0.31
Sn	mg/kg	1.1	0.97	1.0	0.25	6.0	0.70	1.4	3.14	15.43	0.32	0.72
Sr	mg/kg	44	16	13	1.7	940	7.8	34	5.75	38.59	0.98	1.22
Te	mg/kg	0.055	0.037	0.040	0.010	0.24	0.020	0.080	1.42	1.98	-0.06	-1.08
Th	mg/kg	4.4	3.8	4.3	0.50	11	3.1	5.6	0.32	0.29	-1.54	3.26
Ti	%	0.0055	0.0039	0.0050	0.0005	0.019	0.0020	0.0080	1.11	0.89	-0.61	-0.20
Tl	mg/kg	0.24	0.20	0.21	0.050	1.2	0.15	0.28	2.39	9.95	-0.01	0.10
U	mg/kg	1.1	0.93	0.90	0.10	4.6	0.70	1.2	2.56	8.32	-0.03	2.13
V	mg/kg	36	30	29	7.0	150	21	43	1.94	5.15	0.26	-0.14
Y	mg/kg	13	9.7	9.1	1.2	57	5.4	18	1.79	3.28	0.13	-0.50
Zn	mg/kg	99	68	67	16	1400	48	88	5.98	36.09	1.97	8.74
Zr	mg/kg	2.2	1.7	1.6	0.30	7.4	1.1	3.0	1.17	0.88	-0.12	-0.53

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/5. Basic statistical parameters for Western Dinarides.
Priloga 1/5. Osnovni statistični parametri za Zahodne Dinaride.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	81	74	74	21	170	55	110	0.49	–0.58	–0.46	0.07
Al	%	2.1	1.9	1.9	0.62	4.7	1.4	2.5	1.06	0.93	0.00	0.01
As	mg/kg	12	10	9.8	4.3	27	6.6	16	0.83	–0.29	0.14	–1.04
Au	µg/kg	2.7	2.1	2.5	0.10	14	1.6	3.1	3.30	17.01	–1.29	4.38
B	mg/kg	2.7	2.3	2.5	0.50	8.0	2.0	4.0	0.79	0.96	–0.84	0.23
Ba	mg/kg	99	90	95	31	310	67	120	1.69	6.07	–0.11	0.15
Be	mg/kg	1.2	0.99	0.93	0.40	2.6	0.60	1.6	0.63	–0.87	0.08	–1.35
Bi	mg/kg	0.40	0.35	0.37	0.090	0.82	0.24	0.52	0.52	–0.64	–0.38	–0.36
Ca	%	3.4	1.2	0.86	0.040	17	0.44	4.5	1.50	0.83	0.31	–0.77
Cd	mg/kg	0.73	0.48	0.40	0.060	2.8	0.23	0.95	1.47	1.07	0.30	–0.75
Ce	mg/kg	34	28	29	9.2	75	19	50	0.46	–1.10	–0.14	–1.27
Co	mg/kg	18	18	17	9.0	29	15	21	0.34	–0.31	–0.31	–0.24
Cr	mg/kg	62	55	51	21	190	39	72	1.82	3.36	0.67	0.04
Cs	mg/kg	1.2	0.96	0.95	0.29	3.9	0.60	1.5	1.52	1.88	0.16	–0.60
Cu	mg/kg	40	33	30	14	240	24	41	4.52	21.98	1.83	5.24
Fe	%	3.0	2.9	3.1	1.5	4.8	2.3	3.6	0.08	–0.92	–0.35	–0.78
Ga	mg/kg	5.9	5.4	5.5	2.1	13	4.0	7.5	0.82	0.15	–0.02	–0.66
Hf	mg/kg	0.11	0.084	0.085	0.010	0.26	0.050	0.16	0.58	–0.94	–0.33	–0.41
Hg	mg/kg	0.096	0.080	0.076	0.016	0.40	0.058	0.11	2.48	7.53	0.28	1.04
In	mg/kg	0.043	0.037	0.040	0.010	0.090	0.030	0.060	0.19	–0.65	–0.86	0.05
K	%	0.16	0.15	0.15	0.050	0.37	0.12	0.19	0.94	1.35	–0.22	0.08
La	mg/kg	16	13	14	3.3	37	7.2	23	0.62	–0.86	–0.14	–1.14
Li	mg/kg	19	18	19	8.3	33	15	22	0.49	–0.46	–0.16	–0.47
Mg	%	0.50	0.40	0.39	0.15	4.3	0.31	0.48	5.40	31.14	1.86	7.49
Mn	mg/kg	1200	1100	980	400	2600	790	1300	1.10	0.49	0.25	–0.38
Mo	mg/kg	1.8	0.94	0.71	0.17	15	0.39	1.8	3.13	11.39	0.67	–0.32
Na	%	0.0061	0.0053	0.0060	0.0005	0.015	0.0040	0.0070	0.55	0.82	–1.85	4.92
Nb	mg/kg	0.78	0.42	0.30	0.050	2.9	0.14	1.5	0.95	–0.33	0.15	–1.50
Ni	mg/kg	64	60	58	22	130	50	78	0.94	0.73	–0.08	0.11
P	%	0.050	0.045	0.046	0.013	0.14	0.036	0.059	1.33	3.51	–0.40	0.78
Pb	mg/kg	33	30	30	13	68	21	44	0.41	–0.65	–0.22	–1.00
Rb	mg/kg	19	18	17	9.7	44	15	22	1.44	1.63	0.66	0.03
S	%	0.049	0.037	0.040	0.010	0.21	0.020	0.060	2.11	5.48	–0.11	–0.34
Sb	mg/kg	0.55	0.45	0.46	0.060	2.7	0.30	0.65	2.94	12.25	–0.06	1.47
Sc	mg/kg	5.2	4.8	4.7	2.1	9.5	3.8	6.7	0.37	–0.70	–0.27	–0.75
Se	mg/kg	0.48	0.40	0.40	0.050	1.7	0.30	0.60	2.07	6.58	–0.89	2.65
Sn	mg/kg	1.4	1.2	1.2	0.30	9.4	0.80	2.0	4.90	32.27	0.37	1.59
Sr	mg/kg	57	27	21	2.9	450	12	55	2.46	7.07	0.67	–0.42
Te	mg/kg	0.076	0.068	0.080	0.010	0.14	0.050	0.10	–0.21	–0.61	–1.37	1.89
Th	mg/kg	4.1	3.7	3.8	1.5	10	2.4	5.6	1.01	0.64	0.07	–0.80
Ti	%	0.0054	0.0035	0.0030	0.0005	0.028	0.0020	0.0080	2.00	4.19	0.23	–0.61
Tl	mg/kg	0.29	0.23	0.20	0.080	0.81	0.13	0.42	0.93	–0.27	0.31	–1.31
U	mg/kg	0.76	0.65	0.60	0.20	1.9	0.40	1.1	0.88	–0.29	0.13	–1.01
V	mg/kg	76	58	46	16	230	31	110	1.17	0.14	0.48	–1.09
Y	mg/kg	15	13	13	2.4	45	9.1	20	1.29	2.11	–0.45	0.60
Zn	mg/kg	70	68	68	39	120	58	81	0.62	0.18	–0.01	–0.34
Zr	mg/kg	3.6	2.7	2.3	0.70	12	1.4	5.8	1.06	0.24	0.22	–1.34

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/6. Basic statistical parameters for Eastern Dinarides.
Priloga 1/6. Osnovni statistični parametri za Vzhodne Dinaride.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	64	55	54	12	240	39	79	1.91	5.34	–0.07	0.32
Al	%	2.2	2.1	2.2	0.35	4.3	1.8	2.7	–0.00	0.40	–1.74	4.89
As	mg/kg	15	14	14	2.9	56	11	18	2.26	8.41	–0.22	1.79
Au	µg/kg	1.9	1.5	1.6	0.10	8.2	1.0	2.4	2.02	6.00	–1.02	2.42
B	mg/kg	2.6	1.6	2.0	0.50	36	1.0	3.0	5.97	47.54	0.35	–0.03
Ba	mg/kg	80	74	77	15	200	58	97	1.28	3.69	–0.75	2.37
Be	mg/kg	1.4	1.2	1.4	0.20	3.3	1.0	1.7	0.28	0.31	–1.21	2.30
Bi	mg/kg	0.39	0.37	0.37	0.10	0.86	0.30	0.47	0.61	0.49	–0.69	1.39
Ca	%	1.7	0.61	0.57	0.0050	14	0.23	1.7	2.76	7.92	–0.01	0.03
Cd	mg/kg	0.86	0.64	0.65	0.060	5.9	0.42	1.1	3.03	13.71	–0.17	0.56
Ce	mg/kg	55	50	56	5.7	130	46	66	0.14	1.91	–1.93	4.83
Co	mg/kg	20	18	19	2.0	65	14	26	1.34	2.92	–0.96	2.08
Cr	mg/kg	47	44	46	6.9	110	39	57	0.16	1.41	–1.69	3.93
Cs	mg/kg	2.0	1.7	2.0	0.23	6.4	1.3	2.6	0.68	1.80	–1.09	1.15
Cu	mg/kg	18	17	16	3.6	99	13	21	3.90	23.05	0.35	2.61
Fe	%	3.0	2.8	3.0	0.48	5.7	2.7	3.5	–0.43	1.64	–2.39	7.95
Ga	mg/kg	6.5	6.0	6.4	1.0	13	5.4	7.6	0.05	1.14	–1.86	4.98
Hf	mg/kg	0.10	0.085	0.090	0.010	0.37	0.055	0.13	1.35	2.36	–0.34	0.23
Hg	mg/kg	0.13	0.12	0.12	0.025	0.45	0.086	0.16	1.63	4.09	–0.16	0.43
In	mg/kg	0.046	0.042	0.040	0.010	0.10	0.030	0.060	0.53	0.63	–1.20	2.63
K	%	0.12	0.10	0.10	0.020	0.86	0.080	0.12	5.66	41.51	0.95	4.48
La	mg/kg	24	22	24	2.8	65	19	30	0.35	1.86	–1.64	3.69
Li	mg/kg	21	19	20	2.7	150	15	25	6.21	48.20	–0.15	4.21
Mg	%	1.0	0.55	0.43	0.10	9.2	0.30	0.74	2.97	9.31	1.10	0.71
Mn	mg/kg	1200	1000	1100	170	4200	680	1600	1.28	2.28	–0.32	–0.21
Mo	mg/kg	3.1	2.0	2.0	0.31	38	1.1	3.1	5.24	35.43	0.49	0.52
Na	%	0.0060	0.0047	0.0060	0.0005	0.019	0.0030	0.0080	0.96	1.24	–1.08	1.09
Nb	mg/kg	1.1	0.93	1.0	0.070	2.5	0.72	1.3	0.50	0.21	–1.48	3.49
Ni	mg/kg	35	31	30	5.4	150	22	44	1.84	6.28	–0.22	0.58
P	%	0.048	0.039	0.038	0.0060	0.44	0.027	0.060	5.56	42.85	0.47	1.96
Pb	mg/kg	38	37	39	13	78	32	44	0.40	1.33	–0.84	1.84
Rb	mg/kg	22	20	22	3.3	52	18	26	0.36	1.38	–1.39	3.16
S	%	0.042	0.033	0.030	0.010	0.23	0.020	0.050	2.63	9.58	–0.01	–0.21
Sb	mg/kg	0.68	0.60	0.58	0.13	3.0	0.46	0.81	2.51	11.21	–0.07	1.35
Sc	mg/kg	4.8	4.4	4.8	0.60	11	3.6	5.9	0.38	0.74	–1.44	3.40
Se	mg/kg	0.44	0.36	0.40	0.050	1.6	0.30	0.50	1.64	3.81	–0.96	1.86
Sn	mg/kg	1.4	1.3	1.3	0.30	5.0	1.0	1.7	2.09	11.11	–0.51	1.93
Sr	mg/kg	21	13	12	2.6	240	7.5	20	4.18	21.95	0.80	0.80
Te	mg/kg	0.057	0.045	0.050	0.010	0.17	0.030	0.070	0.93	0.80	–0.72	–0.14
Th	mg/kg	5.7	5.1	5.6	0.30	17	4.6	7.1	0.45	2.37	–2.03	5.65
Ti	%	0.0076	0.0064	0.0070	0.0005	0.021	0.0040	0.010	0.74	0.37	–0.84	1.25
Tl	mg/kg	0.53	0.46	0.48	0.10	1.3	0.34	0.68	0.80	0.56	–0.59	0.21
U	mg/kg	1.6	1.4	1.4	0.30	6.2	1.1	2.0	2.06	9.77	–0.53	1.65
V	mg/kg	74	67	70	13	200	54	87	1.25	2.52	–0.63	1.41
Y	mg/kg	16	13	14	2.1	59	9.0	20	1.90	4.96	–0.20	0.52
Zn	mg/kg	65	62	64	17	130	50	76	0.53	0.38	–0.64	1.08
Zr	mg/kg	4.0	3.5	3.5	0.60	11	2.6	4.9	0.93	0.77	–0.60	0.74

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/7. Basic statistical parameters for Pannonian basin.
Priloga 1/7. Osnovni statistični parametri za Panonsko nižino.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	µg/kg	67	57	57	11	280	39	79	2.00	4.92	0.05	0.44
Al	%	1.6	1.5	1.6	0.57	2.9	1.3	1.8	0.20	0.42	-0.82	1.30
As	mg/kg	10	9.3	9.3	3.5	92	7.2	12	7.94	83.02	0.77	4.07
Au	µg/kg	3.2	2.1	2.1	0.30	110	1.4	3.1	11.72	142.89	1.20	6.48
B	mg/kg	2.5	1.7	2.0	0.50	11	1.0	3.0	1.85	3.61	-0.02	-0.80
Ba	mg/kg	84	79	81	27	230	64	100	1.16	3.55	-0.23	0.37
Be	mg/kg	0.76	0.72	0.70	0.30	2.5	0.60	0.90	1.91	9.49	-0.22	0.93
Bi	mg/kg	0.26	0.25	0.25	0.080	0.69	0.21	0.31	1.21	5.25	-0.45	1.61
Ca	%	1.1	0.33	0.25	0.020	17	0.16	0.55	4.28	19.94	0.90	0.91
Cd	mg/kg	0.38	0.25	0.25	0.0050	2.9	0.18	0.36	3.59	14.25	-0.94	6.28
Ce	mg/kg	39	37	39	13	80	31	46	0.43	0.32	-0.49	0.26
Co	mg/kg	13	12	13	4.7	32	9.9	15	1.15	3.21	-0.16	0.64
Cr	mg/kg	30	29	29	8.9	65	25	35	1.09	2.36	-0.30	1.55
Cs	mg/kg	1.3	1.2	1.3	0.30	4.4	1.0	1.5	2.04	11.44	-0.39	2.14
Cu	mg/kg	24	21	20	3.2	200	16	27	5.99	46.94	0.53	4.06
Fe	%	2.7	2.6	2.6	1.1	9.3	2.3	3.0	3.72	30.30	-0.00	4.48
Ga	mg/kg	4.6	4.4	4.5	1.5	8.6	3.8	5.3	0.28	0.65	-0.81	1.58
Hf	mg/kg	0.030	0.020	0.015	0.010	0.15	0.010	0.040	1.85	3.18	0.68	-0.89
Hg	mg/kg	0.081	0.069	0.067	0.026	0.96	0.054	0.086	8.28	79.68	1.66	7.85
In	mg/kg	0.025	0.022	0.025	0.010	0.080	0.010	0.030	1.06	1.80	-0.17	-0.94
K	%	0.13	0.12	0.12	0.040	0.35	0.090	0.15	1.51	2.99	0.26	0.34
La	mg/kg	18	17	18	5.1	32	14	21	0.18	-0.22	-0.75	0.85
Li	mg/kg	18	17	19	5.0	37	14	22	0.20	0.21	-0.89	1.10
Mg	%	0.57	0.46	0.46	0.040	5.0	0.34	0.59	4.90	32.38	0.30	3.33
Mn	mg/kg	700	640	670	140	2100	510	810	1.24	3.63	-0.51	0.83
Mo	mg/kg	0.80	0.63	0.61	0.18	6.6	0.41	0.89	4.55	25.48	0.95	1.85
Na	%	0.0086	0.0076	0.0080	0.0020	0.023	0.0050	0.011	0.93	0.64	-0.32	-0.02
Nb	mg/kg	0.57	0.52	0.57	0.11	1.5	0.41	0.69	0.52	0.84	-0.76	0.61
Ni	mg/kg	28	26	26	8.7	66	21	35	0.95	0.96	-0.16	0.06
P	%	0.061	0.057	0.058	0.022	0.13	0.044	0.074	0.85	0.79	-0.16	-0.11
Pb	mg/kg	27	24	23	11	210	19	28	5.58	40.63	1.70	5.55
Rb	mg/kg	18	17	18	9.1	39	14	21	0.89	1.55	0.03	-0.17
S	%	0.030	0.024	0.030	0.010	0.21	0.020	0.030	4.20	25.34	0.27	0.58
Sb	mg/kg	0.58	0.53	0.51	0.16	1.7	0.43	0.65	1.96	4.96	0.24	1.47
Sc	mg/kg	3.7	3.5	3.5	1.4	11	2.8	4.4	1.54	5.64	0.07	0.61
Se	mg/kg	0.34	0.27	0.30	0.050	1.5	0.20	0.40	1.62	4.65	-0.67	0.34
Sn	mg/kg	0.95	0.88	0.90	0.40	5.1	0.70	1.1	4.75	37.66	0.87	2.57
Sr	mg/kg	33	16	13	2.6	750	9.4	21	6.34	46.06	1.62	3.76
Te	mg/kg	0.025	0.019	0.020	0.010	0.15	0.010	0.030	2.59	11.07	0.49	-0.81
Th	mg/kg	4.3	4.0	4.2	1.1	8.9	3.1	5.3	0.48	0.07	-0.63	0.36
Ti	%	0.015	0.010	0.012	0.0005	0.14	0.0050	0.020	4.30	32.05	-0.31	-0.01
Tl	mg/kg	0.19	0.18	0.17	0.090	0.81	0.14	0.21	3.58	16.73	1.29	3.35
U	mg/kg	1.1	1.0	1.0	0.30	3.7	0.85	1.2	2.48	10.12	0.39	1.91
V	mg/kg	34	32	32	15	76	26	39	1.27	2.61	0.14	0.40
Y	mg/kg	10	9.5	9.8	2.6	64	7.9	12	5.89	55.02	-0.05	3.11
Zn	mg/kg	77	70	69	32	660	57	86	7.97	78.25	1.60	8.20
Zr	mg/kg	0.90	0.60	0.60	0.050	4.4	0.30	1.1	1.90	3.89	-0.43	0.24

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 1/8. Basic statistical parameters for Interior basins.
Priloga 1/8. Osnovni statistični parametri za Notranje kotline.

	Unit	$\bar{X}$	X(G)	Md	Min	Max	P25	P75	A	E	A(L)	E(L)
Ag	μg/kg	120	88	93	18	1200	55	140	5.57	33.04	0.97	4.28
Al	%	1.8	1.8	1.9	0.60	2.9	1.5	2.3	−0.05	−0.37	−1.04	2.00
As	mg/kg	11	10	11	5.6	15	7.8	13	−0.03	−1.30	−0.37	−1.09
Au	μg/kg	2.6	2.0	1.9	0.60	12	1.2	2.7	2.51	7.36	0.48	0.10
B	mg/kg	2.6	1.9	2.0	0.50	7.0	1.0	4.0	0.63	−0.55	−0.39	−1.12
Ba	mg/kg	95	78	83	21	560	51	110	4.46	24.05	0.38	2.10
Be	mg/kg	0.88	0.83	0.90	0.30	1.6	0.70	1.0	0.45	0.08	−0.63	0.71
Bi	mg/kg	0.33	0.32	0.35	0.18	0.56	0.24	0.40	0.03	−0.44	−0.45	−0.81
Ca	%	2.1	0.54	0.60	0.0050	20	0.17	2.9	3.65	16.81	−0.34	−0.52
Cd	mg/kg	0.70	0.55	0.61	0.050	1.6	0.42	0.98	0.41	−0.53	−1.42	2.11
Ce	mg/kg	33	30	35	7.4	56	24	42	−0.10	−0.84	−1.14	1.19
Co	mg/kg	11	10	10	2.8	29	8.2	12	1.15	1.66	−0.33	0.45
Cr	mg/kg	28	26	28	8.3	56	20	35	0.57	0.49	−0.71	0.82
Cs	mg/kg	1.4	1.2	1.4	0.24	2.7	0.96	1.8	0.22	−0.36	−1.11	1.73
Cu	mg/kg	21	20	20	8.2	40	16	24	0.97	1.11	−0.04	0.34
Fe	%	2.6	2.5	2.7	1.2	4.5	2.2	3.1	−0.04	0.01	−0.79	0.04
Ga	mg/kg	5.0	4.7	5.0	1.6	8.0	3.8	6.1	−0.02	−0.43	−1.01	1.98
Hf	mg/kg	0.091	0.074	0.080	0.010	0.24	0.050	0.12	0.95	0.51	−0.93	1.38
Hg	mg/kg	0.17	0.15	0.15	0.057	0.60	0.12	0.19	3.05	13.64	0.42	1.73
In	mg/kg	0.038	0.036	0.040	0.010	0.060	0.030	0.050	−0.41	0.17	−1.71	3.73
K	%	0.12	0.11	0.10	0.050	0.34	0.090	0.14	1.75	3.83	0.57	0.17
La	mg/kg	15	13	15	2.7	30	11	18	0.45	0.07	−1.10	1.89
Li	mg/kg	18	16	18	4.3	38	14	22	0.32	0.55	−1.12	1.31
Mg	%	0.89	0.54	0.41	0.030	4.7	0.29	0.80	2.13	4.17	0.18	1.27
Mn	mg/kg	800	640	820	100	1600	350	1200	0.22	−1.03	−0.81	−0.21
Mo	mg/kg	0.79	0.73	0.72	0.31	1.6	0.56	1.0	0.52	0.08	−0.31	−0.52
Na	%	0.0074	0.0066	0.0065	0.0020	0.022	0.0050	0.010	1.70	4.48	−0.22	0.84
Nb	mg/kg	0.60	0.50	0.54	0.12	1.2	0.36	0.82	0.42	−0.90	−0.67	−0.13
Ni	mg/kg	24	21	22	7.2	64	20	26	1.64	4.73	−0.48	1.33
P	%	0.073	0.063	0.067	0.0080	0.20	0.050	0.10	0.83	1.80	−1.16	2.27
Pb	mg/kg	44	42	42	21	67	33	53	0.05	−0.65	−0.55	−0.06
Rb	mg/kg	18	17	18	5.4	45	14	22	0.84	1.97	−0.60	0.13
S	%	0.060	0.044	0.040	0.010	0.37	0.030	0.060	3.75	14.17	0.58	2.75
Sb	mg/kg	0.58	0.54	0.54	0.26	1.6	0.40	0.76	1.93	5.71	0.55	0.27
Sc	mg/kg	3.5	3.3	3.3	1.4	6.1	2.8	4.4	0.20	−0.81	−0.43	−0.51
Se	mg/kg	0.54	0.44	0.40	0.10	2.6	0.30	0.60	3.01	10.74	0.60	1.44
Sn	mg/kg	1.7	1.4	1.4	0.40	11	1.0	1.8	4.88	27.09	1.08	4.10
Sr	mg/kg	23	14	12	2.9	210	6.9	27	4.37	21.67	0.62	0.69
Te	mg/kg	0.037	0.029	0.035	0.010	0.090	0.010	0.060	0.59	−0.45	−0.39	−1.15
Th	mg/kg	3.6	3.3	3.8	0.90	7.0	2.6	4.5	0.04	−0.27	−1.13	0.98
Ti	%	0.0051	0.0040	0.0050	0.0005	0.014	0.0030	0.0070	0.95	1.39	−0.97	0.72
Tl	mg/kg	0.27	0.25	0.26	0.090	0.60	0.20	0.33	0.85	1.10	−0.37	0.19
U	mg/kg	1.4	1.1	1.1	0.30	10	0.80	1.5	4.53	22.66	1.33	4.42
V	mg/kg	39	36	40	13	89	30	44	0.93	2.59	−0.48	0.52
Y	mg/kg	12	10	9.8	2.0	30	7.6	15	1.08	1.28	−0.47	0.45
Zn	mg/kg	78	74	75	29	120	63	99	0.03	−0.48	−0.86	0.86
Zr	mg/kg	2.5	2.3	2.3	1.1	5.8	1.5	3.2	1.07	0.57	0.26	−0.82

$\bar{X}$ – aritmetična sredina/arithmetic mean; X(G) – geometrijska sredina/geometric mean; Md – mediana/median (Q2); Min – minimium/minimum; Max – maksimum/maximum; P25 – 25. percentil/ 25th percentile (Q1), P75 – 75. percentil/75th percentile (Q3); A – asimetričnost/skewness; E – sploščenost/kurtosis; A(L) – asimetričnost (logaritmirane vrednosti)/skewness (logarithmic values); E(L) – sploščenost (logaritmirane vrednosti)/kurtosis (logarithmic values)

Appendix 2/1. Determined thresholds for Western Alps.
Priloga 2/1. Zgornje meje naravne variabilnosti za Zahodne Alpe.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	180	180	190	250	140	190	200	350
Al	%	3.6	3.7	3.7	6.8	3.9	6.2	4.7	9.6
As	mg/kg	30	34	34	43	24	37	29	53.0
Au	µg/kg	4.8	5.2	8.8	8.9	3.4	8.0	4.7	13.7
B	mg/kg	12	14	11	17	6.0	10	9.5	19.8
Ba	mg/kg	130	140	130	240	130	150	150	310
Be	mg/kg	2.3	2.3	2.2	3.7	2.0	3.2	2.6	5.0
Bi	mg/kg	0.86	0.94	0.84	1.1	0.70	0.99	0.97	1.5
Ca	%	16	21	15	42	5.8	130	17	620
Cd	mg/kg	6.4	6.5	5.7	8.7	3.2	11	4.9	20.5
Ce	mg/kg	67	70	69	130	73	160	89	270
Co	mg/kg	25	26	25	47	25	40	30	72.6
Cr	mg/kg	67	78	69	99	57	100	78	180
Cs	mg/kg	3.3	3.6	3.3	6.3	3.0	6.4	4.0	13.1
Cu	mg/kg	49	56	49	70	40	56	49	84.4
Fe	%	4.2	4.3	4.8	9.2	4.9	6.1	6.1	11.9
Ga	mg/kg	8.8	10	10	18	10	17	12	28.6
Hf	mg/kg	0.22	0.27	0.21	0.32	0.17	0.37	0.22	0.61
Hg	mg/kg	0.56	0.71	0.83	0.81	0.42	0.71	0.60	1.4
In	mg/kg	0.070	0.090	0.085	0.13	0.070	0.094	0.11	0.17
K	%	0.24	0.28	0.26	0.37	0.23	0.33	0.27	0.47
La	mg/kg	39	39	38	65	31	68	42	140
Li	mg/kg	29	38	33	70	35	61	43	120
Mg	%	7.2	8.1	6.0	8.4	1.4	3.1	5.2	40.5
Mn	mg/kg	2100	2400	2440	4000	2000	3900	2700	7700
Mo	mg/kg	3.6	5.1	3.1	2.8	1.3	1.9	1.6	2.8
Na	%	0.017	0.024	0.023	0.023	0.013	0.019	0.018	0.028
Nb	mg/kg	1.9	2.4	1.9	2.8	1.2	3.1	1.6	5.4
Ni	mg/kg	71	77	64	120	61	110	73	200
P	%	0.24	0.25	0.20	0.25	0.12	0.17	0.17	0.31
Pb	mg/kg	130	150	120	150	90	140	130	240
Rb	mg/kg	27	33	31	54	31	45	37	79.1
S	%	0.23	0.24	0.20	0.29	0.14	0.23	0.18	0.47
Sb	mg/kg	1.3	1.6	1.5	1.8	1.2	1.8	1.6	2.7
Sc	mg/kg	8.7	9.3	8.8	14	8.4	15	11	26.8
Se	mg/kg	1.4	2.1	1.5	1.9	0.99	1.7	1.6	3.5
Sn	mg/kg	3.2	3.4	3.0	4.3	2.8	3.9	3.2	5.1
Sr	mg/kg	75	82	67	93	49	110	73	240
Te	mg/kg	0.17	0.20	0.17	0.28	0.15	0.39	0.20	1.3
Th	mg/kg	7.6	8.1	7.1	13	6.5	13	8.1	26.0
Ti	%	0.056	0.12	0.066	0.042	0.009	0.014	0.014	0.046
Tl	mg/kg	0.77	0.88	0.82	1.1	0.75	1.5	1.1	2.7
U	mg/kg	1.5	1.7	1.5	1.8	1.3	1.9	1.8	2.8
V	mg/kg	73	79	81	120	80	130	89	170
Y	mg/kg	58	60	49	71	24	52	37	95.6
Zn	mg/kg	180	190	210	280	160	230	190	290
Zr	mg/kg	6.8	7.7	6.0	8.6	5.0	8.8	6.5	18.3

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/2. Determined thresholds for Eastern Alps.
Priloga 2/2. Zgornje meje naravne variabilnosti za Vzhodne Alpe.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	250	340	270	410	140	270	240	660
Al	%	3.5	3.7	3.9	4.8	3.7	4.3	4.2	5.5
As	mg/kg	39	70	50	42	19	29	22	46.2
Au	µg/kg	10	22	18	14	3.4	7.6	4.9	11.2
B	mg/kg	7.0	9.0	6.3	9.4	6.4	16	6.8	44.1
Ba	mg/kg	220	240	200	250	140	200	190	290
Be	mg/kg	1.6	1.9	1.6	2.0	1.5	1.6	1.7	2.2
Bi	mg/kg	0.64	0.74	0.66	0.86	0.54	0.75	0.67	1.1
Ca	%	4.9	13	6.9	5.4	0.67	2.0	1.1	4.7
Cd	mg/kg	1.3	2.0	1.3	1.6	0.75	1.6	1.1	2.9
Ce	mg/kg	60	61	63	86	64	81	74	110
Co	mg/kg	35	39	33	42	27	36	29	40.9
Cr	mg/kg	88	150	100	120	64	91	80	130
Cs	mg/kg	4.2	4.7	4.5	6.0	4.2	7.0	5.1	11.6
Cu	mg/kg	63	85	85	100	49	71	58	93.0
Fe	%	5.1	7.5	6.3	7.7	5.1	5.6	5.6	6.7
Ga	mg/kg	12	14	13	16	11	14	13	17.5
Hf	mg/kg	0.085	0.11	0.086	0.080	0.010	0.010	0.060	0.16
Hg	mg/kg	0.21	0.49	0.31	0.30	0.15	0.25	0.22	0.40
In	mg/kg	0.075	0.10	0.081	0.096	0.060	0.070	0.063	0.081
K	%	0.41	0.89	0.53	0.54	0.31	0.44	0.35	0.52
La	mg/kg	25	28	29	40	31	41	35	53.0
Li	mg/kg	55	64	61	77	45	57	54	76.0
Mg	%	3.1	8.9	4.5	3.7	1.4	2.0	1.9	3.1
Mn	mg/kg	1600	2300	1630	1800	1200	1600	1400	2100
Mo	mg/kg	2.4	3.3	2.9	3.1	1.5	2.4	2.0	3.7
Na	%	0.034	0.040	0.033	0.051	0.028	0.047	0.035	0.074
Nb	mg/kg	3.4	4.0	3.5	5.3	2.0	7.2	2.8	11.5
Ni	mg/kg	54	92	71	96	58	72	65	97.4
P	%	0.15	0.18	0.14	0.16	0.12	0.14	0.14	0.19
Pb	mg/kg	130	160	110	130	64	90	84	140
Rb	mg/kg	51	67	54	62	34	44	42	61.5
S	%	0.065	0.075	0.068	0.095	0.060	0.10	0.085	0.32
Sb	mg/kg	1.4	2.0	1.8	1.9	1.0	1.8	1.3	2.8
Sc	mg/kg	9.8	12	10	12	7.7	12	10	17.1
Se	mg/kg	0.90	1.1	0.90	1.4	0.79	1.0	0.95	2.0
Sn	mg/kg	2.5	4.4	7.0	3.5	1.6	2.0	2.2	3.3
Sr	mg/kg	49	59	110	67	32	62	46	100
Te	mg/kg	0.070	0.085	0.073	0.10	0.059	0.24	0.085	0.32
Th	mg/kg	7.9	8.2	8.2	14	8.0	12	10	19.1
Ti	%	0.17	0.21	0.15	0.29	0.052	0.85	0.14	3.3
Tl	mg/kg	0.44	0.55	0.46	0.56	0.39	0.57	0.52	0.81
U	mg/kg	3.2	4.8	3.2	3.7	1.8	3.0	2.7	4.7
V	mg/kg	140	170	120	130	73	94	100	160
Y	mg/kg	18	22	19	22	17	23	20	31.9
Zn	mg/kg	200	290	210	210	140	160	160	200
Zr	mg/kg	2.5	3.7	2.5	4.4	1.4	7.5	2.1	10.5

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/3. Determined thresholds for Western Prealps.
Priloga 2/3. Zgornje meje naravne variabilnosti za Zahodne Predalpe.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	170	200	220	240	160	210	180	280
Al	%	3.3	3.4	3.5	4.5	3.5	4.5	4.2	5.9
As	mg/kg	27	36	28	35	22	31	27	42.5
Au	µg/kg	6.5	10	7.4	9.2	3.9	5.7	4.7	7.2
B	mg/kg	7.0	7.0	6.8	11	5.0	16	8.5	32.0
Ba	mg/kg	150	180	160	210	140	210	190	320
Be	mg/kg	2.3	2.5	2.4	3.9	2.2	3.3	2.7	4.7
Bi	mg/kg	0.85	0.92	0.86	1.0	0.83	1.1	0.94	1.4
Ca	%	8.7	9.2	6.6	12	1.6	8.5	3.0	22.8
Cd	mg/kg	3.2	4.0	2.8	5.1	1.6	5.0	3.1	15.9
Ce	mg/kg	74	81	78	120	76	130	93	200
Co	mg/kg	27	30	30	56	31	41	39	80.0
Cr	mg/kg	69	88	81	130	82	140	98	220
Cs	mg/kg	3.1	3.2	3.2	5.2	3.3	6.3	4.1	10.0
Cu	mg/kg	78	94	70	89	58	95	71	150
Fe	%	4.1	4.4	4.6	6.5	4.6	5.1	5.2	6.1
Ga	mg/kg	8.5	8.9	9.1	12	9.3	11	11	15.3
Hf	mg/kg	0.24	0.27	0.22	0.35	0.18	0.32	0.22	0.45
Hg	mg/kg	1.2	2.1	1.8	1.5	0.63	1.2	0.81	1.8
In	mg/kg	0.080	0.10	0.084	0.11	0.070	0.094	0.080	0.11
K	%	0.24	0.27	0.24	0.28	0.21	0.28	0.27	0.38
La	mg/kg	44	55	45	66	36	65	44	110
Li	mg/kg	54	61	52	81	42	60	51	86.8
Mg	%	4.0	5.8	3.5	3.5	0.97	1.4	1.4	2.6
Mn	mg/kg	2700	2900	3000	5400	2400	3900	2900	6400
Mo	mg/kg	4.8	6.1	4.6	4.0	1.3	2.4	1.7	3.4
Na	%	0.013	0.016	0.013	0.019	0.015	0.020	0.016	0.035
Nb	mg/kg	1.7	2.2	1.8	3.0	1.2	4.5	2.1	10.4
Ni	mg/kg	97	140	120	190	98	200	120	460
P	%	0.17	0.21	0.16	0.22	0.15	0.23	0.19	0.39
Pb	mg/kg	85	100	86	98	76	90	87	120
Rb	mg/kg	32	36	33	41	31	41	38	53.5
S	%	0.10	0.12	0.11	0.14	0.099	0.13	0.11	0.17
Sb	mg/kg	1.9	3.7	2.9	2.0	0.93	1.1	1.2	1.7
Sc	mg/kg	7.6	8.3	8.3	11	8.1	11	9.1	13.8
Se	mg/kg	1.3	1.3	1.2	1.4	1.1	1.9	1.3	2.5
Sn	mg/kg	2.9	3.7	3.2	3.8	2.9	4.7	3.8	7.9
Sr	mg/kg	61	72	72	70	30	62	44	110
Te	mg/kg	0.16	0.17	0.15	0.26	0.15	0.23	0.16	0.35
Th	mg/kg	7.6	8.0	7.6	9.6	6.5	8.7	8.4	12.7
Ti	%	0.014	0.015	0.013	0.019	0.009	0.023	0.014	0.088
Tl	mg/kg	0.78	0.84	0.75	0.90	0.52	0.78	0.85	1.8
U	mg/kg	2.4	3.3	2.6	3.1	1.8	3.0	2.5	5.5
V	mg/kg	110	140	110	150	89	150	110	210
Y	mg/kg	43	98	55	67	32	48	38	98.6
Zn	mg/kg	160	170	160	210	150	190	170	240
Zr	mg/kg	7.4	8.4	6.7	9.0	4.8	8.7	7.0	16.6

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/4. Determined thresholds for Eastern Prealps.
Priloga 2/4. Zgornje meje naravne variabilnosti za Vzhodne Predalpe.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	130	220	270	190	100	150	120	170
Al	%	3.1	3.3	2.9	3.7	2.8	3.5	3.2	4.6
As	mg/kg	26	36	28	34	22	38	26	37.6
Au	µg/kg	5.5	10	10	7.1	3.6	4.2	4.5	7.5
B	mg/kg	9.0	12	8.8	13	5.3	3.6	8.5	32.0
Ba	mg/kg	200	300	260	250	150	170	180	320
Be	mg/kg	2.2	2.4	2.0	2.4	1.6	3.5	2.1	3.4
Bi	mg/kg	0.53	0.62	0.56	0.68	0.54	1.1	0.63	0.86
Ca	%	13	14	10	25	1.3	8.3	5.9	170
Cd	mg/kg	3.6	6.3	3.8	4.5	1.4	3.3	2.1	7.2
Ce	mg/kg	67	80	73	110	70	150	81	130
Co	mg/kg	45	60	42	51	25	20	32	56.2
Cr	mg/kg	72	77	81	94	58	65	77	160
Cs	mg/kg	3.0	3.4	3.1	4.6	3.1	5.2	3.7	7.6
Cu	mg/kg	47	52	85	70	39	37	50	86.6
Fe	%	4.3	4.6	4.6	5.9	4.3	4.6	5.0	6.4
Ga	mg/kg	8.6	9.3	8.6	11	7.8	10	9.5	14.7
Hf	mg/kg	0.16	0.17	0.16	0.25	0.11	0.33	0.18	0.47
Hg	mg/kg	0.36	0.41	0.92	0.50	0.26	0.28	0.34	0.66
In	mg/kg	0.070	0.14	0.10	0.11	0.060	0.10	0.095	0.20
K	%	0.28	0.43	0.31	0.30	0.20	0.22	0.26	0.39
La	mg/kg	33	37	35	50	31	87	38	65.1
Li	mg/kg	35	48	37	46	29	33	34	49.9
Mg	%	7.7	8.2	5.4	5.5	0.93	0.70	1.5	4.4
Mn	mg/kg	2900	3100	2480	3600	1800	1500	2200	5300
Mo	mg/kg	2.6	3.1	2.3	2.4	1.3	5.8	1.6	2.6
Na	%	0.017	0.023	0.019	0.028	0.016	0.016	0.020	0.036
Nb	mg/kg	1.4	1.7	1.3	2.0	1.1	8.2	1.4	3.3
Ni	mg/kg	66	120	130	85	45	44	59	100
P	%	0.16	0.25	0.18	0.19	0.11	0.10	0.14	0.26
Pb	mg/kg	69	120	200	100	53	99	60	74.3
Rb	mg/kg	32	34	32	41	30	26	37	58.9
S	%	0.090	0.10	0.088	0.11	0.060	0.10	0.070	0.11
Sb	mg/kg	1.7	2.3	1.6	1.7	0.96	1.5	1.1	1.5
Sc	mg/kg	9.2	9.7	8.1	9.1	6.1	8.1	7.5	11.4
Se	mg/kg	0.70	0.80	0.76	1.2	0.60	0.70	0.95	2.0
Sn	mg/kg	2.4	3.3	2.6	2.8	1.9	3.3	2.4	4.0
Sr	mg/kg	180	410	270	170	36	86	74	320
Te	mg/kg	0.14	0.19	0.15	0.23	0.13	0.077	0.17	0.64
Th	mg/kg	7.5	8.0	8.1	12	7.9	14	9.3	13.5
Ti	%	0.015	0.016	0.014	0.025	0.014	0.030	0.017	0.064
Tl	mg/kg	0.51	0.62	0.56	0.66	0.40	0.86	0.48	0.71
U	mg/kg	2.3	3.5	2.6	2.9	1.8	3.0	2.0	2.7
V	mg/kg	80	110	82	94	62	110	76	130
Y	mg/kg	39	51	37	49	23	27	37	110
Zn	mg/kg	140	1100	480	250	120	110	150	220
Zr	mg/kg	5.1	6.1	5.2	7.1	3.9	10	5.9	14.5

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/5. Determined thresholds for Western Dinarides.
Priloga 2/5. Zgornje meje naravne variabilnosti za Zahodne Dinaride.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	140	140	150	180	140	200	190	300
Al	%	4.0	4.3	3.8	4.3	3.4	4.3	4.2	5.9
As	mg/kg	24	25	23	28	21	33	29	55.8
Au	µg/kg	6.1	6.6	6.6	9.5	5.0	6.3	5.3	8.4
B	mg/kg	5.0	6.0	5.8	8.9	4.0	4.6	7.0	11.3
Ba	mg/kg	160	200	190	220	180	230	210	310
Be	mg/kg	2.3	2.4	2.4	3.0	2.2	4.7	3.1	7.0
Bi	mg/kg	0.71	0.80	0.77	0.97	0.75	1.3	0.94	1.7
Ca	%	14	15	13	23	2.6	20	11	150
Cd	mg/kg	2.4	2.6	2.2	3.0	0.97	2.5	2.0	8.0
Ce	mg/kg	66	69	71	95	76	130	97	220
Co	mg/kg	28	29	28	31	27	29	30	34.5
Cr	mg/kg	160	170	130	140	95	130	120	180
Cs	mg/kg	3.2	3.7	3.0	3.7	2.3	3.7	2.8	5.8
Cu	mg/kg	81	230	120	92	51	60	65	88.0
Fe	%	4.2	4.4	4.6	5.0	5.1	5.7	5.5	6.9
Ga	mg/kg	12	12	11	13	10	14	13	19.3
Hf	mg/kg	0.21	0.24	0.24	0.35	0.22	0.56	0.33	0.92
Hg	mg/kg	0.24	0.33	0.23	0.26	0.15	0.19	0.19	0.28
In	mg/kg	0.080	0.090	0.085	0.12	0.099	0.13	0.11	0.17
K	%	0.26	0.30	0.28	0.32	0.25	0.30	0.30	0.38
La	mg/kg	35	37	36	51	36	79	48	140
Li	mg/kg	31	33	31	35	31	40	34	42.6
Mg	%	0.90	3.0	1.7	1.2	0.64	0.72	0.73	0.92
Mn	mg/kg	2300	2400	2210	2500	1800	2100	2200	3000
Mo	mg/kg	6.7	13	7.3	8.3	2.0	6.3	3.9	18.1
Na	%	0.011	0.013	0.012	0.019	0.012	0.014	0.012	0.016
Nb	mg/kg	2.2	2.6	2.4	4.4	0.85	5.4	3.5	50.9
Ni	mg/kg	120	130	110	130	98	120	120	150
P	%	0.089	0.097	0.095	0.11	0.079	0.096	0.094	0.12
Pb	mg/kg	53	67	61	73	63	91	78	130
Rb	mg/kg	37	40	35	37	27	30	34	42.6
S	%	0.13	0.19	0.13	0.17	0.099	0.13	0.12	0.31
Sb	mg/kg	1.0	1.8	1.4	1.6	0.94	1.3	1.2	2.1
Sc	mg/kg	8.5	9.3	9.0	10	9.0	12	11	15.7
Se	mg/kg	0.90	1.6	1.1	1.4	0.70	0.94	1.0	1.7
Sn	mg/kg	2.5	3.1	3.8	3.8	2.4	4.0	3.8	7.9
Sr	mg/kg	220	280	220	280	53	130	120	530
Te	mg/kg	0.13	0.13	0.14	0.20	0.14	0.15	0.18	0.28
Th	mg/kg	8.0	10	8.3	9.9	8.3	13	10	20.0
Ti	%	0.019	0.021	0.017	0.023	0.009	0.018	0.017	0.064
Tl	mg/kg	0.64	0.71	0.67	0.85	0.43	0.81	0.85	2.4
U	mg/kg	1.6	1.7	1.6	2.0	1.5	2.0	2.2	5.0
V	mg/kg	200	220	190	240	97	170	230	740
Y	mg/kg	29	40	32	42	26	38	36	65.6
Zn	mg/kg	110	110	110	110	100	110	120	130
Zr	mg/kg	9.8	11	9.3	13	5.8	14	12	48.9

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/6. Determined thresholds for Eastern Dinarides.
Priloga 2/6. Zgornje meje naravne variabilnosti za Vzhodne Dinaride.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	130	160	140	170	110	150	140	230
Al	%	3.5	3.7	3.7	4.7	3.5	3.9	4.0	4.9
As	mg/kg	27	36	30	33	23	28	28	36.1
Au	µg/kg	4.1	5.6	4.6	7.0	3.4	5.3	4.5	8.9
B	mg/kg	8.0	11	9.9	9.9	5.0	16	6.0	15.6
Ba	mg/kg	120	150	140	170	130	160	150	210
Be	mg/kg	2.2	2.4	2.4	3.1	2.6	2.9	2.8	3.8
Bi	mg/kg	0.65	0.68	0.67	0.78	0.61	0.70	0.72	0.92
Ca	%	7.2	11	7.1	11	1.8	8.4	3.9	33.2
Cd	mg/kg	2.0	3.1	2.4	3.0	1.5	2.8	2.2	5.1
Ce	mg/kg	83	87	94	130	85	94	96	110
Co	mg/kg	40	50	42	56	34	45	43	64.7
Cr	mg/kg	75	79	81	110	72	81	83	99.1
Cs	mg/kg	3.5	3.7	3.9	5.8	3.8	5.1	4.5	7.0
Cu	mg/kg	32	40	40	40	28	34	34	44.8
Fe	%	4.2	4.4	4.7	6.0	4.1	4.4	4.6	5.1
Ga	mg/kg	9.9	11	11	14	9.7	11	11	12.7
Hf	mg/kg	0.22	0.25	0.22	0.29	0.21	0.30	0.24	0.47
Hg	mg/kg	0.28	0.30	0.27	0.32	0.23	0.30	0.27	0.41
In	mg/kg	0.080	0.090	0.080	0.10	0.070	0.094	0.11	0.17
K	%	0.21	0.27	0.29	0.25	0.16	0.19	0.18	0.22
La	mg/kg	39	39	42	58	39	46	46	58.5
Li	mg/kg	33	35	53	51	34	41	39	52.2
Mg	%	4.4	6.0	4.1	3.8	0.90	1.5	1.4	2.9
Mn	mg/kg	2600	3100	2640	3500	2400	4000	2900	5600
Mo	mg/kg	11	12	12	11	5.0	11	6.1	15.3
Na	%	0.013	0.015	0.013	0.023	0.012	0.020	0.016	0.035
Nb	mg/kg	2.1	2.2	2.1	3.1	1.9	2.4	2.2	3.3
Ni	mg/kg	72	84	76	91	58	80	77	120
P	%	0.094	0.14	0.14	0.13	0.079	0.12	0.11	0.20
Pb	mg/kg	56	61	59	65	56	61	61	69.3
Rb	mg/kg	34	38	37	46	34	39	38	44.9
S	%	0.11	0.14	0.11	0.14	0.060	0.10	0.095	0.20
Sb	mg/kg	1.2	1.6	1.4	1.6	1.0	1.3	1.3	1.9
Sc	mg/kg	8.1	8.7	8.5	11	8.2	9.6	9.4	12.4
Se	mg/kg	1.0	1.2	0.99	1.4	0.70	0.94	0.80	1.1
Sn	mg/kg	2.3	2.4	2.5	2.8	2.2	2.8	2.8	3.8
Sr	mg/kg	71	110	80	74	28	49	39	86.0
Te	mg/kg	0.13	0.15	0.13	0.20	0.11	0.14	0.13	0.25
Th	mg/kg	9.4	9.9	10	16	9.2	11	11	13.6
Ti	%	0.015	0.017	0.016	0.022	0.016	0.020	0.019	0.040
Tl	mg/kg	1.1	1.2	1.1	1.4	0.95	1.3	1.2	1.9
U	mg/kg	2.7	3.0	3.0	3.6	2.6	3.5	3.3	4.9
V	mg/kg	130	170	140	170	120	140	140	180
Y	mg/kg	36	40	36	44	29	44	37	69.0
Zn	mg/kg	100	110	110	130	100	120	120	150
Zr	mg/kg	7.9	8.9	8.0	10	6.8	8.9	8.4	12.7

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/7. Determined thresholds for Pannonian basin.
Priloga 2/7. Zgornje meje naravne variabilnosti za Panonsko nižino.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	180	210	160	180	120	160	140	230
Al	%	2.3	2.5	2.4	2.7	2.3	2.6	2.6	3.0
As	mg/kg	18	22	26	22	16	19	18	24.2
Au	µg/kg	6.5	8.9	21	8.5	4.2	6.7	5.6	9.9
B	mg/kg	7.0	9.0	6.9	9.7	5.0	16	6.0	15.6
Ba	mg/kg	140	150	140	160	130	170	160	210
Be	mg/kg	1.2	1.2	1.3	1.5	1.3	1.5	1.4	1.7
Bi	mg/kg	0.37	0.43	0.42	0.46	0.40	0.43	0.46	0.56
Ca	%	5.6	10	6.3	4.8	0.63	1.4	1.1	3.6
Cd	mg/kg	1.2	2.1	1.3	1.5	0.52	0.74	0.64	1.0
Ce	mg/kg	61	66	63	70	61	67	68	82.4
Co	mg/kg	20	23	21	23	20	23	22	27.5
Cr	mg/kg	51	54	49	53	44	48	50	57.7
Cs	mg/kg	2.1	2.2	2.2	2.4	2.0	2.3	2.3	2.7
Cu	mg/kg	44	50	63	56	35	44	44	60.3
Fe	%	3.7	4.0	4.3	4.4	3.7	4.0	4.1	4.6
Ga	mg/kg	6.6	7.6	7.0	7.8	6.7	7.2	7.5	8.7
Hf	mg/kg	0.10	0.11	0.088	0.11	0.030	0.050	0.085	0.32
Hg	mg/kg	0.14	0.16	0.25	0.17	0.11	0.14	0.13	0.17
In	mg/kg	0.050	0.060	0.053	0.067	0.040	0.048	0.060	0.16
K	%	0.24	0.29	0.23	0.25	0.21	0.26	0.24	0.32
La	mg/kg	28	29	29	33	28	33	32	38.9
Li	mg/kg	27	29	30	35	31	36	34	43.2
Mg	%	1.6	2.2	1.6	1.6	0.82	1.0	0.96	1.3
Mn	mg/kg	1200	1400	1280	1500	1100	1300	1300	1600
Mo	mg/kg	1.7	3.3	2.4	2.2	1.3	2.0	1.6	2.8
Na	%	0.018	0.020	0.017	0.021	0.017	0.027	0.020	0.036
Nb	mg/kg	0.94	1.0	1.0	1.3	1.0	1.3	1.1	1.5
Ni	mg/kg	52	59	51	58	46	55	56	75.6
P	%	0.11	0.12	0.11	0.12	0.10	0.12	0.12	0.16
Pb	mg/kg	51	100	69	57	37	44	42	50.6
Rb	mg/kg	27	30	28	30	27	30	31	36.4
S	%	0.060	0.080	0.078	0.082	0.060	0.10	0.045	0.055
Sb	mg/kg	1.1	1.4	1.1	1.2	0.81	0.91	0.97	1.2
Sc	mg/kg	6.1	6.4	6.2	6.7	5.6	6.8	6.7	8.5
Se	mg/kg	0.70	0.90	0.78	1.2	0.60	1.0	0.70	1.1
Sn	mg/kg	1.6	1.9	1.9	1.8	1.5	1.9	1.7	2.2
Sr	mg/kg	83	300	200	100	26	40	38	68.6
Te	mg/kg	0.060	0.070	0.065	0.075	0.050	0.16	0.060	0.16
Th	mg/kg	7.3	8.5	7.6	9.2	7.3	8.8	8.6	11.8
Ti	%	0.036	0.043	0.043	0.060	0.034	0.079	0.042	0.16
Tl	mg/kg	0.39	0.54	0.39	0.37	0.26	0.30	0.31	0.39
U	mg/kg	1.9	2.4	2.0	2.1	1.6	1.8	1.8	2.1
V	mg/kg	55	69	56	59	50	59	59	71.6
Y	mg/kg	17	19	22	22	16	18	18	22.3
Zn	mg/kg	120	140	190	150	110	130	130	160
Zr	mg/kg	2.7	3.7	2.6	4.2	1.5	4.7	2.4	8.6

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

Appendix 2/8. Determined thresholds for Interior basins.
Priloga 2/8. Zgornje meje naravne variabilnosti za Notranje kotline.

	Unit	P95	P97.5	X2S	X2S(L)	MD2MAD	MD2MAD(L)	TIF	TIF(L)
Ag	µg/kg	200	1200	480	350	210	330	270	570
Al	%	2.7	2.9	2.9	3.3	3.0	3.4	3.4	4.3
As	mg/kg	15	15	17	19	19	24	22	30.2
Au	µg/kg	8.1	12	7.3	8.4	4.4	6.1	5.0	9.1
B	mg/kg	6.5	7.0	6.3	11	6.4	16	8.5	32.0
Ba	mg/kg	170	560	270	260	180	240	200	370
Be	mg/kg	1.5	1.6	1.5	1.7	1.5	1.8	1.5	1.7
Bi	mg/kg	0.44	0.56	0.51	0.57	0.55	0.58	0.64	0.86
Ca	%	7.1	20	9.4	27	2.2	43	7.1	210
Cd	mg/kg	1.5	1.6	1.5	2.9	1.4	2.3	1.8	3.4
Ce	mg/kg	55	56	60	82	67	79	69	99.2
Co	mg/kg	21	29	22	27	17	19	19	23.1
Cr	mg/kg	53	56	50	61	49	62	56	77.0
Cs	mg/kg	2.5	2.7	2.5	3.4	2.7	3.9	3.0	4.6
Cu	mg/kg	39	40	35	38	33	41	36	44.7
Fe	%	3.8	4.5	4.2	4.8	4.0	4.3	4.4	5.1
Ga	mg/kg	7.3	8.0	7.8	9.0	8.4	9.7	9.5	12.4
Hf	mg/kg	0.22	0.24	0.20	0.31	0.17	0.32	0.22	0.45
Hg	mg/kg	0.28	0.60	0.35	0.37	0.27	0.31	0.30	0.40
In	mg/kg	0.060	0.060	0.062	0.079	0.070	0.077	0.080	0.11
K	%	0.23	0.34	0.24	0.26	0.17	0.21	0.22	0.27
La	mg/kg	28	30	28	38	24	30	28	35.4
Li	mg/kg	33	38	33	44	32	40	35	45.3
Mg	%	3.4	4.7	3.0	3.9	0.86	1.5	1.6	3.7
Mn	mg/kg	1600	1600	1710	2800	1900	3200	2400	7200
Mo	mg/kg	1.3	1.6	1.4	1.6	1.3	1.5	1.7	2.4
Na	%	0.016	0.022	0.015	0.018	0.011	0.014	0.018	0.028
Nb	mg/kg	1.1	1.2	1.2	1.8	1.2	1.8	1.5	2.8
Ni	mg/kg	50	64	45	54	33	35	36	40.4
P	%	0.13	0.20	0.15	0.21	0.14	0.20	0.18	0.28
Pb	mg/kg	64	67	67	74	71	84	83	110
Rb	mg/kg	32	45	34	43	30	36	34	44.8
S	%	0.33	0.37	0.20	0.19	0.070	0.094	0.11	0.17
Sb	mg/kg	1.1	1.6	1.1	1.2	1.0	1.5	1.3	2.0
Sc	mg/kg	5.5	6.1	5.9	6.8	6.0	7.4	6.9	8.9
Se	mg/kg	1.6	2.6	1.5	1.5	0.70	0.94	1.0	1.7
Sn	mg/kg	3.5	11	5.1	4.3	2.5	3.2	3.0	4.3
Sr	mg/kg	100	210	96	91	33	90	57	210
Te	mg/kg	0.085	0.090	0.084	0.13	0.11	0.18	0.14	0.88
Th	mg/kg	6.3	7.0	6.6	9.0	6.6	8.2	7.3	10.2
Ti	%	0.013	0.014	0.011	0.018	0.011	0.016	0.013	0.025
Tl	mg/kg	0.50	0.60	0.49	0.58	0.46	0.55	0.53	0.70
U	mg/kg	5.2	10	4.8	3.8	1.8	2.3	2.5	3.9
V	mg/kg	59	89	68	79	68	89	66	80.1
Y	mg/kg	29	30	24	32	22	29	27	42.8
Zn	mg/kg	120	120	130	150	120	140	150	190
Zr	mg/kg	5.5	5.8	5.0	5.8	4.8	7.0	5.8	10.0

P95 – 95. percentil/95th percentile, P97.5 – 97,5. percentil/97.5th percentile; X2S – srednja vrednost+2×standardni odklon/mean+2×standard deviation; MD2MAD – mediana+2×absolutna deviacija mediane/median+2×median absolute deviation; TIF – Tukeyeva zgornja meja/Tukey upper fence; (L) – izračun na osnovi logaritemskih vrednosti/(calculated based on logarithmic values)

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Review of geological and seismotectonic investigations related to 1998 M_w5.6 and 2004 M_w5.2 earthquakes in Krn Mountains

Pregled geoloških in seizmotektonskih raziskav povezanih s potresoma 1998 M_w5,6 in 2004 M_w5,2 v Krnskem pogorju

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Ključne besede: potres, seizmotektonika, učinki potresa, skalni podori, Evropska potresna lestvica, intenzitetna lestvica potresnih učinkov na okolje (ESI lestvica), Krnsko pogorje, Ravenski prelom

Abstract

A review of geological and seismotectonic investigations conducted in the two decades after the 12 April 1998 earthquake in Krn Mountains, according to its magnitude the strongest earthquake in Slovenia in the 20th century, is given. Many of these studies have wider scientific meaning than expected from the size of the earthquake. This was the first case in Slovenia that a strong earthquake was undoubtedly related to a particular fault. Seismotectonic studies of seismogenic Ravne fault revealed that it is an actively propagating strike-slip fault growing by interaction of individual right stepping fault segments and breaching of local transtensional step-over zones. Airborne laser scanning (LiDAR) of Idrija and Ravne faults, which resulted in high resolution bare earth digital elevation model, was in 2005 for the first time used to study surface expression of an active fault in Europe. Among the primary characteristics of the 1998 earthquake were extensive environmental effects expressed mainly as massive rockfalls. They were systematically documented and evaluated for intensity assessment using European Macroseismic Scale (EMS-98) and Environmental Seismic Intensity (ESI) scale introduced in 2007, because application of the data on damage to buildings was limited in sparsely populated high mountains epicentral area. These studies were pioneering due to novelty of both intensity scales, indicating their strong points and weaknesses. Large variations in damage to buildings in the upper Soča valley at similar epicentral distances pointed to strong site effects due to very heterogeneous glacial and fluvial deposits in sedimentary basins and valleys. Therefore, different seismic microzonation maps were prepared to evaluate the influence of soft sediments on seismic ground motion. Conducted studies fostered development of several earthquake geology research methods in Slovenia as tectonic geomorphology, evaluation of environmental seismic effects and seismotectonics. They had positive impact also on the university education in the fields of geophysics, seismology and structural geology.

Izvleček

Podan je pregled geoloških in seizmotektonskih raziskav opravljenih v dveh desetletjih po potresu 12. aprila 1998 v Krnskem pogorju, ki je bil po magnitudi najmočnejši potres v Sloveniji v dvajsetem stoletju. Mnoge od teh študij imajo širši znanstveni pomen kot bi pričakovali glede na velikost potresa. Prvič v Sloveniji, da je bil močan potres nedvoumno pripisan nekemu prelomu. Seizmotektonske študije seizmogenega Ravenskega preloma so pokazale, da je to aktivno napredujoč zmični prelom, ki raste z interakcijo med posameznimi segmenti in preskoki med lokalnimi transtenzijskimi conami. Letalsko lasersko skeniranje (LiDAR), s katerim pridobimo visokoločljiv digitalen model višin golega površja brez vegetacije, je bilo v letu 2005 na območju Idrijskega in Ravenskega preloma prvič uporabljeno v Evropi za študij površinskega odraza aktivnega preloma. Med glavnimi značilnostmi potresa 1998 so bili obsežni učinki v naravnem okolju, izraženi predvsem kot veliki skalni podori. Ti so bili sistematično dokumentirani in ovrednoteni za določitev intenzitete po Evropski potresni lestvici (EMS-98) in Environmental Seismic Intensity (ESI) lestvici, ki je bila uvedena v letu 2007, ker je bila uporaba podatkov le o poškodbah objektov v nadžariščnem območju zelo omejena, saj je zaradi visokogorja to redko poseljeno. Ker sta obe lestvici novi, so bile te študije v mnogih vidikih pionirske in so pokazala na njihove prednosti in slabosti. Velike razlike v poškodbah objektov v zgornjem Posočju na primerljivih nadžariščnih oddaljenostih, so pokazale na velik seizmični vpliv heterogenih ledeniških in rečnih sedimentov, ki zapolnjujejo kotline in doline. Zato so bile izdelane različne karte potresne mikrorajonizacije in ocenjen vpliv mehkih sedimentov na potresno nihanje tal. Izvedene raziskave so imele pomemben vpliv na razvoj raziskovalnih metod potresne geologije v Sloveniji kot so tektonska geomorfologija, analiza učinkov potresov na naravno okolje in seizmotektonika. Pozitivno so vplivale tudi na razvoj univerzitetnega izobraževanja na področju geofizike, seizmologije in strukturne geologije.

Introduction

The earthquake on 12 April 1998 in Krn Mountains was according to its magnitude M_w5.6 the strongest earthquake in Slovenia in the 20th century. According to its maximum intensity VII-VIII EMS-98 it was surpassed only by the VIII EMS-98 Brežice earthquake (Cecić et al., 2018) and by the Friuli 1976 earthquake, which reached maximum intensity VIII-IX in Slovenia in Podbela (Breginjski kot), but its epicentre was in NE Italy. In Krn Mountains another strong earthquake occurred on 12 July 2004 with M_w5.2 and maximum intensity VI-VII EMS-98. Both earthquakes had strong impact on the development of seismological and earthquake geology sciences in Slovenia. The 20th anniversary of the 1998 earthquake is an opportunity for a review of very extensive investigations and developments in the multidisciplinary field of earthquake research. In this paper a review of geological and seismotectonic investigations related to both earthquakes is given. Many of these studies had strong influence on the development of different important scientific disciplines in Slovenia as tectonic geomorphology, environmental earthquake effects studies, site effects studies and paleoseismology. These disciplines undergone very fast development in the world in the last two decades, facilitated by new techniques as airborne laser scanning (LiDAR), advances in microtremors method and geophysical shallow subsurface characterisation etc. A complementary review paper in this issue is devoted to advances in extensive seismological investigation related to both Krn Mountains earthquakes (Gosar, 2019b).

Krn Mountains earthquakes in 1998 and 2004

The 12 April 1998 M_w5.6 earthquake occurred on the Ravne fault approximately 8 km SE from Bovec. It caused extensive damage to buildings in the upper Soča valley, but no casualties. The maximum intensity VII-VIII EMS-98 was observed in four villages: Lepena, Magozd, Spodnje Drežniške Ravne and Tolminske Ravne (Živčić et al., 1999; Zupančič et al., 2001). Mainly older buildings, built of rubble and simple stone, were damaged (fig. 1), but also some newer masonry buildings. The problem of macroseismic evaluation of this event was that the application of intensity scales based on damage to buildings and effects on humans and objects was limited

Fig. 1. In 1998 earthquake mainly older buildings, built of rubble and simple stone, were damaged (left), but also several monuments (right) (photo: A. Gosar).

Sl. 1. Ob potresu 1998 so bile poškodovane predvsem starejše stavbe zgrajene iz neobdelanega kamna (levo) in tudi številni spomeniki (desno) (foto: A. Gosar).

in the epicentral area, because it is very sparsely populated high mountain area. The earthquake was followed by long aftershocks sequence. Another strong earthquake with M_w5.2 occurred on 12 July 2004 on the same fault, with only slightly different focal mechanism. The maximum intensity of this event was VI-VII EMS-98, and it caused a casualty of a mountaineer hit by a fallen rock. The distance of both earthquakes to the towns of Bovec and Kobarid was 6-9 km (Zupančič et al., 2001). In the scientific literature there is a slight confusion regarding the name of the 1998 event, because in some early studies, especially those conducted by Italian researchers, they named it Bovec or Kobarid earthquake (Di Giacomo et al., 2014). Later some authors used also the name upper Soča valley (Posočje) earthquake. However, we believe that the only correct name is Krn Mountains earthquake and this name now prevails in the published literature (Di Giacomo et al., 2014).

Seismotectonic investigations

A preliminary evaluation of seismotectonic characteristics of 1998 earthquake was performed by Bernardis et al. (2000), but it was based mainly on focal mechanisms and aftershock distribution, without any geological field work. The earthquake was attributed to Čez Potoče fault named after Čez Potoče pass located 2 km north of Mt. Krn. However, such a name is not known in a geological literature and the correct name of this fault is Ravne fault after Tolminske Ravne (Buser, 1986). In the work of Bernardis et al. (2000), the fault was put in a regional tectonic context of the general crustal structure of NW Slovenia and Friuli area.

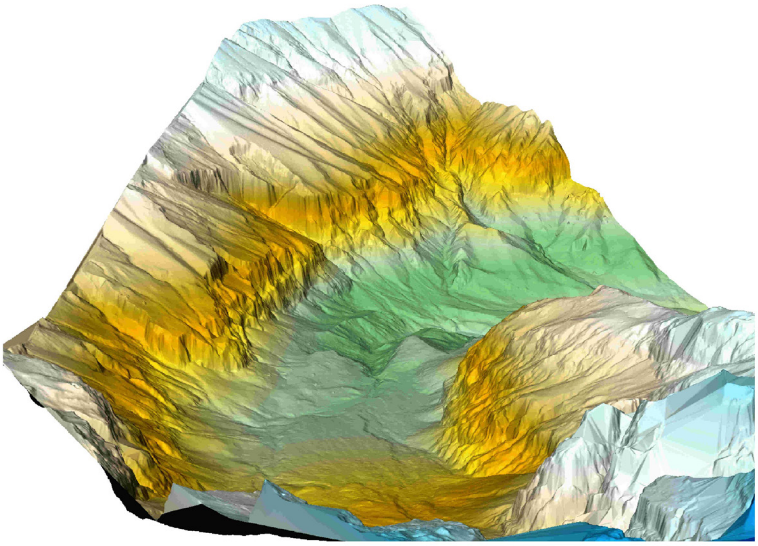
The first seismotectonic analysis of the 1998 earthquake has shown that it occurred on a dextral strike-slip subvertical Ravne fault (figs. 2 and 3) oriented in NW-SE direction (Zupančič et al., 2001). This was the first case in Slovenia that a strong earthquake was undoubtedly related to a particular fault mapped in the field. Earlier, such seismotectonic relations were mainly precluded by large errors in earthquake foci locations due to very sparse distribution of seismological stations. The hypocentral depth of the 1998 event was 7.6 km No surface rupture was found and based on distribution of aftershocks the fault rupture dimensions were assessed on 10 km × 7 km. The seismotectonic analysis was based on focal mechanisms, field observations and ortho photo aerial images. It was revealed that recent seismic activity in NW Slovenia is related to strike-slip Dinaric faults (fig. 3) as well as to thrusting along Southalpine thrust front and parallel planes (Zupančič et al., 2001). The area is located at the kinematic transition between E-W striking thrust faults of the Alpine system in Friuli and NW-SE striking dextral

Fig. 2. The view of seismogenic Ravne fault across Tolminka spring basin towards NW (photo: A. Gosar).

Sl. 2. Pogled na seizmogeni Ravenski prelom prek območja izvira Tolminke proti NW (foto: A. Gosar).

Fig. 3. Detailed view of the Ravne fault plane in a gully above Planina na Polju with clear indications of strike-slip character of this fault (photo: A. Gosar).

Sl. 3. Pogled na drsno ploskev Ravenskega preloma v grapi nad planino Na Polju, kjer se jasno vidijo strukture, ki kažejo na zmičen značaj tega preloma(foto: A. Gosar).



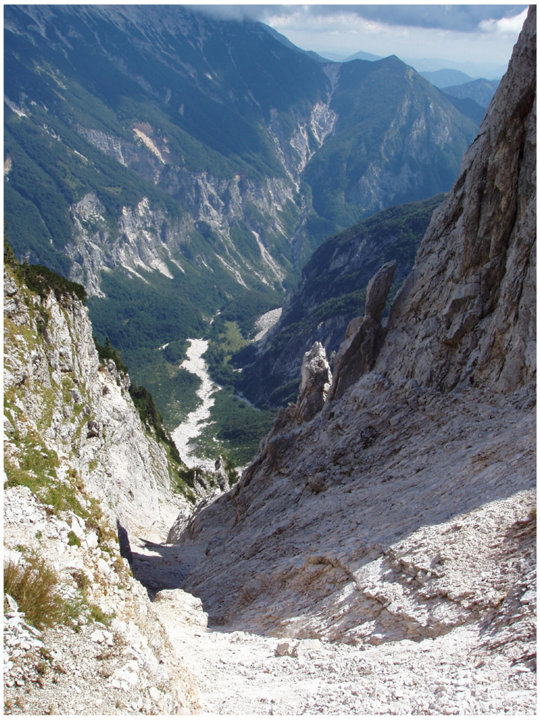


Fig. 4. 3D view of a Digital Elevation Model of the Ravne fault and Tolminka spring basin towards SE derived from LiDAR survey (left) and photo of the same area (right) (photo: A. Gosar).

Sl. 4. 3D pogled na Ravenski prelom in območje izvira Tolminke proti SE na digitalnem modelu višin izdelanem iz LiDARskega snemanja (levo) in fotografija istega območje (desno) (foto: A. Gosar).

strike-slip faults of the Dinarides system in NW Slovenia. The fault plane solution of 1998 event shows almost pure strike-slip mechanism with only minor reverse component.

Further seismotectonic analysis of the 1998 earthquake (Bajc et al., 2001) was based on relocation of hypocentres, strong motion (accelerograms) data inversion, field geological inspection and study of digital elevation models. From strong motion inversion it was revealed that the rupture was confined between 3 and 9 km depth and that it propagated bilaterally between two structural barriers. In the NW the barrier is related to the junction between Dinaric and Alpine structures and related sharp change in the geometry of faulting. The SE barrier is within the Dinaric system and at the surface expressed as Tolminka spring perched basin (fig. 4), a 1 km restraining step-over (Bajc et al., 2001). First evidence of the segmentation of more than 40 km long Ravne fault has strong implications for seismic hazard assessment and motivated further detailed research.

The second strong earthquake on 12 July 2004 opened many new questions on its seismotectonic characteristics, because the distribution of damage was slightly different, although the epicentre was very close (1.5 km distance) to the 1998 event (Vidrih & Ribičič, 2004). Seismological analyses showed slightly different focal mechanism with more pronounced reverse component (Kastelic et al., 2006). In addition, aftershocks were mostly distributed NW to WWN from those of 1998 event and do not show such a uniform spatial distribution. Spatial and temporal distribution of aftershocks depicts a contemporary seismic activity on NW-SE and WWN-EES to W-E oriented faults (Kastelic et al., 2006).

In 2005, when airborne laser scanning (LiDAR) was still very rare and expensive (Gosar, 2007), we had, through international cooperation, an unique opportunity to survey Idrija and Ravne faults with this very promising method (Cunningham et al., 2007), which after a decade strongly changed the science of tectonic geomorphology, through providing high resolution bare earth digital elevation models. Measurements were very successful especially on the Idrija fault where details of near fault structures and Quaternary terraces were revealed. Based on this study a location in Kanomljica valley was proposed for later paleoseismological studies. On the Ravne fault the most interesting results were obtained in the Tolminka spring basin (fig. 4), where LiDAR images revealed several branches of the fault. It was interpreted as active transtensional basin within overall transpressional regime (Cunningham et al, 2006). This investigation represents the first application of airborne LiDAR in Europe for the purpose of mapping the surface expression of seismogenic faults.

The most comprehensive seismotectonic analysis of the Ravne fault was done within the Ph.D. thesis of Kastelic (2008) and Kastelic et al. (2008). It was revealed that Ravne fault is an actively propagating strike-slip fault growing by interaction of individual right stepping fault segments and breaching of local transtensional step-over zones. The spatial distribution of aftershocks shows that activity on strike-slip segments and thrust faults is contemporaneous. The Ravne fault is a structure that lies in an area subjected to multiple tectonic events under different regional stress conditions. At epicentral depths, the fault system is accommodating recent strain along newly formed fault planes, whereas in the upper parts of the crust, the activity is distributed over a wide deformation zone that includes reactivated thrust faults (Kastelic et al., 2008).

Investigations of the effects of earthquakes on natural environment

Most prominent characteristics of the 1998 earthquake is that it had extensive effects on the natural environment in Julian Alps expressed mainly as rockfalls, which where is some cases very large. For the moderate magnitude (M_w5.6) event, such a great extent of rockfalls was not expected, therefore it immediately draws attraction of researchers and many thorough studies followed. Besides rockfalls, several other environmental effects occurred as well, which were also systematically documented and analysed.

Fig. 5. Very large rockfall caused by the 1998 earthquake in which the whole SE face of the Osojnica Mountain above Tolminka valley collapsed (photo: A. Gosar in May 1998).

Sl. 5. Zelo velik skalni podor nastal ob potresu 1998 v katerem se je podrlo celotno SE ostenje Osojnice nad dolino Tolminke (foto: A. Gosar, maj 1998).

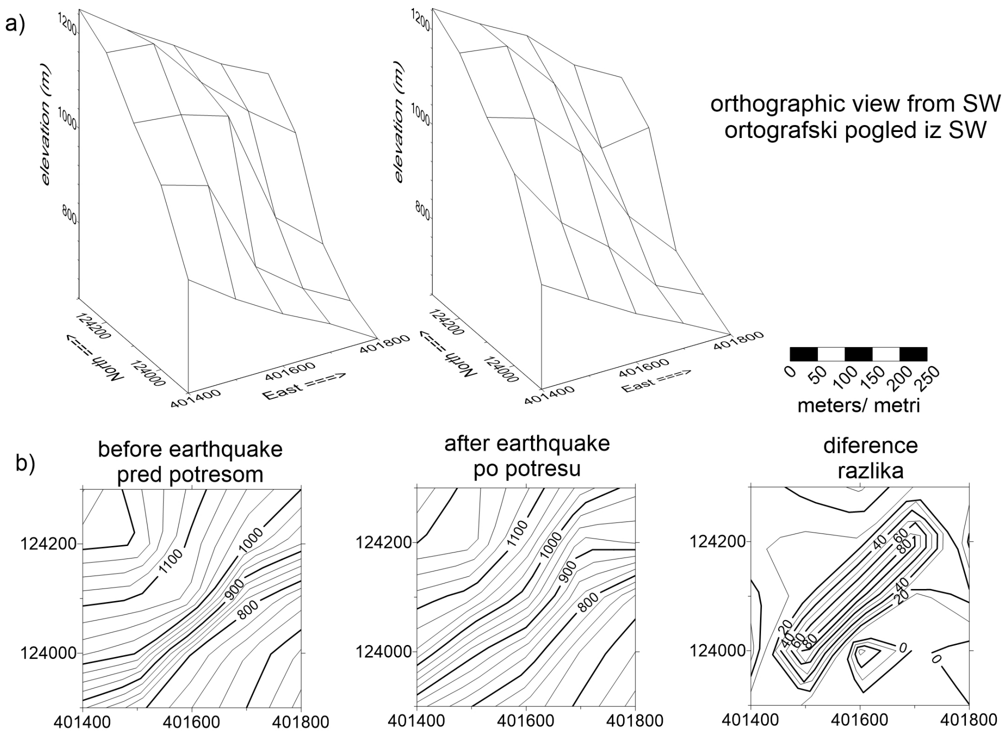


Fig. 6. Rockfall on the Osojnica Mountain was clearly reflected in Digital Elevation Models (DEM) showing pre- and post-earthquake topography. From the difference between both DEMs the volume of the rockfall was estimated on $3{\cdot}10^6$ m^3 (after Gosar, 1999b).

Sl. 6. Skalni podor na Osojnici se jasno odraža v digitalnem modelu višin (DMV), ki kaže topografijo pred in po potresu. Iz razlike obeh DMV je bila prostornina podora ocenjena na $3{\cdot}10^6$ m^3 (po Gosar, 1999b).

Analyses of rockfalls and seismic intensity scales

All rockfalls were systematically mapped soon after the 1998 earthquake to assess further risks to infrastructure and buildings (Ribičič, 1998). From the seismogeological point of view a further in-depth study was performed by Vidrih & Ribičič (1999). They documented all larger rockfalls and did the first evaluation of the applicability of a new European Macroseismic Scale (EMS-98) to assess intensity. For the epicentral area between Lepena and Tolminka valleys they proposed, based on effects on nature, maximum intensity VII-VIII EMS-98, which is in accordance to damage related intensity assessment in four villages in the same area. Since some of the rockfalls were very large (fig. 5), Gosar (1999b) investigated the possibility to use Digital Elevation Models (DEM) derived from aerial photography surveys before and after the earthquake to estimate their volumes (fig. 6). The volumes of the two largest rockfalls were quantitatively assessed to be $15{\cdot}10^6$ m^3 (Veliki Lemež in Lepena valley) and $3{\cdot}10^6$ m^3 (Osojnica in Tolminka valley).

In a further study (Vidrih et al., 2001) on the applicability of EMS-98 for assessing intensities for 1998 event, it was realized that the EMS-98 scale (Grünthal, 1998) is not sufficiently detailed in the description and evaluation of effects on the natural environment. It is deficient especially in quantitative description of environmental effects characteristic for particular intensity degrees. In EMS-98 environmental effects are rather briefly described on two pages and corresponding table (Grünthal, 1998). In this table for each type of effects three intensity ranges are presented: a) the possible range of observations, b) the range of intensities that is typical for this effect, and c) the range of intensities for which this effect is most usefully employed as diagnostic (Grünthal, 1998). One of the main problems of this table is that the same phenomenon is ascribed to a very wide range of intensity degrees, which prevents its practical use in assessing intensities. Therefore, Vidrih et al. (2001) proposed a different approach, reducing the intensity extent of phenomena appearance by introducing, in analogy to buildings, terrain vulnerability regarding strong shaking, the frequency of appearance and the level of damage with individual phenomena.

The introduction of a completely new and first scale at all devoted only to environmental effects - Environmental Seismic Intensity scale (ESI) in 2007 (Guerrieri & Vittori, 2007) motivated a new research on effect on natural environment aimed to evaluate the applicability of ESI to 1998 earthquake (Gosar, 2012; Gosar, 2014). All environmental effects were described, classified and evaluated again. These effects include rockfalls (fig. 7), landslides, fallen boulders (fig. 8), secondary ground cracks and hydrogeological effects. It was realized that only rockfalls (all together 78 were registered) are widespread enough to be used for intensity assessment. They

Fig. 7. A typical example of medium size rockfall occurred at V. Šmohor in Krn Mountains. The top of not very steep mountain collapsed (photo: A. Gosar in August 2003).

Sl. 7. Značilen primer srednje velikega podora se je zgodil na V. Šmohorju v Krnskem pogorju. Vrh ne preveč strme gore se je podrl (foto: A. Gosar, avgust 2003).

Fig. 8. A huge boulder in Dolič valley, very close to the epicentre of the 1998 earthquake, resulted from the rockfall on the Lipnik Mountain. The hight of the boulder is 5 m (photo: A. Gosar in September 2004).

Sl. 8. Ogromen balvan v dolini Doliča, zelo blizu nadžarišča potresa, je nastal zaradi podora na Lipniku. Višina balvana je 5 m (foto: A, Gosar, september 1998).

were classified into five categories according to their volume. Distribution of very large, large and medium size rockfalls has clearly defined an elliptical zone, elongated along the strike of the seismogenic fault, for which the intensity VII-VIII was assessed. This isoseismal line was compared to the VII-VIII EMS-98 isoseism derived from damage-related macroseismic data, which has similar elongated shape, but is slightly larger. This isoseism is defined by four points only and its size is strongly controlled by a single intensity point (Tolminske Ravne) lying quite far from other three points (Lepena, Magozd, Spodnje Drežniške Ravne), at the location where local amplification is likely. In this study the ESI 2007 scale has proved to be an effective tool for intensity assessment in sparsely populated mountain regions not only for very strong, but for moderate earthquakes as well (Gosar, 2012).

The size of the area affected by earthquake induced rockfalls depends on the magnitude (M_w) and on the maximum intensity (I_{max}). The established 180 km^2 area (r=7.6 km) for 1998 M_w 5.6 event was compared with two worldwide datasets for magnitude dependence (Gosar, 2019a). For the given magnitude the affected area is considerably below the upper bound limit established from both datasets. The same is valid for the Friuli M_w 6.4 earthquake with a 2050 km^2 affected area. However, comparison with the ESI scale definitions has shown that the area affected by the 1998 I_{max} VII–VIII event is significantly larger than the one proposed by this scale, but smaller for the 1976 I_{max} X event. This could not be explained by differences in hypocentral depth or focal mechanisms of both events. The results of this study have implications for seismic hazard assessment and for understanding environmental effects caused by moderate earthquakes in mountain regions (Gosar, 2019a).

The 2004 earthquake caused significantly less rockfalls than 1998 one. This was expected due to lower magnitude and the fact that most vulnerable slopes had already broken in stronger 1998 event. Anyway, 44 rockfalls were analysed, but only five of them were a bit larger (Vidrih & Ribičič, 2004). However, a fallen rock hit a mountaineer in Krn Mountains who died. Two very big landslides in Log pod Mangrtom and in Koseč near Kobarid fortunately did not react to seismic shaking due to relatively low intensity at their epicentral distance. Some very long cracks were developed along the edge of the Soča river terraces, which have contributed somewhere to the damage to buildings (Vidrih & Ribičič, 2004). The most complete review and documentation of all effects of 1998 and 2004 events on natural environment was prepared in Ph.D. thesis of Vidrih (2006) and later published in a monograph (Vidrih, 2008).

Rockfalls and landslides in several cases reached valley streams and rivers and significantly changed normal input of rock material. Therefore, Mikoš et al. (2006) studied sediment production and delivery from earthquake-induced rockfalls in the Upper Soča valley.

Analyses of other seismic effects on natural environment

The 1998 earthquake had curiously enough a substantial effect on the groundwater levels on Sorško and Kranjsko polje, located 60 km east of the epicentre. As recorded by four piezometers, it caused fluctuations in groundwater levels ranging from 23 to 82 cm (Uhan & Gosar, 1999). No fluctuations were recorded before or after the main shock, and no other fluctuations were reported from elsewhere. Therefore, an (hydro)geological interpretation of the observed phenomenon is not possible.

A short part of the Bohinj lake southern shore built of glaciofluvial debris slid into the water (Vidrih & Ribičič, 1999), but no evidence of liquefaction was found. It is located 25 km east of the epicentre where the intensity of 1998 event was VI EMS-98 and liquefaction is very unlikely at expected ground shaking.

In the areas of highest intensities VII-VIII EMS-98 there were some reports of cracks in the flat ground (in Magozd) (Vidrih & Ribičič, 1999). They resulted from strong ground shaking and cannot represent possible surface faulting or slope movements.

Since at the time of the 1998 earthquake there was a large amount of fresh snow (more than 0.5 m) in Krn Mountains, some interesting phenomena, which can be classified in-between snow avalanche, landslide and debris flow occurred. The most characteristically one occurred in Lepena valley (fig. 9). A mixture of snow, soil and rock slid down a steep ravine as an avalanche for more than 500 m of elevation difference. When it reached the valley floor, the debris was deposited as a debris flow in a wide fan (Vidrih & Ribičič, 1999; Gosar, 2012).

Seismic microzonations

Among important characteristics of 1998 and 2004 earthquakes were large variations in damage to buildings of similar vulnerability class at comparable epicentral distances. These variations were explained by prominent site effects within sedimentary basins (Bovec basin, Kobarid basin etc.) filled with heterogeneous glacial and fluvial sediments (fig. 10). In addition, strong resonance effects between soft sediments and buildings were proved at several locations using microtremor HVSR method (Gosar, 1999a). However, extensive studies using this method are presented in a complementary review paper on seismological investigation (Gosar, 2019b). Here only seismic microzonations motivated by observed prominent site effects that are based on geological and geotechnical data will be reviewed.

Within the project aimed to support retrofitting of damaged buildings several maps in different scales were prepared (Ribičič et al., 2000). In the general engineering-geological map of the upper Soča area was classified in hard rocks, medium hard rocks, slope sediments and alluvial sediments with geological and geotechnical description of each unit with relation to conditions for building foundations. Based on this division, a general seismic microzonation map of the area was prepared with soil classification to three

Fig. 9. Triggered by the 1998 earthquake, a mixture of snow, soil and rocks slid down a steep ravine in Lepena valley as an avalanche and created a fan shaped debris flow in the valley floor (photo: A. Gosar in May 1998).

Sl. 9: Mešanica snega, zemlje in skal je sprožena s potresom 1998 zdrsnila po strmi grapi v pobočju doline Lepene in v dnu doline povzročila nastanek pahljačastega drobirskega toka (foto: A. Gosar, maj 1998).

groups. At that time a new seismic hazard map showing ground acceleration for Slovenia was not yet available. Therefore, the seismic microzonation map was prepared to be used with the old seismic hazard map showing expected intensities for a return period of 500 years. According to this map NW Slovenia was characterized by expected intensities of VIII and IX on MSK scale and seismic microzonation provides intensity increments. For a Bovec basin a more detailed geotechnical map was prepared in which rocks and sediments were classified in eight types. Based on it, a detailed seismic microzonation of the Bovec basin was prepared, which shows that most of the area is characterised by $VIII_2$ and $VIII_3$ intensities (Ribičič et al., 2000; Ribičič, 2011). Considering also resonance effects between sediments and structures, preliminary microtremor method investigations were carried out in affected area to explain large variations in damage to buildings due to site effects (Gosar, 1999a; Gosar, 1999c). It turned out that resonance effect could play important role in distribution of damage especially in the Bovec basin filled with heterogeneous sediments (fig. 10).

A step forward in seismic microzonation based on detailed engineering geological mapping was performed for Breginjski kot (the most western part of Slovenia) (Kokošin, 2011), which suffered the highest damage (intensity VIII-IX EMS-98) in the Friuli 1976 earthquake sequence and significantly lower damage (VI-VII EMS-98 in Kobarid) in the 1998 earthquake due greater distance from the epicentre and lower magnitude event. According to the old seismic hazard map, the whole Breginjski kot is assessed as intensity IX MSK and according to the new hazard map to design ground acceleration of 0.250 g. First, a detailed engineering geological mapping in scale 1: 5000 was conducted. On the basis of this mapping, a soil classification was carried out according to the Medvedev method (intensity increments) and the Eurocode 8 standard (soil factors) and two microzonation maps prepared to be applied with both seismic hazard maps. The microzonation clearly points out the dependence of damage distribution to local site effects in the case of Friuli earthquake (Kokošin & Gosar, 2013).

Within the project Earthquake risk in Slovenia (POTROG – Potresna ogroženost Slovenije), there was a need to prepare a seismic microzonation maps of all areas where according to the official seismic hazard map of Slovenia a design ground acceleration for 475 years return period is assessed on 0.225 and greater. This includes also the whole upper Soča River territory. A seismic microzonation of this area in accordance to the Eurocode 8 standard was prepared in the frame of a diploma thesis (Trobec, 2012). However, this microzonation was based on existing data only (basic geologic maps, engineering geological maps and seismic microzonation of Breginjski kot) without any field investigations. Therefore, it is intended only for the general risk assessment studies and civil protection planning and not for the purpose of earthquake engineering design. The classification of rocks and sediments accord-

Fig. 10. Heterogeneous glacial and fluvial sediments in the Bovec basin were responsible for large variations in seismological site effects and consequently to the degree of buildings damage. A rockfall occured in the wall above the Soča river during the 1998 earthquake (photo: A. Gosar in May 1998).

Sl. 10. Zaradi heterogenih ledeniških in rečnih sedimentov v Bovški kotlini, so bile tam velike razlike v seizmoloških vplivih na potresno nihanje tal in posledično razlike v stopnji poškodovanosti stavb. Med potresom 1998 je v steni nad reko Sočo nastal tudi večji skalni podor (foto: A, Gosar, maj 1998).

Fig. 11. Soft lacustrine sediments as exposed in abandoned clay pit near Srpenica can significantly amplify seismic ground motion and are classified as ground type E according to the Eurocode 8 standard. a) General view of thin bedded lacustrine deposits, b) close view of very soft sediment (photo: A. Gosar).

Sl. 11. Mehki jezerski sedimenti, kot so razgaljeni v opuščenem glinokopu pri Srpenici, lahko znatno ojačajo potresno nihanje tal in jih klasificiramo v vrsto tal E po standardu Evrokod 8. a) pogled od daleč na tanko plastovite jezerske sedimente, b) bližnji pogled na zelo mehek sediment (foto: A. Gosar).

ing to Eurocode 8 was as follows. Solid rocks as carbonates, marlstone, sandstone, breccia, flysch rocks and shale represents ground type A. Alluvium of Lepenjica river represents ground type B, older Quaternary sediments ground type C and younger Quaternary sediments and fluvial sediments of Bovec basin ground type D. Ground type E is represented by fine grained river sediments, diamicts overlying ground type A, lacustrine chalk (fig. 11) and alluvium near Kobarid (Trobec, 2012). By application of soil factors the maximum design ground acceleration for a return period of 475 years in the area is 0.425 g on ground type E (soil factor 1.7, design ground acceleration on rock 0.250) in Breginjski kot, which is close to the highest values assessed in Slovenia. This value is surpassed only in the Ljubljana Moor where on very soft lacustrine and marsh sediments (ground type S_1) the design ground acceleration on solid rock of 0.250 g can be increased in the northern part by soil factor of 2.55 on 0.635 g and in other parts the design ground acceleration on solid rock of 0.225 g can be increased on 0.575 g (Zupančič et al., 2004).

Macroseismic data collected for strong earthquakes are not used only to study particularities of the macroseismic field related to distribution and properties of soft sediments in epicentral area where highest intensities are observed. They are valuable also at larger epicentral distances. In such study macroseismic data was used to investigate the influence of geological site effects on earthquake intensities (for all together 11 earthquakes) in greater Ljubljana area located around 80 km from epicentres of Krn Mountains earthquakes. The maximum intensities of 1998 and 2004 earthquakes in wider Ljubljana area and for the strongest 1998 aftershock were V EMS-98. The results showed a systematic increase in observed seismic intensities as the seismogeological characteristics of the ground deteriorated (Jerše et al., 2013; Jerše et al., 2015). Only one ground type (D) showed slightly lower intensity than expected. This may be due to some unrevealed geological factors or very limited macroseismic data available for this particular ground type which is relatively rare in wider Ljubljana area.

Conclusions

Geological and seismotectonic investigations related to the 1998 and 2004 earthquakes in Krn Mountains performed in two decades had in several cases much wider scientific meaning that could be expected from the size and effects of both events. This is reflected also in large number of citations of many studies obtained in international scientific literature. Since new European Macroseismic Scale (EMS-98) was after preliminary version from 1992 in its final form presented in 1998 (Grünthal, 1998), this was one of the first strong European earthquakes macroseismicaly evaluated by using this scale (Cecić et al., 1999; Zupančič et al., 2001). Especially important were first attempts to apply EMS-98 to evaluate seismogeological effects expressed as massive rockfalls in extent not expected for the magnitude of the event (Vidrih & Ribičič, 1999; Vidrih et al., 2001). It was realised that EMS-98 scale is not sufficiently detailed in description of effects on the natural environment, especially in quantitative description of effects characteristic for particular intensity. Later presentation of Environmental Seismic Intensity Scale (ESI) (Guerrieri & Vittori, 2007) motivated a new study which proved that it is an effective tool for intensity assessment in sparsely populated mountain regions also for moderate earthquakes (Gosar, 2012). Application of airborne laser scanning (LiDAR) of the Ravne and Idrija faults to reveal their geomorphological and structural features was a pioneering LiDAR study applied for tectonic geomorphology in Europe (Cunningham et al., 2006). Both earthquakes motivated first thorough, modern and quantitative seismotectonic studies of an active fault in Slovenia. The seismogenic Ravne fault was recognized as a typical example of actively propagating strike-slip fault which is growing by interaction of segments and breaching of local transtensional step over zones (Kastelic et al., 2008). During recent preparation of a seismotectonic model for a new seismic hazard map of Slovenia, it was realised that thorough understanding of segmented faults behaviour is of key important for realistic earthquake hazard modelling. Studies of geological and seismotectonic characteristics of the 1998 and 2004 earthquakes were important also for university education of geology in Slovenia as two Ph.D. thesis were prepared (Vidrih, 2006; Kastelic, 2008) and at least eight diploma theses related to these topics at the University of Ljubljana, Faculty of Natural Sciences and Engineering. These studies foster education in different geological fields: structural geology and active tectonics, geophysics, seismology, engineering geology and Quaternary geology.

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Review of seismological investigations related to 1998 M_w5.6 and 2004 M_w5.2 earthquakes in Krn Mountains

Pregled seizmoloških raziskav povezanih s potresoma 1998 M_w5,6 in 2004 M_w5,2 v Krnskem pogorju

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Ključne besede: potres, seizmologija, seizmotektonika, makroseizmika, žariščni mehanizem, popotresni niz, statična sprememba napetosti, lokalni seizmološki vplivi, metoda mikrotremorjev, Krnsko pogorje, Ravenski prelom

Abstract

Overview of extensive seismological studies of Krn Mountains earthquakes performed in two decades is given. Detailed macroseismic studies by using a new European Macroseismic Scale EMS-98 showed large variations in damage to buildings due to the influence of very heterogeneous sediments and partly also due to the differences in source radiation pattern. Site effects were carefully studied and it was proven by microtremor HVSR method that soil-structure resonance effects severely enhanced the damage in many places. Particularly important were seismotectonic studies based mainly on focal mechanisms and distribution of aftershocks. Combined with geological data these studies pointed to the complex structure of segmented Ravne fault, which is growing by interactions between individual fault segments. A wider area is characterised by a kinematic transition between Dinaric (NW-SE) strike-slip faults in W Slovenia and E-W trending Alpine structures with predominantly reverse faulting in Friuli. Other investigations included static stress changes on neighbouring faults, analyses of the time decay of extensive aftershock sequences and magnitude-frequency relations. All these studies have significantly fostered seismological research in Slovenia and have enhanced international cooperation. Following the 1998 earthquake a modern national seismological network was built composed of 26 stations equipped with broadband sensors, accelerometers and high-resolution digitizers. Together with cross-border exchange of real-time data the seismological monitoring has been significantly improved.

Izvleček

Podan je pregled obsežnih seizmoloških raziskav, ki so v dveh desetletjih sledile potresoma v Krnskem pogorju. Podrobne makroseizmične raziskave z uporabo nove Evropske potresne lestvice EMS-98 so pokazale velike razlike v poškodovanosti stavb zaradi vpliva zelo heterogenih sedimentov in deloma tudi zaradi sevalne funkcije posameznih potresov. Vplivi mehkih sedimentov so bili natančno raziskani, z uporabo metode spektralnih razmerij mikrotremorjev je bilo mogoče dokazati velik vpliv resonančnih učinkov med sedimenti in stavbami, ki so ponekod bistveno povečali škodo zaradi potresa. Posebno pomembne so bile seizmotektonske študije, ki so temeljile predvsem na žariščnih mehanizmih potresov in prostorski porazdelitvi popotresov. Skupaj z geološkimi podatki so razkrile zapleteno strukturo segmentiranega Ravenskega preloma, ki raste z interakcijo med posameznimi segmenti preloma. Za širše območje je značilen kinematični prehod med zmičnimi prelomi Dinarske smeri (NW-SE) v zahodni Sloveniji in Alpsko usmerjenimi (E-W) strukturami v Furlaniji s prevladujočim reverznim prelamljanjem. Druge raziskave so vključevale tudi analizo statičnega prenosa napetosti na sosednje prelome, analize časovnega poteka obsežnih popotresnih nizov in odnosa med magnitudo in frekvenco potresov. Vse te študije so pomembno spodbudile razvoj seizmologije v Sloveniji in razmahnile mednarodno sodelovanje. Po potresu leta 1998 je bila zgrajena moderna seizmološka mreža, ki je sestavljena iz 26 opazovalnic opremljenih s širokopasovnimi seizmometri, pospeškometri in visoko-ločljivimi digitalizatorji. Skupaj s čezmejno izmenjavo podatkov v stvarnem času se je bistveno izboljšala kvaliteta seizmološkega monitoringa.

Introduction

The earthquake on 12 April 1998 in Krn Mountains was according to its magnitude M_w5.6 the strongest earthquake in Slovenia in the 20th century. According to its maximum intensity VII-VIII EMS-98 it was surpassed only by the intensity VIII EMS-98 Brežice earthquake (Cecić et al., 2018) and by the Friuli 1976 earthquake, which reached maximum intensity VIII-IX in Slovenia in Podbela (Breginjski kot), but its epicentre was in Italy. In Krn Mountains another strong earthquake occurred on 12 July 2004 with M_w5.2 and maximum intensity VI-VII EMS-98 (fig. 1). Both earthquakes had strong impact on the development of seismological and earthquake geology sciences in Slovenia. The 20th anniversary of the 1998 earthquake is an opportunity for a review of extensive studies and developments in the interdisciplinary seismological research. In this paper a review of seismological investigations related to both earthquakes is given. These studies had positive impact on the development in many areas as seismological monitoring, seismotectonics, studies of aftershock sequences, stress change studies, macroseismics and site effects studies. Most of the studies related to both earthquakes were published by Slovenian and Italian researchers (Di Giacomo et al., 2014). A complementary review paper in this journal issue is devoted to extensive geological and seismotectonic investigation related to Krn Mountain earthquakes (Gosar, 2019). In the introductory part of that paper an overview of both earthquakes and their consequences is also given (Gosar, 2019).

Macroseismic investigations

After the 1998 earthquake the largest macroseismic survey in Slovenia so far was conducted. Macroseismic questionnaires were distributed to all voluntary observers (more than 4300) in the database of Uprava RS za geofiziko (Geophysical Survey of Slovenia) and 68 % were returned, which is very high percentage comparing to similar surveys (Cecić et al., 1999). Macroseismic data on damage to buildings and other effects were collected in the field by seismologists and integrated with the data contributed by official damage inspection commissions. Data were evaluated by means of the European Macroseismic Scale (EMS-98), which was in its final version published in the same year of earthquake occurrence (Grünthal, 1998). Therefore, this was one of the first comprehensive macroseismic surveys of a strong earthquake in Europe using a new scale. In Slovenia data were evaluated for more than 2000 localities (fig. 1) and macroseismic data collected from all other Central European countries to reveal the whole macroseismic field (Zupančič et al., 2001). The maximum intensity VII-VIII EMS-98 was observed in four villages: Lepena, Magozd, Spodnje Drežniške Ravne and Tolminske Ravne. Average radii of the areas of the same EMS-98 intensity were VII-13 km, VI-25 km, V-66 km, IV-180 km, III-422 km. More than 3000 damaged houses were examined (Godec et al., 1999). Older objects built of rubble and simple stone with wooden floors and poor quality mortar suffered damage most frequently, including partial collapse of walls or corners. Numerous houses had damage on roofs and chimneys and extensive cracks in walls. Some newer masonry buildings were also damaged, in many cases due to strong site effects (Zupančič et al., 2001). Large variations in damage within short distances were a very prominent characteristic of this earthquake. They cannot be explained by different vulnerability, because the building construction is similar in the whole area, but should be attributed to the amplifications in soft sediments (Gosar, 2007).

The 2004 earthquake had maximum intensity VI-VII EMS-98 in Čezsoča, Vodenca, and some parts of Bovec (Cecić et al., 2006). It was soon realized that the distribution of damage is slightly different in comparison to the 1998 event, although both epicentres were very close (Vidrih & Ribičič, 2006). Intensive retrofitting activities took place after the 1998 earthquake, but were not completely finished before the 2004 event (Godec et al., 2006). This partly influenced the assessment of the 2004 event intensities. Due to much higher magnitude of the 1998 earthquake, the intensities in most localities in the upper Soča river territory were from 0.5 to 2.0 degrees higher with respect to that observed for 2004 earthquake. But this was not the case for Čezsoča and Žaga, where the same intensities were observed, and for Srpenica and Trnovo ob Soči, where for the 2004 event even a higher intensity for 0.5 degree was observed (Zupančič et al., 2001; Cecić et al., 2006).

Gosar (2014) performed an analysis of the impact of fault mechanism radiation patterns on macroseismic fields to explain the observed differences. Although both earthquakes occurred on the Ravne fault, the focal mechanism of the first event was almost pure strike-slip, and a strike-slip with a small reverse component for the second one (fig. 1). This was explained as an active growth of the fault at its NW end (Kastelic et al., 2008). Radiation amplitude lobes were computed for three orthogonal directions. The

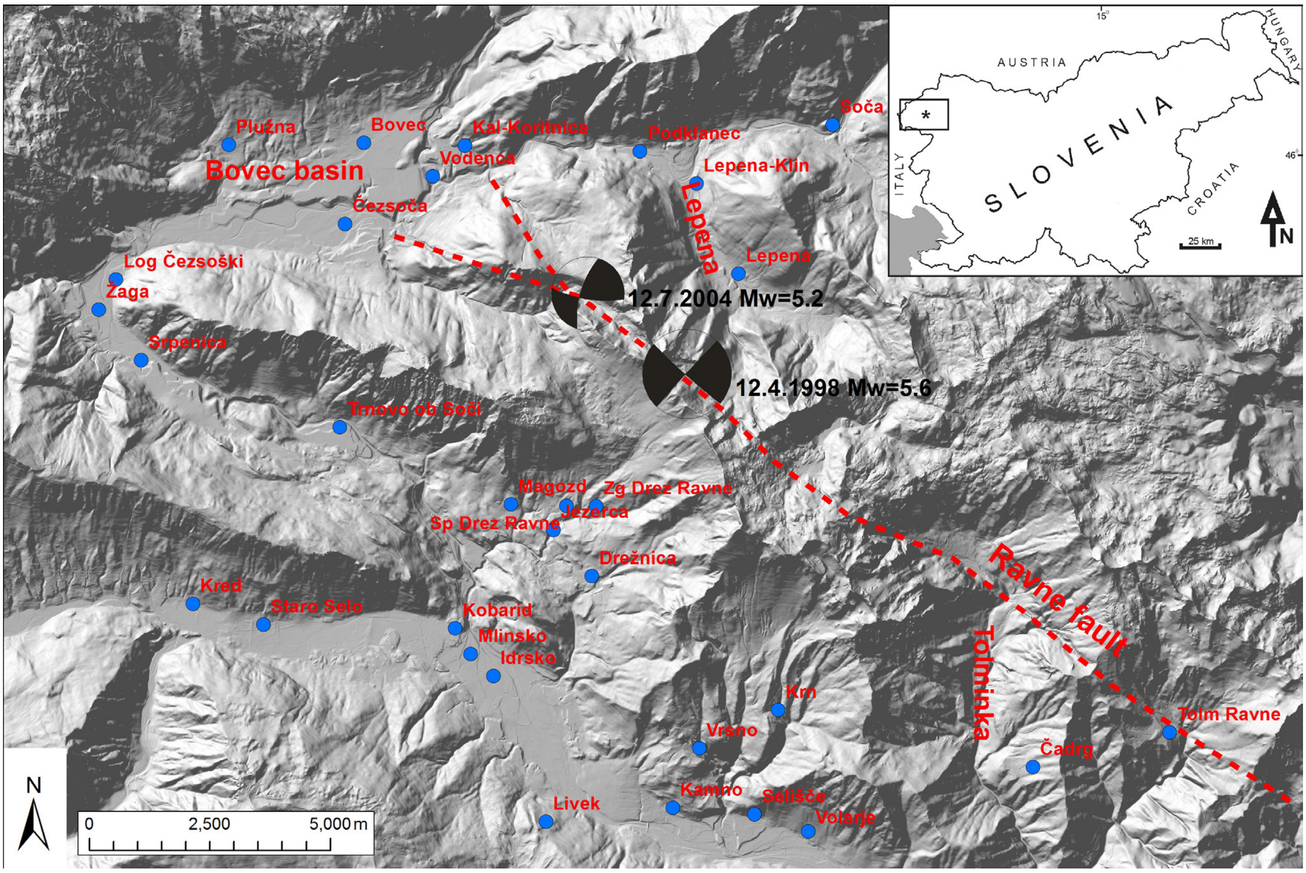

Fig. 1. The epicentral area of the Krn Mountains earthquakes with focal mechanisms of the 1998 (after Zupančič et al., 2001) and 2004 (after Kastelic et al., 2006) main shocks, the trace of the Ravne fault and locations for which the intensities were assessed. The estimated error for the location of epicentres is 1 km.

Sl. 1. Nadžariščno območje potresov v Krnskem pogorju z žariščnima mehanizmoma obeh glavnih potresov 1998 (po Zupančič et al., 2001) in 2004 (po Kastelic et al., 2006), traso Ravenskega preloma in lokacijami, na katerih so bile opredeljene intenzitete. Ocenjena napaka položaja nadžarišč je 1 km.

highest intensities of both earthquakes were systematically observed in directions of four (1998) or two (2004) large amplitude lobes in SH component (which corresponds mainly to Love waves), which have significantly different orientation for both events. As expected for the strike-slip mechanism of the 1998 event, the radiation pattern shows a very symmetrical four-lobe shape with all four amplitude lobes of almost the same size. On the other hand the small reverse component in the mechanism of the 2004 event results in a distinctively larger amplitude lobe in SW direction when compared to the other three lobes. The two settlements (Srpenica and Trnovo ob Soči) where the intensity of the 2004 event exceeds the intensity of the 1998 event are located in the direction of the highest P amplitude lobe of the radiation pattern. The study has shown that although both macroseismic fields are very complex due to influences of multiple earthquakes, retrofitting, site effects, and sparse distribution of settlements, unusual differences in observed intensities can be explained to some extent with different radiation patterns (Gosar, 2014).

Krn Mountain earthquakes and seismic hazard maps of Slovenia

At the time of the 1998 earthquake the official seismic hazard map in Slovenia was intensity map showing expected intensities in MSK scale for 500 years return period (Ribarič, 1987). According to this map the most western part of the upper Soča territory, which extends close to the towns of Bovec and Tolmin, belongs to the intensity IX and the rest mainly to the intensity VIII. The comparison of the 1998 event maximum intensities (VII-VIII EMS-98) with this map has shown that the predicted values were not exceeded (Zupančič et al., 2001). It should be noted that the differences in MSK and EMS-98 scales could be neglected in such a comparison. In 1998 there were no accelerographs installed in the area to measure ground motion accelerations. The nearest seismic station was in Italy, 16 km from the epicentre and the nearest seismic station in Slovenia in Vojsko, 36 km from the epicentre, equipped at that time with analogue seismograph.

After the 1998 earthquake several temporary seismological stations were deployed in wider epicentral area including three strong motion instruments (accelerographs) in Bovec, Kobarid and Drežnica, which are located less than 10 km from the epicentre of 2004 earthquake. Obtained accelerograms were the first modern digital strong motion data of a relatively strong earthquake recorded at close epicentral distances in Slovenia and are thus important for engineering seismology (Šket Motnikar & Prosen, 2006). However, it turned out that several factors could influence the measurements including site and building effects and instrument fixation. In Drežnica (5 km from the epicentre) peak horizontal acceleration of 0.38 g was recorded (fig. 2), but strong motion instrument was not fixed to the ground and its sliding during the earthquake could not be totally excluded, although it is not likely. In Bovec (7 km from the epicentre) peak horizontal acceleration of 0.48 g was recorded in a public library. Due to the damage to ceiling and falling of the books from the shelf close to the instrument, the accelerogram was significantly deformed. However, it is believed that basic accelerogram corrections removed the noise. In Kobarid (7 km from the epicentre) peak horizontal acceleration of 0.15 g was recorded. In comparison to established attenuation models, these values are much higher than expected for M_w5.2 earthquake. However the duration of strong shaking above the selected threshold was in all cases very short, and higher values appeared at short periods. Measured peak accelerations also do not correlate with observed damage and assessed intensities, which were expected for an earthquake of such magnitude. Although accelerograms were corrected, peak values could not be treated as effective ground accelerations (Šket Motnikar & Prosen, 2006).

According to the official seismic hazard map of Slovenia (Lapajne et al., 2001) all three stations are located in the area of 0.225 g design ground acceleration for return period of 475 years. This raised a question, if seismic hazard is underestimated in the upper Soča territory. Because for the 1998 much stronger earthquake, for which no measurements are available, even higher peak acceleration are expected in comparison to the measured 2004 values. The opinion of Lapajne et al. (2006) is that high uncertainties and measurement errors are possible due to the inappropriate installation of instruments. In addition such high values can be explained by several causes: increased vulnerability of building in which measurements were taken, local site effects, near-filed and fault directivity effects. The observed intensities also does not support the exceedance of effective values of ground acceleration (Lapajne et al., 2001).

Seismotectonic investigations based on seismological data

In a complementary paper on geological and seismotectonic investigations (Gosar, 2019), a review of seismotectonic investigations, which involved also field geological work and remote sensing studies is given. Here, a review will be given on investigations based mainly on seismological data that includes computation of earth-

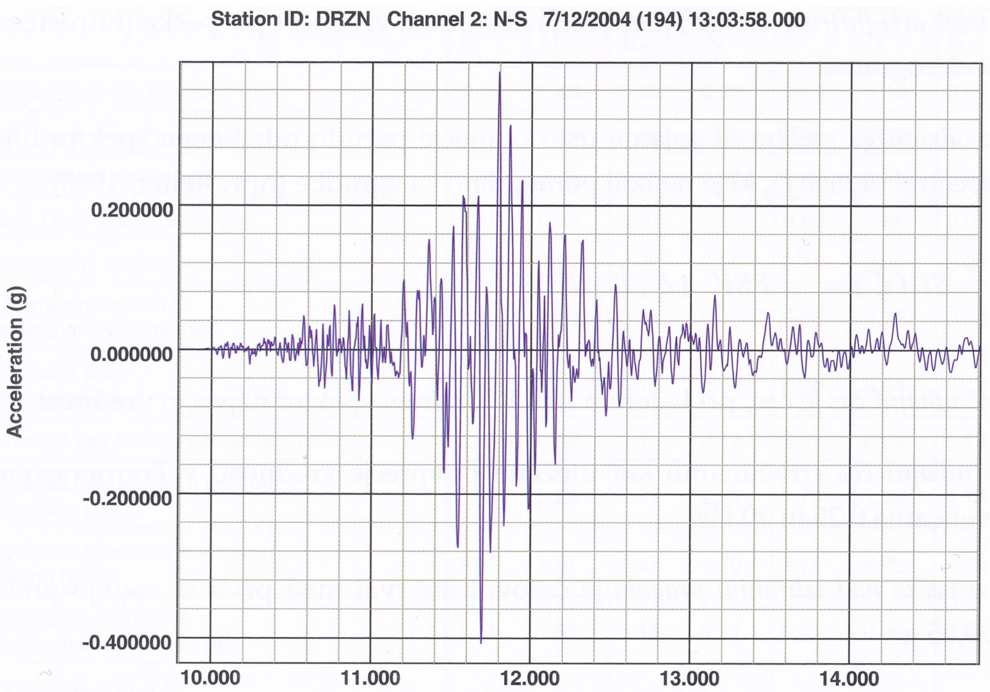

Fig. 2. The accelerogram of the 2004 Krn Mountains earthquake recorded at Drežnica (DRZN) station located 5 km from the epicentre. On the N-S component the peak acceleration of 0.38 g was recorded (after Šket Motnikar & Prosen, 2006).

Sl. 2. Akcelerogram potresa 2004 v Krnskem pogorju, zabeležen na seizmološki postaji Drežnica (DRZN), ki se je nahajala 5 km od nadžarišča. Na komponenti N-S je bil zabeležen največji pospešek 0,38 g (po Šket Motnikar & Prosen, 2006).

quake focal mechanisms, studies of a spatial distribution of aftershocks and moment distribution on the fault etc.

For any in-depth seismological study accurate locations of hypocentres are needed, taking into account distances of seismological stations and azimuthal coverage. For the 1998 earthquake the hypocentral parameters of aftershocks were obtained using adapted joint hypocentre determination (JHD) method (Bajc et al., 1999), and the average estimated location error is approximately 500 m. Hypocentres of the majority of the aftershocks stretch in a NW-SE elongated belt that is 10 km long and 3 km wide. They occurred along almost vertical fault plane at depths from just below the surface to 7 km (Zupančič et al., 2001). The ruptured area was estimated to be around 10 km × 7 km, which is close to published expected values for M_w5.6 earthquake that vary from length 8 km or area 42 km^2 to length 13 km or area 107 km^2. The fault plane solution of the main 1998 shock is almost pure dextral strike-slip (NW-SE plane) (fig. 1), but many aftershocks, which were mostly shallower, show different mechanisms. They mainly contain also a reverse component in the WNW-ESE plane. The major principal stress is approximately N-S (Zupančič et al., 2001).

Another preliminary study of the 1998 earthquake and its aftershock sequence was based mainly on data recorded by seismic stations located in Friuli-Venezia Giulia (Bernardis et al., 2000). Similar focal mechanisms as those by Zupančič et al. (2001) were obtained for the main shock and nine stronger aftershocks with magnitude 3.5-4.0. On the other hand, aftershocks with magnitude 3.0-3.5 show transtensional or even extensional focal mechanisms with orientation of planes from NW-SE to N-S. This type of focal mechanisms prevails over the fault plane solutions typical of low-angle NW-SE to NE-SW trending reverse faults. This suggests that the deformation recovery of the crustal volume affected by the main shock may be achieved through reactivation of several pre-existing faults (Bernardis et al., 2000).

An advanced relocation followed, which was based on 4000 aftershocks recorded by seismic networks in Slovenia, Italy, Austria and Croatia by adapting the joint hypocentre determination (JHD) method for teleseismic data to local earthquakes (Bajc et al., 2001). The relocated aftershocks are well organized along a trend of about N125° and the area of epicentres is 12 km × 3 km. Only five hypocentres were deeper than 10 km, all of them off-fault. The accelerograms of four stations of the Friuli network were inverted to study the source process of the main shock. The seismic moment of 4.5×10^{17} Nm was obtained and the average slip of 18 cm. The moment distribution shows the maximum energy release around the hypocentre of the main shock, confined into a region of 10 km × 6 km and decreasing towards the edges of the fault. The rupture was growing in a bilateral way starting from the hypocentre within 3 s (Bajc et al., 2001). The distribution of aftershocks is compatible with the slip; they are more frequent in shallower areas that didn't break during the main shock. The majority of the main shock energy release occurred towards the SE end, where there is a diffuse aftershock activity at the shallowest part. At the NW end, the aftershock distribution clearly shows an abrupt cut-off in activity, connected with the area of low energy release during the main shock (fig. 3). These observations indicate that the NW barrier close to the Bovec basin is stronger and related to the sharper change of the strike at the transition from Dinaric to Alpine structures than SE barrier at the Tolminka spring basin, which is within the Dinaric system (Bajc et al., 2001).

Seismotectonic characteristics of the 2004 earthquake were studied by Kastelic et al. (2006). The main shock occurred very close to the 1998 earthquake, but shows slightly different focal mechanism (fig. 1) with more pronounced reverse component in addition to prevailing strike-slip one. The aftershocks of the 2004 event are mostly located in the NW to WWN direction from those of the 1998 event and do not show such a uniform distribution (fig. 3). A group of aftershocks that have a prevailing strike-slip focal mechanisms continues in a NW-SE direction, while the aftershocks oriented in a WWN-EES to W-E direction show more pronounced reverse component. Such temporal and spatial distribution of the aftershocks depicts a contemporary activity on both NW-SE and WWN-EES to W-E oriented faults. The principal stress axis is oriented generally in N-S direction with only slight deviations for individual aftershocks (Kastelic et al., 2006). Integrated with structural geological data a further seismotectonic interpretation of the Ravne fault was given in Kastelic et al. (2008). The fault is growing by interaction of individual right stepping fault segments and breaching of local transtensional step-over zones. The fault geometry is controlled by the original geometry of the NW-SE trending thrust zone, modified by successive faulting within the fault zone. In a recent stress

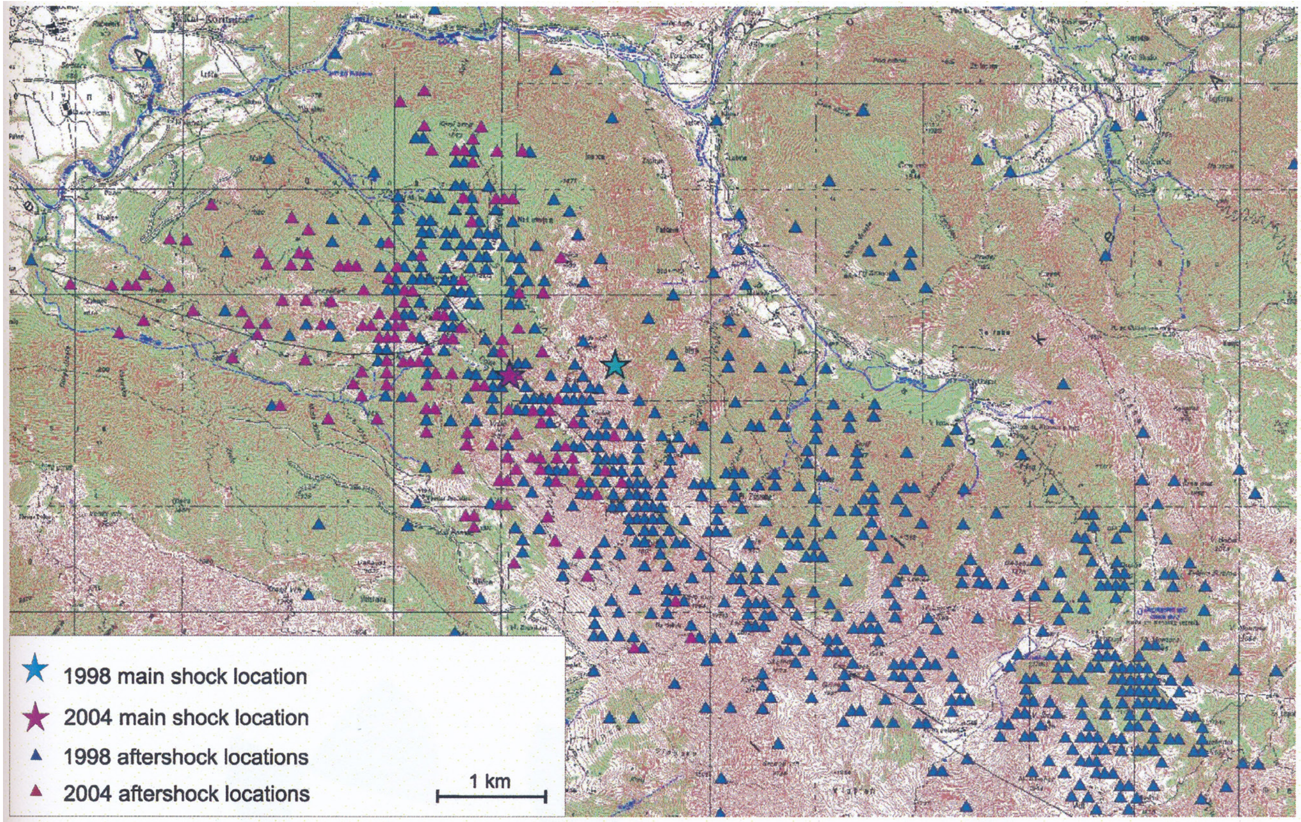

Fig. 3. Spatial distribution of aftershocks that followed the 1998 and 2004 earthquakes in Krn Mountains The estimated error for the location of epicentres is 0.5 km (after Kastelic, 2008).

Sl. 3. Prostorska porazdelitev popotresov, ki so sledili glavnima potresoma 1998 in 2004 v Krnskem pogorju. Ocenjena napaka položaja nadžarišč je 0,5 km (po Kastelic, 2008).

regime, the segmented fault is lengthening by active growth at its NW end. At epicentral depths, the fault system is accommodating recent strain along newly formed fault planes, whereas in the upper parts of the crust the activity is distributed over a wider deformation zone that includes reactivated thrust faults (Kastelic et al., 2008).

Herak et al. (2003) studied azimuthal anisotropy of P-wave velocity in Krn Mountains by measuring differences of travel times and travel paths towards the seismic stations located at different azimuths. The P-wave velocity varies from 6.0 km/s in the ENE-WSW direction to 6.4 km/s in NNW-SSE direction. Both directions closely match those of the mean regional principle stress components obtained from focal mechanisms. A large part of observed anisotropy may be explained by assuming that the hypocentral volume is pervaded by a system of vertical/subvertical extensive-dilatancy cracks aligned under the influence of local tectonic stress field (Herak et al., 2003)

Source parameters of the 2004 main shock and of 165 aftershocks ($0.8<M_L<3.5$) were investigated using records of Friulian stations in order to determine the corresponding source scaling relations (Franceschina et al., 2013). The main shock of the sequence is characterized by a seismic moment of $3.5 \cdot 10^{16}$ Nm and a corner frequency of 0.8 Hz, corresponding to a fault radius of approximately 1.5 km m and a stress drop of 4.9 MPa.

Bressan et al. (2016) studied the spatial organization of seismicity and the relation between fracture pattern and earthquakes in Friuli and W Slovenia. The orientation of planes that fit through the hypocentres shows a different disposition at the two depth intervals analysed. The shallower interval (0–10 km) is characterized by planes with highly variable orientations. These zones are characterized by high heterogeneity due to the superposition of different tectonic phases and by the maximum interference between Dinaric and Alpine domains. The orientation of the planes fitting the seismicity at 10–20 km depth is less dispersed, coinciding with the trend of Dinaric subvertical faults in the northern and eastern parts of the studied area, and with Alpine low-angle faults in the western and southern parts (Bressan et al., 2016).

In a recent study Bressan et al. (2018) investigated the stress and strain inversions from focal mechanisms in a revised seismotectonic zonation of NE Italy and W Slovenia inferred from 203 focal mechanisms, corresponding to earthquakes that occurred between 1984 and 2016. A dominant strike-slip stress field characterizes the eastern part of the area (Slovenia), while the seismotectonic zones of the central part (Friuli) are undergoing thrusting regime (Bressan et al., 2018).

Investigations of the time distribution of aftershocks and magnitude-frequency relations

Aftershock sequences of both earthquakes are the most thoroughly studied sequences ever performed in Slovenia. This was possible because the first portable seismograph was installed in Trenta already 9 hours after the 1998 earthquake and many followed in the next days. They recorded more than 7000 aftershocks till the end of 1998 (Zupančič et al., 2001). At the time of 2004 earthquake there was already a dense network of seismological stations in place. Extensive aftershock sequences after both events with several thousands of shocks lasted for more than one year. In 400 days the 1998 earthquake was followed by 104 and the 2004 one by 89 aftershocks with $M_L \geq 2,0$ (Gosar, 2008a). Both strongest aftershocks had magnitudes smaller for 1.4 and 1.3 with respect to the main shocks, which is slightly more than proposed by Bath's law (1.2). Time distribution of aftershocks has shown that the parameters of the modified Omori's law that describes the hyperbolic decay of aftershock activity with time, are very similar. This corresponds to the fact that both earthquakes occurred in the same hypocentral area. The value of the p parameter is around p=1.02. Aftershocks of the 1998 event clearly show secondary aftershock sequence which started with the strongest aftershock on 6 May 1998 (M_L=4.2), but there was no secondary sequence for the 2004 main shock. Analysis of the Gutenberg-Richter's magnitude-frequency relation has given the value of b parameter for the 1998 aftershock sequence between b=0.77 and 0.83 and for the 2004 sequence between 0.97 and 0.98. This means that the first earthquake was followed by more strong aftershocks. Obtained parameters of Omori's law and Gutenberg-Richter's relation are in good agreement with the values for similar aftershock sequences (Gosar, 2008a).

Gentili & Bressan (2008) studied eight aftershock sequences that occurred from 1977 and 2007 in NE Italy and W Slovenia, including 1998 and 2004 sequences. Among them the 1998 M_w5.6 earthquake was the strongest. For Omori's aftershock decay with time they obtained p parameter of p= 0.80 and 1.04 for 1998 and 2004 events respectively. Other sequences had values between p=0.80 and 1.00. The b parameter of the Gutenberg-Richter's relation was b=1.04 and 1.10 for 1998 and 2004 events respectively. Other sequences had values between b=0.80 and 1.10 (Gentili & Bressan, 2007; Gentili & Bressan, 2008). They computed also the probabilistic estimate of the aftershock rates and the largest aftershock in given time intervals.

Telesca et al. (2000) studied time-scaling behaviour for the 1998 aftershock sequence using Allan Factor (AF) method. The sequence of the occurrence times of the events with threshold magnitude 2.0 is characterised by scale-invariant behaviour from the time scale $\tau \sim 2 \cdot 10^4$ s with a scaling coefficient $\alpha \sim 0.9$, evaluated by a least-square method. By gradually increasing the threshold magnitude up to 2.9, the AF curves, associated, respectively with the processes of selected events with magnitude $M \geq M_{th}$, indicate a monotonic decrease of the value of the scaling exponent α. This monotonic power-law increase indicates the presence of fluctuations on many time scales and therefore of fractal clustering (Telesca et al., 2000).

Investigations of stress changes on neighbouring faults

Large earthquakes can trigger future earthquakes along neighbouring faults at short distances from the epicentre by transferring static or dynamic stresses. Two independent studies of Coulomb static stress changes were performed for the 1998 and 2004 earthquakes. In the first study (Ganas et al., 2008) they show that stress levels have increased along the active Ravne fault for all considered models, stress levels have decreased along the parallel (NW-SE) Idrija fault, stress levels in the crust have increased along the E-W direction, but have decreased in the N-S direction, because of stress shadow effect. A better correlation of the off-fault aftershock locations with stress maps incorporating the regional stress field was also obtained (Ganas et al., 2008).

Without knowing the previous study, although published, Bressan et al. (2009) performed a new study that includes also Coulomb stress changes analysis. They found a positive correlation of the Coulomb stress increase with the largest aftershock (M 4.6) and with a part of the aftershocks. Their modelling also shows that the Coulomb stress changes caused by the 1998 main shock and its largest aftershock were not sufficient to trigger the 2004 main shock. The spatial distribution of the 1998 and 2004 aftershocks correlate well with areas of increased Coulomb stress changes when the regional tectonic loading is also taken into account (Bressan et al., 2009).

In the next study Barnaba & Bressan (2013) compared 2002 Mount Sernio and the 2004 Krn Mountains aftershock sequences regarding static stress changes and seismic moment release. The Coulomb stress changes, calculated on the receiver fault of the largest aftershock, show that the aftershock sequences are mostly located in a stress shadow zone. The modelling of the Coulomb stress variations, which incorporates the regional stress field, fits better the aftershock pattern. The lack of correlation between the Coulomb stress perturbations and some of the aftershocks is attributed to stress heterogeneities not accounted in the model. The decay rate of the seismic moment release is different in the 2002 and 2004 sequences. According to this model, the distribution of stress in the aftershock volume appears more uniform in the 2004 sequence (Barnaba & Bressan, 2013).

Investigations of seismological site effects

As described in a review paper on geological and seismotectonic investigations (Gosar, 2019), strong variations in the damage to the buildings were observed within short distances in the upper Soča valley and especially in the Bovec basin. The variations in the damage can be attributed only in part to differences in building vulnerability, since the building typology is similar throughout the area. Soon after the 1998 earthquake, it became clear that seismological site effects had to play the most important role (Gosar, 2007). However, seismic microzonation study of the Bovec basin based on surface geological data and data from shallow geotechnical boreholes (Ribičič et al., 2000) has shown that it is not possible to explain most of the observed variations in the distribution of the damage with these data. One of the reasons for this is that the Bovec basin is filled with very heterogeneous glacial and fluvial deposits, which have different seismogeological properties and variate not only laterally but also vertically. At that time the microtremor horizontal-to-vertical spectral ratio (HVSR) method gained popularity in site effect studies and first portable instruments became available for effective measurements in the field. Two months after the 1998 earthquake a quick preliminary study using this method was performed at six points in the Bovec basin and two points in Drežniški kot (Mucciarelli & Monachesi, 1999). It was revealed that large variations in the shape of the HVSR curve exist between different parts of the town of Bovec, in village Kal-Koritnica and between Drežnica and Drežniške Ravne, which can be correlated with large variations in observed damage to buildings.

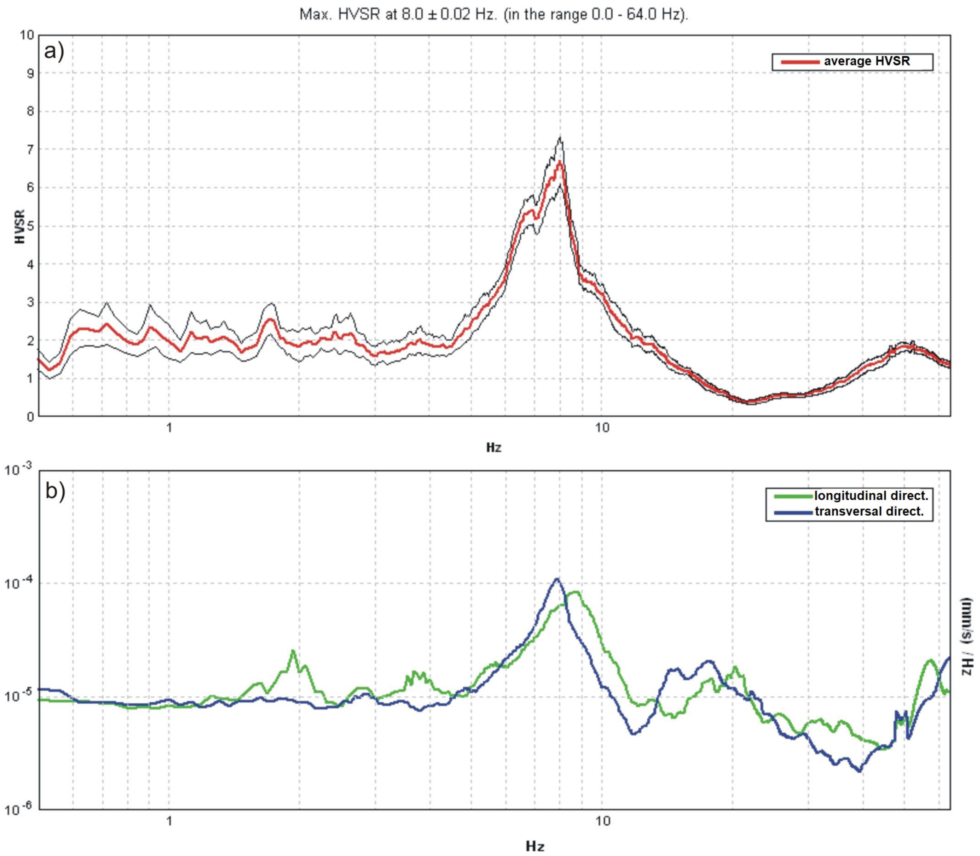

Fig. 4. An example of microtremor measurements in the Bovec basin that indicates probable resonance effects between soft sediments and buildings; a) The horizontal-to-vertical spectral ratio (HVSR) of the free-field measurement, b) The amplitude spectra of the microtremor measurement in the building (data after Gosar, 2007).

Sl. 4. Primer meritev z mikrotremorji v Bovški kotlini, ki kaže na verjetne resonančne učinke med mehkimi sedimenti in stavbo; a) Spektralno razmerje med horizontalnima in vertikalno komponento (HVSR) za meritve na prostem površju, b) Amplitudna spektra za meritve v stavbi (po Gosar, 2007).

This was the first indication that resonance effects between soft sediments and buildings could in some places enhance the damage. However, no subsurface geophysical or geotechnical information was available to explain the variations in observed resonance frequencies of sediments. Therefore geophysical investigations combining seismic refraction method, seismic velocity measurements in boreholes, and vertical electrical soundings were performed to reveal subsurface structures, lithology, the depth to the stiff rock, and to provide quantitative parameters on the distribution of the S-wave velocities with depth. Based on these data one-dimensional modelling of ground motion amplification was performed and the results were compared with the microtremor HVSR data (Gosar et al., 2001). Both methods showed significantly higher amplification in the frequency range of building vulnerability (2–10 Hz) in the Mala vas area of Bovec than in the central part of Bovec, which is consistent with the distribution of the damage. In Mala vas also several newer masonry buildings were highly damaged. Similar large differences in the HVSR peaks were observed between Spodnje Drežniške Ravne, where much higher damage (intensity VII-VIII EMS-98) was observed in comparison to nearby Drežnica (intensity VI-VII EMS-98) (Gosar et al., 2001).

Successful preliminary studies and further improvements of the microtremor HVSR method motivated a more in-depth study with this method in the Bovec basin (Gosar, 2007). The main advantage of the microtremor method is that with the measurements in the free-field it provides a resonance frequency of the sediments without knowing the S-wave velocity profile and the depth to the bedrock. In addition it can be efficiently applied to measure main resonance frequencies of buildings and thus enables soil-structure resonance studies (fig. 4). In the Bovec basin the method was applied in a 200 m dense grid of free-field measurements at 124 points. Large variations in the sediment frequency (3-22 Hz) were obtained (fig. 5), which cannot be related solely to

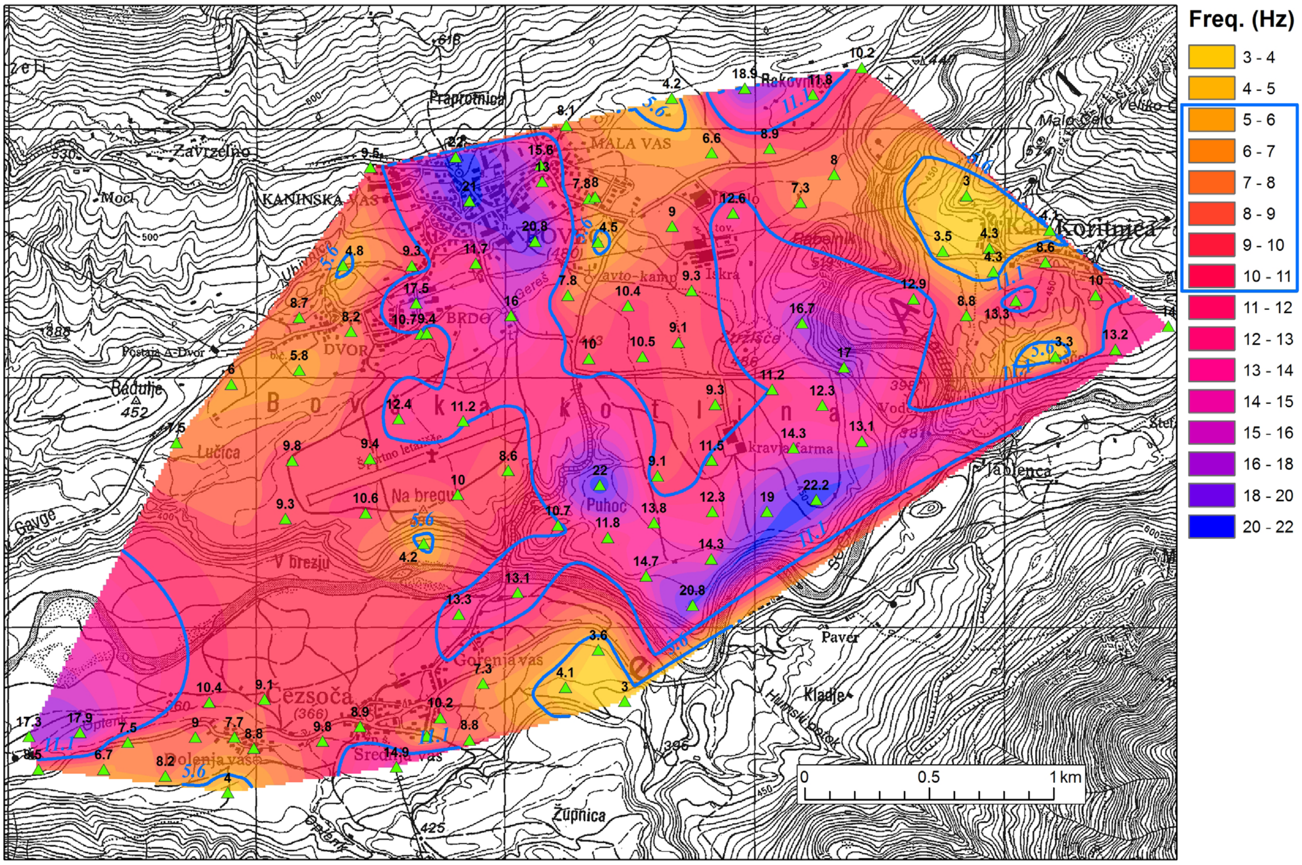

Fig. 5. The map of the resonance frequencies derived from microtremor measurements at 124 points in the Bovec basin. Blue contour lines indicate the borders of the areas in which the frequency range is between 5.6 Hzand 11.1 Hz. In the areas coloured orange, orange-red, light rose, or rose the probability of the occurrence of the resonance effects between soft sediments and buildings is high (as indicated in the legend on the figure), whereas in the areas coloured yellow, dark rose, red-violet, or blue, this probability is low (after Gosar, 2012).

Sl. 5. Karta resonančnih frekvenc v Bovški kotlini, izdelana na podlagi meritev v 124 točkah. Modra kontura omejuje območja, kjer so resonančne frekvence med 5,6 Hz in 11,1 Hz. V območjih, obarvanih z oranžno barvo in svetlimi lila odtenki, obstoja velika verjetnost resonančnih učinkov med mehkimi sedimenti in stavbami (kot je označeno tudi na legendi na sliki), medtem ko je v območjih, obarvanih z rumeno ali s temno lila oziroma modro barvo, ta verjetnost majhna (po Gosar, 2012).

the total thickness of the Quaternary sediments composed mainly of sand and gravel, but can be explained only by the presence of conglomerate or lithified moraine (more stiff sediments) at shallow depths. Considerable changes in fundamental frequencies were obtained especially in the town of Bovec with values as high as 22 Hz in the central part and values 6 Hz to 11 Hz in the adjacent Brdo and Mala vas districts. Additional measurements were performed in several houses of different heights (from two to four stories). Areas of likely soil-structure resonance were identified in Brdo, Mala vas, Čezsoča, and Kal-Koritnica (figs. 4 and 5). This is in agreement with the distribution of the damage due to both earthquakes, which was considerably higher in Brdo and Mala vas than in the central part of the town of Bovec, although the houses there are older. The microtremor method has proved to be an effective tool for assessment of the site effects in cases of complex geological structure commonly encountered in young Alpine basins filled with glaciofluvial sediments that are partly cemented (Gosar, 2007).

Following the 2004 earthquake, six accelerographs were deployed in a line across the Bovec basin to record aftershock sequence. Recorded data allowed comparison of different methods of site effect studies: standard spectral ratio using a reference station located on a bedrock at the edge of a basin and horizontal-to-vertical (H/V) methods using earthquake data and microtremors (Gosar, 2008b). Spectral ratio analyses showed that ground motion amplification occurs mainly in the frequency range of 5 Hz to 10 Hz, with corresponding amplitudes in the range of 6 to 11, but spectral ratios are quite complex and show a broad range of amplifications. Comparison of the results of the two H/V methods showed that the amplitudes obtained from microtremors are always lower than the amplitudes obtained from earthquake data. The difference was as high as for a factor of two. It was again revealed that the main reason for complex amplification spectra are irregular layers of stiff sediments (conglomerate, tillite) within sand and gravel, which result in large impedance contrasts at several interfaces within the Quaternary sediments (Gosar, 2008b).

The next microtremor HVSR study was performed in the Kobarid basin, because the town of Kobarid was also damaged in the 1998 (intensity VI-VII EMS-98) and the 2004 (intensity VI EMS-98) earthquakes. In a 100 m dense grid the measurements were taken at 106 free-field points (Gosar, 2010). The eastern part of the basin is characterized by the two well separated HVSR peaks, which indicate distinct shallow and deep impedance contrasts caused by shallow conglomerate inside sandy gravel or lacustrine chalk and the bedrock built of Cretaceous flysch. In the western part the observed frequencies are related to the total thickness of the Quaternary sediments. Microtremor measurements were also performed inside 19 characteristic buildings of different heights (from two to four stories). Longitudinal and transverse fundamental frequencies were determined from amplitude spectra. The hazard/probability of the occurance of the soil-structure resonance was assessed by comparing building frequencies with the free-field sediments frequencies. For two examined buildings a high danger of soil-structure resonance was predicted and for three buildings the estimated danger is of medium level. It turned out that the danger of soil-structure resonance exists in a relatively narrow transition zone between the deeper western part (low frequencies) and the thinner eastern part (high frequencies) of the basin (Gosar, 2010).

In the last decade the microtremor measurements were performed in five Slovenian towns (including Bovec and Kobarid) exposed to high seismic hazard. In the studies the free-field measurements to derive maps of sediment frequencies were combined with the measurements in 66 masonry buildings of different heights. Therefore, additional statistical analysis of the fundamental frequencies of the buildings versus number of floors (height) was performed to generalize the identification of possible soil-structure resonance (Gosar, 2012). Most Slovenian towns are located in shallow sedimentary basins where the free-field soft sediments frequencies are in the range of 2 Hz to 20 Hz. On the other hand, masonry houses with two and three floors represent the large majority of the building stock. To assess the possible occurrence of soil-structure resonance in general, an average fundamental frequency ± one standard deviation interval was computed for two and three floors high masonry buildings, which resulted in fundamental frequencies in the range of 5.6 Hz to 11.1 Hz. Comparison with the free-field maps has shown that this frequency range occupies 59 % of the area of the Bovec basin (fig. 5) and 22 % of the surveyed area of the Kobarid basin (Gosar, 2012). These findings have therefore important implications for seismic risk assessment, spatial planning, and retrofitting of damaged buildings in Bovec and Kobarid.

For the 1998 earthquake the amplification of the seismic ground motion was studied also for the town Gemona in Friuli, located 40 km from the epicentre. In the studies numerical modelling along the simplified structural model of a sedimentary basin was compared with the records from three seismic stations (Marrara et al., 2001). Accelerations between 0.01 and 0.04 g were recorded on bedrock and on alluvium respectively, indicating 4-5 times acceleration of the seismic ground motion due to soft sediments. The numerical simulations agree relatively well with the available observations and some discrepancies can be probably related to the inaccurate knowledge of the subsurface. The maximum peak ground accelerations, the Arias intensity and the response spectra show a significant amplification, especially for a station located on the alluvial fan sediments.

Influence of the Krn Mountains earthquakes on seismological monitoring in Slovenia

In 1998 the seismic network of Slovenia consisted of seven stations, six of them equipped with digital seismographs connected to the central computer in Ljubljana over dial-up phone lines, and one analogue seismograph in Vojsko. Vojsko was the closest Slovenian seismic station to the epicentral area in Krn Mountains at the distance of 36 km. The 1998 earthquake showed that the Slovenian seismological service is not adequately equipped to deliver basic earthquake parameters with sufficient accuracy and fast enough to the civil protection organizations, media, and general public. The earthquake on 31 August 1998 near Trebnje only emphasised the need for measures that would increase the effectiveness of the seismological service. In May 1999 the Government of Slovenia laid down a time schedule and financial plan for the modernisation of the national seismological network (Vidrih et al., 2006). Seismic stations are regarded as infrastructure of special importance for the performance of state public services for defence and protection. The project named Modernisation of the national network of seismic stations had the following primary goals:

- to set up a national earthquake alarm system with real-time communication with data processing centre and automatic data analyses,
- to define basic earthquake parameters (epicentre coordinates, focal depth, magnitude and intensity) as precisely as possible on the basis of the geophysical model of Slovenia's territory,
- to assess seismic hazard more accurately to provide better input for the needs of earthquake resistant design of buildings based on better knowledge of seismotectonic conditions in Slovenia,
- to integrate Slovenia's alarm system into the earthquake alarm systems of neighbouring countries and European seismological centres.

During the following seven years 26 modern seismological stations were built all over Slovenia (fig. 6). They were equipped with broadband three-component seismometers and high-resolution data loggers. Real-time seismic data are continually transmitted to the Data Processing Centre in Ljubljana, where two servers automatically process and store seismic records. Bearing in mind the importance of seismic observation in areas of high seismic hazard and risk, the network is denser in three areas:

- in the area of Ljubljana, characterised by high seismic hazard, that together with the fact that this is the most densely populated area of Slovenia, represents the highest seismic risk,
- in the upper Soča territory, which is the second area of the highest seismic hazard in Slovenia,
- in the area around Krško, because it is the location of the Nuclear Power Plant and also the area of increased seismic hazard.

The Slovenia national network was completed and officially opened in October 2006 (Vidrih et al., 2006). Through signed agreements with neighbouring countries, the seismic waveform data are exchanged in a real-time between all responsible institutions to ensure better seismological monitoring in the wider area at the junction of large geotectonic units of Alps, Dinarides and Pannonian basin. The whole area, which is located at the northern margin of the Adiatic microplate, is characterized by relatively high earthquake activity. The enlarged cross-border network substantially contributes to a more precise location of earthquakes and allows better seismotectonic characterization, which is important for realistic seismic hazard assessment.

The national seismic network is not a static one. It is continuously upgraded with better data loggers, more sensitive and precise seismometers and more reliable communication, storage and power supply systems. In addition, completed in the year 2018, all 26 stations are now equipped also with accelerometers, which significantly increases the dynamic range of observations.

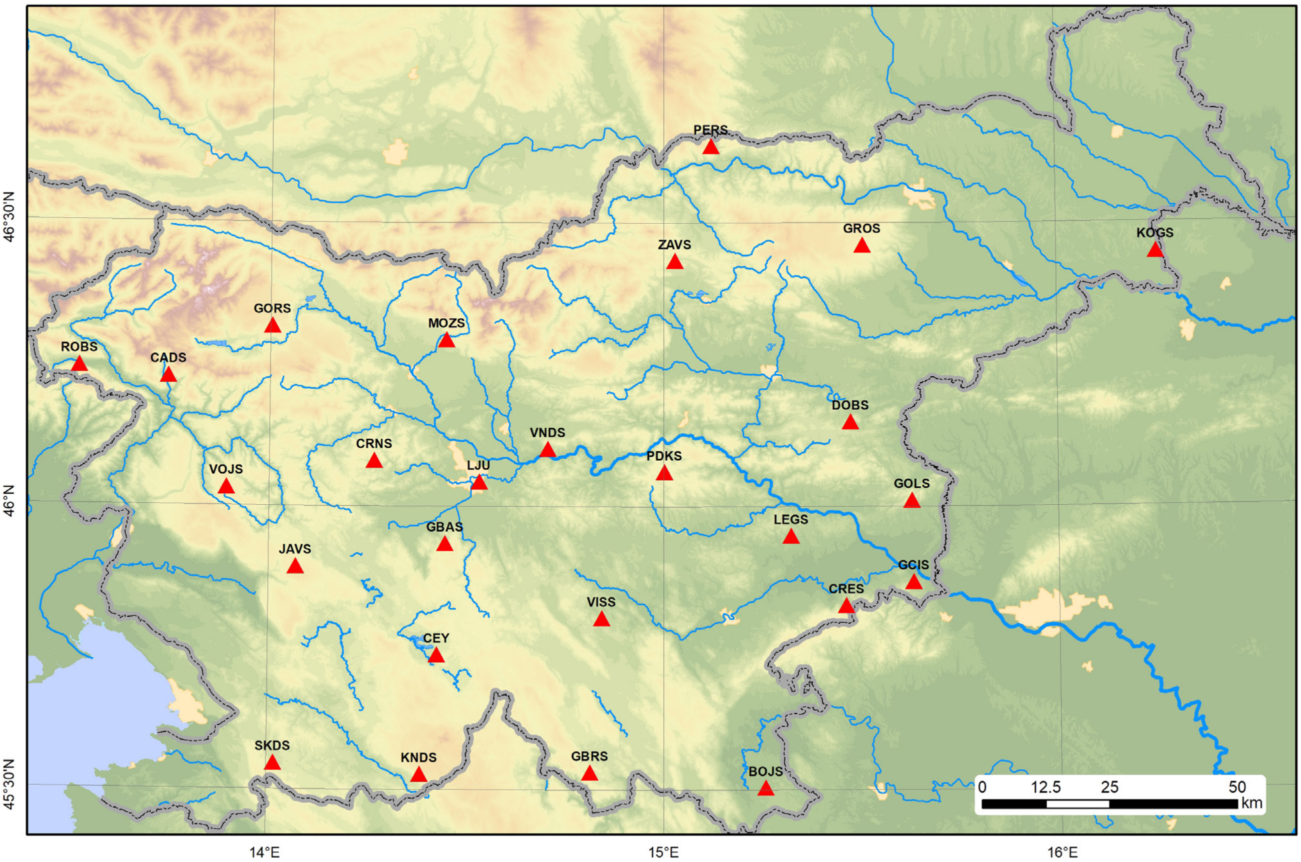

Fig. 6. The locations of the broadband seismic stations of a new Slovenian seismological network, which was built after the Krn Mountain earthquakes.

Sl. 6. Lokacije širokopasovnih potresnih opazovalnic nove državne mreže potresnih opazovalnic, ki je bila zgrajena po potresih v Krnskem pogorju.

Conclusions

The 1998 and 2004 earthquakes in Krn Mountains motivated a large number of researches in different branches of seismological science. The final version of European Macroseismic Scale (EMS-98) was published in the same year, and the 1998 earthquake was therefore one of the first strong events in Europe, for which the intensities were assessed using a new scale. Many advantages in statistical evaluation of macroseismic data and better definitions of vulnerability classes were clearly demonstrated in this cross-border study. Before 1998 the Julian Alps region was known for relatively small seismic activity in comparison to nearby Friuli region. Both earthquakes had changed the situation and many seismotectonic studies followed. The transition area between NW-SE oriented Dinaric strike-slip structures in W Slovenia and E-W oriented Alpine faults with predominantly reverse faulting in Friuli due to N-S oriented principal stress is of particular interest, because this is the region of the highest seismic hazard in the Alps and in Central Europe. Detailed studies of focal mechanisms and spatial distribution of aftershocks shed a light on complex structures related to segmented Ravne fault, which is lengthening by active growth at its NW end. Extensive aftershock sequences of both main shocks lasted for more than one year and it was important to study the exponential time decay of aftershocks and Gutenberg-Richter's magnitude-frequency relation and compare the results with similar sequences elsewhere. Studies of the static stress changes on neighbouring faults contributed to the understanding of the distribution of aftershocks. Large variations in damage to buildings at small distances motivated several site effect studies. Especially the microtremor HVSR method was proven to be very effective in identification of soil-structure resonance effects that took place at many locations in the Bovec basin.

The 1998 earthquake motivated a modernisation of the national seismological network. As a result, today Slovenia has a modern network of 26 seismic stations equipped with broadband sensors, accelerometers, and high-resolution digitizers. The international cooperation was also enhanced and thanks to it in Central Europe we currently have a real-time virtual network that has significantly improved the seismological monitoring. Krn Mountains earthquakes and a new Slovenian seismic network had significantly fostered a seismological research in Slovenia and motivated many interdisciplinary seismological studies.

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Calpionellid biostratigraphy and sedimentation of the Biancone limestone from the Rudnica Anticline (Sava Folds, eastern Slovenia)

Kalpionelidna biostratigrafija in sedimentacija Biancone apnenca Rudniške antiklinale (Posavske gube, vzhodna Slovenija)

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Ključne besede: Rudnica, Dinaridi, potopljena platforma, biancone – maiolica apnenec, kalpionelide, biostratigrafija, berriasij

Abstract

Mt Rudnica in eastern Slovenia structurally belongs to the Sava Folds. The mountain itself is an exposure of the Mesozoic core of the Rudnica Anticline. The major part of the core is composed of Triassic rocks deposited on the NE margin of the Dinaric (Adriatic) Carbonate Platform, overlain locally by deep-marine Berriasian Biancone limestone. The latter formation was logged in a newly discovered section on the northern slopes of Mt Rudnica near the village of Loka pri Žusmu. The Biancone limestone of Mt Rudnica is mostly monotonous, calpionellid-bearing limestone with only minor up-section differences in colour, chert presence, and clay content. It is characteristic pelagic facies for the entire Tethyan Realm of the time. Using calpionellid as well as dinocyst biostratigraphy, the formation was subdivided into Early Berriasian Calpionella Zone - Alpina and Ferasini Subzones, Middle Berriasian Calpionella Zone - Elliptica Subzone and upper Berriasian Calpionellopsis Zone - Oblonga Subzone. Within the Early Berriasian part of the formation a synsedimentary slump was documented, whereas the largest increase in clay content is observed in the topmost, i.e. Late Berriasian part of the formation.

Izvleček

Gora Rudnica v vzhodni Sloveniji strukturno pripada Posavskim gubam. V osrednjem delu gore izdanja mezozojsko jedro Rudniške antiklinale. Večji del jedra sestavljajo triasne kamnine, ki so se odlagale na severovzhodnem obrobju Dinarske (Jadranske) karbonatne platforme, nad njimi pa je mestoma odložen globokomorski, berriasijski biancone apnenec. Slednji je bil posnet v novo odkritem profilu na severnih pobočjih Rudnice pri vasi Loka pri Žusmu. Biancone apnenec iz Rudnice je povečini monoton apnenec s kalpionelami, ki vzdolž zaporedja kaže le manjše spremembe v barvi, prisotnosti roženca in vsebnosti gline. Predstavlja značilen pelagični facies celotne Tetidine province tega časa. Na podlagi kalpionelidne in tudi dinocistne biostratigrafije je bila formacija razdeljena na spodnji berriasij (Calpionella cona - Alpina in Ferasini podconi), srednji berriasij (Calpionella cona - Elliptica podcona) in zgornji berriasij (Calpionellopsis cona - Oblonga podcona). V spodnjeberriasijskem delu formacije je bil dokumentiran sinsedimentni plaz, medtem ko v vrhnjem, zgornjeberriasijskem delu formacije opazujemo povečano vsebnost glinene komponente.

Introduction

At present, the GSSP of the Jurassic-Cretaceous boundary remains undefined (Cohen et al., 2018) and as such encourages the search for precise biostratigraphic markers within different fossils groups. Calpionellids are an example of such group, owing to their uniform occurrence and diversification; as a result they are widely used in biostratigraphic analyses of the Late Jurassic and Early Cretaceous pelagic sequences throughout the Tethyan Realm (Allemann et al., 1971; Remane, 1971; Remane et al., 1986; Pop, 1974, 1994; Reháková & Michalík, 1997; Lakova, et al., 1999; Boughdiri et al., 2006; Houša et al., 2007). From the point of view of calpionellid biostratigraphic potential, we note that alongside *Calpionellites darderi*, the index marker for the Berriasian/Valanginian stage boundary (Bulot, 1996), *Calpionella alpina* is considered to be most useful marker for determination of the Jurassic/Cretaceous boundary (Andreini et al., 2007; Houša et al., 2007; Wimbledon, 2008; Michalík et al., 2009; Grabowski et al., 2010a,b; Lukeneder et al., 2010; Pruner et al., 2010; Michalík & Reháková, 2011; Petrova et al., 2012; Guzhikov et al., 2012; Lakova & Petrova, 2013; López-Martínez et al., 2013, 2015; Wimbledon et al., 2013, 2017; Hoedemaeker et al., 2016; Michalík et al., 2016; Svobodová & Košťák, 2016; Grabowski et al., 2017; Elbra et al., 2018 a,b; Kowal-Kasprzyk & Reháková, 2019).

This study presents the calpionellid biostratigraphy (supplemented by dinocyst data) of the Biancone limestone from Mt Rudnica (fig. 1). Biancone limestone is found on the northern slopes of Mt Rudnica, where it overlies, with a prominent stratigraphic gap, the Late Ladinian to Early Carnian dolomite (Aničić et al., 2004). Pioneering work on calpionellids from Mt Rudnica was provided by Babić (1979), who already recognized most of the calpionellids described in our paper. However, in this study, sample, locations were scattered along the wider area and only point-samples were taken. We revisited the area and found, logged, and sampled a near-fully exposed section of the Biancone limestone. This paper provides a description of the section as well as detailed calpionellid biostratigraphy combined with calcareous dinocyst determinations. We also provide data from a supplementary section that we logged, which is likely from the GK-1418 sampling site of Babić (1979). We describe and discuss the sedimentological particularities of the Biancone limestone from Mt Rudnica.

Geological setting

The Sava Folds of E Slovenia are characterized by post-Miocene N-S shortening inside the Sava compressive wedge that originated in the triangle between the W-E striking Periadriatic tectonic zone, the NW-SE Idrija tectonic zone, and the WSW-ENE mid-Hungarian tectonic zone (fig. 1a) (Placer, 1999, 2008). The entire region is composed of a series of anticlines and synclines with generally E-W striking fold-axes. In the synclines, Oligocene to Neogene Paratethys sediments are preserved. In the anticlines, this sedimentary cover is eroded, and anticline cores reveal Carboniferous, Permian and Mesozoic successions (Buser, 1978; Aničić & Juriša, 1985a; Aničić et al., 2004; Buser, 2009). Older structures, particularly thrust-faults, show the clear overprint of a young compression of the Sava Folds, namely, the folding of thrust planes (Placer, 1999).

The studied sections are situated in the eastern part of the Sava Folds – more precisely, in the Mesozoic core of the Rudnica Anticline that is a large scale, morphologically well-expressed anticline. It is embraced by the Laško Syncline to the north and the Planina Syncline to the south (fig. 1b), both of which are composed of Oligocene and Miocene sediments that show only minor deformation as the result of young N-S compression (Placer, 1999, 2008). Unlike the synclines, the anticline core is composed of more intensively deformed Mesozoic, mostly Triassic rock successions (Buser, 1978; Aničić & Juriša, 1985a) (fig. 1c). It begins with Anisian limestone and dolomite. Upwards it passes on to the highly diverse Ladinian succession, which is characterized either by mafic volcanic rocks (diabase) or by alternating shales, limestones with chert, and sandstone. Further upwards it passes on to coarse crystalline (saharoid) massive dolomite that locally alternates to limestone (Buser, 1978, 1979; Aničić & Juriša, 1985a, b; Aničić et al., 2004). Traditionally, this formation is considered to be Carnian in age, but more recent studies from other parts of Slovenia indicate that it is, at least in part, still Ladinian (Celarc, 2004, 2008; Čar, 2010). At Mt Rudnica, it can contain limestone with chert and shale in the upper part of the formation (Aničić et al., 2004). On the northern slopes of Mt Rudnica, near the village of Loka pri Žusmu, this formation is overlain by Biancone limestone that is considered to be a latest Jurassic to earliest Cretaceous in age (Aničić et al., 2004). The stratigraphic contact is marked by a prominent gap that covers the major part of the Upper Triassic

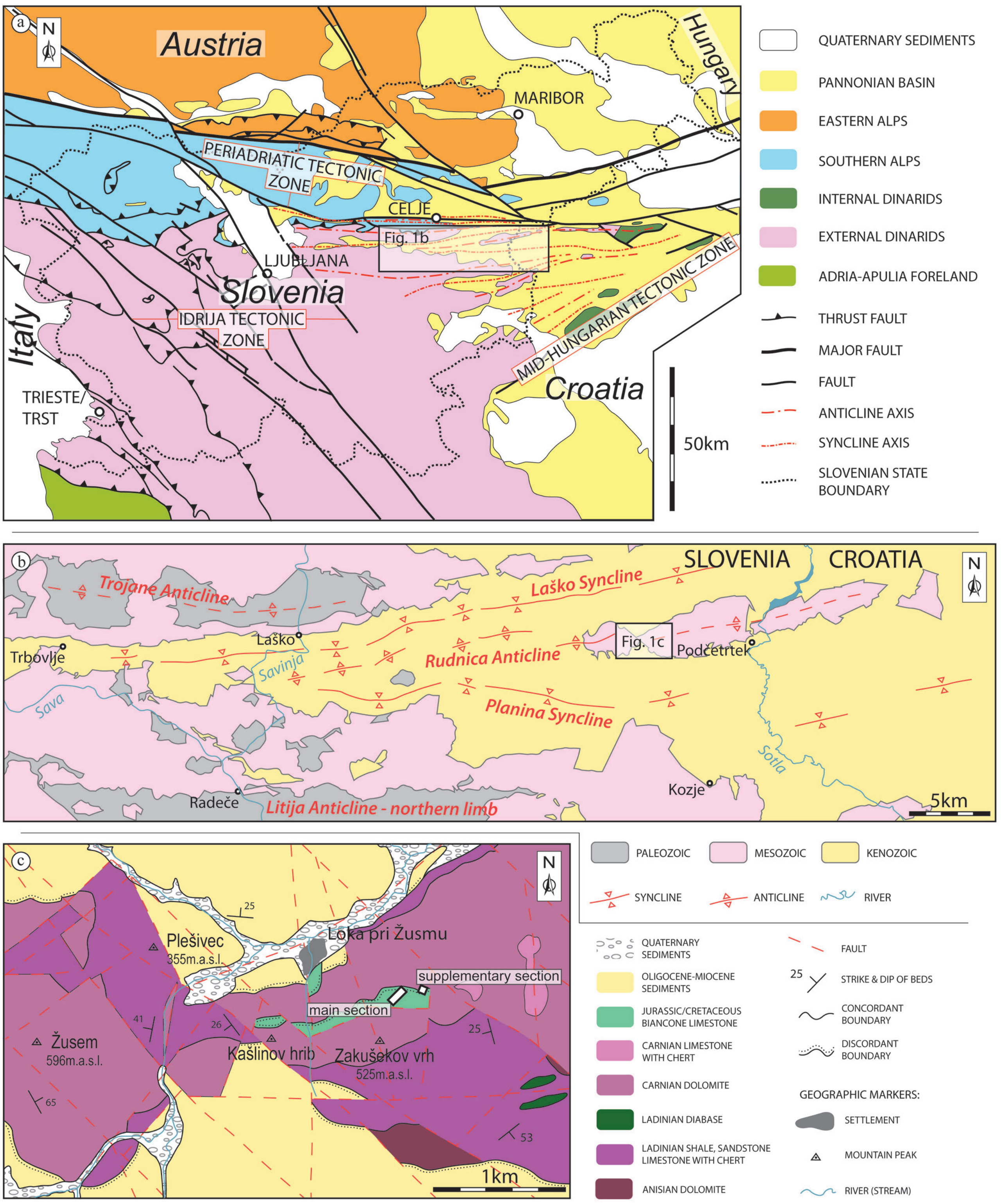

Fig. 1. a) Geostructural subdivision of the Alpine-Dinaric-Pannonian transition zone with axes of the Sava Folds (compiled from Placer, 1999, 2016); boxed area is enlarged in Figure 1 b. b) Eastern Sava Folds with positions of major structures marked (simplified from Buser, 1978; Aničić and Juriša, 1985a); boxed area is enlarged in Figure 1 c (national border follows the Sotla River). c) Geological map of the eastern part of the Rudnica Anticline (after Aničić et al., 2004) with positions of studied sections marked.

as well as most all of the Jurassic. Outcrops of the Biancone limestone are limited to the rather narrow area between the village of Loka pri Žusmu and two minor peaks (Zakušekov vrh and Kašlinov hrib) of Mt Rudnica.

Methods

Biancone limestone was logged in two sections. The main section was logged on the northern slope of the small peak (N46°09’21’’, E15°31’26’’), some 300 m NNE of the Zakušekov vrh peak. The supplementary section was logged along the forest road, some 200 m further NW of the main section (N46°09'25'', E15°31'31''). Samples were taken in closely-spaced intervals. Beds have been numbered with the RA prefix designating the main section and RB the supplementary section. A total of 17 samples were selected for the thin sections, which were used for microfacies analyses and to document successions of stratigraphically important calcareous microfossils, namely calpionellids and calcareous dinoflagellates. Thin sections were studied under the LEICA DM 2500 polarizing microscope, and selected bioclasts and allochems were identified. The Axiocam ERc 5s camera was used to document microfacies and bio markers. The thin-sections will be stored in the archive of the Faculty of Natural Sciences and Engineering, University of Ljubljana. The Calpionellid zonal scheme sensu Reháková and Michalík (1997) combined with cyst distribution (Reháková, 2000) were applied. Microfacies types are named according to the terminology of Dunham (1962); standard microfacies type (SMF) and facies zones (FZ) as proposed by Wilson (1975) and modified by Flügel (2004) were determined.

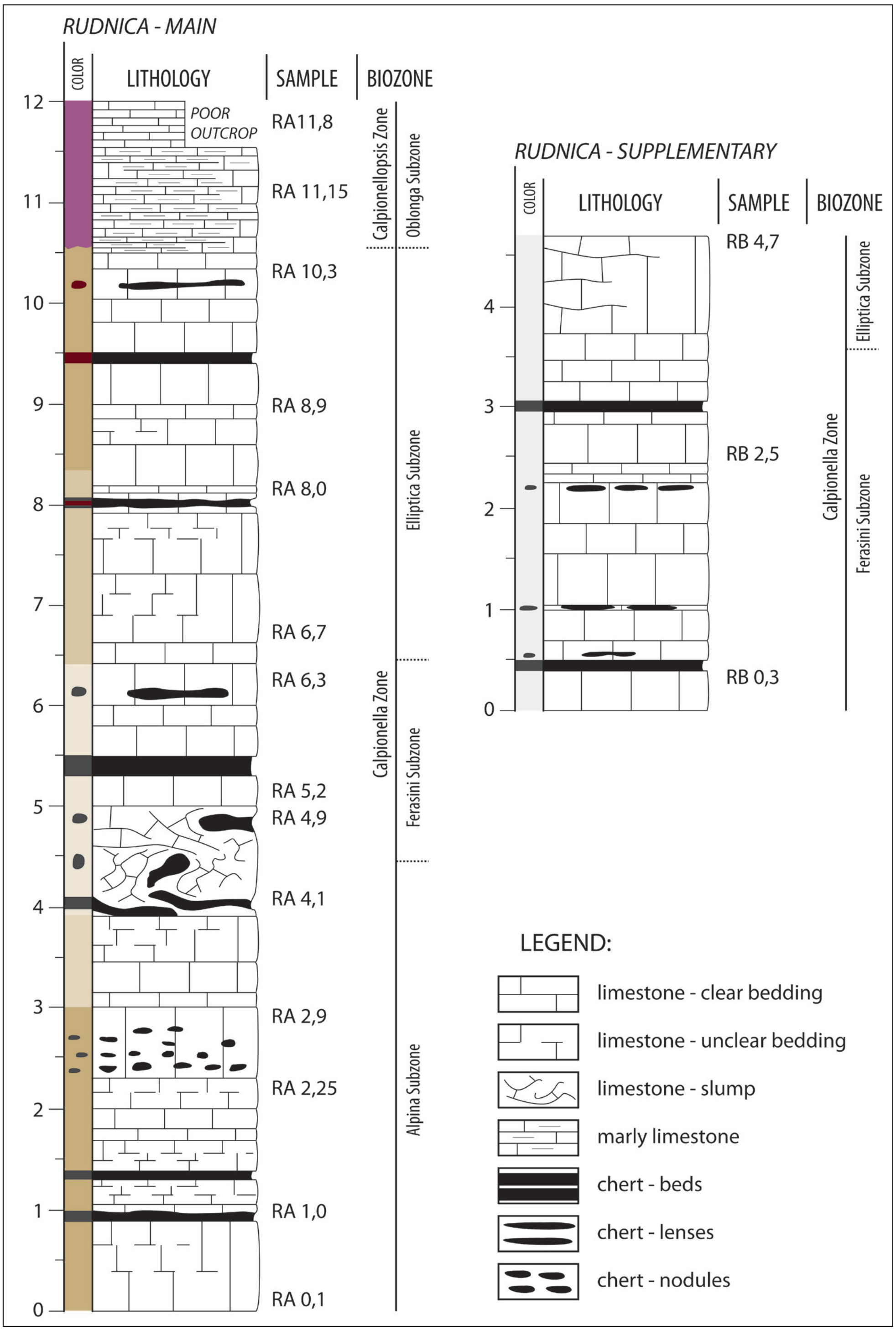

Fig. 2. Detailed sedimentological sections of the Biancone limestone from the Rudnica Anticline, with positions of samples and calpionellid biozones marked.

Description of the studied sections

In the main studied section of the Biancone limestone from Mt Rudnica, both boundaries are covered. The first outcrops of coarse-crystalline dolomite occur some 5 m below the logged section. In the covered interval, dolomite and subordinate chert particles are found in the soil. The top of the section is also covered. Fragments of dark-coloured shale are present in the soil. Our field observations indicate that the upper boundary is also stratigraphic. We propose that the overlying succession belongs to the very spatially limited Aptian-Albian Lower Flyschoid formation, which in the wider region either lies over the Biancone limestone or directly over Triassic strata (Buser, 1978; Aničić & Juriša, 1985a).

In the main section, the Biancone limestone was logged for 12 m (figs. 2, 3a). It forms a monotonous succession of well-bedded, micritic, variably-coloured limestone. It is light yellowish-brown in the lower 3 m, becomes brighter in the next meter, and is almost white in the next 2.5 m. Upwards, in the next 5 m the opposite trend is observed. In the uppermost 1.5 m the limestone is coloured violet-red (fig. 3b). This part of the formation also shows a slight increase in clay content, is laminated, and beds are thinner than in the major part of the formation.

Chert occurs in the form of beds (up to 20 cm), lenses and nodules. Generally speaking, it is black/dark grey in colour in the lower part of the formation and dark red in the upper part of the formation. From the 4th to 5th m of the section, the chert is folded. Folded bedding planes are also expressed within the limestone, albeit less clearly, and this interval probably represents a synsedimentary slumping of the pelagic sediment (fig. 3c).

According to the description by Babić (1979), the location of the supplementary section most likely corresponds to his sampling site GK-1418. In this section, contacts of the Biancone limestone with the surrounding formations are also not exposed, but the nature of the outcrops indicates that they are represented, at least partly, by fault contacts. 4.5 m of the Biancone limestone were logged. As a rule, the succession corresponds to the main section, but colours are largely light-grey to white, whereas cherts are black to dark-grey in colour. In the topmost part, bedding planes are wavy and laterally discontinues.

Fig. 3. a) General up-section field view of the Biancone limestone from Mt Rudnica main section. b) Violet-red coloured and thin-bedded limestone and chert from uppermost part of the formation. c) Synsedimentary slump between the 4th and 5th meter of the main section.

Microfacies, calpionellid zonation

The studied limestone belongs to the standard microfacies SMF 3. Biomicritic mudstone to wackestone contains rare calpionellids, dinoflagellate cysts, calcified radiolarians, ostracods, globochaetes, and crinoids. Silt-size quartz grains are locally present. Facies indicates a basin to lower slope depositional environment (facies zones 1–3 in Flügel, 2004). Despite the fact that bioclasts are quite rare and some are not particularly well preserved, it was possible to determine the main calpionellid index markers, on which basis the limestone sequence was dated as Early to Late Berriasian (standard Calpionella Zone with the Alpina, Ferasini and Elliptica subzones and the standard Calpionellopsis Zone, Oblonga Subzone). The Ferasini and Oblonga subzones were established and could improve the calpionellid zonation scheme previously identified by Babić (1979).

Early Berriasian Calpionella Zone, Alpina Subzone (sensu Pop, 1974, Remane et al., 1986); samples RA 0,1; RA 1,0; RA 2,25; RA 2,9; RA 4,1

The lowest part of the studied section is built of variable bedded light Biancone limestone bearing chert nodules and chert layers. Slump structures appear at the top of the interval containing the samples RA 4,1 and RA 4,9 (note that the last one already belongs to the succeeding Ferasini Subzone). Biomicritic limestone is mudstone with rare to infrequent calpionellids (figs. 4a–e) and cysts of calcareous dinoflagellates (figs. 5m, n). Very rare *Calpionella alpina, Crassicollaria parvula* dinoflagellate cysts of *Colomisphaera minutissima, Colomisphaera lapidosa, Colomisphaera carpathica* were observed in the micrite matrix. The matrix contains frequent planar euhedral dolomite (figs. 4a–c, e). These burial-stage dolomite crystals are impregnated by Fe-hydroxide. Planar fabrics are favoured at lower precipitation temperatures. There are also thin dissolution seams filled with Fe-hydroxides and nests of pyrite (fig. 5t) visible in a slightly recrystallized matrix.

Early Berriasian Calpionella Zone, Ferasini Subzone (Pop, 1994); samples RA 4,9; RA 5,2; RA 6,3; RB 0,3; RB 2,5

The first occurrence (FO) of *Remaniella ferasini*, the index marker of the Ferasini Subzone, was identified in sample RA 4,9 (fig. 4i). Mudstone also contains rare *Calpionella alpina* (fig. 4h), *Calpionella elliptalpina, Calpionella* sp., *Remaniella duranddelgai, Remaniella catalanoi* (fig. 5k) *Crassicollaria parvula, Tintinnopsella carpathica* (figs. 4j,k), dinoflagellate cysts *Colomisphaera cieszynica* (fig. 5o), *Colomisphaera lapidosa, Colomisphaera carpathica* (fig. 5p), *Stomiosphaera mulluccana* (fig. 5s), *Globochaete alpina* spores, fragments of ostracods, crinoids, calcified radiolarians, and foraminifera with calcite tests – *Spirillina* sp. A few deformed loricae, dissolution seams, scattered pyrite and rare dolomite rhomboeders were all documented in the matrix.

Middle Berriasian Calpionella Zone, Elliptica Subzone (Pop, 1974); samples RA 6,7; RA 8,0; RA 8,9; RA 10,3; RB 4,7

The FO of *Calpionella elliptica*, the index marker of the Elliptica Subzone, was observed in sample RA 6,7 (fig. 4l, m, s). The mudstone and local wackestone of this interval also contain rare *Calpionella alpina* (fig. 4r), *Calpionella minuta* (fig. 4n), *Remaniella catalanoi* (fig. 5b), *Crassicollaria parvula* (fig. 4t), *Tintinnopsella carpathica* (fig. 5c), *Lozenziella hungarica* (figs. 4p,q), *Lorenziella plicata* (figs. 4o, 5a), locally common cysts of *Colomisphaera carpathica* (fig. 5q), *Colomisphaera cieszynica* (fig. 5r), *Colomisphaera lapidosa*, rare fragments of aptychi, ostracods, calcified radiolarians, crinoids, foraminifera *Spirillina* sp., and *Globochaete alpina* cysts. Some loricae are deformed (fig. 5l), some bioclasts and the local matrix are slightly silicified. Pyrite is commonly scattered in the matrix.

Late Berriasian Calpionellopsis Zone, Oblonga Subzone (Allemann et al., 1971); samples RA 11,15; RA 11,8

Few loricae of the genus Calpionellopsis were identified in the uppermost interval, starting in sample RA 11,15 (figs. 5d, e, g). The beds are more regular and thinner in this part of the sequence. *Calpionellopsis* cf. *simplex* (fig. 5g), *Calpionellopsis oblonga* (fig. 5d, h–j), *Calpionella elliptica, Calpionella minuta*, *Tintinnopsella carpathica* (fig. 5f), cysts of *Colomisphaera lapidosa*, calcified radiolarians, and ostracods were observed among the bioclasts. The matrix contains silt-size quartz grains and muscovite. Pyrite occurs in the walls of calcite veins (fig. 5u), which indicates that at least part of the pyrite formed after lithification.

Discussion

The Biancone limestone of Mt Rudnica corresponds to the pelagic, calpionellid-bearing limestones (known also as Maiolica limestone) that are common Late Tithonian to Lower Cretaceous facies of Western and Central Europe

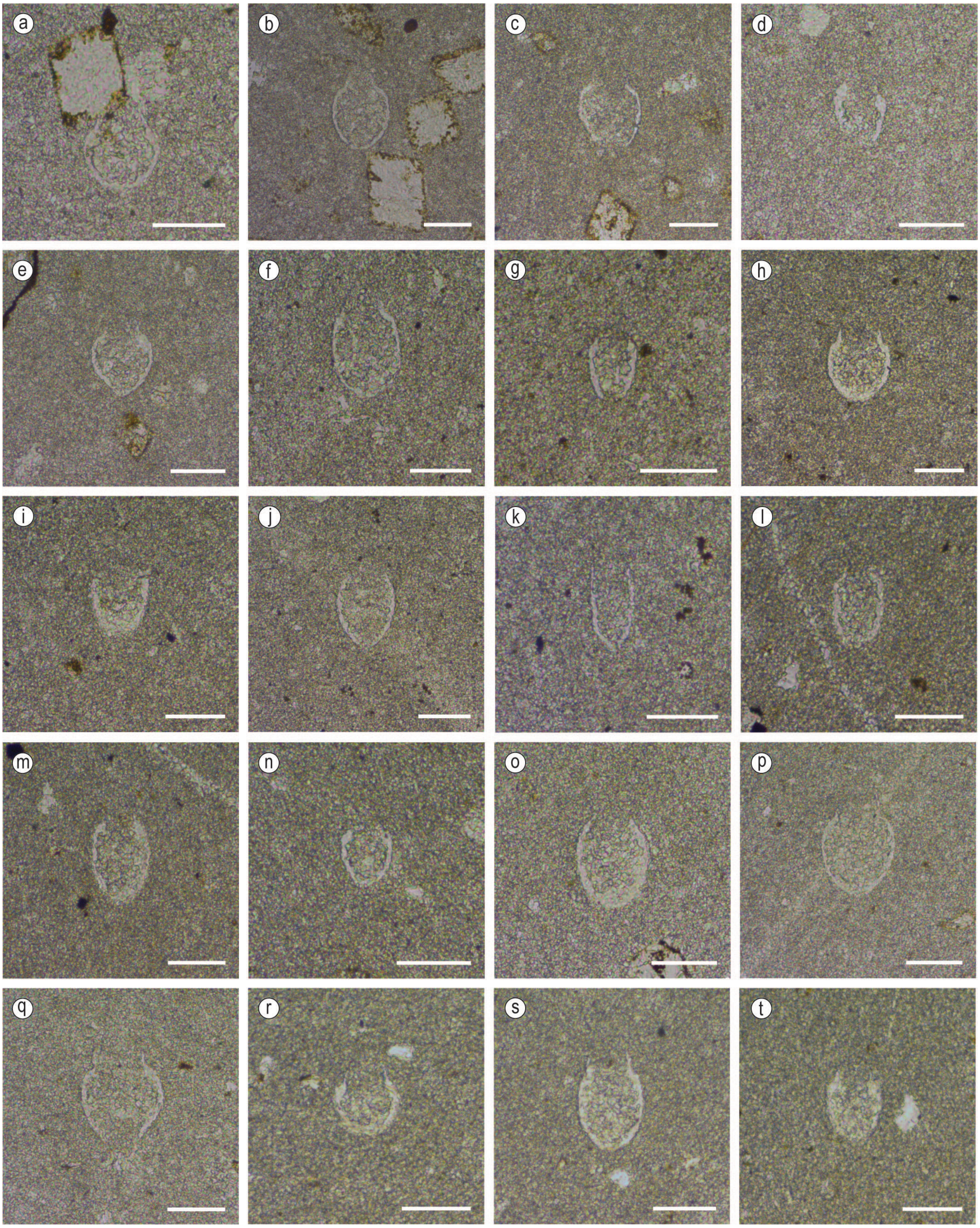

Fig. 4. Calpionellids from Rudnica main section (scale bar is 50 µm); a) *Calpionella alpina* (sample *RA 0,1*), b) *Calpionella grandalpina* (sample *RA 0,1*), c) *Calpionella alpina* (sample *RA 1,0*), d) *Crassicollaria parvula* (sample *RA 0,1*), e) *Calpionella alpina* (sample *RA 2,25*), f) *Calpionella elliptalpina* (sample *RA 4,1*), g) *Crassicollaria parvula* (sample *RA 4,1*), h) *Calpionella alpina* (sample *RA 4,9*), i) *Remaniella ferasini* (sample *RA 4,9*), j) *Tintinnopsella carpathica* (sample *RA 4,9*), k) *Tintinnopsella carpathica* (sample *RA 6,3*), l–m) *Calpionella elliptica* (sample *RA 6,7*), n) *Calpionella minuta* (sample *RA 8,0*), o) *Lorenziella plicata* (sample *RA 8,9*), p–q) *Lorenziella hungarica* (sample *RA 8,9*), r) *Calpionella alpina* (sample *RA 10,3*), s) *Calpionella elliptica* (sample *RA 10,3*), t) *Crassicollaria parvula* (sample *RA 10,3*).

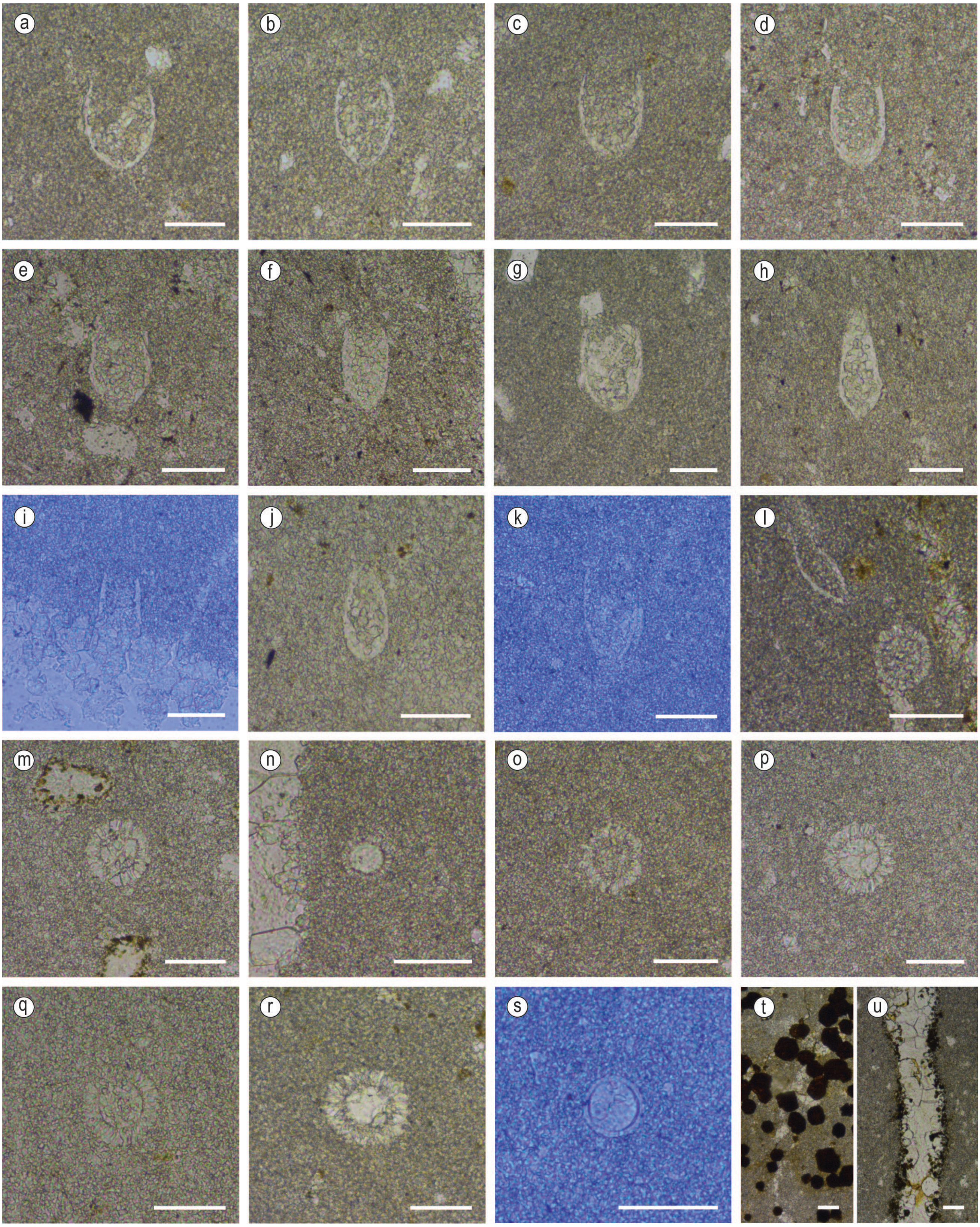

Fig. 5. Calpionellids from topmost part of Rudnica main section and supplementary section, and calcareous dinocysts from both sections (scale bar is 50 µm); a) *Lorenziella plicata* (sample *RA 10,3*), b) *Remaniella catalanoi* (sample *RA 10,3*), c) *Tintinnopsella carpathica* (sample *RA 10,3*), d) *Calpionellopsis oblonga* (sample *RA 11,15*), e) *Calpionellopsis* sp. (sample *RA 11,15*), f) *Tintinnopsella carpathica* (sample *RA 11,15*), g) *Calpionellopsis simplex* (sample *RA 11,15*), h–i–j) *Calpionellopsis oblonga* (sample *RA 11,8*), k) *Remaniella catalanoi* (sample *RB 2,5*), l) deformed lorica of *Tintinnopsella carpathica* and *Colomisphaera lapidosa* (sample *RA 6,7*), m) *Colomisphaera lapidosa* (sample *RA 0,1*), n) *Colomisphaera minutissima* (sample *RA 1,0*), o) *Colomisphaera cieszynica* (sample *RA 4,9*), p) *Colomisphaera carpathica* (sample *RA 6,3*), q) *Colomisphaera carpathica* (sample *RA 8,9*), r) *Colomisphaera cieszynica* (sample *RA 10,3*), s) *Stomiosphaera moluccana* (sample *RB 2,5*), t) subhedral pyrite within micrite matrix (sample *RA 2,9*), u) framboidal pyrite along the vein-wall (sample *RA 11,15*).

(*Wieczorek, 1988;* Weissert, 2010), and characterize all deep-water paleogeographic domains of the Southalpine-Dinaric Realm (Weissert, 1981; Goričan, 1994; Šmuc, 2005; Rožič, 2009; Goričan et al., 2012, 2018). Biancone limestone also occurs on the north-eastern margin of the Dinaric Carbonate Platform, where it overlies (with a prominent stratigraphic gap) the Lower Jurassic or Upper Triassic platform carbonates, and locally Middle to Upper Jurassic cherty limestone (Babić, 1973; Aničić & Dozet, 2000), which is known as the Izvir Formation (Rižnar, 2006; Poljak et al., 2017). The Biancone limestone on Mt Rudnica probably represents the distal, drowned part of the Dinaric Carbonate Platform.

The onset of the Biancone limestone sedimentation in the continuous basinal successions of the Southalpine-Dinaric Realm is dated as Late Tithonian (Goričan et al., 2012). The calpionellid biostratigraphy of the Mt Rudnica section (presented in this paper) indicates a slightly postponed, i.e. Early Berriasian onset of sedimentation. Three possible solutions are here proposed for the delay: A) Biancone limestone is not fully exposed in the studied sections, and the Late Tithonian part of the limestone is covered (in light of our field observations, this option is less likely); B) the drowning unconformity of Mt Rudnica area was prolonged until the Berriasian as the result of certain paleogeographic conditions; and C) the Late Tithonian part of the Biancone limestone is dolomitized and consequently does not outcrop, because dolomites are more prone to weathering. This last option is supported by field observations, where weathered chert (and also dolomite) particles were observed in the soil just below the main section. Additionally, partial, upwardly-decreasing dolomitisation was also observed in the thin sections. Similar conditions are reported from the northern part of the Trento Plateau, from the area where the Biancone limestone directly overlies the Hauptdolomit/Dolomia Principale Formation (Lukeneder, 2011, 2015).

In the Early Berriasian part of the Mt Rudnica main section (Calpionella Zone, the transition from the Alpina to Ferasini subzones) a synsedimentary slump was observed, which indicates an inclined bottom in this part of the drowned platform margin. Slumps, though they are more poorly dated or more widely time-distributed, are also known from other sections of the Southern Alps and Dinarides, (Weissert, 1981; Goričan, 1994; Šmuc, 2005), where most locations are situated on the drowned platforms. A generally coeval Bohinj Formation, which is a prominent mass-movement breccia and calcarenite bed, is reported from the Bled Basin (Kukoč et al., 2012). Today, the outcrops of this basin are found in the Julian Alps in NW Slovenia but were once located paleogeographically closer to the Neotethys Ocean (Goričan et al., 2018), and probably quite close to the Mt Rudnica area.

The Late Berriasian, i.e. uppermost part of the Mt Rudnica main section (Calpionellopsis Zone, Oblonga Subzone) sees a slightly higher clay content. This may indicate changing global climate conditions, namely a gradual change from the arid Early Berriasian to the humid Valanginian climate (Föllmi, 2012). A similar trend is observed in the western part of the Slovenian Basin (Rožič and Reháková, in prep.). A Lower Cretaceous upwardly-increasing siliciclastic input is well documented in the Bled Basin, where the so-called Transitional unit lies above the Bohinj Formation. This is generally attributed to the Berriasian, which still contains beds of Biancone-type limestone, but shows a gradual upward increase in clay interlayers. Finally, it passes into flysch-type deposits of the Valanginian-Hauterivian Studor Formation, characterized by ophiolite debris (Kukoč et al., 2012; Goričan et al., 2018). A similar, albeit delayed (proposed as starting in the Barremian) turn is reported from Mt Ivanščica in Croatia, which is another inselberg that represents a direct, eastern continuation of the Mt Rudnica anticline, with corresponding outcrops located approximately 40 km to the east (Babić and Zupanič, 1973; Lužar-Oberiter et al., 2009; 2012).

Conclusions

The Biancone limestone of Mt Rudnica is a typical latest Jurassic-early Lower Cretaceous calpionellid-bearing pelagic limestone of the Tethyan Realm. It sedimented on the submarine swell, i.e. on the drowned NE margin of the Dinaric (Adriatic) Carbonate Platform. With a prominent drowning unconformity, it overlies the Upper Triassic platform dolomite. Using calpionellid biostratigraphy, the studied sections were determined as Berriasian in age. The formation was further subdivided into Early Berriasian Calpionella Zone - Alpina and Ferasini Subzones, Middle Berriasian Calpionella Zone - Elliptica Subzone, and Late Berriasian Calpionellopsis Zone - Oblonga Subzone. The monotonous pelagic succession is interrupted by a synsedimentary slump in the Early Berriasian. The Late Berriasian part of the formation shows an increase in the clay content, which may suggest a gradual shift to a humid Valanginian climate.

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List of microfossils mentioned in the text in alphabetical order.

Calpionellids

Calpionella alpina Lorenz,1902
Calpionella elliptalpina Nagy, 1986
Calpionella elliptica Cadisch, 1932
Calpionella minuta Houša, 1990
Calpionellopsis oblonga (Cadisch, 1932)
Calpionellopsis cf. *simplex* (Colom, 1939)
Crassicollaria parvula Remane, 1962
Lorenziella hungarica Knauer and Nagy, 1964
Lorenziella plicata Remane, 1968
Remaniella catalanoi Pop, 1996
Remaniella ferasini (Catalano, 1965)
Remaniella duranddelgai Pop, 1996
Tintinnopsella carpathica (Murgeanu and Filipescu,1933)

Calcareous dinoflagellates

Colomisphaera carpathica (Borza, 1964)
Colomisphaera cieszynica Nowak, 1968
Colomisphaera lapidosa (Vogler, 1941)
Colomisphaera minutissima Nowak,1968
Stomiosphaera molluccana Wanner, 1940

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Primeri ocene temperatur na površini trdnih tal pri projektiranju zajetij plitve geotermalne energije

Examples of the assessment of temperatures on the surface of solid ground in the design of the shallow geothermal energy extractions

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Key words: shallow geothermal energy, heat pumps, ground surface temperature, air temperature, thermograms, borehole heat exchangers, Slovenia

Izvleček

Na dimenzioniranje zajetij plitve geotermalne energije z zaprtimi sistemi zemlja-voda imajo največji vpliv toplotna prevodnost kamnin in zemljin ter srednja letna temperatura tal. Predstavljen je postopek določanja temperature tal na štiri načine glede na razpoložljive podatke na določeni lokaciji: 1) imamo podatek o srednji letni temperaturi zraka, 2) imamo samo podatek o nadmorski višini kraja, 3) v bližini je meteorološka postaja z meritvami temperature tal, in 4) v bližini je vrtina s termogramom. Uporabo teh štirih načinov in razlike med njimi ponazarjamo s petimi primeri v različnih predelih Slovenije (Cerkno, Lucija, Brnik, Babno Polje in Maribor). Pokazalo se je, da je temperatura tal merjena na meteoroloških postajah v povprečju višja od temperature, izračunane iz termogramov vrtin. Temperaturo tal lahko dobro ocenimo z regresijsko premico med nadmorsko višino in izmerjenimi temperaturami tal na meteoroloških postajah le za celinski del. V primorskem delu Slovenije taka ocena ni bila izvedljiva, ker sta na voljo samo dve postaji z meritvami temperature tal. Vrtin s termogrami je bistveno več, kar 458, kot meteoroloških postaj z meritvami temperature tal (le 9). Zaradi tega je uporaba termogramov vrtin smiselna. Poleg tega nam termogrami vrtin omogočajo izračun gostote toplotnega toka, ki ga prav tako potrebujemo pri dimenzioniranju zajetij geotermalne energije. Za bolj primerljivo oceno temperatur tal iz termogramov bi morali imeti na voljo več termogramov iz novejšega obdobja 1981-2010, kajti to obdobje že vsebuje vpliv globalnega segrevanja ozračja. Ker temu ni bilo tako, smo dobili pri vseh lokacijah po načinu izračuna iz termograma najnižje vrednosti. Po drugi strani v večini vrtin manjka temperaturni zapis v zgornjih 20 metrih, zato smo v pravilni ekstrapolaciji T-z profila iz globljega odseka profila zajeli večinoma odseke med 20 in 100 m globine. S tem smo zajeli tak potek T-z profila, ki še nosi v sebi spomin običajno malo nižjih temperatur na površju v preteklosti.

Abstract

The thermal conductivity of rocks and soils and the mean annual temperature of the ground have the biggest impact on the dimensioning of the extraction of geothermal energy with closed ground-water systems. The method of determining the ground temperature is presented in four ways according to the available data at a given location: 1) we have data on the mean annual air temperature, 2) we only have information about the altitude of the place, 3) nearby is a meteorological station with soil (ground) temperature measurements, and 4) a borehole with a thermogram is in the vicinity. The use of these four methods and the differences between them are illustrated by five examples in different parts of Slovenia (Cerkno, Lucija, Brnik, Babno Polje and Maribor). It has been shown that the ground temperature measured at meteorological stations is on average higher than the temperature calculated from the borehole thermograms. The ground temperature can be well estimated with a regression line between the altitude and the measured ground temperatures at meteorological stations only for the continental part. In the coastal part of Slovenia, such an assessment was not feasible, as only two stations with ground temperature measurements are available. There are significantly more boreholes with thermograms (as much as 458) than meteorological stations with measurements of ground temperature (only 9). For this reason, the use of borehole thermograms makes sense. In addition, the borehole thermograms allow us to calculate the heat-flow density, which is also needed in the dimensioning of geothermal energy extractions. For more comparable assessment of the ground temperature from the thermograms, several thermograms from the recent period 1981-2010 should be available, because this period already contains the effect of global warming of the atmosphere. Since this was not the case, we obtained at all locations according to the method of calculation the lowest value from the thermograms. On the other hand, in most boreholes, the temperature record in the upper 20 m is missing, so in the correct extrapolation of the T-z profile from the deeper section of the profile, we mainly covered sections between 20 and 100 m depth. With this we captured such a course of the T-z profile, which still contains in itself a memory of usually slightly lower temperatures on the surface in the past.

Uvod

Geotermalne toplotne črpalke (angl. ground-source (geothermal) heat pumps, GSHP) kot visoko učinkovita tehnologija obnovljivih virov energije (OVE) omogočajo ogrevanje in hlajenje prostorov, pripravo sanitarne tople vode in shranjevanje energije (npr. Curtis et al., 2005; Omer, 2008; REGEOCITIES; Sarbu & Sebarchievici, 2014). Toplotne črpalke nudijo energetsko učinkovit in trajnostni način za ogrevanje in hlajenje v mnogih rabah, saj uporabljajo OVE iz zemlje, podzemne in površinske vode ter zraka v naši okolici. Pri tem izkoriščajo toploto shranjeno tik pod zemeljskim površjem, tj. že od globine 0,8 m pod površjem in globlje. Plitvi geotermalni sistemi za ogrevanje in hlajenje so sistemi za prenos zemljine toplote iz ali v tla v izvedbi z ali brez geotermalnih toplotnih črpalk (GTČ). Največje prednosti sistemov s plitvo geotermalno energijo so, da imamo isti vir za ogrevanje in hlajenje, ter dostopnost vse dni v letu in zelo nizek okoljski odtis te energije (Prestor et al. 2016), po katerih se tudi razlikuje od drugih virov obnovljive energije.

Pri načrtovanju sistema z GTČ je pomembno čim natančneje določiti toplotne lastnosti plitvega podzemlja (toplotne prevodnosti in difuzivnosti zemljin in kamnin), na katere večinoma vplivata geološka sestava (litologija) in prisotnost podzemne vode. S tem se bistveno poveča učinkovitost in zmanjšajo stroški naprave. Poleg tega je pri načrtovanju potrebno upoštevati dejavnike, kot so temperatura tal, temperature do globin 200 m, gladina podzemne vode in njen pretok ter lastnosti vodonosnika, trajanje sončnega obsevanja, ki je odvisno tudi od topografije, ter še zemeljski toplotni tok in padavine (Busby et al., 2009; Grunert et al., 2010).

Izkoriščanje Zemljinega toplotnega toka predstavlja neizčrpen, povsod prisoten in stalen vir energije za ogrevanje in hlajenje. Zemljin toplotni tok je odraz geotermalnega polja. Geotermalno polje pa je posledica njenih notranjih in zunanjih virov toplote, kar se odraža v toplotnem polju in temperaturnem polju.

Geosolarni toplotni tok je s strani Zemlje absorbiran del solarnega oz. Sončevega toplotnega sevanja, ki dospe do Zemljine površine (npr. Milivojević, 1994; Banks, 2008). Jakost energije tega sevanja znaša v povprečju 628 W/m^2, to je približno 45,7 % vsega sončnega obsevanja, ki prihaja do vrha Zemljine atmosfere v iznosu 1373 W/m^2 (sončna konstanta), ko je Zemlja na razdalji ene astronomske enote od Sonca (Clauser, 2006).

Sončno sevanje predira zemeljsko površje in povzroča temperaturne spremembe v plitvem podzemlju. Globina prenosa sončne energije je odvisna od lokalnega podnebja (npr. sončnega sevanja, sprememb temperature okolice, vetra, padavin) in specifičnih dejavnikov za posamezno lokacijo, kot so lokalna topografija, površinski pokrov in usmerjenost glede na Sonce (npr. proti jugu na severni polobli). Povprečni zemeljski toplotni tok na celinah z 0,071 W/m^2 (Davies & Davies, 2010) pa je 8850-krat manjši od sončnega sevanja.

Glavni notranji vir Zemljinega toplotnega toka je toplota razpada radioaktivnih izotopov U, Th, ^{40}K (≈ 62 % celotne toplote v Zemlji). Ostali notranji viri (38 %) so precej manjši: prvotna toplota med nastajanjem planeta (≈ 17 %), gravitacijsko ločevanje jedra od plašča, tonjenje železa v jedro, sproščena potencialna energija med tvorjenjem nove skorje, tektonski procesi (toplota trenja iz elastične energije sproščene v potresih), metamorfni in diagenetski procesi, plimovanje in kemične reakcije (Clauser, 2006).

Temperatura tal je funkcija prenosa toplote s pomočjo sevanja, konvekcije in prevajanja v tleh in kamninah (Kurevija et al., 2011; Seward & Prieto, 2015). Na splošno lahko razlikujemo tri temperaturne cone (npr. Popiel et al., 2001): (1) površinsko (solarno) cono, kjer je temperatura tal občutljiva na dnevne spremembe (vrhnji 0,5 do 1 m), (2) plitvo območje, kjer so tla (oz. plitvo podzemlje) občutljiva na sezonske vremenske spremembe (do približno 10 m) in (3) globoko cono, kjer je temperatura v plitvem podzemlju skoraj stalna skozi vse leto (globlje od približno 10 m). Obe zgornji coni lahko imenujemo tudi cono letnih sprememb temperature ali geosolarno termocono. Ugotovili smo ju tudi na opazovalnici pri Kostanjevici na Krki (Strgar et al., 2017). Globoko cono, katere vrh nekateri znanstveniki postavljajo tudi malo globlje (pri 14 do 15 m, odvisno od toplotne difuzivnosti plitvega podzemlja), pa imenujemo zemeljsko (terestrično) ali geotermocono (Milivojević, 1994; Busby et al., 2009). Vrh te cone označuje nemotena temperatura plitvega podzemlja, za katero lahko rečemo, da se nahaja v globini, kjer se amplituda letne temperature zniža na samo 0,1 °C (Kurevija et al., 2011, 2014). Letne spremembe temperature sicer prodrejo približno 19-krat globlje kot dnevne (znano kot razmerje kožnih globin, angl. skin depth ratio, npr. Gosar & Ravnik, 2007), to je do globine približno 20 m. Amplituda dnevnih in sezonskih temperaturnih sprememb v plitvem podzemlju se z globino zmanjšuje, spremlja pa jo fazni premik, ki se veča z globino (Bodri & Čermák, 2007; Seward & Prieto, 2015; Rajver et al., 2006; Strgar et al., 2017).

Nadalje je specifični odvzem toplote (angl. specific heat extraction) odvisen od trajanja odvzema (letne ure delovanja), premera vrtine in lege oz. postavitve cevi v geosondi ter v primeru več geo--sond od medsebojnih vplivov le-teh (n.pr. Busby et al., 2009; Banks, 2008). Napake v dimenzioniranju zaprtih sistemov zemlja-voda se lahko odrazijo v poddimenzioniranih ali predimenzioniranih sistemih (Grunert et al., 2010).

Pri načrtovanju geosonde je potrebno poznavanje dveh najvažnejših parametrov, to sta toplotna prevodnost kamnin in zemljin v globinskem dosegu geosonde ter temperatura tal na lokaciji izvedbe. Ta dva parametra najbolj vplivata na dimenzioniranje zaprtih sistemov zemlja-voda in na vrednotenje nizko-temperaturnih virov, ki jih ti sistemi uporabljajo (Signorelli & Kohl, 2004; Eugster et al., 2010). Druga dva pomembna parametra pa sta prostorninska toplotna zmogljivost in gostota geoloških plasti, ki vplivata na njihovo toplotno difuzivnost (Prestor et al., 2016, 2018, str. 27; Eugster et al., 2010). Glede temperature tal smo menili, da je smiselno preveriti, kako lahko ocenimo temperaturo tal za poljubno lokacijo z uporabo podatkov iz termogramov vrtin. To je tudi glavni cilj članka. Termogramov vrtin je namreč razmeroma veliko glede na postaje z merjeno temperaturo zraka, še zlasti pa glede na postaje z merjenimi temperaturami tal.

Metodologija

V projektu GRETA smo pri kartiranju v lokalnem merilu potrebovali podatke o temperaturah tal celotne občine Cerkno za določitev potenciala plitve geotermalne energije (Casasso et al., 2017, 2018). Ker se naprej opisana metodologija v Sloveniji do sedaj še ni izvajala, smo v letih 2016-2017 za boljše načrtovanje zaprtih sistemov izdelali grafe temperatur na površini trdnih tal po algoritmu iz švicarskega standarda SIA 546 384/6 (Eugster et al., 2010). Izvedli smo kalibracijo rezultatov z rezultati dejanskih meritev temperatur v vrtinah, ki je zajela: sortiranje (izločitev neustreznih meritev) z ocenjevanjem reprezentativnosti, določanje anomalij, porazdelitev ugotovljenih površinskih temperatur iz temperaturnih profilov iz vrtin na značilne za primorsko in celinsko podnebje Slovenije, informacije, kdaj so bile meritve opravljene, zanesljivost podatka in upoštevanje lege vrtine. V članku je ta, redkokdaj uporabljena metodologija po švicarskem standardu (sploh pa prvič na slovenskem primeru), za določanje temperature na površini trdnih tal podrobneje opisana, vključno z detaljnim preverjanjem izmerjenih termogramov iz vrtin.

Temperatura površja tal

Srednja letna temperatura površja tal (»temperatura tal«) je linearno odvisna od nadmorske višine (Powell et al., 1988), kjer višinski gradient približno odgovarja atmosferskemu gradientu. Seveda pa je na splošno temperatura tal za 1 do 4 K višja od temperature zraka (Powell et al., 1988; Lewis & Wang, 1992), ki je običajno merjena na 2 m višine nad tlemi. Tolikšna razlika je posledica kombiniranega učinka snežnega izolacijskega pokrova in latentne toplote vlažnih tal, ki vzdržujeta temperaturo tal pri 0 °C tudi v daljših obdobjih zmrzovanja (Lewis & Wang, 1992; Signorelli & Kohl, 2004). Temperatura tal praktično pomeni temperaturo v globini 2 cm. Temperatura tal je odvisna tudi od izpostavljenosti površja osončenju, ki pa je samo po sebi odvisno od nagnjenosti površja in njegove usmerjenosti (Blackwell et al., 1980; Šafanda, 1999). Na severni polobli je običajno, da so proti severu usmerjena pobočja zaradi manjše osončenosti tudi za nekaj stopinj hladnejša od tistih obrnjenih proti jugu.

Druga pomembna dejavnika, ki vplivata na temperaturo tal, sta vegetacija in stanje (tekstura, preperelost ipd.) površinskih kamnin (Lewis, 1998; Lewis & Wang, 1992). Tako sta že Kappelmeyer in Haenel (1974) ugotavljala v globini 1 m za okoli 1 K nižje temperature v gozdu od temperatur pod bližnjimi travniki, podobno ali malo večjo razliko temperature tal so navajali Lewis (1998) ter Nitoiu in Beltrami (2005) kot učinek krčenja gozdov.

V švicarskem standardu SIA 384/6 za Švico navajajo, da je srednja letna temperatura tal za 1,55 °C višja od srednje letne temperature zraka (enačba 1). Ta navidezna linearna odvisnost velja približno za kraje pod nadmorsko višino 1000 m.

Za višje ležeče kraje odvisnost ni več linearna, pač pa se razlika med temperaturo tal in zraka zvišuje z nadmorsko višino. Tako je na nadmorski višini 1800 m temperatura tal že za približno 4 °C višja od temperature zraka (enačba 2).

$$\theta_{g,a} = \theta_{e,a,m} + 1{,}55 \tag{1}$$

$$\Theta_{G,s} = \theta_{e,a,m} + 1{,}55 + \frac{H_S - 1000}{800} \cdot 2{,}45 \tag{2}$$

kjer so:
$\Theta_{g,a}$ srednja letna temperatura površja tal, °C
$\Theta_{e,a,m}$ srednja letna zunanja temperatura (zraka), °C
$\Theta_{G,s}$ površinska temperatura tal (zemlje), °C
H_S nadmorska višina kraja, m n.m.

Zaradi lokalnih negotovosti, na primer vpliva izpostavljenosti kraja, se uporablja tolerančna vrednost $dT_{\text{tolerančni}}$ = 1 K, ki se odšteje za ogrevanje in doda za hlajenje. Odstopanje pri oceni temperature površja po izračunu po SIA 384/6 standardu torej znaša – 1 K za ogrevanje ter + 1 K za hlajenje (Eugster et al., 2010).

Površinska temperatura tal s tolerančno vrednostjo za *ogrevanje* je določena, ker v režimu ogrevanja odvzemamo toploto iz tal in jih hladimo. Zato je srednja letna površinska temperatura tal znižana za 1 °C in smo tako »na varni strani«, saj s tem zajamemo sipanje vrednosti (enačba 3). Na primeru slike 2 je temperatura tal z upoštevano toleranco za ogrevanje nižje od zelene premice. Izračuna se po enačbi 3:

$$\theta_{g,a,H} = \theta_{g,a} - 1 \tag{3}$$

Površinska temperatura tal s tolerančno vrednostjo za *hlajenje* je določena, ker v režimu hlajenja vnašamo toploto v tla. Zato je srednja letna površinska temperatura tal povišana za 1 °C in smo tako spet »na varni strani« (enačba 4). Na primeru slike 2 je temperatura tal z upoštevano toleranco za hlajenje nad rdečo premico. Izračuna se po enačbi 4:

$$\theta_{g,a,C} = \theta_{g,a} + 1 \tag{4}$$

Navedene enačbe temeljijo na primerjavi številnejših podatkov o temperaturi tal v Švici, ki se jih da primerjati s podatki o temperaturah zraka. Za Slovenijo razpolagamo z zelo redkimi podatki meritev temperature tal.

Vrednost za celinsko Slovenijo smo dobili kot povprečje razlik trendnih črt povprečne temperature zraka (2 m) ter povprečne temperature tal (-2 cm) med nadmorsko višino 0 m (1,3 °C) in višino vrha Triglava 2864 m (0,7 °C). Za primorsko Slovenijo tak izračun ni bil možen zaradi premajhnega števila podatkov. Ocenili smo, da je temperatura tal vsaj 1,0 °C višja od temperature zraka na dveh metrih. Za primerjavo omenimo, da smo tudi iz opazovanj v vzhodni Sloveniji (Malence) po prvih treh letih ugotovili razliko okrog 1 °C med srednjimi letnimi temperaturami tal in zraka (Rajver et al., 2006; Šafanda et al., 2007).

Zaradi pomanjkljivih podatkov o temperaturi tal v Sloveniji smo si pomagali s korelacijo med temperaturami zraka in temperaturami tal, ocenjenimi iz termogramov vrtin.

Korelacija med temperaturami zraka in temperaturami tal, ocenjenimi iz termogramov vrtin

Najprej smo obdelali podatke izmerjenih temperatur v 458 vrtinah po vsej državi. Dodali smo tudi 9 točk v različnih krajih po državi, za katere imamo povprečja mesečnih temperatur tal v različnih globinah v obdobju 1971-2000 (Internet 1). Tako smo preverili izmerjene termograme (T-z profile) iz vrtin za določitev temperatur na površini trdnih tal. Upoštevali smo podatek za leto zadnje ali najboljše (ko je bila vrtina toplotno stabilizirana z okoliškimi kamninami) meritve temperature v vrtini. Nato smo iz teh podatkov izračunali regresijsko premico odvisnosti temperature na globini nič od nadmorske višine ustja vrtine (Rajver et al., 2018 – metapodatek za sloj ABC) in sicer posebej za primorski in posebej za celinski del Slovenije. Meja med celinskim in primorskim delom je ista, kot velja za meteorološke postaje (Ogrin & Plut, 2009) in je opredeljena na sliki 3. Območje primorske Slovenije je prostorsko tisto, kjer vlada zmerno sredozemsko podnebje (oranžna barva za obalno in rumena za zaledno podnebje).

Določili smo kakovost interpretacije, in sicer : A – »normalen« termogram (večinoma linearno naraščanje temperature z globino, vsaj v vrhnjih 50 do 100 metrih vrtine), B – odvisnost temperature z globino interpretirana z ekstrapolacijo, potek temperature z globino je lahko nelinearen in C - interpretacija vprašljiva in težavna (glej sliko 4). Glede na podatke o lokacijah (GKX, GKY) in nadmorski višini (*z*) vrtin so bile le-te razvrščene bodisi v celinsko bodisi primorsko Slovenijo. S pomočjo Atlasa okolja so bile opredeljene tudi lege obravnavanih vrtin: S - sončna lega, obrnjena pretežno proti jugu, odprti prostor ter T – temačna senčna lega, obrnjena pretežno proti severu, v gozdu ali na manjši jasi v gozdu ipd. Na podlagi karte temperatur zraka za zadnje referenčno obdobje 1981-2010 je mag. Mojca Dolinar (Agencija RS za Okolje, osebno sporočilo) izračunala višinska gradienta letne povprečne temperature zraka na 2 m za primorsko in celinsko Slovenijo, v odvisnosti od nadmorske višine *z* (enačbi 5 in 6):

primorska Slovenija:

$$T_P = 13{,}5\,°C - 6{,}4\frac{K}{km} \times z\,(km) \qquad (5)$$

celinska Slovenija:

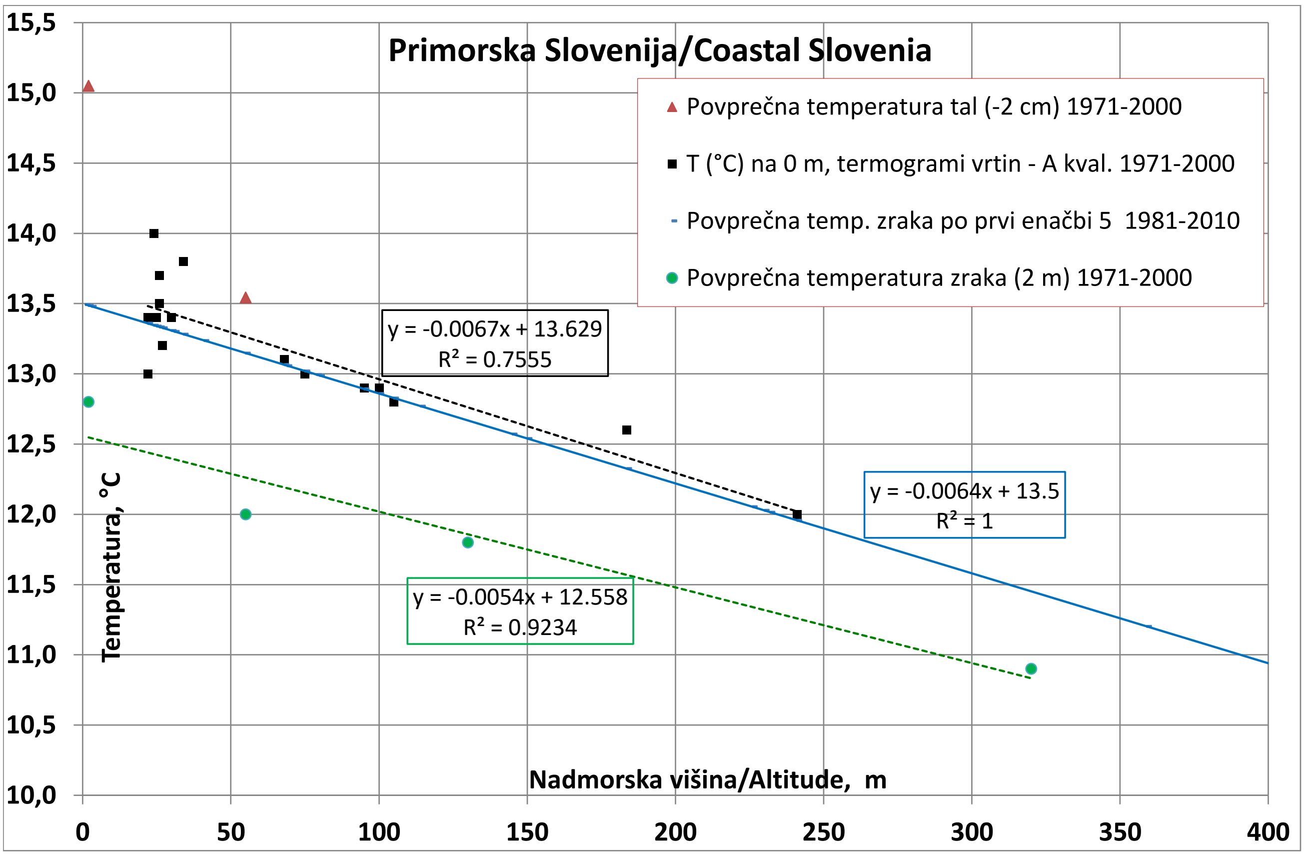
$$T_C = 11{,}6\,°C - 4{,}9\frac{K}{km} \times z\,(km) \qquad (6)$$

Obe enačbi višinskih gradientov smo uporabili za izračun povprečne letne temperature zraka na 2 m nad tlemi za lokacijo vsake vrtine. Na podlagi izračunov za zadnje referenčno obdobje 1971–2000 smo izrisali grafe temperatur iz termogramov vrtin, temperatur tal v globini 2 cm, povprečne temperature zraka (iz višinskih gradientov lokacij vrtin) ter zraka na višini 2 m, vse v odvisnosti od nadmorske višine za primorsko in celinsko Slovenijo (sl. 1 in 2).

Grafi so uporabni za projektiranje geosond. Postopek se izvaja po korakih. Podrobneje so vsi štirje načini za določitev temperature na površini tal opisani v poglavju »Štirje osnovni načini za izračun temperature (T_0) na površini trdnih tal«.

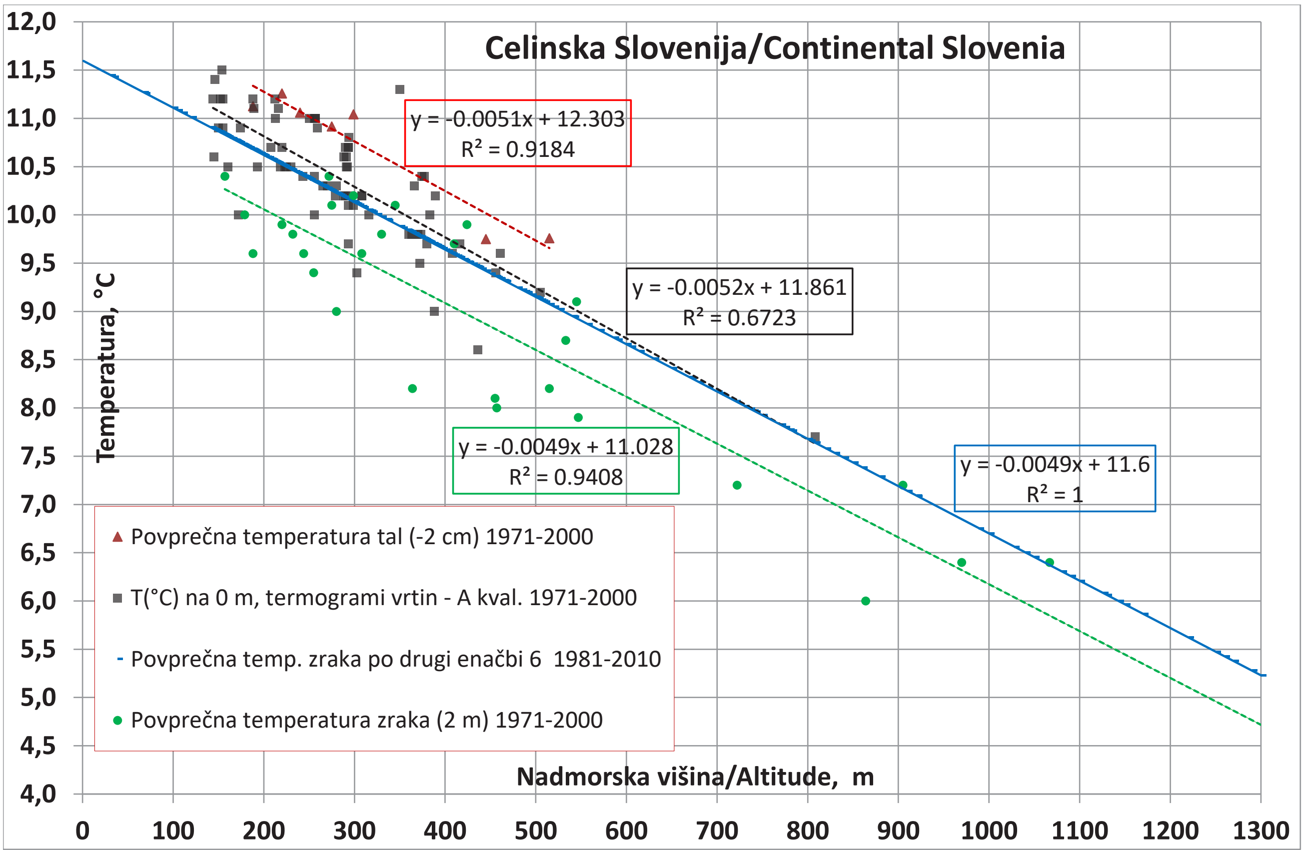
Za Slovenijo smo ugotovili, da je potrebno prišteti $dT_{tla\text{-}zrak}$ = 1,2 °C k povprečni letni temperaturi zraka, da dobimo podatek o srednji letni temperaturi tal na površju celinske Slovenije (sl. 2, tabela 1). Če primerjamo s Švico, tam velja popravek 1,55 °C, za katerega predvidevamo, da je posledica dejstva, da je povprečna nadmorska višina Švice višja od tiste za Slovenijo, posledično so torej srednje letne temperature zraka v Švici nižje in je večja razlika do temperature tal.

V primeru primorske lege, povprečni letni temperaturi zraka prištejemo 1,0 °C in v primeru celinske lege, povprečni letni temperaturi zraka prištejemo 1,2 °C ter na ta način dobimo podatek o temperaturi tal na površju.



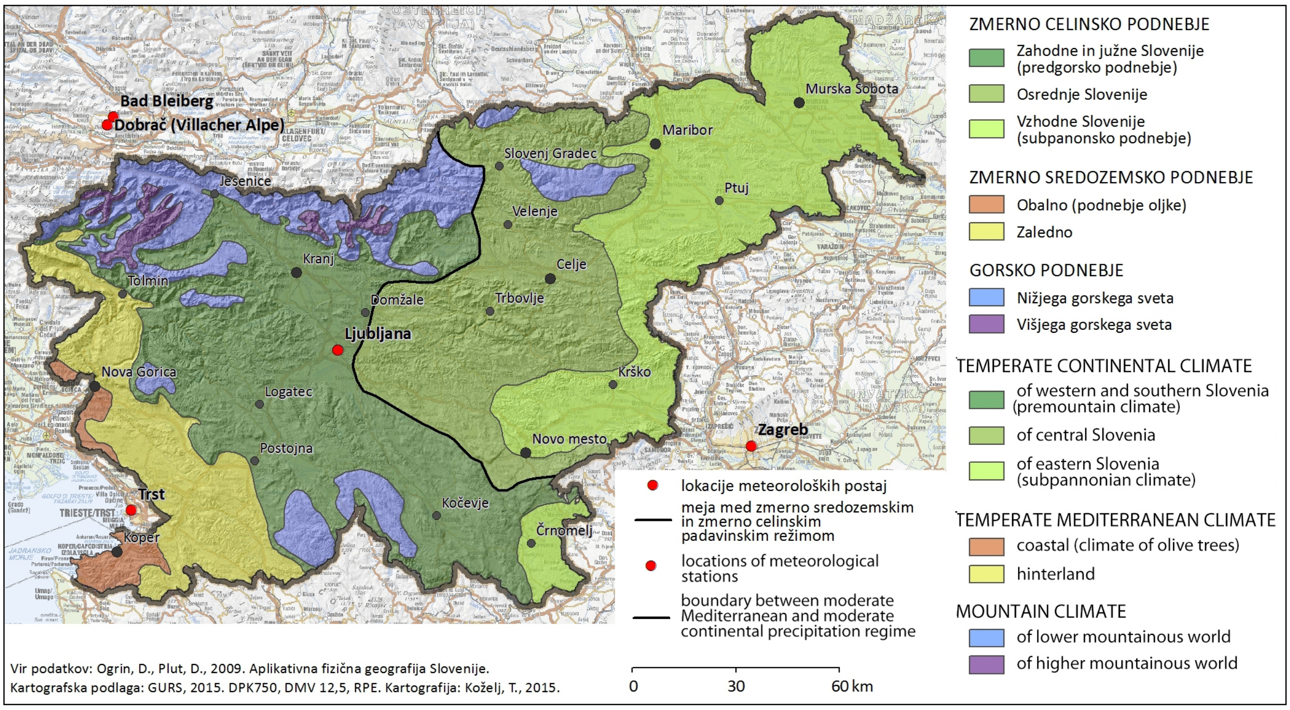
Sl. 1. Odvisnost temperatur iz termogramov vrtin, temperatur tal v globini 2 cm, povprečne temperature zraka po enačbi 5 (iz višinskih gradientov lokacij vrtin) ter zraka na višini 2 m od nadmorske višine za primorsko Slovenijo.

Fig. 1. Dependence of temperatures from borehole thermograms (squares), soil temperatures at a depth of 2 cm (triangles), mean air temperature after equation 5 (from altitude gradients of borehole locations)(quadrangles) and air at a height of 2 m (circles) from altitude for the coastal Slovenia.



Sl. 2. Odvisnost temperatur iz termogramov vrtin, temperatur tal v globini 2 cm, povprečne temperature zraka po enačbi 6 (iz višinskih gradientov lokacij vrtin) ter zraka na višini 2 m od nadmorske višine za celinsko Slovenijo.

Fig. 2. Dependence of temperatures from borehole thermograms (squares), soil temperatures at a depth of 2 cm (triangles), mean air temperature after equation 6 (from altitude gradients of borehole locations)(quadrangles) and air at a height of 2 m (circles) from altitude for the continental Slovenia.



Sl. 3. Podnebni tipi v Sloveniji (Ogrin & Plut, 2009).
Fig. 3. The climate types in Slovenia (Ogrin & Plut, 2009).

Celinska / Continental Slovenija sl. 2 / fig. 2			x: nadmorska višina/altitude, m			
	k	n	200	500	1000	1500
tla / ground:	-0,0051	12,30	11,28	9,75	7,20	4,65
zrak / air:	-0,0049	11,03	10,05	8,58	6,13	3,68
			1,23	1,17	1,07	0,97
dT tla-zrak / dT ground-air	-0,0002	1,27	1,2	1,2	1,1	1,0
Primorska / Coastal Slovenija sl. 1 / fig. 1			x: nadmorska višina/altitude, m			
	k	n	0	50	100	150
tla / ground:	-0,0092	13,69	13,69	13,23	12,77	12,31
zrak / air:	-0,0054	12,56	12,56	12,29	12,02	11,75
			1,13	0,94	0,75	0,56
dT tla-zrak / dT ground-air	-0,0038	1,13	1,1	0,9	0,8	0,6

Tabela 1. Določitev temperaturne razlike dT med premicama **kx+n** iz slik 1 in 2.

Table 1. Determination of the temperature difference dT between the lines **kx + n** from figs. 1 and 2.

Izračuni

Splošen postopek sledi zgledu švicarskega standarda SIA 384/6 (Eugster et al., 2010) in se ga uporablja v vsakem od štirih osnovnih načinov izračuna.

V prvem koraku preverimo, kakšni so podnebni podatki za dano lokacijo. Podnebni podatki so dostopni na spletni aplikaciji pregledovalnika podnebnih podlag na spletni strani Agencije RS za okolje (Internet 2). Te podatke lahko pridobimo za poljubno lokacijo (GKX, GKY). Koordinate (GKX, GKY) in nadmorsko višino (*z*) pa lahko dobimo s pomočjo pregledovalnika Atlas okolja (Internet 3).

Drugi korak: če v kraju, kjer dimenzioniramo zajetje plitve geotermalne energije z geosondami, nimamo nobenih meritev temperature tal, lahko temperaturo na površini trdnih tal ocenimo na štiri osnovne, v nadaljevanju opisane načine. Pri tem izberemo med grafoma (sl. 1 in 2) glede na to ali podatek o lokaciji kaže na primorski ali celinski del Slovenije.

Tretji korak: Zaradi lokalnih negotovosti, na primer vpliva izpostavljenosti, se uporablja tolerančna vrednost $dT_{toleran\check{c}ni}$ = 1 K, ki se odšteje za ogrevanje in doda za hlajenje. Odstopanje pri oceni temperature površja po izračunu po SIA 384/6 standardu torej znaša – 1 K za ogrevanje ter + 1 K za hlajenje (Eugster et al., 2010).

Štirje osnovni načini za izračun temperature (T_0) na površini trdnih tal

1. **Imamo podatek o srednji letni temperaturi zraka**

Podatek lahko dobimo iz meritev na bližnji meteorološki postaji (Internet 4) ali pa vnesemo koordinate v spletni aplikaciji pregledovalnika podnebnih podlag na spletni strani Agencije RS za okolje (Internet 2).

Dobljenemu rezultatu prištejemo vrednost za pretvorbo temperature zraka v temperaturo tal, pri tem si pomagamo z interpolacijo med nadmorskimi višinami (tabela 2).

Celinska / Continental Slovenija				
x: nadmorska višina / altitude, m	200	500	1000	1500
$dT_{tla\text{-}zrak/ground\text{-}air}$ (°C)	1,2	1,2	1,1	1,0
Primorska / Coastal Slovenija				
x: nadmorska višina / altitude, m	0	50	100	150
$dT_{tla\text{-}zrak/ground\text{-}air}$ (°C)	1,1	0,9	0,8	0,6

Tabela 2. Vrednosti za pretvorbo temperature zraka v temperaturo tal (poenostavljeno iz tabele 1).

Table 2. Values for converting the air temperature to the soil temperature (simplified from Table 1).

Končnemu rezultatu odštejemo vrednost 1 °C, če dimenzioniramo zajetje pretežno za ogrevanje (enačba 3) ali prištejemo vrednost 1 °C, če dimenzioniramo zajetje s pomembnim deležem hlajenja (enačba 4).

2. **Imamo samo podatek o nadmorski višini kraja**

Način je lahko uporaben v predelih, ki sploh niso pokriti s potrebnimi podatki za prvi, tretji in četrti način. Izberemo enačbo za višinski gradient letne povprečne temperature zraka za celinsko ali primorsko Slovenijo in v njo vnesemo podatek nadmorske višine. S tem načinom dobimo pričakovano povprečno temperaturo zraka na neki lokaciji iz višinskega gradienta glede na karto za zadnje referenčno obdobje za katerega veljata enačbi.

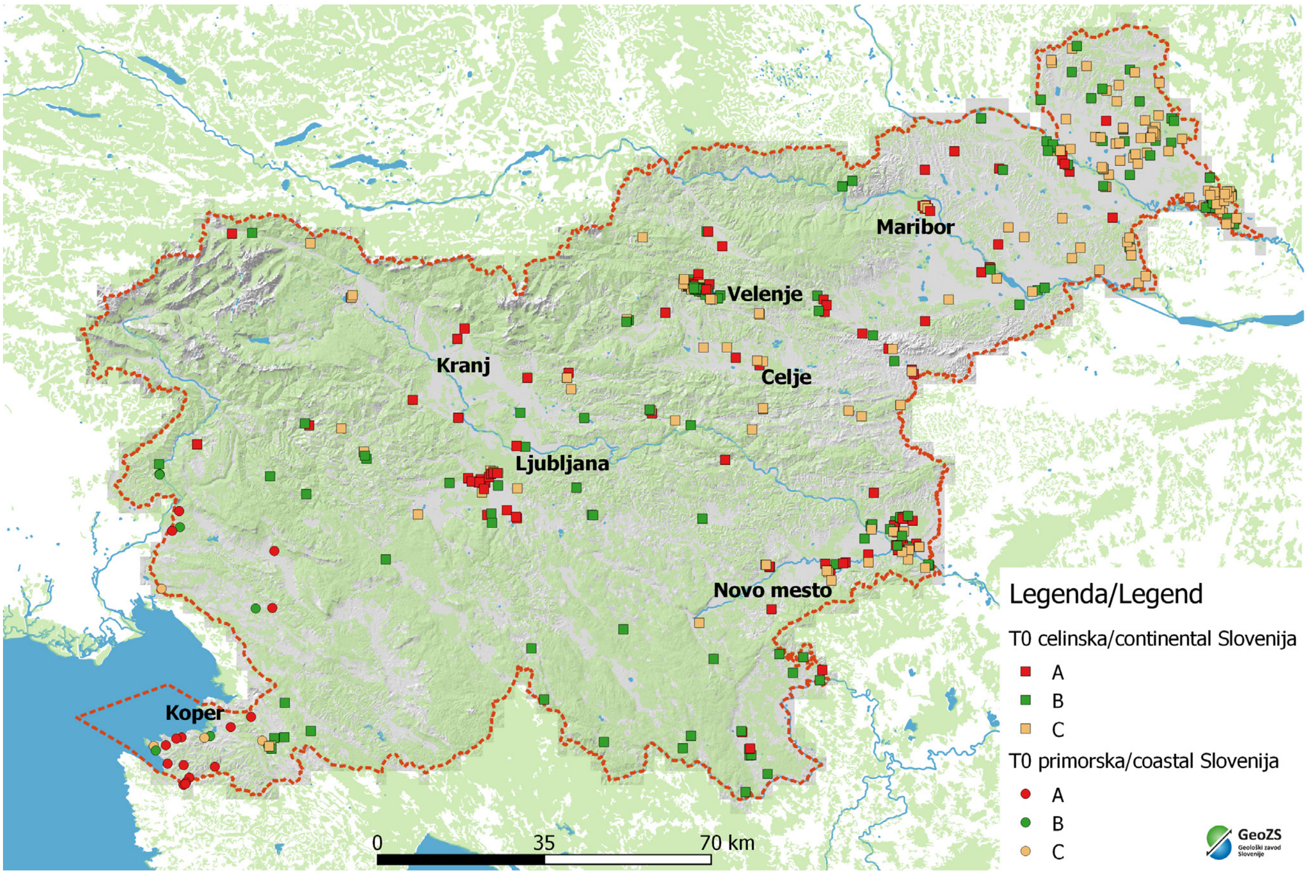
Dobljenemu rezultatu prištejemo ustrezno vrednost za pretvorbo temperature zraka v temperaturo tal (glej prejšnjo točko za prvi način).

V končnem rezultatu upoštevamo še tolerančno vrednost za ogrevanje ali hlajenje kot je navedeno v prvem načinu.

3. **V bližini je merilna postaja temperature tal**

Upoštevamo merjene temperature v tleh, to so podatki iz najbližje samodejne meteorološke postaje, kjer izvajajo meritve temperature tal v globinah 2, 5, 10, 20, 30, 50 in 100 cm. Ti podatki so na voljo v pregledovalniku MOP ARSO (Internet 1), v katerem najdemo povprečja mesečnih temperatur tal v različnih globinah v obdobju 1971-2000. Povprečna mesečna temperatura tal v izbrani globini je izračunana iz dnevnega povprečja terminskih meritev temperature tal ob 7., 14. in 21. uri. Povprečna mesečna temperatura tal v globini enega metra je izračunana iz dnevnih meritev ob 14. uri. Kot bomo videli iz primerov izračuna, smo se opredelili za temperature tal v globini 5 cm, ker menimo, da še dovolj dobro odražajo površinsko temperaturo tal, hkrati pa niso preveč podvržene nenadnim mehanskim dejavnostim, kot je to lahko primer s temperaturnimi tipali v globini 2 cm.

Tudi tu v končnem rezultatu upoštevamo še tolerančno vrednost za ogrevanje ali hlajenje kot je navedeno v prvem načinu.



Sl. 4. Lokacije s termogrami vrtin za določitev temperatur na površini trdnih tal v Sloveniji. Vrtine so razvrščene med celinsko in primorsko Slovenijo glede na njihovo lokacijo in nadmorsko višino. Opredeljena je kvaliteta interpretacije: A - normalen termogram temperature z globino, B - odvisnost temperature z globino interpretirana z ekstrapolacijo, potek temperature je lahko nelinearen, C - interpretacija je vprašljiva ali težavna.

Fig. 4. Locations with borehole thermograms for determination of temperatures on the surface of solid ground in Slovenia. Boreholes are classified between continental and coastal Slovenia according to their location and altitude. The quality of interpretation is defined: A - normal temperature thermogram with depth, B - dependence of temperature with depth is interpreted by extrapolation, the temperature course can be nonlinear, C - interpretation is questionable or problematic.

4. **V bližini je vrtina z izračunano temperaturo tal iz geotermičnih meritev**

Upoštevamo temperaturo tal, ki je bila določena iz termograma bližnje vrtine (izmerjeni T-z profil v vrtini). Uporabimo podatkovni GIS sloj z lokacijami geotermalnih vrtin in preverimo ali je najbližji podatek reprezentativen za izbrano mesto. Iz najbližje vrtine, s primerno izmerjenim profilom temperature z globino, določimo temperaturo T_0, če je potrebno tudi z ekstrapolacijo proti površju. Primerno izmerjen termogram je tisti, ki je opravljen v vrtini po daljšem času toplotne stabilizacije vrtine, tj. dalj časa po končanem vrtanju, po črpalnih preskusih, ipd. Izberemo torej ekstrapolirano temperaturo iz najbližje vrtine ali pa npr. naredimo interpolacijo med dvema vrtinama. Prostorski podatki bodo dostopni preko spletnega portala eGeologija v WMS storitvi.

V dobljenem rezultatu upoštevamo še tolerančno vrednost za ogrevanje ali hlajenje kot je navedeno v prvem načinu.

Slika 4 prikazuje lokacije vrtin s termogrami, ki so uporabni za določitev temperatur na površini trdnih tal. Lokacije označene s kvadratki so v celinskem delu, tiste v primorskem delu pa s krogci. Barve oziroma oznake A, B in C označujejo kvaliteto interpretirane temperature na površini tal iz izmerjenega termograma posamezne vrtine.

Rezultati

Primeri izračuna temperature na površini trdnih tal za izbrane lokacije

V nadaljevanju predstavljamo pet različnih lokacij v Sloveniji s primeri izračuna temperature na površini trdnih tal po vseh štirih omenjenih načinih, če so seveda merodajni za vsako izbrano lokacijo. Izbrali smo takšne lokacije, ki predstavljajo različne regije in s tem geološke ter podnebne pogoje v Sloveniji. Podrobneje opisujemo postopke le za prvi primer v Cerknem.

Izbrana lokacija za postavitev geosonde je na območju **občine Cerkno**, **v Cerknem pri stavbi Centra šolskih in obšolskih dejavnosti,** s koordinatama: GKY: 422039, GKX: 109742 in nadmorsko višino: 319,2 m.

Zajetje z geosondo bo namenjeno pretežno ogrevanju in le zelo malo tudi hlajenju. Poglejmo si vse štiri možne načine:

a) *izračun temperature iz meteorološke postaje (ki je najbližje lokaciji)*

Na spletni aplikaciji pregledovalnika podnebnih podlag na spletni strani Agencije RS za okolje (Internet 2) z vnosom koordinat dobimo na desni strani dolge preglednice **podatek o povprečni letni temperaturi (zraka)** in lokaciji:

$\Theta_{e,a,m} = 9{,}5\ °C$ srednja letna zunanja temperatura (zraka)

V primeru naselja Cerkno imamo celinsko lego, zato povprečni letni temperaturi zraka prištejemo 1,2 °C (glej tabelo 2) ter na ta način dobimo podatek o **temperaturi tal na površju**:

$$\Theta_{g,a} = \Theta_{e,a,m} + 1{,}2 = 10{,}7\ °C$$

Površinska temperatura tal, s tolerančno vrednostjo za ogrevanje:

$$\Theta_{g,a,H} = \Theta_{g,a} - 1 = 9{,}7\ °C$$

b) *izračun temperature iz nadmorske višine*

Izberemo enačbo 6 za višinski gradient letne povprečne temperature zraka za celinsko Slovenijo:

11,6 °C - 4,9 K/km · z (v km)

in v njo vnesemo podatek nadmorske višine z (v km), v tem primeru 0,3192 km. Dobimo:

11,6 °C – 4,9 K/km · 0,3192 km = 10,0 °C

S tem načinom dobimo pričakovano povprečno temperaturo zraka na lokaciji glede na karto za zadnje referenčno obdobje 1981 – 2010.

V primeru celinske lege povprečni letni temperaturi zraka prištejemo 1,2 °C (glede na nadmorsko višino lokacije (tabela 2)) ter na ta način dobimo podatek o temperaturi tal na površju:

$$\Theta_{g,a} = \Theta_{e,a,m} + 1{,}2 = 11{,}2\ °C$$

Površinska temperatura tal s tolerančno vrednostjo za ogrevanje je potem:

$$\Theta_{g,a,H} = \Theta_{g,a} - 1 = 11{,}2 - 1{,}0 = 10{,}2\ °C$$

c) *izračun, ki je uporaben le v primeru, če so v bližini primerne meteorološke postaje, kjer so merili temperaturo tal*

Temperaturo tal v globini 5 cm poiščemo v pregledovalniku (Internet 1).

Če naša lokacija ni blizu nobeni od navedenih postaj, ta način ni uporaben, in takšen je slučaj z lokacijo Cerkno.

Tabela 3. Primeri izračuna temperature na površini trdnih tal za pet izbranih lokacij.
Table 3. Examples of temperature calculation on the surface of solid earth for five selected locations.

1. Lokacija

Cerkno, pri stavbi CŠOD	Predvideno zajetje plitve geotermalne energije z geosondo bo namenjeno predvsem ogrevanju in le zelo malo tudi hlajenju.		
GKX: 109742 GKY: 422039 Z=319,2 m			
	1. korak	2. korak	3. korak
Način	povprečna letna temperatura zraka	povprečna temperatura površja tal celinska lega (tab. 2)	temperatura površja tal (TPT) tolerančna vrednost za ogrevanje
1) Izračun temperature iz meteorološke postaje (ki je najbližje lokaciji) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/climate/tables/pravilnik-ucinkoviti-rabi-energije/	$\Theta_{e,a,m} = 9{,}5$ °C	$\Theta_{g,a} = \Theta_{e,a,m} + 1{,}2 = 10{,}7$ °C	$\Theta_{g,,a,H} = \Theta_{g,a} - 1 = 10{,}7 - 1 = 9{,}7$ °C
2) Enačba za višinski gradient letne povprečne temperature zraka za celinsko Slovenijo (v tem primeru):	11,6 °C - 4,9 K/km · z (v km) 11,6 °C – 4,9 K/km · 0,3192 km = 10,0 °C	$\Theta_{g,a} = \Theta_{e,a,m} + 1{,}2 = 11{,}2$ °C	$\Theta_{g,,a,H} = \Theta_{g,a} - 1 = 11{,}2 - 1 = 10{,}2$ °C
3) V bližini je meteorološka postaja, kjer merijo temperaturo tal (iščemo temp. tal v globini 5 cm) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/agromet/period/soiltemp/		naša lokacija v Cerknem ni blizu nobeni od navedenih postaj	
4) Primerno izmerjen T-z profil (termogram) iz najbližje vrtine: iz termograma vrtine Ce-1/94 (Cerkno, Na Rajdi):		povprečna temperatura površja tal $T_0 = 10$ °C (A kvaliteta interpret.)	$\Theta_{g,,a,H} = \Theta_{g,a} - 1 = 10{,}0 - 1 = 9{,}0$ °C

2. Lokacija

Lucija pri Portorožu, pri vrtcu Morje Lucija	Predvideno zajetje plitve geotermalne energije z geosondami bo namenjeno ogrevanju, morda pa še bolj hlajenju.		
GKX: 041043 GKY: 391551 Z=2 m			
	1. korak	2. korak	3. korak
Način	povprečna letna temperatura zraka	povprečna temperatura površja tal primorska lega (tab. 2)	temperatura površja tal (TPT) tolerančna vrednost za hlajenje
1) Izračun temperature iz meteorološke postaje (ki je najbližje lokaciji) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/climate/tables/pravilnik-ucinkoviti-rabi-energije/	$\Theta_{e,a,m} = 13{,}5$ °C	$\Theta_{g,a} = \Theta_{e,a,m} + 1{,}1 = 14{,}6$ °C	$\Theta_{g,,a,C} = \Theta_{g,a} + 1 = 14{,}6 + 1 = 15{,}6$ °C
2) Enačba za višinski gradient letne povprečne temperature zraka za primorsko Slovenijo (v tem primeru):	13,5 °C - 6,4 K/km · z (v km) 13,5 °C – 6,4 K/km · 0,002 km = 13,5 °C	$\Theta_{g,a} = \Theta_{e,a,m} + 1{,}1 = 14{,}6$ °C	$\Theta_{g,,a,C} = \Theta_{g,a} + 1 = 14{,}6 + 1 = 15{,}6$ °C
3) V bližini je meteorološka postaja, kjer merijo temperaturo tal (iščemo temp. tal v globini 5 cm) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/agromet/period/soiltemp/		naša lokacija v Luciji je blizu meteorološki postaji Portorož - Letališče; za letno povpre-čje dobimo: $\Theta_{g,a} = 14{,}7$ °C	$\Theta_{,,a,C} = \Theta_{g,a} + 1 = 14{,}7 + 1 = 15{,}7$ °C
4) Primerno izmerjen T-z profil (termogram) iz najbližje vrtine: - na voljo imamo dva termograma: (a) iz termograma vrtine Lu-1/94 (Lucija): (b) iz termograma vrtine LIV-1/01 (Izola):		povprečna temperatura površja tal $T_0 = 13{,}5$ °C (B kvaliteta interpret.) $T_0 = 13{,}4$ °C (A kvaliteta interpret.)	odločimo se npr. za primer (a): $\Theta_{g,,a,C} = \Theta_{,a} + 1 = 13{,}5 + 1 = 14{,}5$ °C

3. Lokacija

Zgornji Brnik, Letališče J.Pučnika Ljubljana	Predviden sistem zajetja plitve geotermalne energije z geosondo bo namenjen pretežno ogrevanju in bolj malo tudi hlajenju.		
GKX: 120709 GKY: 458131 Z=382,4			
	1. korak	2. korak	3. korak
Način	povprečna letna temperatura zraka	povprečna temperatura površja tal celinska lega (tab. 2)	temperatura površja tal (TPT) tolerančna vrednost za ogrevanje
1) Izračun temperature iz meteorološke postaje (ki je najbližje lokaciji) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/climate/tables/pravilnik-ucinkoviti-rabi-energije/	$\Theta_{e,a,m} = 9{,}4$ °C	$\Theta_{g,a}=\Theta_{e,a,m} + 1{,}2 = 10{,}6$ °C	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 10{,}6 - 1 = 9{,}6$ °C
2) Enačba za višinski gradient letne povprečne temperature zraka za celinsko Slovenijo (v tem primeru):	11,6 °C - 4,9 K/km · z (v km) 11,6 °C – 4,9 K/km · 0,3824 km = 9,7 °C	$\Theta_{g,a}=\Theta_{e,a,m} + 1{,}2 = 10{,}9$ °C	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 10{,}9 - 1 = 9{,}9$ °C
3) V bližini je meteorološka postaja, kjer merijo temperaturo tal (iščemo temp. tal v globini 5 cm) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/agromet/period/soiltemp/		naša lokacija v Zg. Brniku je nekje vmes med postajama Lesce in Ljubljana; privzamemo srednjo letno vrednost obeh postaj: $\Theta_{g,a} = 10{,}5$ °C	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 10{,}5 - 1 = 9{,}5$ °C
4) Primerno izmerjen T-z profil (termogram) iz najbližje vrtine: iz termograma vrtine BR-1/86 (Brdo pri Kranju):		povprečna temperatura površja tal $T_0 = 9{,}3$ °C (A kvaliteta interpret.)	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 9{,}3 - 1 = 8{,}3$ °C

4. Lokacija

Babno Polje, pri Župnijski cerkvi Sv. Nikolaja	Predviden sistem zajetja plitve geotermalne energije z geosondo bo namenjen pretežno ogrevanju in le zelo malo tudi hlajenju.		
GKX: 055825 GKY: 465233 Z=754,8 m			
	1. korak	2. korak	3. korak
Način	povprečna letna temperatura zraka	povprečna temperatura površja tal celinska lega (tab. 2)	temperatura površja tal (TPT) tolerančna vrednost za ogrevanje
1) Izračun temperature iz meteorološke postaje (ki je najbližje lokaciji) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/climate/tables/pravilnik-ucinkoviti-rabi-energije/	$\Theta_{e,a,m} = 7{,}0$ °C	$\Theta_{g,a}=\Theta_{e,a,m} + 1{,}1 = 8{,}1$ °C	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 8{,}1 - 1 = 7{,}1$ °C
2) Enačba za višinski gradient letne povprečne temperature zraka za celinsko Slovenijo (v tem primeru):	11,6 °C - 4,9 K/km · z (v km) 11,6 °C – 4,9 K/km · 0,7548 km = 7,9 °C	$\Theta_{g,a}=\Theta_{e,a,m} + 1{,}1 = 9{,}0$ °C	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 9{,}0 - 1 = 8{,}0$ °C
3) V bližini je meteorološka postaja, kjer merijo temperaturo tal (iščemo temp. tal v globini 5 cm) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/agromet/period/soiltemp/		naša lokacija na Babnem Polju ni blizu nobeni od navedenih postaj.	
4) Primerno izmerjen T-z profil (termogram) iz najbližje vrtine: iz termograma vrtine SK-1/98 (Stari Kot pri Čabru):		povprečna temperatura površja tal $T_0 = 7{,}9$ °C (B kvaliteta interpret.)	$\Theta_{g,,a,H}=\Theta_{g,a} - 1 = 7{,}9 - 1 = 6{,}9$ °C

5. Lokacija

Maribor - Brezje, na vzhodnem robu Stražunskega gozda	Predviden sistem zajetja plitve geotermalne energije z geosondo bo namenjen pretežno ogrevanju, nekoliko pa tudi hlajenju.		
GKX: 154860 GKY: 552805 Z=256 m			
	1. korak	2. korak	3. korak
Način	povprečna letna temperatura zraka	povprečna temperatura površja tal celinska lega (tab. 2)	temperatura površja tal (TPT) tolerančna vrednost za ogrevanje
1) Izračun temperature iz meteorološke postaje (ki je najbližje lokaciji) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/climate/tables/pravilnik-ucinkoviti-rabi-energije/	$\Theta_{e,a,m}$ = 9,9 °C	$\Theta_{g,a}=\Theta_{e,a,m}$ + 1,2 = 11,1 °C	$\Theta_{g,,a,H}=\Theta_{g,a}$ - 1 = 11,1 - 1 = 10,1 °C
2) Enačba za višinski gradient letne povprečne temperature zraka za celinsko Slovenijo (v tem primeru):	11,6 °C - 4,9 K/km · z (v km) 11,6 °C – 4,9 K/km · 0,256 km = 10,3 °C	$\Theta_{g,a}=\Theta_{e,a,m}$ + 1,2 = 11,5 °C	$\Theta_{g,,a,H}=\Theta_{g,a}$ - 1 = 11,5 - 1 = 10,5 °C
3) V bližini je meteorološka postaja, kjer merijo temperaturo tal (iščemo temp. tal v globini 5 cm) - spletna stran ARSO: http://meteo.arso.gov.si/met/sl/agromet/period/soiltemp/		naša lokacija v Mariboru-Brezje je dokaj blizu meteorološki postaji Maribor; za letno povprečje dobimo: $\Theta_{g,a}$ = 10,96 =11,0 °C	$\Theta_{g,,a,H}=\Theta_{g,a}$ - 1 = 11,0 - 1 = 10,0 °C
4) Primerno izmerjen T-z profil (termogram) iz najbližje vrtine: iz termograma vrtine MB-1/90 (Maribor - Stražun):		povprečna temperatura površja tal T_0 = 10,4 °C (A kvaliteta interpret.)	$\Theta_{g,,a,H}=\Theta_{g,a}$ - 1 = 10,4 - 1 = 9,4 °C

The calculation mode:

1) calculation of temperature from the meteorological station (closest to the location) - ARSO website,

2) the equation for the height gradient of the annual mean air temperature, for continental or coastal Slovenia,

3) nearby is a meteorological station measuring the soil temperature (we are looking for a temperature at 5 cm depth) - ARSO website.

4) properly measured T-z profile from the nearest borehole.

d) *izračun iz najbližje vrtine, s primerno izmerjenim termogramom (T-z profilom), določimo temperaturo T_0, če je potrebno tudi z interpolacijo.*

V primeru izbrane lokacije Centra za šolske in obšolske dejavnosti (CŠOD) upoštevamo zanesljive in kvalitetne meritve temperature v vrtinah, torej v tem primeru na termogramu iz vrtine Ce-1/94 (Cerkno - Na Rajdi) razberemo: T_0 = 10 °C (A kvaliteta interpretacije).

Površinska temperatura tal s tolerančno vrednostjo za ogrevanje je potem:

$$\Theta_{g,a,H} = \Theta_{g,a} - 1 = 10{,}0 - 1{,}0 = 9{,}0\ °C$$

Za to prvo lokacijo, kakor tudi za naslednje štiri v krajih Lucija pri Portorožu, Zgornji Brnik (Letališče Jožeta Pučnika Ljubljana), Babno Polje in Maribor-Brezje predstavljamo vhodne podatke, postopke izračunov in rezultate v tabeli 3.

Kot primer uporabljenega tretjega načina prikazujemo rezultat za Lucijo pri Portorožu (glej tudi tabelo 3). Zanjo se temperatura tal v globini 5 cm najde v pregledovalniku (Internet 1), saj se meri na glavnih agrometeoroloških postajah v Sloveniji. V primeru lokacije vrtec Morje Lucija v Luciji izberemo najbližjo ali najbolj primerljivo agrometeorološko postajo Portorož – letališče z mesečnimi povprečji (tabela 4). Za letno povprečje v obdobju 1971-2000 dobimo 14,7 °C.

Pridobljene vrednosti smo pregledno strnili v tabeli 5 in komentirali v diskusiji.

Diskusija

Kriteriji izbire ustreznega načina izračuna

Med štirimi načini izračuna temperature na površini trdnih tal izberemo najbolj ustreznega (obrazloženo v nadaljevanju), lahko seveda tudi več načinov, in sicer glede na vse znane razmere. Četrti način z uporabo ekstrapolacije temperature iz izmerjenega termograma v vrtini proti površini je obremenjen predvsem s tem, da so marsikje meritve temperatur v vrtinah starejše od 10, 20 ali celo 30 let, tako da lahko starejše meritve že doprinesejo k odstopanju od rezultatov po prvih treh načinih.

Globalno segrevanje v 20. stoletju je povzročilo dvig povprečnih temperatur zraka globalno za 1,0 °C do leta 2000, relativno na referenčno obdobje 1961-1990 (Bodri & Čermák, 2007; Internet 5). Poleg tega je potrebno dobro poznati mikrolokacijo vrtine (Signorelli & Kohl, 2004), tj. ali leži ustje vrtine na odprtem prostoru, ima sončno lego, je na pobočju, nagnjenem proti jugu (soncu) ali pa ima senčno lego, se nahaja na jasi sredi gozda, na pobočju, nagnjenem proti severu, ipd. Za tretji način je potrebno vedeti, da temelji na povprečju mesečnih temperatur tal v eni od sedmih različnih globin v obdobju 1971-2000, kar pomeni, da se v teh povprečjih ne odraža segrevanje podnebja v zadnjih 18 letih. Podobno velja tudi za prvi način, za katerega smo prav tako upoštevali obdobje 1971-2000. Edino v drugem načinu je za višinska gradienta upoštevano novejše obdobje 1981-2010. Vse to se je računsko odrazilo v razlikah.

Rezultate po vseh štirih načinih za izbranih pet lokacij lahko povzamemo v naslednji Tabeli 5, oceno ustreznosti izbranega načina izračuna pa v tabeli 6. Kriterija za najprimernejšo (referenčno) metodo pravzaprav ni. Najbolj smo uporabljali zanesljivost podatka, sicer pa sta verjetno prvi in drugi način bolj merodajna.

Za lokacijo 1) CŠOD, Cerkno sta očitno najbolj primerna prvi in drugi način. Rezultat po četrtem načinu je tudi v redu, vendar morda nanj nekoliko vpliva položaj vrtine (nekoliko izven naselja) s sicer kvalitetno izmerjenim temperaturnim profilom.

Za lokacijo 2) vrtec Morje, Lucija so najbolj primerni prvi, drugi in tretji način, medtem ko četrti način odstopa, ne glede na to, ali upoštevamo manj zanesljiv termogram iz bližje globoke vrtine ali bolj kvaliteten termogram iz vrtine pri Izoli, oba pokažeta skoraj enako vrednost. Bolj verjetno je, da T-z profil iz obeh vrtin še vedno odraža malo nižje temperature na površju iz preteklega obdobja.

Za lokacijo 3) Babno Polje sta se za najbolj primerna pokazala prvi in četrti način, drugi način pa manj, vendar je morda pogojen z nadmorsko višino kraja. Morda pa je drugi način boljši od prvega in četrtega, saj izhaja iz novejšega 30-letnega obdobja.

Tabela 4. Povprečja mesečnih temperatur tal v globini 5 cm v obdobju 1971-2000 za Portorož.
Table 4. The average monthly temperatures of the soil at a depth of 5 cm in the period 1971-2000 for Portorož.

	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Avg	Sep	Okt	Nov	Dec	Letno povprečje/ Annual average
T (°C)	4,1	4,4	8,8	13,5	19,7	23,6	26,1	26,1	20	14,8	9,4	5,3	14,7

Tabela 5. Rezultati izračunanih temperatur (°C) na površini trdnih tal za vseh pet lokacij po štirih načinih.
Table 5. Results of calculated temperatures (°C) on the surface of solid earth for all five locations in four calculation modes.

Način izračuna / Calculation mode	Lokacija / Site	Cerkno, CŠOD	Lucija, vrtec Morje	Babno Polje	Maribor-Tezno	Zgornji Brnik, Letališče
1. Temperatura zraka v temperaturo tal / Air temp. into Ground temp.		9,7	15,6	7,1	10,1	9,6
2. Višinski gradient / Height gradient		10,2	15,6	8,0	10,5	9,9
3. Meteo. postaja / Meteo station: 5 cm		-	15,7	-	10,0	9,5
4. T-z termogram / T-z profile		9,0	14,5	6,9	9,4	8,3

Za lokacijo 4) Maribor - Brezje sta najbolj primerna prvi in tretji način, morda tudi drugi način, medtem ko četrti način odstopa, verjetno zaradi mikrolokacije vrtine, ki je na robu Stražunskega gozda in to vpliva na malo nižjo temperaturo tal, kot odčitano iz interpolacije termograma.

Za lokacijo 5) Brnik – Letališče J. Pučnika Ljubljana so najbolj primerni prvi in drugi način ter tretji način, pri četrtem načinu je verjetno spet vzrok mikrolokacija vrtine, ki leži na večji jasi ob potoku blizu gozda. Rezultat po drugem načinu nekoliko odstopa od tistih po prvem in tretjem načinu, razlog je morda v bližini oziroma oddaljenosti agrometeoroloških postaj oziroma porazdelitvi postaj državne meteorološke mreže, in zato pride do manjšega neskladja. Podobno kot za lokacijo Babno Polje pa lahko razglabljamo, če ni drugi način celo boljši.

Glede izbire izračuna se lahko odločamo na več načinov. Na primer, načrtovalec se lahko odloči za bolj varen pristop in izbere najslabši rezultat, ali drugače, s temi načini lahko načrtovalec ugotovi, kakšna so možna odstopanja in ali je smiselno opraviti še podrobnejšo analizo (ugotavljanje osončenosti lokacije, mikroklimatskih razmer, ipd.).

Problematika ustreznega referenčnega obdobja in ustreznost termogramov

Pri dimenzioniranju zaprtih sistemov rabe plitve geotermalne energije je pomembno poznati temperature tal na lokacijah izvedbe. Za temperaturo tal je bilo do nedavno v Sloveniji razmeroma malo postaj (sedem za celinsko in le dve za primorsko Slovenijo; po novem (nekje od leta 2016) jih je 17, tj. za celinsko Slovenijo 13, za primorsko pa 4, od tega 2 v obalnem zmernem sredozemskem podnebju in 2 v zalednem zmernem podnebju) (Internet 6). Zaradi tega je dobro imeti enačbo za izračun temperature tal na podlagi nadmorske višine za poljubno lokacijo (2. način).

Iz tabele 7 sledi, da je termogramov vrtin razmeroma veliko glede na postaje z merjeno temperaturo zraka, še zlasti pa glede na postaje z merjenimi temperaturami tal. Dokaj dobro so razporejene tudi po nadmorskih višinah. Zaradi

Tabela 6. Ocena ustreznosti načina izračuna za vseh pet lokacij (iz Tab. 5).
Table 6. Assessment of the calculation modes for all five locations (from Tab. 5).

Način izračuna / Calculation mode	Cerkno, CŠOD	Lucija, vrtec Morje	Babno Polje	Maribor-Brezje	Zgornji Brnik, Letališče
1. Temp. zraka v temp. tal / Air temp. into Ground temp.	***	***	***	***	***
2. Višinski gradient/ Height gradient	***	***	** - nadmorska višina kraja/altitude of location	**	**
3. Meteo. postaja/ Meteo station: 5 cm	-	***	-	***	***
4. T-z termogram/ T-z profile	** - vpliv mikrolokacije vrtine/influence of borehole's microlocality	** - T-z profil iz preteklega desetletja/T-z profile from the past decade	***	** - vpliv mikrolokacije vrtine/influence of borehole's microlocality	** - vpliv mikrolokacije vrtine/influence of borehole's microlocality

Legenda za klasifikacijo / Legend for classification: *** bolj primeren / more appropriate; ** primeren / appropriate; * manj primeren/less appropriate tega smo preverili, kako lahko ocenimo temperaturo tal iz nadmorske višine za poljubno lokacijo z uporabo podatkov iz termogramov vrtin, kar je bil tudi glavni cilj tega članka.

Praviloma bi morale biti temperature tal enake kot temperature, ki jih izračunamo iz termogramov vrtin, razen če ne gre v vrtini za občutne vplive konvekcije zaradi pretakanja podzemne vode. Iz vseh termogramov iz naših meritev oziroma v našem arhivu (vseh skupaj je 458), smo izračunali temperaturo na površini tal, oziroma v globini 0 (nič) metrov. Izračune smo razvrstili v tri razrede A, B in C. Razred A so tisti termogrami, iz katerih se je dalo najbolj zanesljivo določiti temperaturo na površini. Na celinskem delu smo imeli tako 73 izračunanih temperatur na površini (globini 0 metrov), na primorskem delu pa 16.

Večina od uporabljenih 458 termogramov vrtin je bila izmerjena v obdobju 1971 – 2000, a imamo v primorskem delu, na primer, v sedmih vrtinah tudi termograme iz novejšega obdobja (po letu 2000). Zato smo za primerjavo izračunanih temperatur na površini (globini 0 m) s temperaturami iz meteoroloških postaj uporabili isto obdobje. Primerjavo smo naredili s srednjimi letnimi temperaturami zraka na 2 m (29 na celinskem delu in 4 na primorskem delu) in s temperaturami tal v globini 2 cm.

Pokazalo se je, da je sipanje vrednosti iz termogramov večje (celinski del R^2 = 0,67 in primorski R^2 = 0,76), kot srednjih letnih temperatur zraka (celinski del R^2 = 0,94, primorski R^2 = 0,92). Standardna deviacija za vrednosti iz termogramov za celinski del je 0,67 °C, za primorski del pa 0,49 °C. Vendar moramo upoštevati, da imamo z izborom samo tistih vrtin s termogrami A kvalitete dejansko izračunane površinske temperature, porazdeljene skoraj izključno na nadmorskih višinah med 140 in 500 m, zato je sipanje večje.

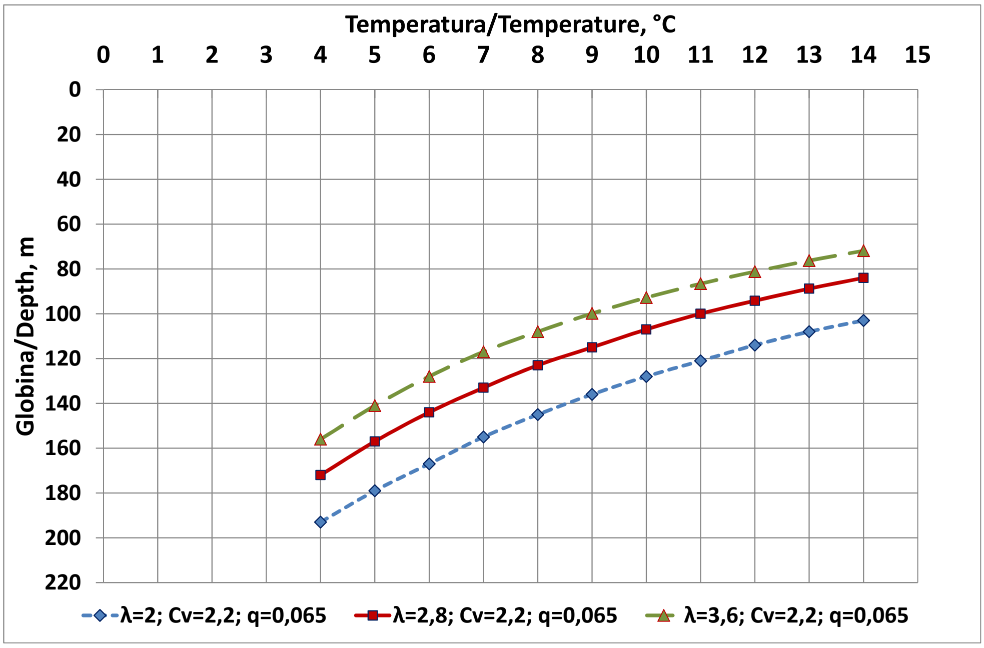
Slika 5 kaže kako pomembno je čim točnejše poznavanje povprečne letne temperature tal, saj ta precej vpliva na določitev potrebne globine vrtanja (za geosondo) pri različnih toplotnih prevodnostih zemljin in kamnin. Modeliranje za ugotavljanje potrebne globine geosonde je bilo izvedeno s programsko opremo Earth Energy Designer (EED), ki upošteva enačbe po Eskilsonu (1987).

Poglavitna razlika med samimi vrednostmi znotraj obeh nizov, tako med temperaturami iz termogramov in tudi med temperaturami zraka, se lahko pripiše pojemanju temperatur z nadmorsko višino (sl. 1 in 2). Iz primerjave regresijskih premic vrednosti iz termogramov in srednjih letnih temperatur za celinski del dobimo, da je razlika med temperaturo iz termogramov in temperaturo zraka 0,74 °C (±0,67 °C) na nadmorski višini 300 m. Za primorski del je razlika 1,01°C (±0,49 °C) na nadmorski višini 50 m. Neujemanje ni nenavadno, saj imajo na posamezne lokacije vrtin lahko vpliv lokalni mikropodnebni učinki. Harris in Chapman (1995) sta npr. ugotovila za Utah razliko do 4 °C med linearnima regresijskima premicama za temperature iz termogramov iz vrtin in za meteorološke povprečne temperature zraka. Na potek izmerjenih termogramov namreč lahko vplivajo razni procesi in lastnosti, ki vključujejo (1) spremembe v toplotni prevodnosti kamnin z globino, (2) radiogeno proizvodnjo toplote v kamninah (zanemarljiva za večino plitvih in srednje globokih vrtin), (3) učinke dvignjenosti ali spuščenosti površja na lokaciji in v njeni bližini, (4) bočne spremembe temperature tal zaradi orientiranosti površja in rastlinskega pokrova, (5) dviganje in erozijo ali pogrezanje in zasipavanje lokacije, in (6) navpični tok podzemne vode (Chisholm & Chapman, 1992; Harris & Chapman, 1995; Bodri & Čermák, 2007).

Tabela 7. Razpon nadmorskih višin meteoroloških postaj in vrtin s termogrami ter število enih in drugih v celinskem in primorskem delu Slovenije.

Table 7. Range of altitudes of meteorological stations and boreholes with thermograms and number of one and the other in the continental and coastal part of Slovenia.

Razpon nadmorskih višin meteoroloških postaj in vrtin s termogrami / število postaj, vrtin Range of altitudes of meteo stations and boreholes with T-z profiles / number of stations, boreholes	Celinski del / Continental part (m n.m.)	Primorski del / Coastal part (m n.m.)
Postaje s temperaturo tal na -2 cm / Stations with ground temperature at -2 cm	188 – 515 / 7	2 – 55 / 2
Postaje s temperaturo zraka na 2 m / Stations with air temperature at 2 m	157 – 2.514 / 29	2 – 320 / 4
Vrtine s termogrami vrtin / Boreholes with T-z profiles	144 – 808 / 73	22 – 241 / 16



Sl. 5. Vpliv povprečne letne temperature tal (T_0) na potrebno globino vrtine pri različnih toplotnih prevodnostih (λ) kamnin in zemljin in gostoti toplotnega toka (q) 0,065 W/m^2 in volumski kapaciteti toplote (Cv) 2,2 MJ/(m^{3}K).

Fig. 5. The influence of the annual average ground temperature (T_0) on the required drilling depth for different thermal conductivities (λ) of rock and soil and for the heat-flow density (q) of 0.065 W/m^2 and the volume heat capacity (Cv) of 2.2 MJ/(m^{3}K).

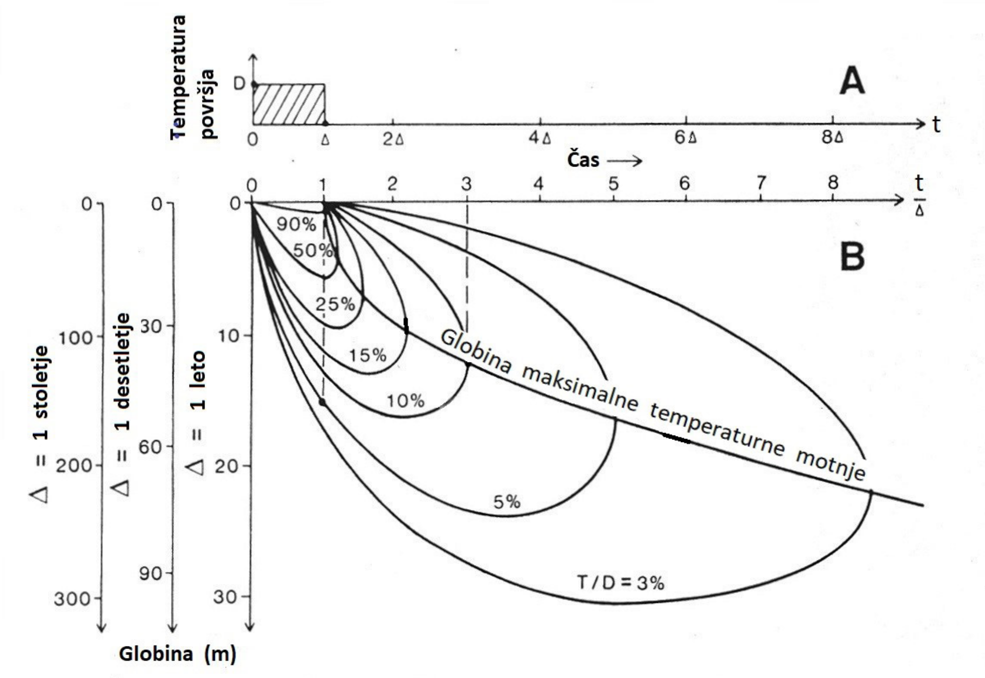
Regresijska premica srednjih letnih temperatur tal iz meteoroloških postaj je na celinskem delu višja za 0,47 °C od premice iz termogramov. Skupna razlika med temperaturo zraka in temperaturo tal tako znaša (0,74 + 0,47) 1,21 °C za celinski del.

Na primorskem delu sta samo dve postaji z meritvami temperature tal, od katerih je na Bilju temperatura višja za približno 0,25 °C, v Portorožu pa za približno 1,4 °C od premice iz termogramov. Zaradi tega teh podatkov ni možno uporabiti za enakovredno primerjavo.

Od obdobja 1971-2000 do obdobja 1981-2010 se je srednja letna temperatura zraka na celinskem delu povečala v povprečju vseh postaj za 0,3 °C. Na primorskem delu je to povečanje srednje letne temperature 0,6 °C. Predvidevamo, da bi se za enako razliko povečala vrednost iz termogramov, če bi bili merjeni v obdobju 1981-2010. Če bi temperaturo tal ocenjevali iz regresijskih premic iz termogramov, bi morali tudi tem vrednostim prišteti povečanje povprečnih temperatur glede na obdobje 1971-2000. Brez tega popravka smo zato dobili pri vseh petih lokacijah po načinu izračuna iz termograma najnižje vrednosti (tabela 5). Vendar je tu kritičen še drug razlog. Zelo malo je bilo vrtin, v katerih je bila temperatura izmerjena postopoma, s korakom 5 m ali gosteje praktično od samega površja. Tovrstne meritve se namreč izvajajo v vodnem stolpcu vrtine, gladina vode pa se je v večini vrtin nahajala globlje od 5 m, velikokrat tudi globlje od 10 m. Zaradi tega v večini vrtin manjka temperaturni zapis v zgornjih 10 do 20 m, in je pravilna ekstrapolacija T-z profila iz globljega odseka tega profila proti površju lahko nekoliko subjektivna. V vseh primerih, kjer imamo iz vrtine normalen potek termograma, smo večinoma povlekli ekstrapolacijo proti površini ne iz najplitvejšega globinskega odseka med 0 in 20 m, ampak iz odseka med 20 in 40 (morda 50) m, ali celo med 20 (tudi 30) m in 100 m globine. To pa ima vpliv na to, da je s tem zajet tak potek T-z profila, ki ima (nosi) v sebi še spomin običajno malo nižjih temperatur na površju v preteklosti.

V nadaljnji raziskavi bi bilo morda smiselno še malo bolj dosledno izločiti neobičajne (»slabe«) T-z profile in obdržati res le dobre T-z profile, čeprav smo dejansko pregledali samo tiste profile A kategorije.

Pojasniti želimo tudi, da Zemljino plitvo in tudi globlje podzemlje hrani »toplotni spomin« o dogodkih na njenem površju še dolgo po njihovem zaključku. Izmerjene temperature v vrtini so odziv na visoko frekvenčne spremembe temperature zraka na površju, ki so bile filtrirane in oslabljene v Zemlji s procesom toplotne difuzije (Lachenbruch & Marshall, 1986; Bodri & Čermák, 2007; Harris & Chapman, 1995). Poglejmo primer enovite temperaturne anomalije v trajanju Δ na površju, ki se razširja v podzemlje, kjer s časom pojenjuje (Lachenbruch & Marshall, 1986). Moč temperaturne anomalije T v globinsko-časovnem polju se lahko izrazi kot odstotek anomalne površinske temperature D. Lachenbruch in Marshall (1986) sta podala tri globinske lestvice (v metrih) za dogodke, ki trajajo 1 leto, 1 desetletje in 1 stoletje, za predvideno toplotno difuzivnost kamnin in zemljin $\alpha=10^{-6}$ m^2/s (sl. 6).



Sl. 6. Termični spomin Zemlje za dogodke na njeni površini. Enovita temperaturna anomalija v trajanju Δ na površini (A) se širi navzdol in izginja (B). Krivulje kažejo jakost temperaturne anomalije T v globinsko - časovnem polju, izražene kot odstotek anomalne površinske temperature D.

Fig. 6. The thermal memory of the Earth for events on its surface. A uniform temperature anomaly of duration Δ at the surface (A) propagates downward and fades away (B). Curves show strength of the temperature anomaly T in the depth-time field expressed as a percentage of anomalous surface temperature D.

Kasneje po zaključku dogodka (n.pr. pri t = 3 Δ), ko maksimalni signal pade na 10 %, se kot tak pojavi pri približno 11 m globine za Δ = 1 leto in pri 110 m za Δ = 1 stoletje. Ob zaključku enotne motnje v trajanju Δ anomalija ni več opazna (njena moč je <5 %) globlje od 50 m za Δ = 1 desetletje in globlje od 150 m za Δ = 1 stoletje. Podajamo še en primer: nenadna sprememba temperature zraka v iznosu 0,5 °C, ki se je dogodila na površju pred 10 do 12 leti in je relativno dalj časa stalna, se odraža kot temperaturna motnja v izmerjenem termogramu (T-z profilu) z velikostjo do ca 0,4 °C še vedno le v zgornjem globinskem odseku do globine 50 do 60 m pod površjem. Ravno zaradi tega so raziskave povezanosti temperatur zraka in plitvega podzemlja (Harris & Chapman, 1995; Bodri & Čermák, 2007; Rajver et al., 2006; Strgar et al., 2017) pomembne z vidika ugotavljanja, kako hitro se temperaturno polje v plitvem podzemlju odziva na spremembe temperature na površju in kakšna je lastnost (značaj) preteklega podnebja, predvsem tistega pred instrumentalnimi zapisi, katerega se lahko pridobi (povrne) z matematično inverzijo iz T-z profilov v vrtinah. V Sloveniji prav tako ugotavljamo naraščanje temperature tal z našimi opazovanji (Strgar et al., 2017)

Zaključki

V članku smo opisali metodologijo določanja temperature na površini trdnih tal s štirimi načini izračuna. Prvi način, ko imamo podatek o srednji letni temperaturi zraka, je uporaben, ker je meteoroloških postaj relativno veliko in so v Sloveniji dokaj enakomerno porazdeljene (spletna stran pa sama izbere najbližjo naši lokaciji). Drugi način, ko imamo samo podatek o nadmorski višini kraja, je uporaben v predelih, kjer ni potrebnih podatkov za prvi, tretji in četrti način. Tretji način, ko imamo v bližini merilno postajo temperature tal, je uporaben le v primeru, če so v bližini primerne meteorološke postaje, kjer so merili temperaturo tal, takih postaj pa je le sedem v Sloveniji. Četrti način, ko imamo v bližini vrtino z izmerjenim termogramom, je uporaben zato, ker izhaja iz ekstrapolacije nemotenih podpovršinskih formacijskih temperatur proti površju. Uporabili smo 458 termogramov vrtin, med njimi je bila večina izmerjena v obdobju 1971 – 2000, le manjši del pa tudi v desetletju kasneje. Od teh smo izbrali 89 termogramov A kategorije, ki najbolj zadostijo pogojem uporabe.

Enačbi višinskih gradientov za celinsko in primorsko Slovenijo smo uporabili za izračun povprečne letne temperature zraka na 2 m nad tlemi za lokacijo vsake vrtine, iz katere smo uporabili termogram. Na podlagi izračunov za zadnje referenčno obdobje 1971–2000 smo dobili grafe odvisnosti temperatur iz termogramov vrtin, temperatur tal v globini 2 cm ter zraka na višini 2 m od nadmorske višine za primorsko in celinsko Slovenijo.

Iz prikazov podatkov in regresijskih premic vidimo, da je temperatura tal iz meteoroloških postaj v povprečju višja od temperature, izračunane iz termogramov vrtin. Dobro je ocenjena z uporabo regresijskih premic za celinski del. Za primorski del taka ocena ni izvedljiva, ker sta za primerljivo obdobje obstajali samo dve postaji z meritvami temperature tal. Sipanje izračunanih površinskih temperatur iz termogramov glede na nadmorsko višino je večje kot pri meteoroloških postajah.

Dobljeni regresijski premici (sl. 1 in 2) za izračunane površinske temperature iz termogramov se dokaj ujemata po nagibu s premicama za temperature zraka in tal iz meteoroloških postaj, razen v primeru temperature tal na primorskem delu, kjer taka primerjava ni bila možna zaradi samo dveh razpoložljivih postaj.

Če regresijski premici izračunanih površinskih temperatur iz termogramov prištejemo standardno deviacijo, se zelo dobro približamo temperaturi tal izmerjeni na meteoroloških postajah.

Termogramov je razmeroma veliko v primerjavi z meteorološkimi postajami, zlasti pa neprimerno več kot pa postaj z meritvami temperature tal. Menimo, da smo smiselno izkoristili poglavitne prednosti termogramov, pa tudi njihova razpršenost po državi je zadovoljivo dobra. Za bolj primerljivo oceno temperatur tal iz termogramov s temperaturami iz meteoroloških postaj bi morali imeti na voljo več termogramov iz novejšega obdobja 1981-2010, saj bi s tem izločili vpliv hladnejšega podnebja iz desetletje starejšega obdobja 1971-2000.

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Pogledi na posledice ekstremnega vremenskega dogodka v Naravnem spomeniku Dovžanova soteska

Aspects of the consequences of the extreme weather event in the Dovžan Gorge Natural Monument

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Key words: extreme weather event, geohazard, relief changes, natural monuments, Dovžan Gorge, Slovenia

Izvleček

Vsa zavarovana območja naravnih vrednot, v katerih živi človek, se soočajo s problemom vzdrževanja ravnovesja med ohranjanjem naravnega okolja in človekovimi posegi vanj zaradi njegovih gospodarskih dejavnosti in njegove varnosti. Ekstremni vremenski dogodek je v noči z 29. na 30. oktober 2018 povzročil velike spremembe v porečju Tržiške Bistrice, ki so najbolj očitne v Naravnem spomeniku Dovžanova soteska. Dogodek je osvetlil več vidikov te problematike. Pri analizi tega vremenskega dogodka, sprememb površja iz fotodokumentacije ter zgodovinskega arhiva se je Naravni spomenik Dovžanova soteska pokazal kot odličen poligon za proučevanje naravnih procesov in antropogenih vplivov ter človekovega dojemanja naravnih nesreč in zgodovinskega spomina nanje.

Abstract

All protected areas of natural values which are populated are faced with the problem of maintaining a balance between preserving the natural environment and human interventions in it for its economic activities and its security. The extreme weather event in the night from 29th to 30th October 2018 caused major changes in the Tržiška Bistrica river basin, which are most evident in the Dovžan Gorge Natural Monument. The event highlighted several aspects of this issue. Through the analysis of this weather event, changes in the surface from photo documentation and historical archives, the Dovžan Gorge Natural Monument has proven to be an excellent polygon for the study of natural processes, anthropogenic influences and the human perception of natural disasters and historical memory of them.

Uvod

Dovžanova soteska je zaradi izjemnih geoloških in geomorfoloških razmer od leta 1988 zavarovana kot naravni spomenik. Je eno tistih ožjih zavarovanih območij Slovenije, ki so poseljena, skozenj pa vodi tudi prometna povezava med naseljem Tržič in njegovim hribovitim zaledjem z obsežnimi, gospodarsko pomembnimi gozdnimi površinami. Zaradi geološke zgradbe in topografije površja v obliki strmih pobočij in hudourniškega toka Tržiške Bistrice je območje podvrženo hitrim in velikim naravnim spremembam, ki so še posebej intenzivne ob ekstremnih vremenskih dogodkih, ko povzročajo gmotno škodo. Nenehno pa predstavljajo nevarnost za ljudi in infrastrukturo.

Analiza vremenske ujme, ki je v noči z 29. na 30. oktober 2018 prizadela območje porečja Tržiške Bistrice, je strokovno zanimiva kot ekstremni vremenski dogodek in še bolj zato, ker je ponovno pokazala na nepremišljeno rabo naravnih virov, predvsem gozda in problem neurejenih hudournikov. Obenem pa je potrdila rezultate mnogih prejšnjih raziskav o človekovem dojemanju in zgodovinskem spominu naravnih nesreč. Z več strani je osvetlila problematiko vzdrževanja ravnovesja med ohranjanjem naravnega okolja v zavarovanih naravnih spomenikih in človekovimi posegi vanje zaradi njegovih ekonomskih dejavnosti in njegove varnosti (Novak & Mrak, 2019).

Reka Tržiška Bistrica ima hudourniški značaj, kljub temu pa običajno ne povzroča večje gmotne škode, saj je njena poplavna ravnica skoraj neposeljena. Tržiška Bistrica težave povzroča prebivalcem naselij Jelendol, Dolina, Čadovlje pri Tržiču in Tržič, kjer je tudi lanska oktobrska ujma povzročila največ gmotne škode. Prav to območje je za analizo posledic ekstremnih vremenskih dogodkov in vzrokov zanje zelo zanimivo iz več spodaj naštetih razlogov, ki so tako naravni kot antropogeni:

- raznovrstna litološka zgradba in (posledično) oblika površja, ki na tem območju pogojujeta različne erozijske procese in pobočne masne premike;
- dobra fotodokumentacija (najlepši motivi v Dovžanovi soteski so zelo pogosto fotografirani, kar omogoča zelo dobro analizo sprememb struge Tržiške Bistrice po ekstremnih vremenskih dogodkih);
- porečje Tržiške Bistrice je že stoletja podvrženo izkoriščanju gozda, prav tako so v zadnjih dveh stoletjih ekstremni vremenski dogodki na tem območju razmeroma dobro dokumentirani;
- območje je zaradi izjemnih geološko-geomorfoloških razmer zavarovano kot naravni spomenik, ki pa je stalno podvržen človekovim posegom tudi v zaledju.

Vsi Zaradi vsega naštetega je območje med Jelendolom in Čadovljami, posebej pa Dovžanova soteska, zelo dober študijski in učni poligon za proučevanje odnosa med naravnim okoljem in človekovimi prilagoditvami ter kljubovanja takemu, za poselitev marsikje neprimernemu okolju.

Metode

Predstavljena študija je rezultat podrobne analize ekstremnega vremenskega dogodka v porečju Tržiške Bistrice v noči med 29. in 30. oktobrom 2018 ter ogleda posledic in analize vzrokov zanje. Pri analizi vremenskih podatkov sta bili uporabljeni poročili Urada za meteorologijo in hidrologijo Agencije Republike Slovenije za okolje (v nadaljevanju ARSO) o tem dogodku. Prvo poročilo obravnava obilne padavine in močan veter (ARSO, 2018a), drugo pa visoke vode in poplave (ARSO, 2018b). Iz obeh poročil in drugih javnih podatkov ARSO (ARSO, 2018c) so bili v detajlni analizi zajeti podatki za območje med naselji Jelendol in Čadovlje pri Tržiču (Novak & Mrak, 2019). V tem članku so povzeti ključni podatki te analize.

Za analizo poškodb so bile uporabljene fotografije članov Gorske reševalne službe Tržič, posnete takoj zjutraj po dogodku in podatki, pridobljeni pri ogledu terena 13. 11. 2018. Pri proučevanju sprememb površja je bila uporabljena arhivska fotodokumentacija Tržiškega muzeja, pregledana baze ortofoto posnetkov, elaborata o izdelavi Kart erozijske in poplavne nevarnosti, plazljivosti in nevarnosti snežnih plazov za območje občine Tržič (Natek et al., 2010) in Katastra zemeljskih plazov, hudournikov in snežnih plazov v občini Tržič (Mrak et al., 2012) ter lastna fotodokumentacija od leta 2000.

Za analizo vzrokov takih posledic so bili uporabljeni podatki dolgoletnih lastnih opazovanj, geološka karta Dovžanove soteske (Novak, 2007) in arhivska poročila o plazovih ter skalnih podorih na širšem območju Tržiča.

Za analizo zgodovinskih ekstremnih dogodkov na območju porečja Tržiške Bistrice, dojemanja naravnih nesreč in varovanja pred njimi so bili uporabljeni zgodovinski viri iz arhiva Tržiškega muzeja in iz monografij o življenju na tem območju.

Rezultati

Ekstremni vremenski dogodek oktobra 2018

Povišana vodostaj in pretok Tržiške Bistrice sta ob močnih padavinah v jesenskem obdobju pogosta pojava, ki običajno povzročata spremembe struge reke, redko pa gmotno škodo. Po ujmi v noči z 29. na 30. oktober 2018 se je postavilo vprašanje, v čem je bil ta dogodek poseben, da je povzročil škodo z razsežnostjo, kakršno opisujejo le še nekateri zgodovinski zapisi.

ARSO je v sistemu Meteoalarm za ponedeljek, 29. 10. popoldan in ponoči izdal vremenska opozorila najvišje (rdeče) stopnje za močne nalive, veter in dež za območje celotne zahodne Slovenije (ARSO, 2018a). Geološki zavod Slovenije pa je v sistemu Masprem izdal opozorilo za povečano verjetnost pojavljanja plazov (Geološki zavod Slovenije, ekipa MASPREM, 29.10.2018).

Padavinski podatki

Najbližja padavinska postaja za obravnavano območje stoji prav v Jelendolu (763 m) (sl. 1). Meritve te samodejne merilne postaje kažejo tri zelo

Sl. 1. Osrednji del porečja Tržiške Bistrice z mestoma padavinske postaje Jelendol (zgoraj) in vodomerne postaje Preska v Bistrici pri Tržiču (spodaj) (po podatkih ARSO; podlaga: Geopedija).

Fig. 1. The central part of the Tržiška Bistrica river basin with locations of the Jelendol weather station (above) and the water gauging station Preska in Bistrica pri Tržiču (below) (according to the ARSO; base map: Geopedija).

močne nalive. V prvih dveh med 19.30 in 21.00 je skupaj v dveh urah padlo 54 mm dežja, v tretjem med 23. in 24. uro, pa je v eni uri padlo 35,7 mm dežja. V tem času je skupaj v samo petih urah padlo kar 103,4 mm dežja (ARSO, 2018c). Ugotovimo lahko, da je bil prav ta, zelo kratek interval močnega naliva prvi vzrok za izstopajoči ekstremni dogodek.

Količina 122 mm padavin v 24 urah, kolikor je izmerila samodejna postaja v Jelendolu, je glede na dolgoletni niz meritev ena od najvišjih, ni pa rekordna vrednost. Od leta 1961 je bilo tam največ padavin izmerjenih 18. septembra 2007 – 161,7 mm, 22. avgusta 1969 – 152 mm in 5. septembra 2009 – 137,8 mm (Vertačnik, 2008; ARSO, 2018a).

Izračunane povratne dobe za ekstremne nalive v obdobju 1977–2012 za sicer višje ležeči območji Javorniški Rovt (940 m) in Zgornje Jezersko (875 m) pokažejo, da se nalivi s 122 mm v 24 urah pojavljajo pogosteje od vsakih 5 let, nalivi s 103,4 mm v petih urah pa s povratno dobo 100 let (ARSO, 2018c). Zgovoren je tudi podatek, da se je kar pet ekstremnih nalivov (2003, 2007, 2009, 2010 in zadnji 2018), ki se uvrščajo med tiste s povratno dobo 50 ali 100 let, zgodilo v zadnjih 16 letih.

Hidrološki podatki

Še bolj kot padavinski podatki so za primerjavo obravnavanega dogodka s preteklimi ekstremnimi padavinskimi dogodki relevantni podatki o pretoku in vodostaju Tržiške Bistrice. Največ škode je reka z njenimi hudourniškimi pritoki naredila ob strugi z močno erozijo ter nanašanjem velikih količin grušča/proda in drugega plavja s strmih pobočij v dolino.

Tržiška Bistrica ima od izvira do sotočja v Medvodju, kjer vanjo pritekata potoka Stegovnik in Košutnik, velik strmec, saj se spusti za več kot 750 m, od tu naprej se ji strmec precej zmanjša in teče po nekoliko širši dolini skozi naselje Jelendol, skoraj ves čas po triasnih dolomitih in lastnih prodnih nanosih. S strmih pobočij se vanjo stekajo številne kratke in strme grape, ki so ob izstopu v glavno dolino nasule manjše vršaje, ter z desne dva večja pritoka: Zali potok in Dolžanka. V naselju Dolina je struga vse strmejša, nato pa se zoži v ozko Dovžanovo soteško. Na tem odseku reka prečka dober kilometer širok pas zgornjepaleozojskih kamnin (kremenov peščenjak, kremenov konglomerat, plastnati apnenec, trbiška breča), ima zelo velik strmec in se v manjših slapovih preliva prek velikih podornih skalnih blokov kremenovega konglomerata pod Borovo pečjo. Pod Dovžanovo sotesko se dolina razširi v srednjepermskih rdečih klastičnih kamninah (meljevcu, peščenjaku in konglomeratu) in po ozki naplavni ravnici do Čadovelj se tok nekoliko umiri (Mrak, 2003; Novak, 2007).

Pretok zgornjega toka Tržiške Bistrice je do leta 1966 merila vodomerna postaja v Jelendolu, od takrat deluje samo še vodomerna postaja Preska v Bistrici pri Tržiču, ki pa meri tudi podatke za oba večja pritoka Tržiške Bistrice, Lomščico in Mošenik (sl. 1).

Meritve pretoka Tržiške Bistrice med 29. in 31. oktobrom kažejo, da je bila najnižja (rumena) opozorilna vrednost pretoka (60 m^3/s) presežena 29. 10. ob 22.30 uri. Med 23. in 24. uro je pretok presegel še oranžno (90 m^3/s) in rdečo (120 m^3/s) stopnjo opozorilnih vrednosti in 30. 10. ob 00.35 uri dosegel maksimalno vrednost 195.35 m^3/s, kar je vrednost, višja od še ene višine opozorilne stopnje (sl. 2). Okrog 1 ure zjutraj, 30. 10., se je v Tržiču zato sprožil alarm. Vrednosti pretoka in vodostaja sta se potem do 2.30 znižali pod rdečo opozorilno vrednost in do jutra postopoma upadali. Najvišja izmerjena vrednost vodostaja je bila 316 cm, dosežena 30. 10. ob 00.35 (ARSO, 2018c).

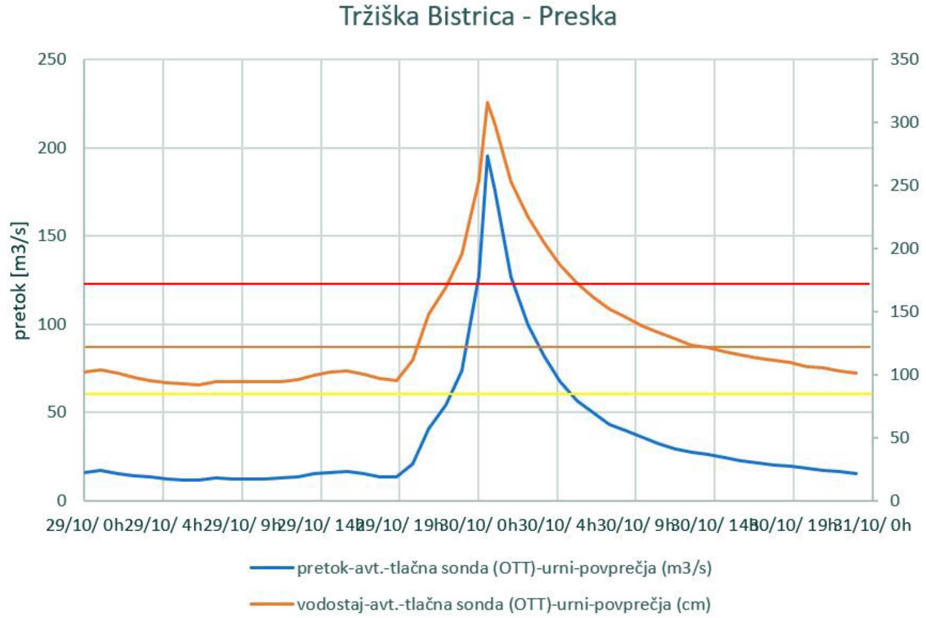
Primerjava hidroloških podatkov s padavinskimi pokaže, da so viški vodostaja in pretoka zelo hitro (s pribl. 1,5 urnim zamikom) sledili viškom padavin med nalivi. Zaradi ozkega zgornjega dela porečja in velikih strmin pobočij je odziv rečnega pretoka na močnejše padavine izjemno hiter, o čemer priča tudi zelo velik specifični odtok (39,3 $l/s/km^2$) in tudi visok odtočni količnik Tržiške Bistrice (63,5 %)(Frantar, 2008). Na hudourniški značaj Tržiške Bistrice poleg tega kažejo tudi velike razlike med največjimi in najmanjšimi ter povprečnimi pretoki. Na vodomerni postaji v Preski so v obdobju 1958–2016 izmerili najmanjše pretoke ob hudi suši poleti 1993 (14. 7.: 0,731 m^3/s), največje pretoke pa ob poplavah 18. 9. 2007 (155 m^3/s), 28. 8. 1986 (133 m^3/s) in 1. 11. 2003 (115 m^3/s). Povprečni pretok je 5,06 m^3/s (vir: ARSO, 2018b).

Na podlagi teh podatkov lahko ugotovimo, da sta bila tako najvišji izmerjeni vodostaj v obravnavanem dogodku (316 cm) kot največji izmerjeni pretok (195,35 m^3/s), rekordna (Novak & Mrak, 2019).

Posledice dogodka

Ekstremni padavinski dogodek in posledično silovit porast vodostaja Tržiške Bistrice s pritoki je povzročil predvsem velike spremembe v strugi in na poplavni ravnici ter škodo na infrastrukturi. Stranski pritoki so nanašali velike količine grušča, proda in lesnega plavja v dolino, kar je povzročilo prestopanje in spreminjanje struge Tržiške Bistrice.

Naselje Jelendol je z velikimi količinami grušča in proda zasipal stranski hudourniški pritok Dolžanke. Škodo na bivalnih objektih ter kmetijskih in gozdnih površinah je utrpelo 32 gospodinjstev in privatna ribogojnica. Največ škode je bilo na infrastrukturi (asfaltna in gozdne ceste, mostovi, zidovi, ograje, kanalizacija) in na vodotokih (jezovi, pregrade, obrežja), 187 vaščanov pa je bilo nekaj časa odrezanih od sveta (Občina Tržič, popis škode; Porenta, 2019). Pobočnih masnih premikov je bilo ob tem dogodku malo. Sprožila sta se dva



Sl. 2. Pretok in vodostaj Tržiške Bistrice v Preski med 29. in 31. 10. 2018 z opozorilnimi vrednostmi pretoka (vir: ARSO, 2018c).

Fig. 2. Tržiška Bistrica river flow and water level at Preska between 29 and 31 October 2018 with warning values of water level (source: ARSO, 2018c).

manjša preperinska plazova. Ocena nastale škode presega 15 milijonov evrov, odprava posledic bo terjala večletno sanacijo (Porenta, 2019).

V Dovžanovi soteski je izredno močan tok Tržiške Bistrice spodjedal brežine, kar je povzročilo uničenje oz. poškodbe treh mostov, usade asfaltne ceste na petih mestih in poškodbe sprehajalnih poti (sl. 3). Posledice ujme niso samo tiste, ki so nastale v času ujme, ampak ima slednja tudi dolgotrajnejši vpliv. Primer je velik skalni blok v brežini Tržiške Bistrice pred cestnim predorom, ki se je v prvem tednu maja 2019 na erozijsko načeti podlagi spodmaknil in poškodoval cestišče (Porenta, 2019).

Zgodovinske vremenske ujme so na tem območju predvsem zaradi gospodarske dejavnosti veleposestnika, barona Carla Borna, zelo dobro dokumentirane. Zanimivo je primerjati opis posledic lanskoletnega dogodka z zgodovinskimi zapisi, ki so si vsi med seboj zelo podobni. Knific (2016) po-

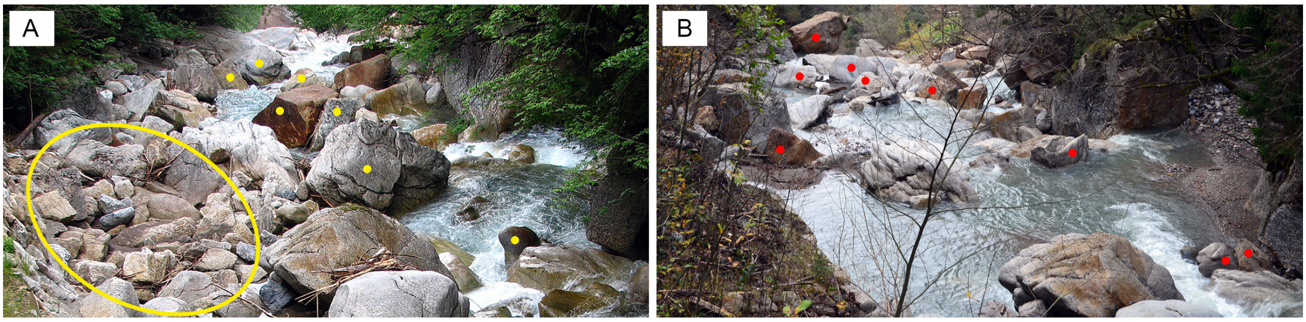
Sl. 3. Posledice ujme v Dovžanovi soteski: A) poplavljena ravnica v Čadovljah; B) erodiran desni breg Tržiške Bistrice in poškodbe sprehajalne poti pri Čadovljah; C) erodiran desni breg in podrt most pred vhodom v Dovžanovo sotesko; D) udori ceste na erodirani brežini; E) kamninski drobir s Kušpegarjevega plazu; F) lesno plavje na cesti v Dolini (D, E: foto Primož Štamcar, GRS Tržič).

Fig. 3. The consequences of the extreme weather event in Dovžan Gorge: A) a flooded plain in Čadovlje; B) eroded right bank of Tržiška Bistrica and damaged walking path near Čadovlje; C) eroded right bank and damaged bridge in front of the entrance to the Dovžan Gorge; D) Damages on the road on the eroded bank; E) rock debris from the Kušpegar landslide; F) floating wood on the road in Dolina (D, E: photo Primož Štamcar, GRS Tržič).

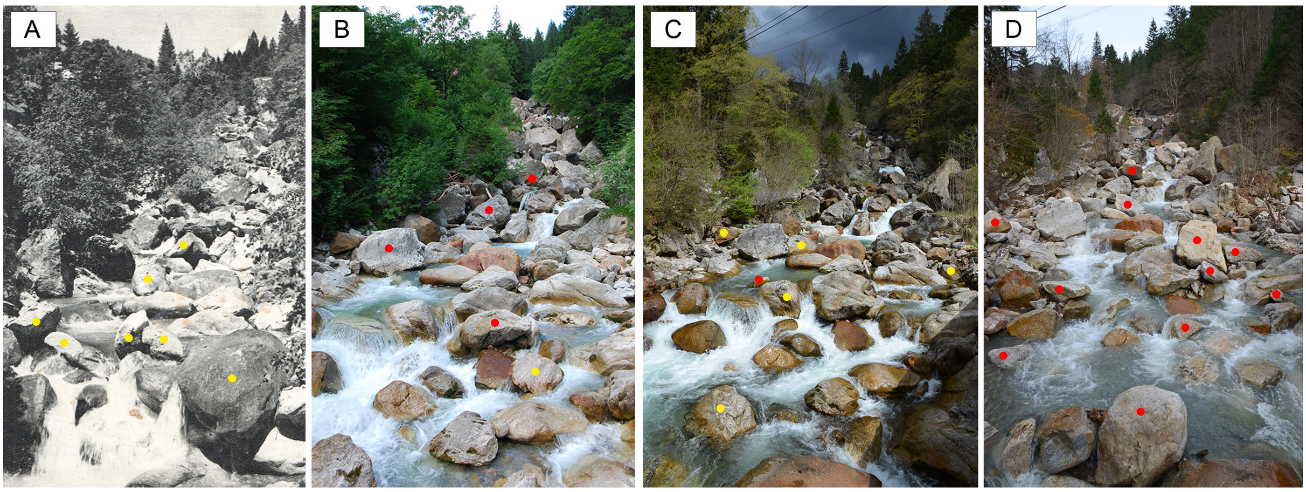
roča, da so bile močnejše povodnji leta 1907, 1922, 1934, 1938, 1940, vse v jesenskih mesecih. V nadaljevnju je odlomek iz opisa najhujše med njimi v časopisu Amerikanski Slovenec, 22. novembra 1938: »*Nenavadno hitro je postala struga Tržiški Bistrici pretesna. Po nočnem nalivu je pričela že zjutraj svoje pogubno delo, ki ga nadaljuje od ure do ure. Cesta v Puterhof* (op.: danes Jelendol) *je na mnogih mestih v velikih dolžinah dobesedno odrezana. Mostove in jezove je voda gladko odnesla. Po vodi se valijo velike množine lesa. Največje je razdejanje v Puterhofu, kjer se ob žagah barona Borna nabirajo ogromne množine hlodov, tramov in desk. Vsa ta zaloga lesa uničuje ceste in naprave. Voda si je marsikje izbrala popolnoma novo strugo. Veliko škodo bo trpel Born, pa tudi številni delavci in vozniki, ki ne bodo našli prej zaslužka, dokler ne bodo naprave in ceste zopet urejene. Bistrica odnaša tudi mostove, ki vodijo do raztresenih kmečkih domov v Dolini, in uničuje jezove kmečkih žag...*« (*Amerikanski Slovenec* 1938, št. 241) (iz: Knific, 2016).

Spremembe rečne struge

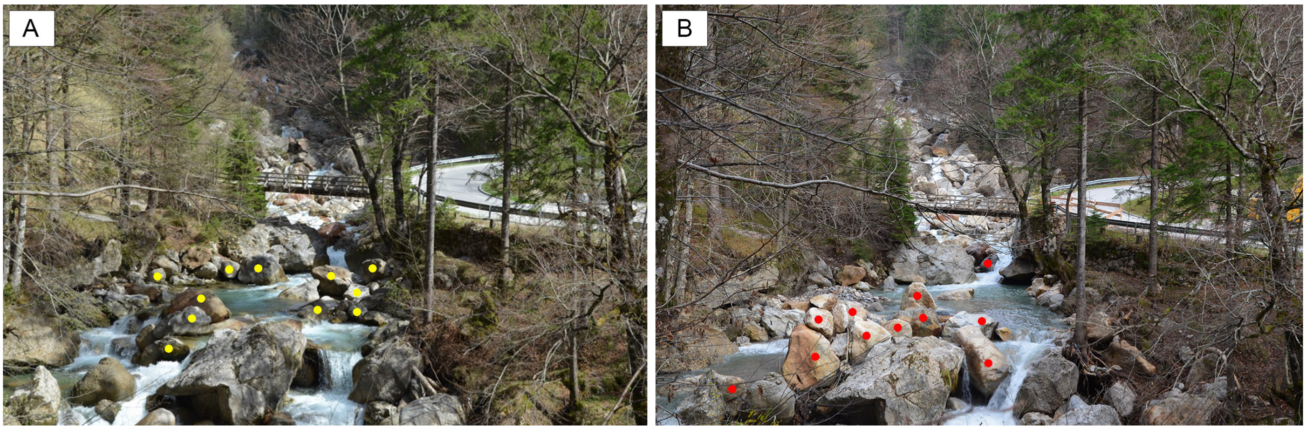
Za spremljanje sprememb okolja po izrednih vremenskih dogodkih je območje Dovžanove soteske še posebej zanimivo, saj ni veliko območij, ki bi bila tako redno foto-dokumentirana. V Dovžanovi soteski so najlepši motivi, npr. slapišče in najožji del ob cestnem predoru, zelo pogosto fotografirani tako rekoč z istih stojišč. To omogoča natančno analizo sprememb struge Tržiške Bistrice, predvsem premike velikih blokov kremenovega konglomerata na območju slapišča pod zaselkom Na Jamah in dolvodno v strugi Tržiške Bistrice proti naselju Čadovlje pri Tržiču. Pri prostorninski masi kremenovega konglomerata okrog 2700 kg/m^3 največji bloki presegajo težo 3 ton, težo povprečno velikih blokov pa lahko ocenimo na 2 toni. Na zaporednih fotografijah so označene spremembe v različnih delih struge v Dovžanovi soteski od zgoraj navzdol. Z rumeno barvo so označeni skalni bloki, ki jih na naslednjem posnetku ni več, z rdečo pa tisti, ki jih na prejšnjem posnetku še ni bilo oz. so bili v zelo drugačni legi (sl. 4–8).



Sl. 4. Struga Tržiške Bistrice nad slapiščem. A) maj 2012; B) november 2018.
Fig. 4. Tržiška Bistrica riverbed above the waterfall. A) May 2012; B) November 2018.



Sl. 5. Slapišče z mostu. A) okrog leta 1910 (iz arhiva Tržiškega muzeja); B) julij 2009; C) april 2016; D) november 2018.
Fig. 5. Cascading waterfall from the bridge. A) around 1910 (from the archives of the Tržič Museum); B) July 2009; C) April 2016; D) November 2018.



Sl. 6. Struga Tržiške Bistrice pod slapiščem. A) april 2014; B) november 2018.

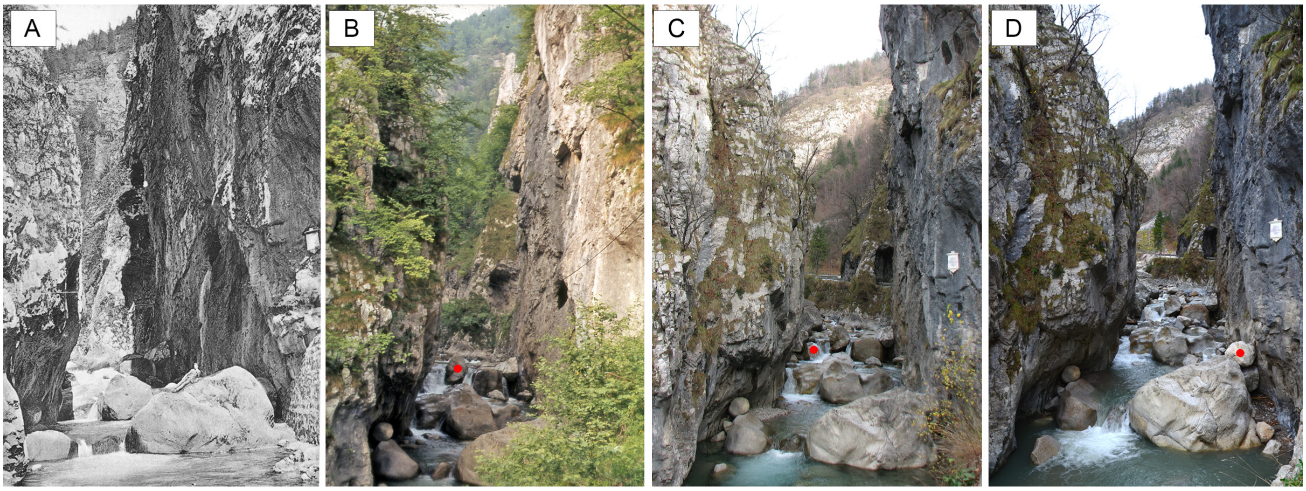
Fig. 6. Tržiška Bistrica riverbed below the waterfall. A) April 2014; B) November 2018.

Sl. 7. Struga med cestnim predorom in malim predorom na desni strani struge (A in B – pogled s severa; C in D – pogled z juga). A) april 2014; B) november 2018; C) oktober 2008; D) november 2018.

Fig. 7. Riverbed between the road tunnel and the small tunnel on the right side of the riverbed (A and B – north view, C and D – view from the south). A) April 2014; B) November 2018; C) October 2008; D) November 2018.

Iz slik je razvidno, da je lanskoletni dogodek v večjem delu struge povzročil velike spremembe. Struga je predvsem nad slapiščem in med predoroma zelo spremenjena, medtem ko je najožji del soteske ostaja nespremenjen. Največje spremembe so tam, kjer je energija rečnega toka najmanjša, torej tam, kjer je struga najširša in/ali ima najmanjši strmec. V delih z najvišjo energijo toka (velik strmec in/ali ozka struga) reka sediment hitro odnese in sproti prazni rečno korito.

Metoda primerjave ortofoto posnetkov različnih datumov za spremljanje sprememb drugih delov površja, predvsem pobočij, ima v Dovžanovi soteski zelo omejeno uporabno vrednost. Razlog je v močni poraščenosti pobočij z gozdom in zelo redkih posnetkih v zimskih obdobjih. Na teh se pokažejo samo manjše spremembe v grapah hudourniških pritokov.



Sl. 8. Najožji del soteske. A) leta 1918; B) april 1982 (foto Stanko Buser); C) november 2008; D) november 2018.

Fig. 8. The narrowest part of the gorge. A) in 1918; B) April 1982 (photo by Stanko Buser); C) November 2008; D) November 2018.

Diskusija

Vzroki za veliko gmotno škodo

Porečje Tržiške Bistrice je območje velike reliefne energije, velike energije površinskih (hudourniških) voda in pobočnih procesov. Pomemben dejavnik je tudi tektonska energija, saj se območje nahaja v aktivni transpresivni coni Periadriatskega prelomnega sistema (Jamšek Rupnik et al., 2012), kjer so kamnine posledično močno tektonizirane, razpokane in prelomljene. Vsako visokoenergijsko okolje je podvrženo relativno hitrim spremembam oz. naravnim procesom, ki jih samo prisotnost človeka prevrednoti v naravne katastrofe z gmotno škodo.

Prevladujoči naravni vzrok za gmotno škodo, ki je posledica opisanih geološko-geomorfoloških lastnosti, je neustrezna podlaga za gradnjo in temeljenje infrastrukturnih objektov. Na sliki 3B–D je vidno, da podlago poškodovane infrastrukture povsod v celoti gradijo nesprijet pobočni grušč in rečne naplavine Tržiške Bistrice. Tako podlago hudourniški tok odnaša in spodjeda temelje objektov, ki jih v tej ozki dolini ni mogoče umestiti drugam, kot tik ob strugo.

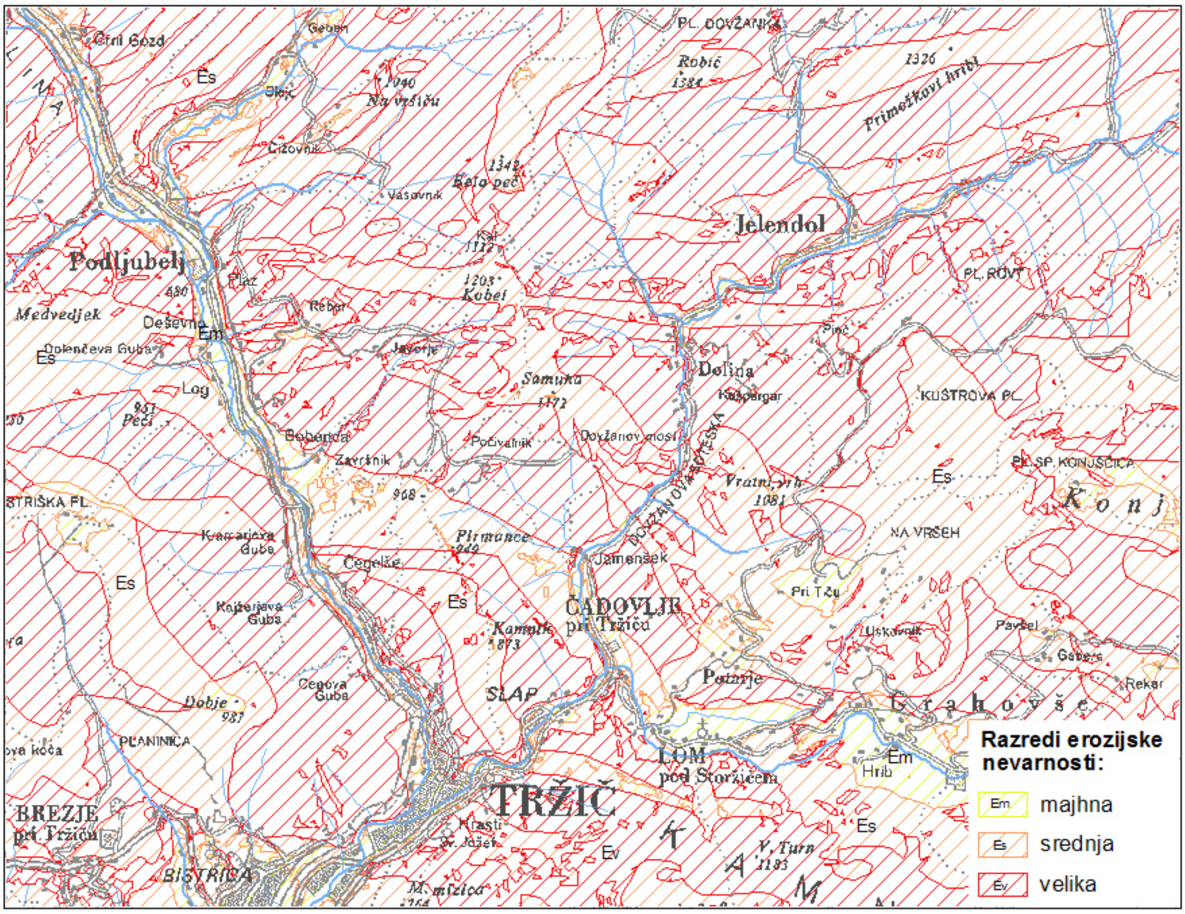
Veliko neposrednih vzrokov za povzročeno škodo lahko pripišemo antropogenim dejavnikom. Med najbolj očitnimi je neprimerno gospodarjenje z gozdom, kar pomeni ne-sonaravno izrabo gozda z goloseki, neurejen gozd po poseku (velike količine ostankov vejevja in drugih lesnih ostankov), prav tako pa tudi gradnja številnih gozdnih cest in vlak v preteklih letih, ki so močno pospeševali erozijo strmih pobočij. Velike količine erodiranega kamninskega gradiva so vodotoki ob tem dogodku naplavili v dolino, plavje (predvsem hlodovina) pa je pripomoglo k spremembam rečne struge (sl. 3E, F).

Dojemanje naravnih nesreč in varovanje pred njimi

Prebivalci naselja Dolina v Dovžanovi soteski so zelo dobra potrditev rezultatov mnogih socioloških raziskav o človekovem dojemanju in zgodovinskem spominu naravnih nesreč. Polič in sodelavci (1995) npr. poročajo, da se včasih prebivalci krajev, kjer so naravne nesreče pogoste, nič bolj ne brigajo za nevarnost, kot tisti iz varnejših območij. Skoraj neverjetne se zdijo ugotovitve anket, da kmetovalci razmeroma točno ocenjujejo nevarnost poplav, kadar so te pogoste (enkrat na leto ali dve), če pa se te pojavljajo "samo" na šest let, nevarnost poplav zanje skoraj ali sploh ni bila pomembna (Whyte, 1986; Polič et al., 1995).

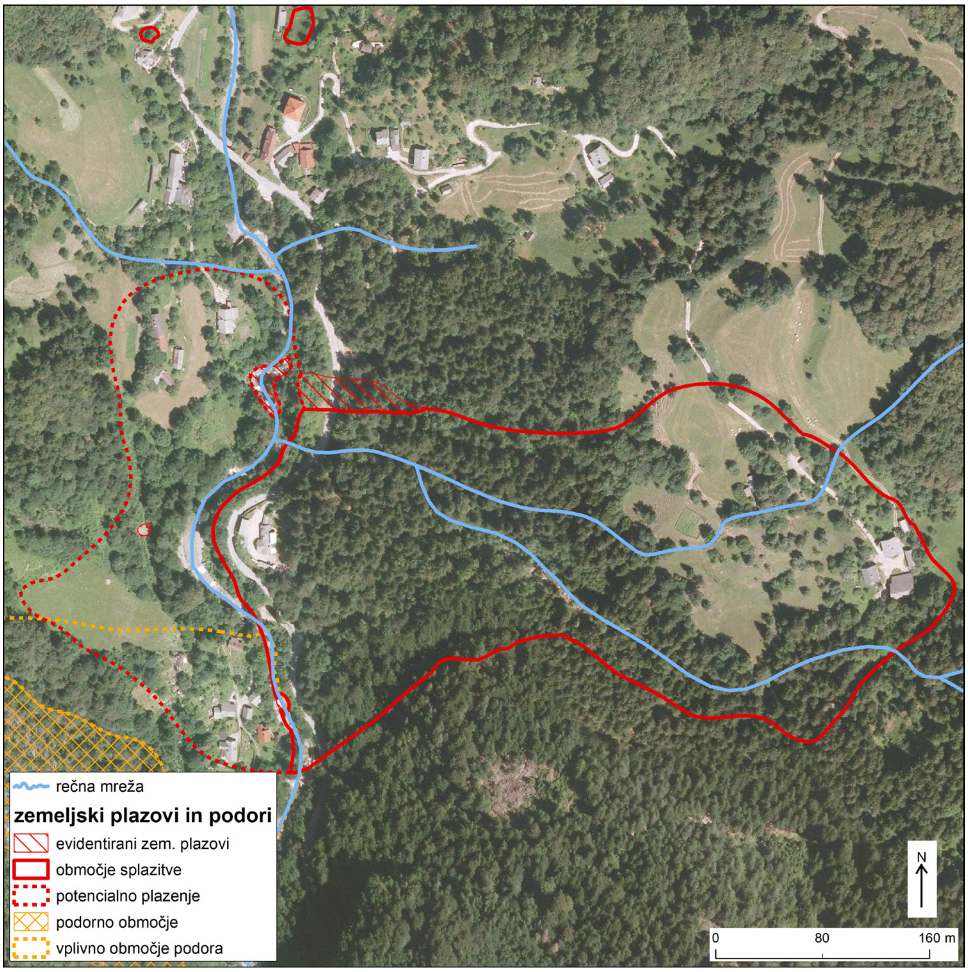
Ozka soteska z zelo strmimi pobočji, ki plazijo ali pa se lomijo in rušijo, in z edino prevozno povezavo s svetom skozi ozek prehod, skozi katerega teče hudourniška reka in nad katerim se dvigajo navpične razpokane skalne stene, ni varno območje za poselitev. O tem pričajo tudi karte erozijske in poplavne nevarnosti občine Tržič za to območje (Natek et al., 2010) (sl. 9).

Na vrtovih hiš v zaselku Na Jamah v osrčju Dovžanove soteske so podorni bloki kremenovega konglomerata z Borove peči nad zaselkom. Nekateri bloki presegajo premer 10 m (sl. 10). Za dva, ki ležita na vrtu Bencetove domačije (Dolina 1), celo vedo, da sta tja priletela leta 1944 (Koder, 2014), pri čemer je eden od njiju uničil gospodarski del hiše, ki je nekoč stala pred Bencetovo, a vendar se ljudje v dveh domačij ne čutijo zelo ogroženi pred novimi skalnimi podori iz močno razpokane skalne pečine.



Sl. 9. Izsek karte erozijske nevarnosti za obravnavano območje (vir: Natek et al., 2010).
Fig. 9. A section of the erosion hazard map for the area under consideration (source: Natek et al., 2010).

Sl. 10. Podorni bloki kremenovega konglomerata pred Bencetovo domačijo Na Jamah.
Fig. 10. Rockfall blocks of quartz conglomerate in front of the Bence's homestead at Na Jamah.



Sl. 11. Območje plazenja Kušpegarjevega plazu v Dolini (vir: Mrak et al., 2012).

Fig. 11. The area of the Kušpegar landslide at Dolina (source: Mrak et al., 2012).

Poleg skalnih podorov z Borove peči je na območju Dovžanove soteske nevarno tudi obsežno območje aktivnih masnih premikov pod Kušpegarjevo domačijo na vzhodnem pobočju Dovžanove soteske (Natek et al., 2010; Mrak et al., 2012) (sl. 11). V tem, t. i. Kušpegarjevem plazu, po za vodo slabo prepustni podlagi zdrobljenih zgornjekarbonskih skrilavih glinavcev in meljevcev drsi kamninski drobir in veliki skalni bloki kremenovega konglomerata in peščenjaka ter apnenca. Na tem kompleksnem plazu deluje več tipov pobočnih premikanj od manjših zemeljskih plazov preperinskega pokrova do drobirskih in blatnih tokov v grapah ter počasnega lezenja tal na položnejšem pobočju v zgornjem delu plazu. Po sestavi, mehanizmih transporta in sedimentacijskih procesih je Kušpegarjev plaz najbolj podoben plazovoma Čikla in Urbas, ki lahko kot aktivni drobirski tok ogrozita naselje Koroška Bela (Jemec Auflič et al., 2018; Peternel et al., 2018). Podobne kompleksne plazove najdemo tako v recentnih, kot tudi fosilnih plazovih v številnih predelih Slovenije. Tak primer je plaz Stogovce, ki je odložen na flišni podlagi, njegove drsne lastnosti materiala, naklon pobočja in hidrografsko zaledje pa kažejo, da se plaz lahko preoblikuje v hiter drobirski tok (Petkovšek et al., 2011). Kompleksni fosilni plazovi, ki so se iz translacijsko-rotacijskih plazov preoblikovali v drobirske tokove, so znani tudi iz geološke preteklosti. V Vipavski dolini številna kvartarna sedimentna telesa in njihovi geomorfološki elementi kažejo lastnosti drobirskih in blatno-drobirskih tokov (Popit et al., 2013, 2014; Verbovšek et al., 2017; Popit, 2017).

Celotna prostornina počasi plazečega telesa Kušpegarjevega plazu grozi, da se ob močnem deževju v obliki drobirskega toka sproži v dolino in strugo Tržiške Bistrice ter povzroči veliko škodo na širšem območju. Ob oktobrski ujmi je hudourniški potok iz glavne grape, v katerem se material akumulira, nanesel samo grušč, z njim zamašil odtočni jašek in ga raznesel po cesti (sl. 3E). Kljub opozorilom strokovnjakov in jasnim znakom nevarnosti v obliki poškodb na stari Kušpegarjevi hiši in manjšim premikom znotraj plazovitega telesa v preteklosti (Ocepek, 2005), na tem plazu ne izvajajo nobenih preventivnih ukrepov.

Pri tem je zanimivo, da namenjajo veliko pozornosti in sredstev zmanjševanju nevarnosti padanja kamenja na manj nevarnih odsekih. Z zaščitnimi in lovilnimi mrežami so ograjene tako rekoč vse skalne stene in grape ob in nad glavno cesto ter sprehajalnimi potmi (sl. 12).

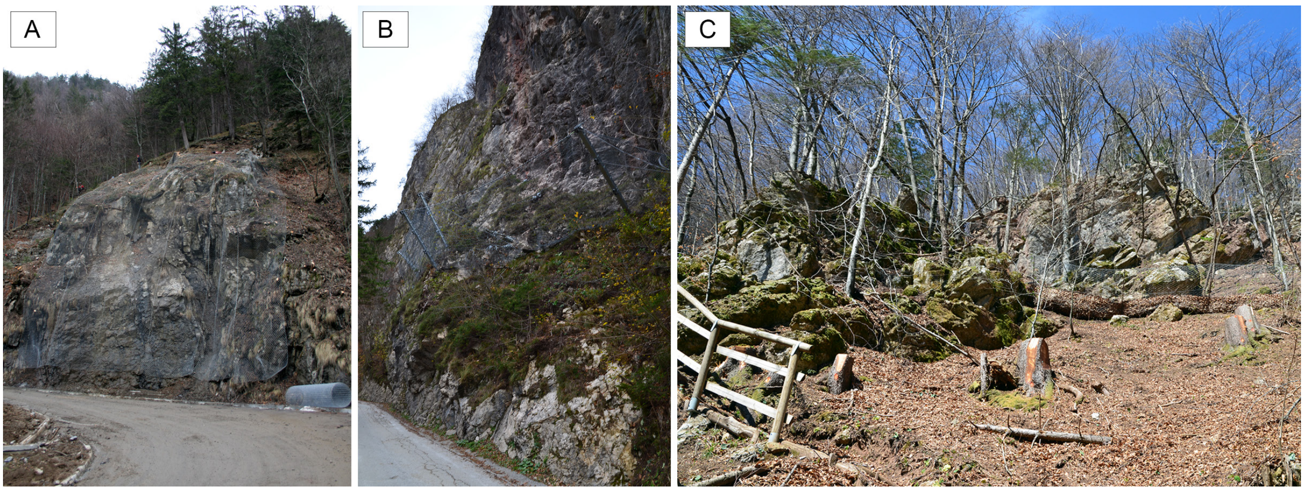
Naštetim naravnim nevarnostim je nemogoče kljubovati in nemogoče je preprečiti zelo podobne posledice ob naslednjem ekstremnem vremenskem dogodku, saj je jasno, da celo opisanih antropogenih vzrokov za nastalo škodo ni mogoče odpraviti, ker domačini ne morejo opustiti gospodarjenja z gozdom in drugih dejavnosti. Nujno pa je premišljeno upravljanje z naravnimi viri, predvsem z gozdom, kar lahko bistveno pripomore k zmanjševanju gmotne škode na infrastrukturi (Horvat, 1995; Komac & Zorn, 2007; Fidej et al., 2018). Ugotovitvi, da se je kar pet ekstremnih nalivov (2003, 2007, 2009, 2010 in zadnji 2018), ki se uvrščajo med tiste s povratno dobo 50 ali 100 let, zgodilo v zadnjih 16 letih, in da so opisi nastale gmotne škode ter njenega odpravljanja v vseh primerih zelo podobni, kažeta na to, da bo treba v strategijah prilagajanja na podnebne spremembe upoštevati zgodovinske in novejše podatke, jih med seboj primerjati in odpraviti ponavljanje enakih odzivov nanje.

Varovanje človeka in naravnega okolja v naravnih spomenikih

Pri obravnavanju opisane problematike se ni mogoče izogniti problematiziranju antropogenih vplivov na območju Dovžanove soteske. Ta je namreč od leta 1988 razglašena za naravni spomenik tako zaradi izjemnih geoloških in geomorfoloških razmer, ki so posebne tako v Sloveniji, kot tudi na svetovni ravni. V odredbah o varovanih območjih je za naravne spomenike vzpostavljen poseben varstveni status z namenom ohranitve območja v obstoječem naravnem stanju oziroma dopustitve odvijanja naravnih procesov (Vidic, 2007).

Naravni gravitacijski pobočni procesi in vodotoki najbolj intenzivno oblikujejo površje v Dovžanovi soteski, kjer se izmenjujejo klastične sedimentne kamnine s karbonatnimi in plastnate z masivnimi, zaradi česar je odvisnost površinskih oblik od litološke sestave in geoloških struktur še posebej lepo izražena (Novak & Mrak, 2013). V poseljenih naravnih spomenikih in tistih, skozi katere vodijo prometne povezave ali druga infrastruktura, kot je to v Dovžanovi soteski, v te procese kot sestavni del okolja posega tudi človek. Večina človeških posegov te procese pospešuje. Po ekstremnih vremenskih dogodkih so velike spremembe opazne strokovni javnosti, prebivalcem in obiskovalcem. Prav te spremembe so lahko dober pokazatelj vzrokov in posledic nepremišljenih človekovih posegov v okolje. Pri tem postaja Dovžanova soteska zelo dober študijski in učni poligon za proučevanje odnosa med naravnim okoljem in človekovimi posegi in prilagoditvami ter kljubovanji takemu, za poselitev marsikje neprimernemu okolju. Žal pa je zaradi antropogenih posegov zelo ogrožen njen status naravnega spomenika.

Poseg v naravo je opredeljen kot poseg v okolje po predpisih o varstvu okolja (ARSO, 2017). Zakon o varstvu okolja opredeljuje poseg v okolje kot vsako trajno ali začasno človekovo dejanje ali opustitev ravnanja, ki s svojim vplivom lahko ogrozi ali ogroža zdravje ali okolje in ima za posledico njegovo umetno spremembo, obremenitev ali zaviranje njegovih naravnih sprememb, nanaša pa se zlasti na izkoriščanje in uporabo



Sl. 12. Zaščitne mreže, velike lovilne konstrukcije in visoke zaščitne ograje v najlepših delih soteske. (A: foto Tadeja Šubic, ZRSVN).

Fig. 12. Protective wire meshes, large catching structures and high protective fences in the most beautiful parts of the gorge. (A: photo Tadeja Šubic, ZRSVN).

naravnih dobrin, posege v prostor, proizvodne in druge dejavnosti, promet in porabo blaga in emisije v vodo, zrak ali tla, odlaganje in kopičenje odpadkov ter druge vplive na okolje (ARSO, 2017). Za naravne vrednote se šteje, da so uničene, če prenehajo fizično obstajati ali ne izkazujejo več vrednostnih lastnosti, zaradi katerih so bili ti deli določeni za naravno vrednoto. Razlog za uničenje je lahko poseg, dejavnost ali ravnanje človeka ali naravni proces. Če so naravne vrednote delno fizično uničene oz. so delno prizadete njihove vrednostne lastnosti, se šteje, da so poškodovane (Vidic, 2007; ARSO, 2017).

Vprašanje je, ali je območje Naravnega spomenika Dovžanova soteska sploh še upravičeno do svojega statusa kategorije IUCN III (IUCN, 2019), saj človek z gospodarsko dejavnostjo, še bolj pa z zaščitnimi ukrepi (npr. postavitvijo mrež za padajoče kamenje) v njem ruši ravnovesje med antropogenimi vplivi in ohranjanjem zavarovanih naravnih vrednot ter procesov. Da se tega dobro zavedajo tudi domačini, je pokazala anketa. Večina anketirancev (74 %), se je strinjala, da je dejavnosti v Dovžanovi soteski potrebno razvijati do razumne meje, ki ne škodi naravi. 78 % anketirancev je ponosnih, da živijo v Dovžanovi soteski oziroma v njeni neposredni bližini, 63 % pa življenje na zavarovanem območju razume kot priložnost in ne oviro (Kuralt, 2012).

Ob tem avtorja pozivava k bolj premišljenemu in bolje načrtovanemu sonaravnemu gospodarjenju z gozdovi, ki imajo velik varovalni učinek (Firm & Rugani, 2013; Fidej et al., 2018), urejanjem hudournikov ter prostorskemu načrtovanju na območju porečja Tržiške Bistrice in še posebej na območju Naravnega spomenika Dovžanova soteska, ki mu sicer po navedenih opredelitvah grozita trajno poškodovanje in uničenje. Vsi posegi v varovana območja se morajo načrtovati in izvajati tako, da ne okrnijo narave do mere porušitve ravnotežja med naravnimi procesi in antropogenimi vplivi.

Zahvala

Avtorja sva za natančen pregled, kritične pripombe in predloge, ki so nama pomagale izboljšati prispevek hvaležna anonimnima recenzentoma. Del raziskav je sofinancirala Javna agencija za raziskovalno dejavnost RS v okviru Raziskovalnega programa P1-0011 Regionalna geologija, ki se izvaja na Geološkem zavodu Slovenije.

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GEOLOGIJA *62/1*, 136-137, Ljubljana 2019

Nove knjige

Tea KOLAR-JURKOVŠEK & Bogdan JURKOVŠEK, 2019: **Konodonti Slovenije**. Geološki zavod Slovenije, Ljubljana, 259 str.
(Conodonts of Slovenia. Geological Survey of Slovenia, Ljubljana, 259 p.)

Sredi pomladi leta 2019 je luč sveta ugledala zelo pomembna težko pričakovana znanstvena monografija z naslovom *Konodonti Slovenije* avtorjev Tee Kolar-Jurkovšek in Bogdana Jurkovška. Knjiga, ki sta jo oblikovala z vso skrbnostjo in strokovnostjo, predstavlja vrhunec njunega več deset let dolgega raziskovalnega dela. V njej se zrcali tisoče ur terenskega in laboratorijskega dela, izjemno poznavanje konodontov in geologije Slovenije ter nenazadnje tudi pritajen občutek, ki pride z desetletji izkušenj. Monografija je posvečena pregledu dosedanjih raziskav konodontov na območju Slovenije in njihovi stratigrafski uporabnosti. Čeprav so vključeni tudi rezultati drugih raziskovalcev, glavnino raziskav predstavljajo podatki, ki sta jih tekom več desetletij zbirala avtorja sama.

Na začetku avtorja na kratko predstavita konodonte, njihov razvoj od kambrija do konca triasa in njihov pomen v geologiji. Sledi poglavje, ki je v celoti posvečeno pregledu pomembnejših paleogeografskih, klimatskih in evolucijskih dogodkov v paleozoiku in triasu. Za vsako od period je podana še biostratigrafska vrednost konodontov. Sledi pregled rezultatov konodontnih raziskav, ki so bile opravljene na ozemlju Slovenije med leti 1968 in 2018. Večinoma gre za izvirne raziskave avtorjev knjige, vključene pa so tudi določitve Antona Ramovša in Katerine Krivic. Konodontne združbe so naštete po starosti formacij, v katerih so bile najdene, nahajališča pa razporejene po strukturnih enotah, kar bralcu olajšuje nadaljnje iskanje informacij. Za lažjo predstavo o geografski in sedanji strukturni legi so vsa navedena nahajališča prikazana tudi na preglednih zemljevidih. Posebna pozornost je posvečena raziskavam permsko-triasne meje v Sloveniji, ki naravoslovce zanima predvsem zaradi množičnega izumrtja v tistem obdobju. Avtorja sta se odločila obdržati izvirne določitve, zato je pomembno, da so primerki prikazani tudi na tablah. V zadnjem poglavju so nanizane in podrobneje opisane konodontne biocone za obdobje triasa, ki so bile vzpostavljene na podlagi dolgoletnih izkušenj avtorjev. Na splošno velja, da je paleobiogeografska razširjenost konodontnih vrst razmeroma slabo poznana, zato pri stratigrafskih razponih nekaterih vrst konodontov v globalnem, včasih tudi že v širšem regionalnem merilu, prihaja do znatnih razlik. Vpeljava in izpopolnitev konodontne conacije, ki temelji na raziskavah »domačih« geoloških profilov, je zato izjemno pomembna.

Knjiga je opremljena z nazornimi risbami, ki prispevajo k lažjemu razumevanju besedila, ter številnimi fotografijami izdankov. Priznana aka-

demska slikarka Barbara Jurkovšek je pripravila izvirni rekonstrukciji morskega dna iz časa mlajšega perma in mlajšega triasa. Za specialiste najpomembnejši del predstavlja 44 tabel z izborom posnetkov devonskih, karbonskih, permskih in triasnih konodontov, najdenih na območju Slovenije. Večino prikazanih primerkov sta pridobila avtorja sama. Besedilo je napisano v slovenskem in angleškem jeziku, zato je knjiga zanimiva tudi za bralce izven meja Slovenije. Besedišče je strokovno, a avtorja ne pretiravata z izrazi, ki se uporabljajo pri taksonomskih opisih. Med literaturnimi viri najdemo najnovejše objave, saj sta avtorja brez prekinitve aktivno udeležena pri razvoju njunega strokovnega področja tudi v svetovnem merilu.

Predstavitev lahko sklenem z mislijo, da je knjiga *Konodonti Slovenije* namenjena širokemu krogu strokovnjakov, deloma pa tudi ljubiteljem geologije. Nedvomno sodi na polico stratigrafa, regionalnega geologa in paleontologa. Marsikateri študent in ljubitelj geologije bo uporabno vrednost našel v omenjenem pregledu razvoja biosfere in geosfere. Najbolj pa bodo delo cenili sedanji in bodoči raziskovalci konodontov. V našem prostoru je pričujoča monografija temelj, na katerem bodo grajene morebitne prihodnje konodontne raziskave, medtem ko za konodontne specialiste v tujini knjiga predstavlja pomemben katalog vrst te davno izumrle skupine.

Luka Gale

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Poročila

Poročilo Slovenskega geološkega društva za leto 2018

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Slovensko geološko društvo (SGD) s sedežem na Dimičeva ul. 14 v Ljubljani je strokovno združenje slovenskih geologov. Društvo je bilo ustanovljeno leta 1951 in povezuje raziskovalce, učitelje, druge poklicne geologe in ljubitelje stroke. Cilj SGD s statusom društva, ki deluje v javnem interesu, je napredek znanosti in prakse na področju vseh vej geologije.

Društvo organizira javna predavanja, strokovne ekskurzije, razstave, znanstvene sestanke in delavnice, skrbi za popularizacijo geologije in za vključevanje geoloških ved v osnovnošolske in srednješolske učne programe, sodeluje pri prizadevanjih za varstvo okolja in pri izdelavi zakonskih aktov in normativov s področja geologije.

Skozi vsa leta društvo deluje v skladu z določili statuta in s programom dela, ki je sprejet na sejah IO društva v vsakem koledarskem letu.

Na rednem občnem zboru SGD, 4. oktobra 2018 v Velenju, je bila sprejeta razrešnica dotedanjim organom društva. Ker ni nihče vložil kandidature za novo sestavo društvenih organov, so bili ti izvoljeni na izredni volilni skupščini SGD, 10. januarja 2019 v Ljubljani. Novi organi društva so: B. Bračič Železnik (predsednica), M. Novak (podpredsednik), N. Rman (tajnica), A. Torkar (blagajničarka), R. Brajković (član IO), M. Križnar (član IO), L. Gale (član IO) in U. Pavlič (članica IO). V okviru društva delujejo naslednje sekcije: Sekcija za sedimentarno geologijo (predsednik A. Košir), Sekcija za geokemijo (predsednica M. Gosar), Sekcija za mineralogijo (predsednik M. Jeršek) in Sekcija za geološko dediščino (predsednica M. Stupar). Na občnem zboru v Velenju so bile formirane še: Sekcija za promocijo geološke znanosti (predsednica P. Žvab Rožič), Terminološka komisija (vodstvo izbere na prvem sestanku) in Stratigrafska komisija (predsednik B. Rožič).

Najave in poročila o društvenih aktivnostih redno objavljamo na spletni strani www.geoloskodrustvo.si.

Strokovna predavanja

Bálazs Székely (Univerza Eötvös Loránd v Budimpešti), **»Attempts to integrate David with Goliath: lessons learnt on differential uplift in a flatland«**, 14. marec 2017 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11.

Martin Gaberšek in **Klemen Teran** (Geološki zavod Slovenije) **»Prah – dragocen vir geokemičnih informacij o okolju«**, 22. marec 2018 ob 17.30 uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Tina Peternel (Geološki zavod Slovenije) **»Spremljanje pobočnih masnih premikov na primeru plazov Urbas in Čikla (SZ Slovenija)«** 29. marec 2018 ob 17.30 uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Teja Čeru (Oddelek za geotehnologijo, rudarstvo in okolje NTF) **»Uporaba georadarja pri geomorfoloških raziskavah na krasu«** 12. april 2018 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Lada Hýlova (Univerza Palacký v Olomoucu, Češka) **»The Petřkovice Member (Ostrava Formation, Mississippian) of the Upper Silesian Basin (Czech Republic and Poland)«** 19. april 2018 ob 17.30 uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Blaž Vičič (Univerza v Trstu, Italija) **»Epizodična aktivnost Idrijskega prelomnega sistema«** 24. april 2018 ob 18. uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02. Predavanje je bilo izvedeno tudi v okviru seminarja doktorskega študija Grajeno okolje.

Daniela Rehákova (Univerza v Bratislavi, Slovaška) **»Calcareous microplankton in the Upper Jurassic/Lower Cretaceous pelagic sediments of the Western Carpathians – a tool for stratigraphical and paleoenvironmental interpretation«** 26. april 2018 ob 17.30 uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Predavanji o dveh evropskih projektih, v katerih sodeluje Slovensko geološko društvo:

Snježana Miletić (Geološki zavod Slovenije) je predstavila **projekt INFACT – Prihodnost raziskovanja mineralnih surovin v Evropi. Timotej Verbovšek** (Oddelek za geologijo Naravoslovnotehniške fakultete) je predstavil **projekt UNEXMIN – Podvodni robot za raziskovanje zalitih rudnikov.** Predavanji sta bili 15. maja 2018 ob 18. uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Lan Zupančič (študent geologije na NTF) **»Geološki potopis s poletne šole o kamninskih plazovih in z njimi povezanih pojavih v Kirgizistanu 2018«** 29. november 2018 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Aškerčeva 12, v predavalnici 210.

5. slovenski geološki kongres

Slovensko geološko društvo je z Geološkim zavodom Slovenije soorganiziralo **5. slovenski geološki kongres**. Kongres, ki je potekal med 3. in 5. oktobrom 2018 v Velenju, je bil za SGD največji in najpomembnejši dogodek leta 2018. Partnerji pri organizaciji so bili Premogovnik Velenje, Fakulteta za gradbeništvo in geodezijo, Slovensko rudarsko društvo inženirjev in tehnikov (SRDIT), Društvo slovenski komite mednarodnega združenja hidrogeologov (SKIAH) in Mestna občina Velenje. Kongres je bil ob izmenjavi novih raziskovalnih rezultatov posvečen pomenu geoznanosti za širšo družbo in njen razvoj.

Na kongresu je sodelovalo 191 udeležencev iz 18 držav. Predstavili so 169 prispevkov, od tega 112 predavanj in 57 posterjev, ki so pokrivali vsa področja temeljne in aplikativne geologije. Štiri plenarna predavanja so povezovala rdečo nit letošnjega kongresa, temo »Geologija in družba«. Osrednji dogodek v okviru kongresa je bila **okrogla miza »Ali je Slovenija pripravljena na uporabo geološkega znanja pri svojem razvoju?«.** Na njej smo soočili različne poglede in izkušnje predstavnikov geoznanosti in uporabnikov geoloških podatkov glede vloge in pomena zbiranja, interpretiranja in javne dostopnosti geoloških podatkov za razvoj družbe.

Kongres so sklenile tri celodnevne kongresne ekskurzije in ena tridnevna pokongresna ekskurzija. Spremljalo ga je veliko dogodkov v organizaciji SGD: Dan geologije z delavnicami, fotografski natečaj in fotografska razstava ter GeoTEK.

Več informacije o kongresu in kongresna gradiva so na spletni strani www.geo-zs.si/5SGK.

Dan geologije

Skupina za popularizacijo geologije SGD je v okviru dejavnosti, ki so spremljale 5. slovenski geološki kongres v Velenju izvedla prvi **Dan geologije**. Geološke delavnice na temo *Geologija v vsakdanjem življenju* za učence in dijake osnovnih in srednjih šol so potekale 2. oktobra 2018 v sodelovanju z Visoko šolo za varstvo okolja v Velenju. Na delavnice se je prijavilo skupaj kar 150 učencev in dijakov. Načrtujemo, da bi Dan geologije postal tradicionalen dogodek z vključevanjem čim večjega števila inštitucij.

Fotografski natečaj in fotografska razstava

SGD je v okviru 5. slovenskega geološkega kongresa razpisalo nagradni fotografski natečaj *Geoznanost za družbo*. Na njem je sodelovalo 15 avtorjev, ki so poslali skupaj 41 fotografij. Ocenjevalna komisija je med njimi izbrala 12 fotografij. Zmagovalne fotografije natečaja in fotografije strokovnjakov Geološkega zavoda Slovenije, ki tematsko dopolnjujejo predstavitev različnih vej geoznanosti in področij njihovih raziskav, so do aprila 2019 razstavljene v velenjski Galeriji na prostem.

Strokovna posvetovanja, seminarji in okrogle mize

SGD je skupaj z društvom SKIAH organiziralo **delavnico na temo priprave zakonske uredbe na področju geologije**, ki je potekala 29. maja 2018 v Ljubljani na Oddelku za geologijo NTF, Privoz 11.

SGD je skupaj z Oddelkom za geologijo Naravoslovnotehniške fakultete soorganiziralo **posvetovanje »Vloga in pomen geologije v formalnem izobraževanju«**, ki je potekalo v okviru tedna Univerze v Ljubljani, 5. decembra 2018 s pričetkom ob 17. uri. Posvetovanje s štirimi predstavitvami in diskusijo je bilo na Oddelku za geologijo NTF, Aškerčeva 12, v predavalnici 210.

SGD je v sodelovanju z Geološkim zavodom Slovenije organiziralo **strokovni posvet »Na poti do ureditve pridobivanja, zbiranja, interpretiranja in dostopnosti geoloških podatkov«**. Na posvetu smo predstavili problematiko v Sloveniji in dve različni sodobni ureditvi tega področja iz Švice (dr. Oliver Lateltin, direktor Swisstopo, Geološkega zavoda Švice) in z Nizozemske (dr. Michiel van der Meulen, glavni geolog, Geološki zavod Nizozemske), ki bi v zasnovah lahko bila primerni tudi za ureditev tega področja v Sloveniji. Posvet je bil 19. decembra 2018 od 10.30 do 12.30 v predavalnici Geološkega zavoda Slovenije, Dimičeva ul. 14, Ljubljana.

Delovna akcija čiščenja geološkega profila

V soboto, 1. decembra 2018 smo izvedli tradicionalno delovno akcijo čiščenja zarasti na geoloških naravnih vrednotah v sodelovanju z Zavodom RS za varstvo narave (ZRSVN). Akcija je potekala na območju Socka – soteska Hudinja.

GeoTEK

Slovensko geološko društvo je 2. oktobra 2018 organiziralo tretji tradicionalni **GeoTEK**, tokrat okrog Škalskega jezera v Velenju. Udeležilo se ga je 26 članov in simpatizerjev.

Sodelovanje na domačih dogodkih in druge aktivnosti

Z razstavo in delavnico *Periadriatski prelomnin sistem* smo z Oddelkom za geologijo NTF in GeoZS sodelovali na tradicionalnih **46. mednarodnih dnevih mineralov, fosilov in okolja MINFOS** v Tržiču, 12. in 13. maja 2018 v Dvorani tržiških olimpijcev.

Z delavnico *Razsekana Slovenija* so člani SGD z GeoZS in Oddelka za geologijo NTF sodelovali na prireditvi **Vrt eksperimentov**. Dogodek je organizirala Hiša eksperimentov v okviru 10. Znanstivala, 2. in 3. junija 2018 od 10. do 18. ure na Stritarjevi ulici v Ljubljani

Mednarodno delovanje SGD in članstvo v tujih in domačih zvezah

SGD je včlanjeno v tuje zveze: European Federation of Geologists (EFG), International Union for Quaternary Research (INQUA), European Association for the Conservation of the Geological Heritage (ProGeo), European Mineralogical Union (EMU) in International Mineral Association (IMA). Včlanjeni smo tudi v Slovensko inženirsko zvezo (SIZ).

Član SGD Marko Komac je bil novembra 2018 izvoljen za predsednika EFG, 24 naših članov pa sodeluje v strokovnih svetovalnih telesih EFG.

Kot član **Evropskega združenja geologov** (European Federation of Geologists – EFG) SGD od leta 2015 sodeluje v evropskih projektih Obzorje 2020 (Horizon 2020). Skupaj z več drugimi nacionalnimi geološkimi društvi sodelujemo kot neodvisni partner preko pogodbe z EFG kot vodilnim projektnim partnerjem. V letu 2018 smo uspešno zaključili aktivnosti v projektu KINDRA – Zbirka znanja za hidrogeološke raziskave (*Knowledge Inventory for Hydrogeology Research*), nadaljuje pa se sodelovanje v projektih UNEXMIN – Podvodni raziskovalec potopljenih rudnikov (*An Autonomous Underwater Explorer for Flooded Mines*) in CHPM 2030 – Soproizvodnja toplotne in električne energije ter pridobivanje kovin (*Combined Heat, Power and Metal extraction from ultra-deep ore bodies*) ter v projektu INFACT – Inovativna, neinvanzivna in popolnoma sprejemljiva tehnologija raziskovanja (*Innovative, Non-Invasive and Fully Acceptable Exploration Technologies*).

SGD je tudi član **Slovenske inženirske zveze** – SIZ. S tem je izpolnjen pogoj o obveznem članstvu SGD v SIZ za pridobitev naziva Evro inženir (EUR ING).

V letu 2019 so načrtovane in delno že izvedene naslednje dejavnosti društva:

Strokovna predavanja

Matija Križnar (Prirodoslovni muzej) »Pozabljeni rajski otoki – geološko naravoslovni sprehod po Makarenskih otokih« 23. marec 2019 ob 17.00 uri v Ljubljani na Geološkem zavodu Slovenija, Dimičeva ulica 14, velika predavalnica v VI. nadst.

prof. Alfred Uchman (Institute of Geological Sciencies, Jagiellonian Univerza, Polska) »Deep--see trace fossils –insight into hidden palaeoenvironment« 28. marec 201 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Privoz 11, v predavalnici P-02.

Blaž Miklavčič (Oddelek za geologijo NTF) z naslovom »Bo dovolj vode za vse« 18. aprila 2019 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Aškerčeva 12.

Polona Kralj (Geološki zavod Ljubljana) in **Tanja Lukežič** (Zavod RS za varstvo narave) z naslovom »Vulkanske kamnine Stopnika 24. aprila 2019 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Aškerčeva 12.

Predavanje **Mateje Gosar** (Geološki zavod Slovenije) z naslovom »Tla Slovenije: geokemično ozadje in zgornja meja naravne variabilnosti za kemične elemente« 29.maj 2019 ob 17. uri v Ljubljani na Oddelku za geologijo NTF, Aškerčeva 12.

V septembru 2019 bo predavanje o prof. Ivanu Rakovcu ob 120 letnici njegovega rojstva.

Strokovne ekskurzije

V oktobru 2019 je predvidena dvodnevna **strokovna ekskurzija v Geopark Karavanke** pod vodstvom Darje Komar in Walterja Poltniga.

Konec jeseni 2019 je predvidena **strokovna paleontološka ekskurzija**.

Strokovna posvetovanja in okrogle mize

Slovensko geološko društvo bo v sodelovanju s Slovenskim mednarodnim komitejem za hidrogeologijo (SKIAH) organiziralo l. 2022 6. Slovenski geološki kongres. V letu 2019 bodo potekale pripravljalne aktivnosti.

SGD bo v sodelovanju z Geološkim zavodom Slovenije sodeloval pri izvedbi 7th Symposium on Mezozoic and Cenozoic Decapod Crustaceans, ki bo od 17.6. -21.6.2019 v Ljubljani.

SGD bo v sodelovanju z Oddelkom za geologijo, NTF soorganizator 24. posvetovanja slovenskih geologov, ki bo v novembru 2019 v Ljubljani.

SGD bo v sodelovanju z Oddelkom za geologijo, NTF soorganizator okrogle mize na temo geoloških vsebin v formalnem izobraževanju v decembru 2019 v Ljubljani.

GeoTEK

Četrti tradicionalni GeoTEK Slovensko geološko društvo bo organiziran v oktobru 2019. Trasa GeoTEKA, bo na Sitarevec.

Sodelovanje na domačih dogodkih in druge aktivnosti v letu 2019

Geološki pojav leta – v letu 2019 bo to 100 let poučevanja geologije na Univerzi v Ljubljani. Aktivnosti bodo potekale celo leto 2019: predavanja, fotonatečaj

Sodelovali bomo na dogodkih za promocijo geološke znanosti: 11. in 12.5.2019 na **MINFOS** v Tržiču, 31.5.2019 na **Dnevu za Savinjo** v Ljublnem ob Savinji, 1. in 2.6.2019 na **Znanstivalu** v Ljubljani in avgusta 2019 na **Koliščarskem dnevu** na Igu.

Avgusta 2019 bomo ponovno sodelovali pri izvedbi **Koliščarskega dneva** v Dragi pri Igu.

Organizirali bomo Dan geologije. Lokacija in datum, še niso določeni.

Jeseni 2019 bomo organizirali okroglo mizo, kjer bodo sodelovali strokovnjaki različnih vej geološke stroke pri izdelavi osnutka Zakona o geosferi.

Konec leta 2019 bomo izdali bilten o delovanju društva.

6. evropski geotermalni kongres v Haagu (Nizozemska) 11. – 14. junij 2019

Dušan RAJVER & Nina RMAN

Geološki zavod Slovenije, Dimičeva ul.14, SI-1000 Ljubljana;
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V Haagu je junija 2019 potekal 6. evropski geotermalni kongres. Zadnji štirje evropski geotermalni kongresi so se odvijali v organizaciji Evropskega sveta za geotermalno energijo (European Geothermal Energy Council, EGEC), tokratni pa tudi v soorganizaciji nizozemske neprofitne organizacije Stichting Platform Geothermie ter podjetja Bodem EnergieNL. Glavni sponzor je bilo podjetje v energetskem sektorju Energie Beheer Nederland B.V. (EBN), ostali sponzorji pa so bili še proizvajalci geotermalnih elektrarn Turboden SpA (Italija), in vrtalne ter druge opreme Huisman Geo (Nizozemska), Baker Hughes (GE družba) in NALCO Water (Ecolab družba). Prejšnji kongresi so se odvijali neenakomerno, namreč septembra 2016 v Strasbourgu, junija 2013 v Italiji (Pisa), maja-junija 2007 v Nemčiji (Unterhaching pri Munchenu), maja 2003 na Madžarskem (Szeged) in septembra 1999 v Švici (Basel), zadnji trije omenjeni pod okriljem evropske veje IGA in EGEC. Pred tem pa so se odvijali t.i. evropski geotermalni seminarji (International Seminar on the Results of EC Geothermal Energy Research) v organizaciji Evropske Komisije z delovnim naslovom »European Geothermal Update«, in sicer aprila 1989 v Italiji (Firence), pod isto organizacijo pa tudi novembra 1983 v Nemčiji (Munchen), marca 1980 v Franciji (Strasbourg) in prvi že decembra 1977 v Belgiji (Bruxelles).

Tokratni kongres je zbral 872 udeležencev in 46 razstavljalcev. Nizozemska se je v neposredni rabi geotermalne energije (GE) povzpela na šesto mesto v Evropi, tako iz globokih geotermalnih sistemov, z zmogljivostjo 186 MW_t in 1.011 GWh izkoriščene geotermalne toplote, kakor tudi s tehnologijo toplotnih črpalk na plitvo GE z zmogljivostjo 2775 MW_t in s 3.052 GWh izkoriščene toplote. Na Nizozemskem ni geotermalnih elektrarn, saj do sedaj niso še zajeli dovolj pretoka termalne vode (ali dvofaznega fluida) primerne temperature. V tej proizvodnji v Evropi prednjačijo Turčija, Italija in Islandija, ki imajo ugodnejše geološke pogoje. Vseeno pa je Nizozemska kongres upravičeno organizirala s predstavitvijo uresničevanja ciljane nacionalne strategije rabe geotermalne energije, s prikazom tehnološkega in znanstveno sodobnega stanja v razvoju geotermalnih polj in izkoriščanju geotermalne energije.

Za kongres je bilo sprejeto 280 prispevkov iz skoraj vseh evropskih držav in tudi nekaterih drugih (Indonezija, Maroko, Mehika, Nova Zelandija, itd.), od teh je bilo 119 posterjev.

Pod okriljem kongresa se je prvi dan dopoldne odvijala **otvoritvena sekcija** z uvodnimi predstavitvami (M. Antics, predsednik EGEC, S. Gaastra, generalni direktor Climate and Energy, A. Richter, predsednik IGA) ter predavanji pomembnih političnih gostov (F. Schoof, predsedujoči Stichting Platform Geothermie, L. van Tongeren, županja mesta Haag, T. Kockelkoren, generalni rudarski inšpektor Nizozemske) in pomembnimi deležniki iz industrije (E. Hoos, DG za energijo iz evropske komisije, J.W van Hoogstraten, direktor podjetja EBN, A. Magalini, prodajni direktor podjetja Turboden, P. de Vin, operativni direktor podjetja Huisman Geo). Popoldne prvega dne kakor tudi drugi in tretji dan so se odvijale **vzporedne sekcije** s predstavitvami in z vodilnimi **semi-plenarnimi predavanji**. Te so vsebinsko zajele naslednjo tematiko: (1) tehnološki trendi v globoki geotermiji, (2) tehnološki trendi v plitvi geotermiji, (3) povzetek o stanju v rabi GE v Evropi (Country updates), (4) perspektive za geotermalni trg in (5) od znanosti k podjetništvu: perspektive globokih geotermalnih raziskav. Od prvega dne je potekala tudi posterska sekcija.

Predstavitve, bodisi kot predavanja ali posterji, so bile v sekcijah porazdeljene na štiri glavne skupine, (1) *Poročila držav o stanju in razvoju v geotermiji* (Country Updates) (2) *Politika* (Policy), (3) *Tehnologija* (Technology) in (4) *Znanost* (Science). Med njimi je bilo uvrščenih 13 semi-plenarnih predavanj. **Poročila držav** o najnovejšem stanju izkoriščanja in razvoja geotermalne energije (Country Update reports) so bila predstavljena le kot posterji, 32 držav pa je poročalo s prispevki. V okviru naslednjih omenjenih treh skupin (2 – 4) so bile predstavitve porazdeljene na več tematik. Skupina (2) **Politika** je vsebovala podsklopa: A) dojemanje javnosti in socialni vidiki (Public perception and social aspects) z 8 prispevki in B) financiranje (Financing) z 10 prispevki. Skupina (3) **Tehnologija** je zajela naslednje podsklope: A) raziskovanje in načrtovanje (Exploration & Planning) z 12 prispevki, B) delovanje (Operation) z 11 prispevki, C) korozija in luščenje (Corrosion & Scaling) s 5 prispevki, D) električna zmogljivost (Power) z 9 prispevki, E) tehnologije ogrevanja in hlajenja (Heating & Cooling technologies) z 10 prispevki, F) tehnologije in inovacije (Technologies & Innovation) s 6 prispevki, G) podzemno skladiščenje toplotne energije (Underground Thermal Energy Storage, UTES) s 14 prispevki, H) geotermalne toplotne črpalke (Geothermal Heat Pumps) s 13 prispevki ter I) vplivi na okolje in rešitve (Environmental Impacts & Solutions) s 3 prispevki. Skupina (4) **Znanost** pa je vsebovala podsklope: A) razvrstitev virov (Resources Classification) s 4 prispevki, B) raziskovanje: regionalna ocena (Exploration: regional assessment) s 4 prispevki, C) raziskovanje: Zgornji renski jarek (Exploration: Upper Rhine Grabben) s 5 prispevki, D) raziskovanje v klastičnih kamninah (Exploration (clastic)) s 5 prispevki, E) raziskovanje v karbonskih kamninah (Exploration (carboniferous)) s 4 prispevki, F) raziskovanje v magmatskih kamninah (Exploration (magmatic)) s 5 prispevki, G) raziskovanje (tipi torišč raziskav) (Exploration (play types)) s 4 prispevki, H) raziskovanje (Exploration) s 53 prispevki, I) geotermalne vrtine (Geothermal Wells) z 10 prispevki, L) inženiring rezervoarjev (Reservoir engineering) z 18 prispevki, M) stimulacija (Stimulation) z 9 prispevki, N) inducirana seizmičnost (Induced seismicity) z 10 prispevki, O) pretvorba elektrike in toplote (Power & Heat conversion) s 6 prispevki ter P) evropske raziskave in razvoj (European Research & Development) s 6 prispevki.

Aktualne geotermalne téme, izjemni predavatelji in aktivna izmenjava mnenj udeležencev je pripomogla k uspešnosti kongresa v celoti. Pokazalo se je, da so posredne in površinske metode (geofizika, geokemija in geologija) še vedno zelo pomembne v raziskavah in upravljanju geotermalnih virov. Številni referati o raziskavah kažejo, kako dejavno je še naprej tudi iskanje novih virov. Pri predstavitvah je potrebno poudarjati zanesljivost in lokalnost oskrbe z GE ter nizke emisije toplogrednih plinov pri njeni rabi. Na Nizozemskem so dosegli klimatski dogovor, da bodo brez CO_2 v ogrevanju stavb do leta 2050, kar pomeni, da potrebujejo 700 novih dubletov (proizvodna in povratna vrtina) oziroma 2 nova projekta na leto. Predstavili so nizozemsko zagotovilo kvalitete (quality assurance): delajo lahko le vrtalci z licenco in le po navodilih, zasebna podjetja izvajajo certificiranje. Leta 2021 bo v zakonodaji Evropske Skupnosti prvič omenjeno hlajenje z obnovljivimi viri (renewable cooling) (Internet 1). Evropski svet EGEC še ni razmišljal, da bi naredil kakšne informativne učne modele o geotermiji za splošno javnost, a bi to lahko razvijali v projektih za promocijo oziroma sprejemljivost rabe.

Tematske sekcije so vključevale nove pristope k oceni virov, za DARLINGe je pomembna UNFC klasifikacija. Veliko poudarka je bilo na zagotavljanju iskanja sprejemljivosti geotermije s strani splošne javnosti ter zagotavljanju varnega obratovanja elektrarn. Poudarek je bil še na naslednjem: spodbuja se dekarbonatizacija energetskega sektorja in decentralizacija virov, upoštevajo se visoki okoljski standardi in družbena sprejemljivost.

Veliko predavanj je imelo poudarek na rabi geofizike v kombinaciji s stratigrafijo za izdelavo 3D modelov, smiselno pa je uporabiti tudi Monte Carlo pristop za oceno negotovosti kvalitete rezervoarja. V laboratoriju že potekajo testiranja izluževanja kovin iz geotermalnih fluidov, kar nekaj raziskav pa se ukvarja z vtiskovanjem CO_2 nazaj v vodonosnik, bodisi za preprečevanje obarjanja v njem ali pa zaradi večje okoljske sprejemljivosti.

Med kongresom se je odvijalo nekaj pomembnih stranskih dogodkov:

- delavnica »Renewable Heating & Cooling RHC-ETIP: Geothermal technology Workshop«.
- delavnica »Workshop on shallow geothermal mapping«.

Na semi-plenarni sekciji »od znanosti k podjetništvu: perspektive za globoke geotermalne raziskave« je G. Johannesson (vodja SET plana, Implementation working group on Deep Geothermal) dejal, da je realno pričakovati 20 % pokritost potreb po ogrevanju iz GE za celo Evropo v letu 2050. F. Batini (ETIP-DG Technology Roadmap for Deep Geothermal) je poudaril potrebo po večji promociji koristi GE, to isto je poudarila tudi I. Berre (vodja JPG, European Energy Research Alliance), saj so viri GE večinoma last državnih organov. Pregledna predavanja so povzela evropski pregled stanja, ki kažejo naraščanje rabe GE, tudi v proizvodnji elektrike.

Zadnji dan kongresa, 14. junija, je bil izveden mednarodni kratki tečaj Geotrainet o napredkih v tehnologiji in izvedbah rabe plitve GE (Geotrainet International short course on advances in shallow geothermal technology and implementation), posvečen načrtovalcem in inštalaterjem pri izkoriščanju plitve geotermalne energije s tehnologijo toplotnih črpalk. Organizatorji so istega dne izvedli tri terenske ekskurzije: (1) obisk dveh geotermalnih toplotnih postaj v krajih Koppert Cress in Aardwarmte Vogelaer južno od Haaga za rastlinjake, (2) obisk geotermalne vrtine Leyweg v JZ predelu Haaga, (3) obisk podjetja Huisman Geo v Schiedamu pri Rotterdamu z demonstracijo vrtalnega stolpa in vrtine pod njim. Gre za podjetje, ki je specializirano v izdelavi vrtalnih stolpov (posebno za največje vrtalne stolpe za vrtanje na morskem dnu) in velikih žerjavov za pristanišča.

Kongres v Haagu je prikazal velik potencial za nadaljno rast rabe GE in geotermalnega razvoja, predvsem neposredne rabe, tako iz termal-

Tabela 1. Sedanje stanje izkoriščanja GE v Evropi, s podatki poročanimi za kongres v letu 2019 (stanje dne 31. dec. 2018) in primerjava s podatki za kongresa v letu 2013 (stanje dne 31. dec. 2012) in v letu 2016 (stanje dne 31. dec. 2015) (Antics et al., 2013; 2016; Sanner, 2019).

Leto	**EGC 2013**	**EGC 2016**	**EGC 2019**
Proizvodnja elektrike			
Instalirana kapaciteta (MW_e)	1847,9	2050	2960,8
Proizvedena elektrika (GWh/leto)	12158,3	13997,3	18302,6
Faktor obremenitve	75,1	77,9	70,6***
Število držav	9	8*	10*
Neposredna raba: srednje do nizko temperaturni viri			
Instalirana kapaciteta (MW_t)	7800,3	9264,2	10612
Izkoriščena energija (GWh/leto)	18763,9	31199,1	35292
Koeficient izkoristka			
Število držav	28	32	27
Neposredna raba: plitva geotermija (GTČ) in UTES			
Instalirana kapaciteta (MW_t)	16506,4	22891,4	26923
Izkoriščena energija (GWh/leto)	34898,9	49366,4	59438
Poprečje na enoto GTČ	58,7	22,2	21
Število enot GTČ na plitvo geotermijo	> 1,33 milijona	> 1,71 milijona	> 1,9 milijona
Število držav	32	31**	31**

*Rusija ni zajeta v tem poročanju.

**Estonija ni zajeta v tem poročanju.

***malo nižji od pričakovanega, ker vse elektrarne niso delovale v polnem delovanju (začetek delovanja geoterm. elektrarne na Hrvaškem šele v dec. 2018) in zaradi težav v zagonu novih elektrarn.

ne vode kot tudi iz plitve geotermalne energije. Skupno 32 držav je poročalo o izkoriščanju GE za proizvodnjo elektrike ali za neposredno rabo toplote iz termalnih fluidov ali za oboje. V nadaljevanju navajamo nekaj skupnih bilanc. Izredno je napredovala raba plitve geotermalne energije s tehnologijo geotermalnih toplotnih črpalk (GTČ). Skupno število enot delujočih GTČ znaša danes v Evropi cca 2 milijona. Med kategorijami rabe termalne vode iz globokih vodonosnikov pa prevladuje daljinsko ogrevanje pred rabo za kopanje in plavanje v bazenih (in balneologijo) ter za rastlinjake.

Instalirana zmogljivost geotermalnih elektrarn se je povečala za 29 % glede na stanje poročano na EGC 2016 in to zavoljo znatnega porasta v Turčiji. Velik potencial, ki bi ga lahko nudila tehnologija vzpodbujenih geotermalnih sistemov (angl. EGS) (prim. Geoelec, 2013), se ne odraža v pričakovani rasti do leta 2025. Večina poročane in pričakovane proizvodnje elektrike iz GE temelji na trenutno razpoložljivih visoko entalpijskih virih in nizko-do-srednje temperaturnih binarnih elektrarnah. Rast po letu 2025 bi lahko izgledala drugače; za uresničitev tega cilja pa bi bila potrebna obsežna razvojna naloga za EGS. Izkoriščanje GE v Sloveniji je še vedno le v neposredni rabi toplote. Instalirana kapaciteta za neposredno rabo znaša 247,47 MW_t, letna izkoriščena geotermalna energija pa 1516,79 TJ ali 421,33 GWh (stanje na 31. dec. 2018), vključno z geotermalnimi toplotnimi črpalkami na toploto plitvega podzemlja (Rajver et al., 2019). Prispevek geotermalnih toplotnih črpalk, ki se neprestano viša, znaša namreč 185,04 MW_t oziroma 938,23 TJ/leto (260,62 GWh) izkoriščene plitve GE. Različne vrste uporabe zajemajo: ogrevanje individualnih prostorov, priprava sanitarne tople vode, daljinsko ogrevanje, klimatizacijo/hlajenje, ogrevanje rastlinjakov, kopanje in plavanje z balneologijo, taljenje snega ter raba plitve GE (s tehnologijo GTČ), pogosto kot zaporedno rabo.

Iz Slovenije sva se kongresa udeležila avtorja tega prispevka, sodelavci iz GeoZS pa smo bili avtorji oziroma soavtorji v skupno sedmih predstavitvah (Ádám et al., 2019; Herms et al., 2019; Nádor et al., 2019; Rajver et al., 2019; Rman, 2019; Rman et al., 2019; Rotár-Szalkai et al., 2019). V sklopu kongresa je potekala še razstava nekaterih najbolj znanih razvojnih inštitucij ter proizvajalcev in serviserjev raziskovalne in proizvodne opreme (za vrtine, cevovode, toplotne postaje, itd.) v geotermalnih raziskavah in razvoju ter izkoriščanju geotermalne energije.

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Navodila avtorjem

GEOLOGIJA objavlja znanstvene in strokovne članke s področja geologije in sorodnih ved. Revija izhaja dvakrat letno. Članke recenzirajo domači in tuji strokovnjaki z obravnavanega področja. Ob oddaji člankov avtorji predlagajo **tri recenzente**, uredništvo si pridržuje pravico do izbire recenzentov po lastni presoji. Avtorji morajo članek popraviti v skladu z recenzentskimi pripombami ali utemeljiti zakaj se z njimi ne strinjajo.

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Članek oddajte uredništvu vključno z vsemi slikami, tabelami in tablami v elektronski obliki po naslednjem sistemu:

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- *Tabele, Slike, Table*

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Pleničar, M. 1993: *Apricardia pachiniana* Sirna from lower part of Liburnian beds at Divača (Triest-Komen Plateau). Geologija, 35: 65–68

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Flügel, E. 2004: Mikrofacies of Carbonate Rocks. Springer Verlag, Berlin: 976 p.

Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M. & Šribar, Lj. 1996: Formacijska geološka karta južnega dela Tržaško-komenske planote – Kredne in paleogenske kamnine 1: 50.000 = Geological map of the southern part of the Trieste-Komen plateau – Cretaceous and Paleogene carbonate rocks. Geološki zavod Slovenije, Ljubljana: 143 p., incl. Pls. 23, 1 geol. map.

Primer citiranja poglavja iz knjige:

Turnšek, D. & Drobne, K. 1998: Paleocene corals from the northern Adriatic platform. In: Hottinger, L. & Drobne, K. (eds.): Paleogene Shallow Benthos of the Tethys. Dela SAZU, IV. Razreda, 34/2: 129–154, incl. 10 Pls.

Primer citiranja virov z medmrežja:

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Pleničar, M. 1993: *Apricardia pachiniana* Sirna from lower part of Liburnian beds at Divača (Triest-Komen Plateau). Geologija, 35: 65–68.

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Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M. & Šribar, Lj. 1996: Formacijska geološka karta južnega dela Tržaško-komenske planote – Kredne in paleogenske kamnine 1: 50.000 = Geological map of the southern part of the Trieste-Komen plateau – Cretaceous and Paleogene carbonate rocks. Geološki zavod Slovenije, Ljubljana: 143 p., incl. Pls. 23, 1 geol. map.

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