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RMZ – MATERIALS AND GEOENVIRONMENT

PERIODICAL FOR MINING, METALLURGY AND GEOLOGY

RMZ – MATERIALI IN GEOOKOLJE

REVIJA ZA RUDARSTVO, METALURGIJO IN GEOLOGIJO

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Historical Rewiev

More than 90 years have passed since in 1919 the University Ljubljana in Slovenia was founded. Technical fields were joint in the School of Engineering that included the Geologic and Mining Division while the Metallurgy Division was established in 1939 only. Today the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy are part of the Faculty of Natural Sciences and Engineering, University of Ljubljana.

Before War II the members of the Mining Section together with the Association of Yugoslav Mining and Metallurgy Engineers began to publish the summaries of their research and studies in their technical periodical Rudarski zbornik (Mining Proceedings). Three volumes of Rudarski zbornik (1937, 1938 and 1939) were published. The War interrupted the publication and not untill 1952 the first number of the new journal Rudarsko-metalurški zbornik - RMZ (Mining and Metallurgy Quarterly) has been published by the Division of Mining and Metallurgy, University of Ljubljana. Later the journal has been regularly published quarterly by the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy, and the Institute for Mining, Geotechnology and Environment.

On the meeting of the Advisory and the Editorial Board on May 22nd 1998 Rudarsko-metalurški zbornik has been renamed into "RMZ - Materials and Geoenvironment (RMZ -Materiali in Geookolje)" or shortly RMZ - M&G.

RMZ - M&G is managed by an international advisory and editorial board and is exchanged with other world-known periodicals. All the papers are reviewed by the corresponding professionals and experts.

RMZ - M&G is the only scientific and professional periodical in Slovenia, which is published in the same form nearly 50 years. It incorporates the scientific and professional topics in geology, mining, and geotechnology, in materials and in metallurgy.

The wide range of topics inside the geosciences are wellcome to be published in the RMZ -Materials and Geoenvironment. Research results in geology, hydrogeology, mining, geotechnology, materials, metallurgy, natural and antropogenic pollution of environment, biogeochemistry are proposed fields of work which the journal will handle. RMZ - M&G is co-issued and co-financed by the Faculty of Natural Sciences and Engineering Ljubljana, and the Institute for Mining, Geotechnology and Environment Ljubljana. In addition it is financially supported also by the Ministry of Higher Education, Science and Technology of Republic of Slovenia.

Editor in chief

Table of Contents – Kazalo

Foreword

The metaphor »standing on the shoulders of giants« has marked the progress of science throughout the centuries. Although it is sometimes attributed to Isaac Newton, in reality, its origins go back much further in human history. But the most important thing is not the saying itself or the time of its first appearance, it is the message that it carries. Knowledge is like a pyramid whose top will collapse by taking away even the smallest part of its foundations. Nobody, regardless of their success and talent, achieves greatness alone, but is shown the right direction by the teachers who help pave part of the way. Without their advice, and sometimes orders, it would be impossible to continue down the path. And this is the message of the saying. All who buildand perfect their knowledge are only sitting on the shoulders of our ancestors.

This jubilee edition is dedicated to our teachers who have paved the way for the present generation of geologists. All of these teachers havededicated their time to a specific part of geology, mastered it, and transmitted the knowledge to younger generations. They have researched vast areas of geology, including petrology, mineralogy, geochemistry, sedimentology, tectonics, regional geology and palaeontology. This is why the papers are also very varied. Their students, especially colleagues who have graduated under their mentorship, have presented us with a short summary of current geological research dealing with previously listed areas of geology and reconfirmed the varied character of Slovene geology. The present collection is therefore a modest compliment to the teaching and scientific contribution of Dragica Strmole, Jože Čar, PhD, Professor; Rajko Pavlovec, PhD, Professor; and Simon Pirc, PhD, Professor. With their work, they have significantly contributed to the development and progress of Slovene geological sciences.

Finally, we would like to thank all the authors of the papers who have kindly responded to our request and thus honoured an important jubilee of their teachers and mentors. Special thanks also go to the editors of this collection who have spent a lot of their time and energy on its realization, and last but not least, to the editorial board of RMZ – Materials and geoenvironment journal, who have included our collection in their program. Everybody has thus not only shown respect for the teachers, but has also added another stone to the colourful mosaic of the knowledge of the geological history of Earth and of its phenomena.

Associate Professor, Mihael Brenčič, PhD,
Head of Department of Geology

Uvodnik

Predgovor

Rek »*Na ramenih velikanov*« zaznamuje pot znanosti skozi stoletja. Čeprav ga velik del literature pripisuje Newtonu, njegove korenine segajo globoko v človekovo preteklost. A ni pomemben zgolj rek in kdaj se je le-ta razvil, pomembnejše je njegovo sporočilo. Znanje je kot piramida, katere vrh se poruši, če mu spodmakneš le del temeljev. Nihče, pa če je še tako uspešen in nadarjen, ne zraste iz sebe, ampak mu njegovo pot tlakujejo učitelji, velik del poti prehodi po poti, ki so mu jo uhodili oni in nakazali njegovo smer. Brez njihovih nasvetov in včasih tudi ukazov, ne bi našel poti naprej. In to je pomen tega reka. Vsi, ki se ukvarjamo z znanjem in ga gradimo ter izpopolnjujemo, le sedimo na ramenih naših predhodnikov.

Tokratno jubilejno številko posvečamo našim učiteljem, ki so sedanji generaciji aktivnih geologov utrli nove smeri. Vsak od naših tokratnih slavljencev se je posvetil delu geološke znanosti in jo izmojstril ter svoje znanje prenesel na mlajše generacije. Učitelji, katerim posvečamo zbornik, so posegli na zelo široka področja geologije: od petrologije, mineralogije, geokemije, sedimentologije, tektonike, regionalne geologije do paleontologije. Zaradi tega je pester tudi naš zbornik. Njihovi učenci, predvsem kolegi, ki so doktorirali pod njihovim mentorstvom, nam predstavljajo kratek pregled aktualnih geoloških raziskav z vseh prej naštetih področij geologije ter tako ponovno potrjujejo pestrost slovenske geologije.

Zbornik, ki je pred nami, naj bo tako skromen poklon učiteljskemu in znanstvenemu prispevku Dragice Strmole, prof. dr. Jožeta Čarja, prof. dr. Rajka Pavlovca in prof. dr. Simona Pirca. S svojim delom so pomembno prispevali k razvoju in napredku slovenske geološke znanosti in šole.

Na koncu velja tudi posebna zahvala vsem avtorjem prispevkov, ki so se prijazno odzvali in s tem počastili pomembno obletnico svojih učiteljev in mentorjev. Prav tako velja zahvala urednikom zbornika, ki so v njegovo pripravo vložili nemalo svoje energije in časa, ter ne nazadnje velja zahvala tudi uredništvu revije RMZ – Materiali in geookolje, ki je zbornik, posvečen našim jubilantom, uvrstilo v svoj program. S tem so vsi skupaj izrazili ne le spoštovanje do jubilantov in njihovega dela, temveč so s svojimi prispevki položili še en kamen v pester mozaik poznanja geološke zgodovine Zemlje in njenih pojavov.

Izr. prof. dr. Mihael Brenčič
predstojnik Oddelka za geologijo

Osemdeset let življenja in dela Dragice Strmole

Dragica Strmole, diplomirana geologinja in dolgoletna asistentka in višja strokovna sodelavka Oddelka za geologijo, je letos spomladi izpolnila jubilejnih osemdeset let. Rojena je bila v Ljubljani, kjer je tudi obiskovala in končala osnovno šolo in gimnazijo. Svojo geološko pot je začela leta 1950 z vpisom na Prirodoslovno-matematično fakulteto Univerze v Ljubljani, Oddelek za geologijo in paleontologijo. Po uspešno končanem študiju se je leta 1956 najprej zaposlila na Geološkem zavodu v Ljubljani kot geolog petrograf in opravila strokovni izpit. Z začetkom študijskega leta 1961 pa se je zaposlila kot asistentka na Katedri za mineralogijo in petrografijo Oddelka za montanistiko na Fakulteti za naravoslovje in tehnologijo Univerze v Ljubljani, kjer je delovala vse do svoje upokojitve v letu 1991. Leta 1974 je bila izvoljena v naziv višja strokovna sodelavka. Po upokojitvi je še vedno ostala aktivna v slovenski geologiji in je še danes zunanja sodelavka Oddelka za geologijo. Za študente geologije, pa tudi drugih ved, ki so v svoj kurikul vključevale geologijo, je vodila vaje iz predmetov Kristalografija, Mineralogija, Petrologija in Laboratorijska preiskava mineralov (kasneje Preiskovalne metode v mineralogiji). Poleg pedagoškega dela je izvajala tudi mikroskopske mineraloške in petrografske preiskave, preiskave trdote mineralov in preiskave z metodo faznega kontrasta. Njen opus raziskovalnih del vsebuje članke s področja mineraloških in petrografskih analiz različnih magmatskih kamnin Slovenije, rudonosnih kamnin Črne gore in glinenih sedimentov. Sodelovala je tudi pri pripravi Geološkega terminološkega slovarja, monografije, ki je bila v slovenskem prostoru težko pričakovana.

Prav vsi študenti geologije, ki smo študirali v obdobju njenega delovanja na Oddelku za geologijo, smo se osnov kristalografije, mineralogije, petrologije in preiskav materialov naučili iz njenih jasnih in nazornih razlag ter z njeno neutrudno pomočjo. Vsakega od nas je dobro poznala in nam vlivala potrebnega poguma za premagovanje prvih in najtežjih ovir, s katerimi smo se srečevali na začetku naše geološke poti. Vedno dostopna in pripravljena na pogovor je marsikomu pokazala pot skozi labirint kristalografije, precej nas pa je navdušila za to, da smo se usmerili v raziskave kristalov in mineralov ter v petrologijo. Tako kot do študentov, je bila vedno spodbudna, razumevajoča in v pomoč pri uvajanju v novo področje dela tudi do vseh sodelavcev. Kot asistentka in sodelavka, tudi in predvsem pa v obdobju, ko je vodila Oddelek za geologijo, je vso energijo vložila v to, da so bile razmere za delo in študij na Oddelku za geologijo optimalne, kolektiv je deloval združno kot enota ter strokovno, kar s(m)o doživeli tudi študenti, ki s(m)o v letih študija osvojili obsežno znanje za uspešno delo geologa.

Meta Dobnikar

Phase contrast method for asbestos fibres determination

Uporaba metode faznega kontrasta za določanje azbestnih vlaken

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Abstract: Certain diseases, such as lung cancer or pleural mesothelioma are highly connected to inhalation of asbestos fibres. Asbestos is therefore considered as hazardous material. Use of chrisotile is forbidden in technologically advanced countries, and defined as asbestos is all material, having more then 1 % asbestos fibres. Using optical microscopy and phase contrast method, asbestos fibres were qualitatively and quantitatively determined in different soil and dust samples. The method was proved to be accurate and convenient. Most of the examined material was determined as asbestos.

Izvleček: Pojavi določenih bolezni, kot je na primer pljučni rak ali plevlarni mezoteliom, imajo močno povezavo z izpostavljenostjo oziroma vdihavanjem azbestnih vlaken. Azbest je zato obravnavan kot zdravju nevaren material in uporaba hrizotila je v industrijsko razvitih državah prepovedana. Kot azbest se obravnava vsak material, ki vsebuje več kot 1 % azbestnih vlaken. Z uporabo optičnega mikroskopa in metode faznega kontrasta je bila kvalitativno in kvantitativno določena vsebnost azbestnih vlaken v vzorcih tal in prahu. Metoda se je izkazala za primerno oz. bolj natančno za namen določanja vsebnosti azbestnih vlaken. Ugotovili smo, da večina preiskanih materialov vsebuje več kot 1 % azbestnih vlaken in jih lahko opredelimo kot azbestne materiale.

Key words: asbestos, phase contrast method, optical microscopy

Ključne besede: azbest, metoda faznega kontrasta, optična mikroskopija

Professional paper

Introduction

The term “asbestos” is used for fibre occurrence of different minerals, silicates from amphibole and serpentine group. Asbestos fibres are defined as crystals with length to diameter ratio at least 3 : 1, if length is more then 5 μm and diameter less then 3 μm (Falini et al., 2003). Amphibole and serpentine group minerals are highly resistant, chemically inert and stable, forming flexible and solid fibres. Asbestos was, due to its chemical and physical properties, commonly used in industry, especially in civil engineering and fire resistant materials. Near to 95 % of asbestos used belongs to mineral chrisotile, with ideal chemical composition $Mg_3Si_2O_5(OH)_4$, fibrous variety of serpentine, trioctahedral magnesia analogue of kaolinite, 1 : 1 alumosilicate. As certain diseases, such as lung cancer or pleural mesothelioma are highly connected to inhalation of asbestos fibres, it is considered as hazardous material (Falini et al., 2003). Asbestos fibres are too small to be expelled from inhalation path by human natural defence system, therefore they enter into the body by inhalation paths and deposit in human lungs. Use of chrisotile is forbidden in technologically advanced countries, EPA (Environmental Protection Agency) defined as asbestos all material, having more then 1 % asbestos fibres (Burdett, 2006).

Recommended method for asbestos fibres determination is optical microscopy in plane polarised light. The method is relatively inaccurate when asbestos content is around 1 %. Analysis results turn out much better in combination of this optical microscopy method with phase contrast method, when content of asbestos fibres down to 0,1 % may be determined. It is worth noting that fibres with diameter less then 1 μm difficult to determine by optical microscope (Burdett, 2006).

The phase contrast method

The resolution of optical microscope depends on its quality and is around 5 μm. For qualitative and quantitative determination of asbestos fibres the two methods (optical microscopy in plane polarised light and phase contrast method) have to be combined. Material is observed in immersion with appropriate refraction index and dispersion. Nitrobenzol is used most commonly.

At phase contrast method optical microscope with polarised light is used. There is phase plate inserted within objectives, to change phase light changes into amplitude light changes in order to enable phase objects (objects as small grains or fibres, that only change the phase of the light) to be seen under the microscope. Con-

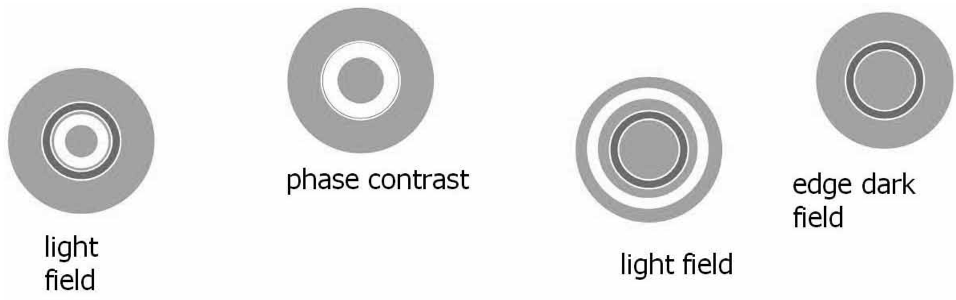

Figure 1. Phase plate (dark circle) and light circle projection at the objective.

denser annulus is used to gather the light into a ring. The size of the light ring can be changed, so we may successively observe bright field (light ring smaller then phase plate ring), phase contrast field (light ring just the same size as phase plate ring), bright field (light ring larger then phase plate ring) and edge dark field (light ring at the edge of visible field) (Figure 1). Asbestos fibres are colourless and therefore hardly visible in polarised light, are typically coloured in phase contrast, so qualitative and quantitative analysis of the fibres is enabled.

Example of asbestos fibres analysis in soil samples and air filters

33 samples of soils and air filters were analysed qualitatively and quantitatively for asbestos fibres content, using the phase contrast method. 26 samples of soil and 7 air filters were analysed.

Samples of soils and filters were examined in phase contrast using Leitz Wetzlar optical microscope (Figure 2), with condenser annulus and objectives with phase plates used.

Samples were analysed at objective 40-times and ocular 10-times. Immersion of nitrobenzole ($C_6H_5NO_2$), with refraction index 1.55 was used. When counting asbestos fibres, those of width less then 3 μm, and length more then 5 μm and less then 15 μm, with width to length ratio ≤1 : 3 were considered.

In air filter samples, all asbestos fibres within 1 cm^2 area of the filter were counted.

In soil samples, mineral grains were counted according to the method of regular profiles. All grains within linear horizontal profile were counted. Vertical distance between the profiles and one step on the profile were 0.4 mm. 500 mineral grains of each sample were counted. Results are presented in the number of respirable asbestos fibres per 100 mineral grains (Table 1).

Table 1. Results of the asbestos fibers counting with optical microscope phase contrast method:

sample	No. of respirable asbestos fibers per 100 mineral grains
S-1	0.5
S-3	3
S-4	4.7
S-5	1.5
S-7	1
S-11	6.2
S-12	5
S-16	2.4
S-20	4.4
MK-4	1
MK-9	11.8
MK-11	0.8
MK-19	0
Uz. iza igr.	6.4
Uz. tlo (igr.)	5
BS1-2	1.6
BS1-5	6.4
BS1-6	5.2
BS1-7	5.6
BS1-8	1.2
BS3-1	1.6
BS3-2	7.4
BS3-3	6.8
BS8-3	17.2
BS9-4	1.6
BS9-5	7.4
Filters	**No. of respirable asbestos fibres per 1 cm^2**
U1	256
U2	177
U3	193
US1	349
UV10	106
UX2	134
UP3	2331

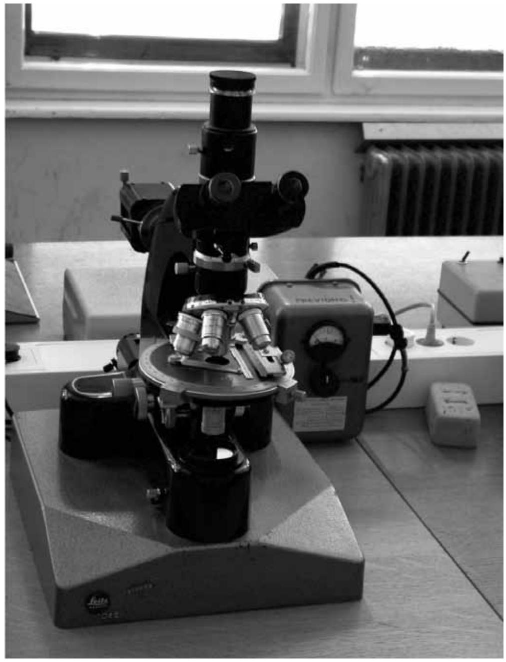

Figure 2. Optical microscope Leitz Wetzlar

Conclusion

Respirable asbestos fibers were quantitatively determined in soil samples as well as in air filters with the use of phase contrast method. The selected method proved to be adequate and accurate. Results of analysis show that the majority of analysed samples contain more then 1 % of asbestos fibres, and should be considered as hasardeous, asbestos containing materials.

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Osemdeset let življenja in dela profesorja geologije dr. Rajka Pavlovca

Letošnjega 15. januarja je profesor Rajko Pavlovec praznoval svoj 80. rojstni dan. Rodil se je v Ljubljani, kjer je obiskoval osnovno šolo, klasično gimnazijo in maturiral leta 1950. Odločil se je za študij geologije na ljubljanski univerzi in leta 1954 diplomiral. Po diplomi se je zaposlil na takratnem Inštitutu za geologijo, ki se je leta 1966 preimenoval v Inštitut za paleontologijo Slovenske akademije znanosti in umetnosti. Leta 1962 je obranil doktorsko disertacijo Stratigrafski razvoj starejšega terciarja v jugozahodni Sloveniji s posebnim ozirom na numulite in asiline pod mentorstvom prof. dr. Ivana Rakovca. Po doktoratu je odšel na izpopolnjevanje kot štipendist ustanove Alexander von Humboldt-Stiftung na univerzi v Münchnu. V obdobju od 1971 do 1975 je uspešno deloval kot knjižni urednik v založbi Mladinska knjiga. V letu 1975 je bil izvoljen v naziv izrednega in leta 1981 za rednega profesorja na Fakulteti za naravoslovje in tehnologijo Univerze v Ljubljani.

Na Fakulteti za naravoslovje in tehnologijo je poučeval vsebine dodiplomskih predmetov: osnove stratigrafije, biostratigrafija, regionalna geologija, stratigrafija in specialna paleontologija za študente različnih letnikov geologije, predmet geologija in paleontologija za študente biologije in pedagogike na Pedagoški fakulteti v Mariboru, predmet geologija in geomorfologija za študente geodezije na Fakulteti za gradbeništvo in geodezijo ljubljanske univerze ter magistrski predmet mikropaleontologija paleogena na univerzi v Ljubljani. Bil je mentor domačim in tujim diplomantom, magistrandom in doktorandom, organiziral je številne strokovne ekskurzije. Dalj časa je bil tudi predsednik komisij pri diplomah, magisterijih in doktoratih ter član številnih drugih komisij. Na takratni Fakulteti za naravoslovje in tehnologijo je imel tudi več pomembnih in vodilnih funkcij. Leta 1974 je bil predstojnik odseka za geologijo pri takratni Montanistiki, v obdobju 1987–1990 prodekan in v letih 1993–1995 dekan FNT. Upokojil se je 1. oktobra 2005. Med študenti je bil priljubljen zaradi svojih živahnih predavanj, med katera je znal vključiti marsikatero šalo ali anekdoto.

S predavanji, referati in posterji je v obdobju od leta 1957 do 2005 sodeloval na številnih kongresih, simpozijih in posvetovanjih doma in v tujini, večinoma s

Predstavitev

problematiko o velikih foraminiferah in z njimi povezano stratigrafijo paleogena. Napisal je okrog 350 znanstvenih razprav in strokovnih člankov, objavljenih v domačih in tujih revijah ter zbornikih.

Celotna bibliografija prof. Pavlovca je zelo obsežna in je po tematiki zelo bogata ter raznovrstna. Objavljenih ima nad tisoč prispevkov. Sodeloval je pri mnogih monografijah in objavil dve samostojni poljudni knjižici. Prva z naslovom Kras je bila dalj časa v šolah obvezno čtivo. V svojem obsežnem opusu je imel tudi veliko predavanj, napisal je več recenzij, ocen in poročil. Samostojno ali skupaj s sodelavci je Pavlovec ugotovil in opisal tudi več novih vrst in podvrst paleogenskih foraminifer: *Nummulites vipavensis* iz Ustij v Vipavski dolini, *N. ustjensis* iz Ustij, *N. quasilaevigatus* iz Vipolž v Brdih, *N. brkinensis* in *N. postbearnensis* iz Podgrada v Brkinih, *Assilina medanica* iz Vipolž v Brdih, *Ass. marinellii similis* iz Podgrada, *Ass. maxima* iz Grožnjana v Istri, *Ass. monacensis* iz Stene ob Dragonji, *Ass. istrana* iz Dola pri Hrastovljah, *Ass. exiliformis* iz Jelšan pri Slovenski Bistrici in dve školjčni vrsti: *Cardium culjinense* iz Čuljine pri Drnišu in *Spondylus variocostatus* iz Gluvače pri Drnišu. Z vsemi navedenimi na novo spoznanimi fosilnimi oblikami organizmov se je prof. Pavlovec za vedno zapisal v register domače in svetovne paleontološke znanstvene litetarture. Marsikatero od navedenih vrst so pozneje ugotovili tudi zunaj naše domovine.

Izredno veliko je naredil za popularizacijo geološke in paleontološke znanosti med mladimi in najmlajšimi bralci s svojimi številnimi preprostimi in razumljivimi prispevki, ki jih je objavljal predvsem v slovenskih poljudnih in poljudnoznanstvenih revijah. Objavil je okrog 600 poljudnih člankov in drobnih vesti v Proteusu, Cicibanu, Pionirju in reviji Življenje in tehnika. Zaradi raznovrstnih in mnogoterih poljudnih prispevkov njegovo ime ostaja v spominu marsikaterega učenca, dijaka, študenta, učitelja in drugih ljubiteljev naravoslovja.

Bil je član več domačih in tujih društev, urednik in član uredniških odborov pri mnogih periodičnih in monografskih publikacijah. V domačih društvih je še vedno aktiven. Prof. Pavlovec je bil v letih od 1965 do 1969 tudi predsednik Slovenskega geološkega društva, v obdobju od leta 1977 do 1980 pa predsednik Prirodoslovnega društva Slovenije. V letu 2002 je postal častni član Društva Ex libris Sloveniae in leta 2005 častni član Društva prijateljev mineralov in fosilov v Tržiču.

Po upokojitvi prof. Pavlovec nikoli ni pretrgal vezi z matičnim Oddelkom za geologijo in je ohranil svojo živahnost in neposrednost do kolegov. Vedno rad pomaga s svojimi nasveti in bogatimi izkušnjami, s predavanji in raznimi napotki pri izvedbi učnega programa za študente geologije, je vodja Naravoslovnotehniške sekcije pri Slovenski matici, tajnik Društva Ex libris Sloveniae in organizator izredno zanimivih in priljubljenih strokovnih ekskurzij. Prav tako vsako leto napiše vsaj po en znanstveni članek in več krajših strokovnih prispevkov v različne publikacije. Nikoli ne odkloni strokovnokritičnih pregledov osnutkov člankov svojih kolegov, z izrednim posluhom za jezik popravi marsikatero nerodno izražanje in svetuje izboljšave. Zaradi njegovih dolgoletnih uredniških izkušenj in v njem zakoreninjenega redoljubja takšna besedila zelo hitro pregleda in nemudoma vrne avtorjem, kar je ena od njegovih številnih pozitivnih osebnostnih značilnosti.

Za svoja dela je prejel tudi več nagrad in odlikovanj. Leta 1955 je prejel Prešernovo nagrado Univerze v Ljubljani za študente, leta 1964 nagrado Sklada Borisa Kidriča, leta 1977 Levstikovo nagrado Mladinske knjige in leta 1980 medaljo Bele vrane s sončnico Društva ljubiteljev knjig v Lublinu. Leta 1984 pa je bil odlikovan z redom republike z bronastim vencem.

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Vasja Mikuž in Jernej Pavšič

Ostanki peresastih koral iz eocenskih plasti pri Gračišću blizu Pazina v Istri

A sea pen remnants from Eocene beds at Gračišće near Pazin in Istria, Croatia

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Izvleček: V prispevku sta obravnavana dva skromna ostanka peresastih koral (Pennatulacea) iz srednjeeocenskih – lutetijskih skladov najdišča Gračišće pri Pazinu v Istri na Hrvaškem. Ugotovljeno je, da sta najdena ostanka od dveh različnih oblik oktokoral iz družine Pennatulidae, ki pripadata rodu *Graphularia*.

Abstract: Discussed are two modest remains of sea pen corals (Pennatulacea) from Middle Eocene – Lutetian beds of Gračišće locality near Pazin in Istria (Croatia). The found remains belong to two distinct forms of octocorals of Pennatulidae family, of *Graphularia* genus.

Ključne besede: peresaste korale (Pennatulacea), Graphularia, nanoplankton, srednji eocen – lutetij, Gračišće, Istra, Hrvaška
Key words: sea pens (Pennatulacea), Graphularia, nanoplankton, Middle Eocene – Lutetian, Gračišće, Istria, Croatia

Uvod

Gračišće blizu Pazina je majhen, tipično istrski zaselek (sliki 1 in 2). Pod njim so ob regionalni cesti Gračišće–Pićan razgaljeni profili paleogenskih apnencev in flišnih kamnin. Na nekaterih odsekih, kjer izdanjajo apnenčeve, grobo klastične eocenske olistostrome (slika 3), je veliko najrazličnejših fosilnih ostankov. V preteklosti smo v omenjenih srednjeeocenskih sedimentih že našli dva inter-

Original scientific paper

nodija roženastih koral (Gorgonacea), ki pripadata vrsti *Isis nummulitica* (Mikuž 2008 in 2010). Med fosilnimi ostanki smo opazili tudi majhne, drobne, kratke paličaste in nepravilne oblike, ki jim dolgo časa nismo posvečali večje pozornosti. V prerezih imajo okroglo, ovalno do subkvadratasto obliko. Na obeh

Slika 1. Geografski položaj najdišča Gračišće pri Pazinu v Istri
Figure 1. Geographical position of site Gračišće at Pazin in Istria

Slika 2. Zaselek Gračišće, jugovzhodno od Pazina na Hrvaškem
Figure 2. The village Gračišće, southeast of Pazin in Croatia
Foto (Photo): V. Mikuž 2008

Slika 3. Izdanki srednjeeocenske olistostrome ob cesti Gračišće–Pićan
Figure 3. The outcrops of Middle Eocene olistostrome along the road Gračišće – Pićan
Foto (Photo): V. Rakovc, 1998

odlomljenih delih apnenčeve paličice opažamo koncentrično-radialno zgradbo z majhno osrednjo votlinico velikosti pike. Glede na opaženo strukturo smo sklepali, da gre za skeletne ostanke nekih organizmov. Izkazalo se je, da smo našli posamezne dele skeleta oktokoral iz skupine peresastih koral (Pennatulacea) oziroma iz rodu *Graphularia*.

Geološka zgradba v najdišču Gračišće

Hagn, Pavlovec in Pavšič (1979: G185–G186) pišejo, da je v Gračišću olistostroma znotraj flišne serije kamnin. Olistostroma je bila formirana v mlajšem delu srednjega eocena oziroma v lutetiju. Starost potrjujejo majhne in velike foraminifere v laporastem vezivu ter številne vrste kalcitnega nanoplanktona. Očitno je tudi, da so bili organizmi iz plitvejših delov bazena preneseni ali postrgani v globlje predele takratnega morskega bazena, saj imamo danes v najdišču povsem mešano združbo različnih fosilnih ostankov. Združba nanofosilov določa plastem pri Gračišću zgornjelutetijsko starost oziroma biocono Discoaster tani nodifer (NP 16).

Paleontološki del

Sistematika po: Bayer 1956, Bałuk & Pisera 1984

Classis Anthozoa Ehrenberg, 1834
Subclassis Octocorallia Haeckel, 1866
Ordo Pennatulacea Verrill, 1865
Subordo Subsessiliflorae Kükenthal, 1915

Genus *Graphularia* Milne Edwards & Haime, 1850

Rod *Graphularia* sta postavila Milne Edwards in Haime leta 1850. Prve primerke tega rodu so našli v londonskih glinah (Branco 1885: 423), vendar Branco (1885) ne omenja podatkov o starosti teh glin. Po podatkih Toulae (1918: 418) so londonske gline spodnjeeocenske starosti. Zittel (1880, 209) navaja, da so fosilne primerke rodu *Graphularia* odkrili v eocenskih skladih Anglije in severne Afrike. Zittel (1895: 98) piše, da je rod *Graphularia* značilen za terciarne sklade in ga uvršča k družini Pennatulidae. Alloiteau (1952: 415) rod *Graphularia* omenja med tistimi rodovi, katerih sistematski položaj ni določen. Bayer (1956: F228) omenjeni rod uvršča v družino Virgulariidae in poddružino Virgulariinae, ki jih je postavil Verill, 1868. Bałuk & Pisera (1984: 205) poročata o najdbi nove peresaste korale vrste *Graphularia transaedina* iz miocenskih badenijskih plasti Poljske, ki ima skeletne ostanke v prerezu kvadrataste oblike. Iz interneta [1, 2] smo izvedeli, da danes rod *Graphularia* uvrščajo k družini Pennatulidae Ehrenberg 1834, torej tako kot Zittel leta 1895.

Graphularia cf. *desertorum* Zittel, 1880

Tab. 1, sl. 1a–1d

cf. 1880 *Graphularia desertorum* Zitt.

– Zittel, 209, Fig. 117
cf. 1880 *Graphularia desertorum* Zittel – Roemer, 116–117
cf. 1885 *Graphularia desertorum* Zittel – Branco, 424, Taf. 20, Figs. 11, 11a–11b
cf. 1895 *Graphularia desertorum* Zitt. – Zittel, 98, Fig. 190
cf. 1912 *Graphularia desertorum* Zittel – Andrée, 207
cf. 1925 *Graphularia desertorum* Zittel 1880 – Felix, 288

Material: Razmeroma skromen fragment oziroma del skeletnega segmenta (tab. 1, sl. 1a–1d) iz srednjeeocenskih – lutetijskih skladov v okolici Gračišća pri Pazinu

Najdišče: Izdanki srednjeeocenske olistostrome pod zaselkom Gračišće (slika 3) z bogato in raznoliko mikro- in makrofavno. Makrofavnistični ostanki so večinoma zelo slabo ohranjeni, razen nekaterih izjem, kot so velike numulitine, poliheti in redki morski ježki. Ob cesti proti Pićnu je velik del profila prekrit z umetno cementno utrditvijo in je od leta 2008 dalje praktično nedostopen.

Opis: Ohranjen je samo krajši del karbonatnega skeletnega segmenta, ki je paličaste in nekoliko sploščene oblike (tab. 1, sl. 1a–1b). V prerezu je nepravilne ovalne do štirikotne oblike. Na ožji ploščati strani poteka vzdolžno ozek zaobljen greben, ki ima ob straneh dve ozki zarezi, na nasprotni ploščati strani pa širok plitev žleb. Na prečno prerezanih površinah segmenta se vidijo koncentrično potekajoče prirastne linije, na sredini prereza je temnejše polje oziroma nekdanji osrednji kanal (tab. 1, sl. 1c). Radialno potekajoče linije so prikrite in manj opazne. Na stranskem, najbolj zašiljenem robu segmenta opazimo poškodbo (tab. 1, sl. 1d), kjer lahko opazujemo lupinasto zgradbo skeletnega elementa. Površina predstavljenega dela peresaste korale je gladka.

Velikost delca (Size of fragment):
dolžina (Length) = 17 mm
premer 1 (Diameter 1) = 4,5 mm
premer 2 (Diameter 2) = 3,2 mm

Primerjava: Opisani skeletni fragment peresaste korale iz Gračišća velikostno in oblikovno zelo ustreza zgornjemu širšemu delu primerka iz libijske puščave, ki ga prikazuje (Zittel 1880: Fig. 117). Razlika je samo v površinski ornamentaciji, gračiški primerek je bolj gladek, severnoafriški ima več tankih vzdolžnih črt. V marsičem je gračiški primerek podoben tudi skeletnemu fragmentu iste vrste, ki ga predstavlja Branco (1885: Taf. 20, Figs. 11, 11a–11b). Andrée (1912: 204) je raziskoval oligocenske ostanke iz Nemčije (Mainza) in postavil novo vrsto *Graphularia crecelii*. Skeletni deli te vrste tudi v marsičem spominjajo na vrsto *Graphularia desertorum*. Mislimo, da med njima ni bistvenih razlik.

Stratigrafska in geografska razširjenost: Branco (1885: 423, Taf. 20, Figs. 11) opisano vrsto *Graphularia desertorum* predstavlja iz eocenskih numuli-

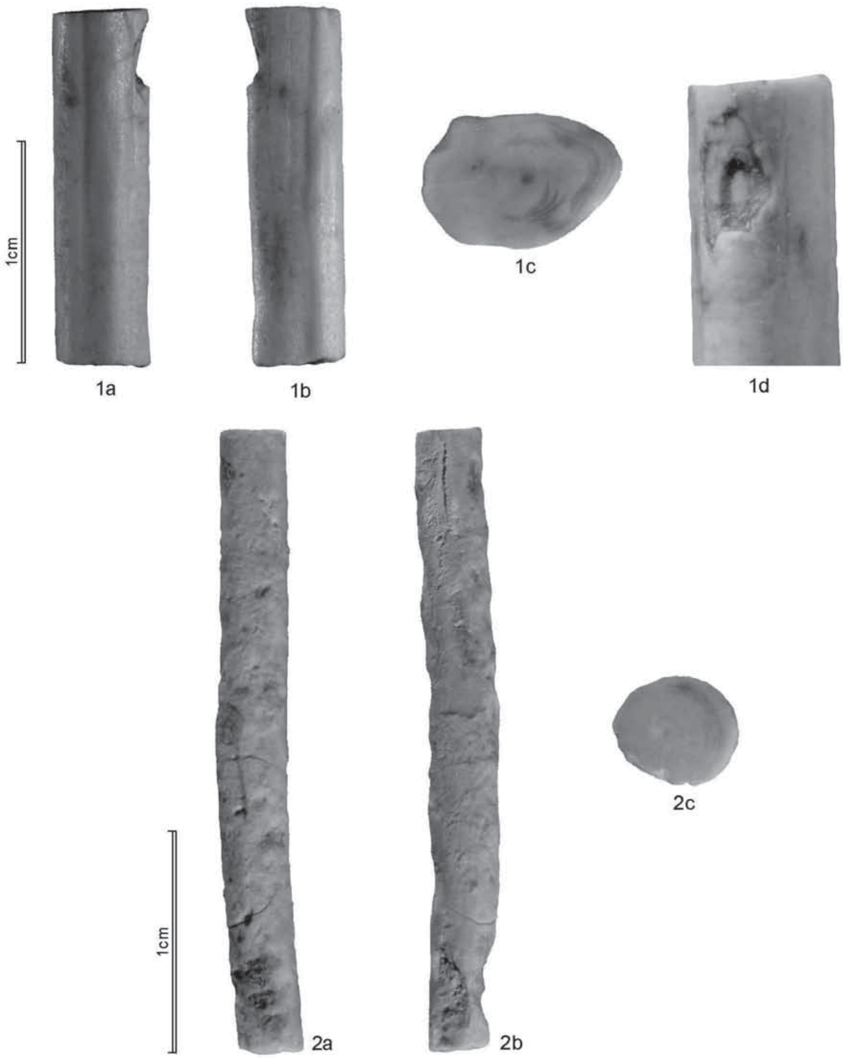

Tabla 1.

1a *Graphularia* cf. *desertorum* Zittel, 1880; apnenčasti del skeleta s sploščene strani, srednjeeocenska olistostroma blizu Gračišća pri Pazinu na Hrvaškem, velikost primerka 17 mm × 4,5 mm × 3,2 mm

1b Isti primerek z druge strani

1c Prerez istega primerka s koncentrično strukturo, povečano

1d Lupinasta zgradba apnenčevega skeleta, povečano

2a *Graphularia incerta* (D`Archiac, 1848); del apnenčevega skeleta, Gračišće pri Pazinu, velikost primerka 29,5 mm × 3 mm × 2,9 mm

2b Isti primerek z druge strani

2c Prerez istega primerka s koncentrično lupinasto zgradbo, povečano

Plate 1.

1a *Graphularia* cf. *desertorum* Zittel, 1880; flat side of calcareous skeletal fragment, Middle Eocene olistostrome near Gračišće at Pazin in Croatia, size of specimen 17 mm × 4.5 mm × 3.2 mm
1b The same specimen from reverse side.
1c The same specimen, cross section with concentric structure, enlarged.
1d Layered structure of calcareous skeleton, enlarged.
2a *Graphularia incerta* (D`Archiac, 1848); calcareous skeletal fragment, Gračišće near Pazin, size of specimen 29.5 mm × 3 mm × 2.9 mm
2b The same specimen from reverse side.
2c Cross section of the same specimen with concentric layered structure, enlarged.
Fotografije (Photos): Marijan Grm

tnih apnencev libijske puščave. Zittel (1895: 98) piše, da je bila najdena v eocenskih numulitnih apnencih v kraju Farafrah v libijski puščavi. Felix (1925: 288) navaja, da so ostanki opisane vrste najdeni v eocenskih numulitnih apnencih libijske puščave v najdišču El-Guss--Abu-Said pri kraju Farafrah. Isti avtor omenja še druga najdišča.

***Graphularia incerta* (D`Archiac, 1848)**
Tab. 1, sl. 2a–2c

1848 *Virgularia incerta*, nov. sp. – D`Archiac, 414, Pl. 9, Figs. 14, 14a
1880 *Graphularia incerta* M. Edw. et H. (*Virgularia incerta* d`Archiac) – Roemer, 117
1885 *Graphularia incerta* Edw. u Haime – Branco, 424
1912 *Graphularia incerta* d`Arch. – Andrée, 207
1925 *Graphularia incerta* d`Archiac sp. 1848 – Felix, 288
1950 *Graphularia incerta* Edw. & Haime – Malaroda, 150

Material: Kratek paličast del manjšega premera (tab. 1, sl. 2a–2c), ki je bil najden v istem najdišču v okolici Gračišća pri Pazinu (slika 3).

Opis: Fragment skeletnega dela peresaste korale je paličast in rahlo ukrivljen (tab. 1, sl. 2a–2b). Površina segmenta je precej korodirana in zato jamičasta ter razpokana. Na površini ni opazne nikakršne ornamentacije. V prerezih je okrogle oblike, lepo se vidi osrednji kanal in okoli njega koncentrično potekajoče prirastne linije (tab. 1, sl. 2c). Tudi tu se vidi značilna lupinasta zgradba apnenčevega segmenta. Na eni strani, kjer je brušena in polirana površina, se v prečnem prerezu vidi tudi zelo tanka radialna struktura.

Velikost delca (Size of fragment):
dolžina (Length) = 29,5 mm
premer (Diameter) = 3 × 2,9 mm

Primerjava: Gračiški primerek je primerljiv s primerkom D`Archiac-a (1848: Taf. 9, Figs. 14, 14a), ki je približno enakega premera in prav tako okroglega prereza. Deloma je primerljiv tudi s primerki vrste *Graphularia pyrenaica* (Doncieux 1926: Pl. 3, Figs. 13–19) iz spodnjelutetijskih plasti v okolici Biarritza v jugozahodnem delu Francije.

Stratigrafska in geografska razširjenost: D`Archiacov primerek (1848) je iz srednjeeocenskih plasti Biarritza v Franciji. Malaroda (1950: 151) jo omenja iz zgornjeeocenskih plasti Italije (Colli Berici), nadalje še piše, da so opisano vrsto *Graphularia incerta* ugotovili v eocenskih skladih angleško-pariškega bazena, v lutetijsko-rupelijskih plasteh Akvitanije v Franciji, v rupelijskih Nemčije in celo v miocenskih Dunajske kotline.

V laporastem vezivu olistostrome ali kaotične breče v Gračišću je ugotovljeno 30 nanoplanktonskih oblik:
Campylosphaera dela (Bramlette et Sullivan)
Chiasmolithus grandis (Bramlette et Riedel)
Coccolithus eopelagicus (Bramlette et Riedel)
Coccolithus formosus (Kamptner)
Coccolithus pelagicus (Wallich)
Cyclococcolithus neogammation (Bramlette et Wilcoxon)
Discoaster aster Bramlette et Riedel
Discoaster barbadiensis Tan
Discoaster binodosus Martini
Discoaster binodosus hirundinus Martini
Discoaster deflandrei Bramlette et Riedel
Discoaster distinctus Martini
Discoaster keupperi (Stradner)
Discoaster saipanensis Bramlette et Riedel
Discoaster tani Bramlette et Riedel
Discoaster tani nodifer Bramlette et Riedel
Girgisia gammation (Bramlette et Sullivan)
Helicosphaera cf. *obliqua* Bramlette et Wilcoxon
Micrantholithus flos Deflandre
Neococcolithes dubius (Deflandre)
Pontosphaera plana (Bramlette et Sullivan)
Prediscosphaera cretacea (Arkhangelsky)
Reticulofenestra bisecta (Hay, Mohler et Wade)
Reticulofenestra coenura (Reinhardt)
Reticulofenestra umbilica (Levin)
Rhabdosphaera tenuis (Bramlette et Sullivan)
Sphenolithus radians Deflandre
Tetralithus obscurus Deflandre
Tribrachiatus orthostylus (Bramlette et Riedel)
Zygrhablithus bijugatus (Deflandre)

Sklepi

Predstavljena ostanka srednjeeocenskih oktokoral iz reda peresastih koral (Pennatulacea) sta najdena v olistostromi blizu Gračišća pri Pazinu v Istri (slika 3). Do zdaj takšna fosilna ostanka iz Istre še nista bila nikoli dokumentirana. Apnenčeva skeletna fragmenta sta zelo skromna, vendar imata vse tiste značilnosti, na podlagi katerih jih lahko uvrstimo k dvema različnima oblikama peresastih koral, k vrstama *Graphularia* cf. *desertorum* Zittel, 1880 (tab. 1, sl. 1a–1d) in *G. incerta* (D`Archiac, 1848) (tab. 1, sl. 2a–2c). Obe obliki sta iz družine Pennatulidae. Priznati moramo, da od vsega začetka nismo pričakovali apnenčevih skeletnih delov oktokoral, zato so v naši zbirki fosilnih ostankov iz Gračišća samo štirje njihovi primerki. Dva ostanka pripadata internodijema vrste *Isis nummulitica* (Mikuž 2008 in 2010). Odslej bomo bolj pozorni tudi na takšne in druge drobne ter podobne ostanke skeletov nekdanjih organizmov.

V vezivu olistostrome je ugotovljeno 30 različnih nanoflorističnih oblik. V seznamu iz Gračišća (tabela 1) je vrsta *Reticulofenestra bisecta* (Hay, Mohlet et Wade) in druge oblike, ki tamkajšnje kamnine uvrščajo v spodnji del biocone NP17 (Martini 1971) ali CP14b (Okada & Bukry 1980).

Conclusion

The remains of Middle Eocene octocorals of the order of sea pens (Pennatulacea) were found in aolistostrome close to Gračišće near Pazin in Istria (figure 3). Up to the present such fossil remains were not documented in Istria. The calcareous skeletal fragments are very modest, but they display all characteristics that permit their attribution to two distinct forms of sea pens, to species *Graphularia cf. desertorum*Zittel, 1880 (pl. 1, figs. 1a–1d) and G. *incerta* (D`Archiac, 1848) (pl. 1, figs. 2a–2c). Both forms belong to family Pennatulidae. We must admit that from the beginning on the calcareous skeletal parts of octocorals were not expected, and only four such specimens occur in our fossil collection from Gračišće. Two remains belong to internodiums of species *Isisnummulitica* (Mikuž 2008 and 2010). From now on we will be more attentive to these and similar tiny skeletal remains of ancient organisms.

30 different nannoplankton species have been found in the olistostrome matrix. The list of species from Gračišće (Table 1) contains *Reticulofenestra bisecta* (Hay, Mohler et Wade) and other species that allow the assignment of the age of the source rock to the lower part of the biozone NP17 (MARTINI 1971) or CP14b (OKADA & BUKRY 1980).

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[1] http://commons.wikimedia.org/wiki/Category:Pennatulidae (12. 9. 2012)

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Osemdeset let življenja in dela zaslužnega profesorja geologije dr. Simona Pirca

V geologiji, kjer merimo čas v milijonih let, 80 let ne pomeni ravno veliko. Seveda pa je drugače, če teh 80 let pomeni življenje in delovanje enega naših cenjenih kolegov, zaslužnega profesorja dr. Simona Pirca.

Dne 2. marca 1932, ko se je v Lipnici pri Radovljici začelo njegovo življenje, si verjetno nihče ni mislil, da ga bo posvetil prav geologiji. Po končani realni gimnaziji v Ljubljani se je namreč najprej vpisal na Fakulteto za gradbeništvo, a že po letu dni je postala in ostala njegova življenjska izbira geologija. Po diplomi leta 1961 se je kot ekonomski geolog zaposlil na Geološkem zavodu Ljubljana. Verjetno so njegov nemirni duh, želja po novih izzivih in obvladovanje več svetovnih jezikov prispevali k odločitvi, da se je priključil skupini Geološkega zavoda, ki je raziskovala rudišča v Alžiriji. Postal je vodja rudnih raziskav in uvedel do takrat za slovensko geologijo popolnoma nov način – geokemično prospekcijo. A usoda ni hotela, da bi še naprej delal kot terenski geolog. Prometna nesreča mu je pustila tako hude posledice pri hoji, da je moral poiskati drugačno karierno pot. Leta 1970 se je zaposlil na Odseku za geologijo Univerze v Ljubljani. Sodeloval je pri predmetih Mikroskopija rud in premogov ter Ocena in metode raziskav koristnih mineralnih surovin. Raziskovalno se je vedno bolj usmerjal v uporabo geokemije in statistike. Po magisteriju leta 1975 se je na študij odpravil v ZDA na pensilvanijsko državno univerzo Penn State, kjer je 1979 doktoriral.

Pridobljeno znanje je prenesel v Slovenijo predvsem z modernizacijo študijskega programa. Leta 1980 je pridobil naziv docenta ter uvedel in predaval dva popolnoma nova predmeta: Geokemija in Statistika v geologiji, svoje bogate izkušnje terenskega geologa pa delil s študenti pri predmetu Ekonomska geologija. Nepozabna so bila tudi njegova predavanja iz uporabe tuje strokovne literature. Njegova predavanja so bolj kot podajanje dejstev zaznamovali spodbujanje k razmišljanju ter poznavanje širših okvirjev vse od naravoslovnih znanosti do filozofije in umetnosti. Vedno se je trudil, da bi študenti razumeli, da je geologija globalna veda, ki se ne konča v geografskih mejah Slovenije. S svojo odprtostjo in človeškim odnosom je pritegnil številne diplomante, magistrante in doktorande.

Na raziskovalnem področju se je usmeril predvsem v geokemično kartiranje in statistične tehnike reprezentativnega vzorčenja. Uspešno je rešil probleme geokemičnega kartiranja na kraških področjih. Kartiranje z uporabo tal, vodnih mahov, vode, rastlin in podstrešnega prahu je odprlo vrata ločevanju geogenih in antropogenih vplivov in s tem novim področjem v geologiji – geologiji okolja, geomedicini in vojaški geologiji. Zavedal se je pomembnosti mednarodnih povezav in že leta 1984 postal vodja skupnih projektov z ZDA, ki so jim sledili projekti Alpe-Jadran ter IGCP-projekti, v okviru katerih je pomagal postaviti temelje geokemične karte Evrope.

Za svoje delo je leta 2005 prejel Lipoldovo medaljo, leta 2006 pa je postal zaslužni profesor ljubljanske univerze.

Tudi po upokojitvi leta 2002 ni opustil stika s stroko – prevaja strokovna in znanstvena besedila, je recenzent v domačih in tujih revijah ter član uredniškega odbora v Journal of Geochemical Exploration. S svojim bogatim znanjem in duhovitostjo občasno popestri tudi redna predavanja študentom.

Zaslužni profesor dr. Simon Pirc v življenju ni bil le pronicljiv raziskovalec in razumevajoč pedagog, temveč vedno in na prvem mestu človek. Ob jubileju mu iskreno čestitamo in želimo, da bi se tudi v njegovem devetem desetletju srečevali ob iskrivih pogovorih.

Nina Zupančič

Regionalna porazdelitev geokemičnih prvin v tleh Slovenije

Regional distribution of geochemical elements in Slovenian soils

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Izvleček: Rezultat okoljske geokemične raziskave v mreži 5 km × 5 km na območju celotne Slovenije je omogočil opredelitev geokemičnega odtisa kamnin v tleh na regionalni ravni, kar je pomembno pri interpretaciji geokemičnih procesov in za ločevanje ter oceno antropogenih obremenitev. Prikazane in komentirane so porazdelitve 28 kemičnih prvin (Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, La, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Sb, Sc, Sn, Sr, Th, Ti, U, V, W, Y, Zn in Zr). Na osnovi primerjave vsebnosti teh prvin v tleh na območju Slovenije ločimo 5 naravnih geokemičnih združb: Ni-Cr-Cu-Sc-Fe-V-Mn-Ti, K-Al-Ba-Na, La-Th-U-Zr-Y-Ti, Sr-Ca-Mg, Pb-Zn-P in združbo, ki pomeni faktor onesnaženja pri pripravi vzorcev tal.

Abstract: Evironmental geochemical investigation of Slovenia on 5 km × 5 km raster grid enabled regional determination of geochemical rock imprint on the soils. Results are important for interpretation of geochmical processes, and to discern and assess anthropogenic pressures. Distribution of 28 elements (Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, La, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Sb, Sc, Sn, Sr, Th, Ti, U, V, W, Y, Zn in Zr) are presented together with commentary. Based on the content of these elements in the soil there could be defined 5 natural geochemical associations in Slovenia: Ni-Cr-Cu-Sc-Fe-V-Mn-Ti, K-Al-Ba-Na, La-Th-U-Zr-Y-Ti, Sr-Ca-Mg, Pb-Zn-P. The sixth association Co-W is reperesentative of polution resulting in the process of soil sample preparation.

Ključne besede: radiometrične raziskave, geokemija, tla, faktorska analiza, Slovenija

Key words: radiometric survey, geochemistry, soil, factor analysis, Slovenia

Original scientific paper

UVOD

Prvo sistematično zbiranje geokemičnih podatkov sega v obdobje takoj po drugi svetovni vojni, ko so podobno kot v drugih državah tudi v Sloveniji začeli iskati radioaktivne kamnine, predvsem tiste, ki vsebujejo uran. Po odkritju uranske mineralizacije v grödenskih skladih Italije in podobnih sedimentih v nekaterih drugih državah je Zavod za nuklearne surovine iz Beograda v letu 1960 začel sistematično prospekcijo grödenskih plasti v Slovenji in preverbo radioaktivnih anomalij, ki so bile odkrite že pri prejšnjih raziskavah. Med večjimi regionalnimi prospekcijami je treba omeniti tudi letalsko radiometrično in hidrogeokemično prospekcijo. V letu 1969 so omenjeni prospekciji izvedli raziskovalci Inštituta za raziskovanje jedrskih surovin iz Beograda z namenom, da bi ugotovili anomalne vsebnosti urana v tleh, vodah in mulju (PETROVIĆ & POKRAJAC, 1969).

Čeprav je bil uran primarnega pomena, so pri raziskavah izkoristili priložnost in opravili več raziskav tudi drugih geokemičnih prvin. Geokemične raziskave na območju Posavskih gub v Sloveniji je povzel PIRC (1977). Po zbranih ocenah količin urana v kamninah, vodah in muljih je Pirc podal osnovne značilnosti vedenja urana v obravnavanih okoljih. Med obratovanjem rudnika urana Žirovski Vrh so bile od leta 1974 do 1989 na območju med Žirovskim Vrhom in Škofja Loko opravljene številne radiometrične in geokemične prospekcije z namenom odkriti nove zaloge uranove rude.

Ob jedrski nesreči v Černobilu leta 1986 se je izkazalo, da ni na voljo dovolj zanesljivih podatkov o kemični sestavi zemeljskega površja. Zato so kmalu nato zasnovali mednarodni projekt (IGCP 259) z naslovom Mednarodno geokemično kartiranje (DARNLEY et. al. 1995). V okviru omenjenega projekta je bil uradno uveden leta 1993 izraz »geokemično ozadje«, ki se nanaša na naravno nihanje vsebnosti prvin v okolju na zemeljskem površju in vključuje geogene vsebnosti prvin (naravnega ozadja) in razpršene antropogene prispevke v okolju. V okviru slovenskega dela projekta so se preučevali na statistični podlagi zasnovani postopki za kartiranje z vzorci tal, vode, vodnega mulja in mahu (PIRC & MAKSIMOVIĆ, 1985; ANDJELOV, 1986; PIRC et al. 1991; PIRC 1993; PIRC & ŠAJN 1997; ŠAJN et. al. 1998). Omenjenemu projektu je sledil projekt Globalne geokemične osnove (IGCP 360), ki se je nadaljeval in končal pod okriljem IUGS. Rezultat tega projekta je bil geokemični atlas Evrope (BIDOVEC & PIRC 2008), ki je bil izdelan na podlagi vzorcev vode, tal, humusa ter potočnega in poplavnega mulja.

Raziskave urana v Sloveniji so bile končane leta 1990, ker ni bilo več potrebe po odkrivanju novih zalog uran. Z novo fazo raziskav smo se lotili na Inštitutu za geologijo, geotehniko in geofiziko Geološkega zavoda Ljubljana sistematične izdelave radiometrične karte Slovenije. Celotno ozemlje države je bilo pokrito s pravilno mrežo 5 km × 5 km, v kateri so bile na 816 lokacijah opravljene meritve gama sevanja in na 819 lokacijah odvzeti vzorci tal za geokemične analize (Andjelov, 1993; Andjelov, 1994; Andjelov & Klaić, 1994; Andjelov et. al. 1995; Andjelov 1999). Namen teh raziskav je bil, da bi dosegli na regionalni ravni popolno pokritost Slovenije z radiometričnimi in geokemičnimi podatki. Ti podatki so omogočili izdelavo radiometričnih in geokemičnih kart, natančnejše ocene naravnega ozadja analiziranih prvin v tleh in zagotovili okvir za različne geološke in okoljske raziskave. Poznanje geokemičnega ozadja v tleh je uporabno za oceno dejanskega stanja v okolju in pri zagotavljanju smernic in standardov kakovosti za okoljsko zakonodajo na področju ocenjevanja onesnaženja tal.

Materiali in metode

Osnova za izbiro izhodišča vzorčne mreže so bile geokemične raziskave v Istri (Pirc & Zupančič, 1989), ki so vključevale analizo variabilnosti v različnih geoloških medijih. Za zagotovitev sistematičnosti meritev smo uporabili vzorčno mrežo s celicami 5 km × 5 km z naključno izbranim izhodiščem. Skupno je bilo v štirih letih opravljenih 817 radiometričnih meritev K, U in Th in na 819 lokacijah odvzet vzorec tal za geokemično preiskavo. Vzorčili smo zgornjih 10 cm talnega profila. Povprečna masa vzorca je bila od 1,5 kg do 2 kg.

Vzorce s povprečno 22-odstotno vlago smo zračno osušili, presejali na 2-milimetrskih sitih in nato zmleli v vibracijskem mlinu do debeline 0,063 mm. Vzorci so bili analizirani v laboratoriju ACME v Vancouvru v Kanadi s plazemsko emisijsko spektrometrijo (ICP-ES) po štirikislinskem razklopu (ACME, 1993): 0,25-gramski vzorec se raztaplja v 10 ml mešanici kislin $HClO_4$, HNO_3, HCl in HF pri temperaturi 200 °C. V vzorcih so določili 35 prvin: Ag, Al, As, Au, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, La, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Sb, Sc, Sn, Sr, Th, Ti, U, V, W, Y, Zn in Zr. Podobno metodo so uporabili Šajn in sodelavci (1998). Uran je bil določen z metodo nevtronske aktivacije (DNC) v laboratoriju XRAL v Don Millsu v Kanadi (XRAL, 1993).

Primerjava rezultatov uporabljenih merilnih tehnik in analitskih metod je pokazala, da je korelacija med terenskimi radiometričnimi meritvami s 4-kanalnim spektrometrom s 348 cm^3 velikim detektorjem natrijevega jodida in določitvami v laboratoriju za kalij (ICP +0,75) in uran (DNC +0,66).

Ocena ponovljivosti je pokazala, da imajo zelo dobro ponovljivost ($d < 10$ %) Al, Ca, Fe, K, Mg, Na, P, Ti, Ba, Co, Cr, La, Mn, Ni, Sc, Sr, U, V, W, Y, Zn in Zr. Relativno razliko med 10 % in 20 % imajo 3 prvine (Cu, Pb, Th). Glede na rezultate primerjalnih meritev in meritev geoloških standardov menimo, da so uporabljene metode zadosti natančne za izdelavo geokemičnih kart prvin in oceno porazdelitve vsebnosti prvin v tleh.

REZULTATI IN RAZPRAVA

Slovenska povprečja vsebnosti kemičnih prvin v tleh

Rezultati kemičnih analiz 819 vzorcev tal v mreži 5 km × 5 km v Sloveniji omogočajo oceno povprečnih vsebnosti 24 kemičnih prvin (tabela 1). Prvin, ki imajo več kot eno četrtino določitev pod mejo detekcije, ne prikazujemo. Ocena vsebnosti urana v tleh je bila narejena z analizo 814 vzorcev tal z nevtronsko aktivacijo.

Približno enake (±25 %) vrednosti svetovnega povprečja so mediane devetih prvin, Al, Cu, Fe, K, Mn, Ni, P, Ti in V (tabela 1). Nekaj večji (do 100 %) sta mediani dveh prvin: Mg in Th in mnogo večje (več kot 100 %) so mediane prvin Co, Pb, U in Zn. Nižje so mediane šestih prvin Ba, Ca, Na, Sr in Zr. O clarku za Cr, La, Sc, W in Y v tleh nimamo podatkov. Glede na primerjavo povprečij prvin v tleh v Sloveniji lahko rečemo, da se bistveno ne odmikajo od svetovnih povprečij v tleh, kot tudi ne od evropskih povprečij. Rezultati kemičnih analiz 819 vzorcev tal v mreži 5 km × 5 km v Sloveniji omogočajo oceno povprečnih vsebnosti 24 kemičnih prvin (tabela 1). Poleg omenjenih prvin je bil v 814 vzorcih tal analiziran tudi uran.

Približno enaka (±25 %) vrednosti clarka so povprečja osmih prvin: Al, Fe, Na, K, Ti, P, Mn in V (tabela 1). Nekaj večja (do 100 %) so povprečja šestih prvin: Ca, As, Cu, Ni, Sr in Th, ter mnogo večja (več kot 100 %) povprečja prvin: Mg, Cd, Co, Pb, U, in Zn. Nižja so povprečja treh prvin: Ba, Cr in Zr. O clarku za Be, La, Nb, Sc in Y v tleh nimamo podatkov. Splošno lahko rečemo, da se povprečja prvin v tleh v Sloveniji ne razlikujejo bistveno od ocen svetovnega in evropskega povprečja.

Naravna porazdelitev kemičnih prvin v tleh Slovenije

V postopku statistične obdelave smo upoštevali analize 814 določitev kemičnih prvin v vzorcih tal. Za oceno povezave med prvinami smo uporabili faktorsko analizo vrste R, ki temelji na povezavi med spremenljivkami na osnovi matrike korelacijskih koeficientov (KOŠMELJ, 1983; DAVIS, 1986). Za optimiranje prostorske razporeditve faktorjev je bila uporabljena metoda ortogonalne

Tabela 1. Določitve vsebnosti kemičnih prvin v tleh Slovenije v primerjavi z vrednostmi evropskega in svetovnega povprečja

Prvina	**Slovenija – meritve v mreži 5 km × 5 km**					$Evropa_{tla}$	$clarke_{tla}$
	min.	**max.**	$\bar{x}$	$\bar{x}_G$	***M***		
Al	0,39	11,12	6,69	6,31	6,92	11,0	7,13
Ca	0,02	28,92	2,58	0,99	0,78	0,92	1,37
Fe	0,21	11,76	3,75	3,47	3,80	3,51	3,8
K	0,06	4,09	1,45	1,30	1,40	1,92	1,36
Mg	0,09	10,87	1,35	0,95	0,83	0,77	0,6
Na	0,02	2,54	0,53	0,43	0,47	0,80	0,63
P	0,011	0,458	0,074	0,064	0,063	0,128	0,08
Ti	0,01	2,23	0,38	0,33	0,36	0,572	0,46
Ba	12	2261	371	323	360	375	500
Co	<2	99	28	25	26	7,78	8
Cr	7	406	90	82	88	60,0	200
Cu	<1	271	28	23	23	13,0	20
La	<2	104	31	28	30	23,5	
Mn	24	7187	1044	857	902	650	850
Ni	<2	548	53	45	47	18,0	40
Pb	4	1112	40	34	34	22,6	10
Sc	<1	41,0	13,2	12,2	13,0	9,19	
Sr	13	1016	98	85	82	89,0	300
Th	<2	26	11	10	11	7,24	6
U+	<0,1	9,8	3,7	3,4	3,4	2,00	1
V	5	357	118	105	113	60,4	100
W	<2	293	62	41	41	<5,0	
Y	<2	116	18	15	15	21,0	
Zn	10	1877	116	103	104	52,0	50
Zr	<2	227	49	40	46	231	300

Legenda: Glavne prvine v deležih (%) in sledne v miligramih na kilogram so bile določene z ICP-metodo, + določitve z DNC metodo, min-max – razpon vrednosti, $\bar{x}$ – aritmetična sredina, $\bar{x}_G$ – geometrična sredina, *M* – mediana, slovensko povprečje vsebnosti prvin v tleh, $clarke_{tla}$ – svetovno povprečje vsebnosti prvin v tleh (Rösler & Lange, 1972), $Evropa_{tla}$ – evropsko p o v - prečje vsebnosti prvin v zgornjem sloju tal (0–25 cm) (Salminen et al., 2005)

rotacije (varimax). S faktorsko analizo smo začetno število 25 obravnavanih kemičnih prvin skrčili na 6 sintetičnih spremenljivk, ki skupno pojasnjujejo 76,9 % celotne variance. Pri interpretaciji smo upoštevali le pet faktorjev, ki pomenijo naravne geokemične združbe, šesti faktor pomeni onesnaženje pri pripravi vzorcev tal. Faktorje smo vsebinsko opredelili na osnovi najvišjih pozitivnih in negativnih vrednosti v matriki faktorskih uteži (tabela 2).

Tabela 2. Dominantne vrednosti rotiranih faktorskih obremenitev (n = 814)

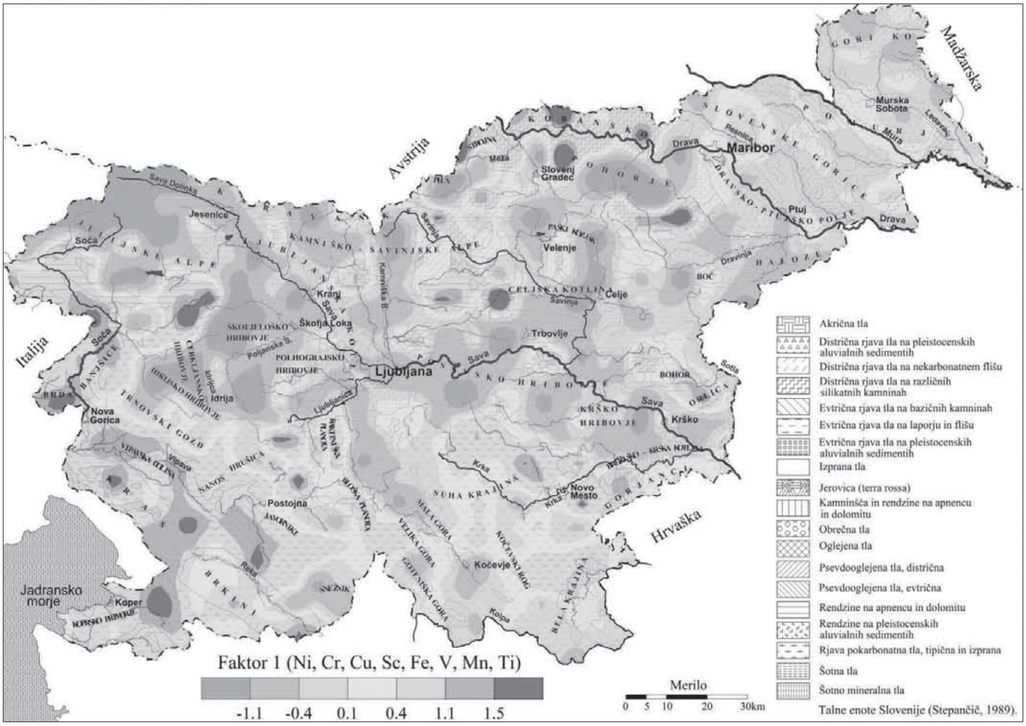
Prvina	***F*1**	***F*2**	***F*3**	***F*4**	***F*5**	***F*6**	***Kom***
Ni	0,91						0,85
Cr	0,83						0,87
Cu	0,75						0,64
Sc	0,73						0,88
Fe	0,72						0,86
V	0,68						0,81
Mn	0,64						0,65
Ti	0,51		0,53				0,81
K		0,83					0,68
Al		0,70					0,90
Ba		0,70					0,82
Na		0,65					0,69
La			0,80				0,80
Th			0,79				0,70
U			0,77				0,64
Zr			0,64				0,61
Y			0,59				0,78
Sr				-0,74			0,52
Ca				-0,68			0,82
Mg				-0,52			0,64
Pb					0,78		0,56
Zn					0,75		0,66
P					0,66		0,45
Co						0,80	0,85
W						0,87	0,79
Var	**21,7**	**13,8**	**15,3**	**7,2**	**8,0**	**10,9**	**76,9**

F*1 … *F*6** – faktorske obremenitve, ***Kom – komunaliteta v deležih (%), ***Var*** – varianca v deležih (%)

Geokemična združba Ni, Cr, Cu, Sc, Fe, V, Mn, Ti

S prvim faktorjem je pojasnjeno 21,7 % skupne variabilnosti in združuje največ prvin (tabela 2). Faktor je pozitivno obremenjen z Ni (0,91), Cr (0,83), Cu (0,75), Sc (0,73), Fe (0,72), V (0,68), Mn (0,64) in Ti (0,51). Visoke pozitivne vrednosti faktorja najdemo v zahodni Sloveniji v distričnih in evtričnih rjavih tleh v Vipavski dolini, na flišu Postojnske kadunje in na ozemlju istrskega ter brkinskega flišnega bazena (slika 1). Višje pozitivne faktorske vrednosti so na Krasu v jerovici, na Primorskem v rendzinah na alveolinsko-numulitnih apnencih in na Dolenjskem v rjavih pokarbonatnih tleh ter v rendzinah na krednih in jurskih apnencih.

V severovzhodni Sloveniji najdemo povišane vrednosti faktorja v dis-

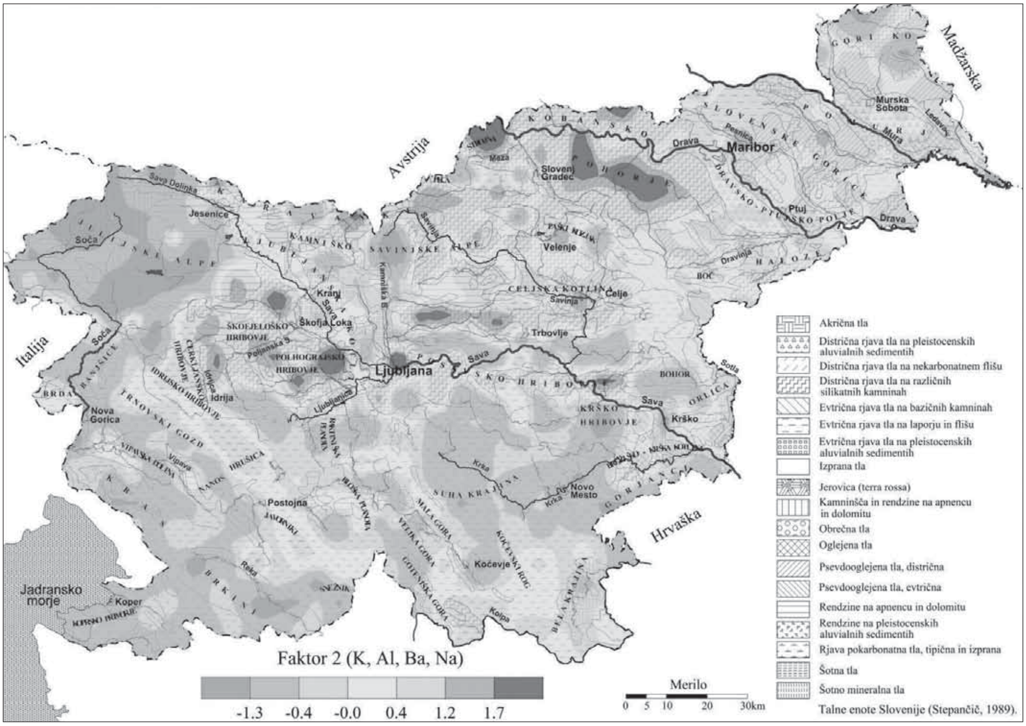


Slika 1. Prostorska porazdelitev prvega faktorja (Cr, Cu, Fe, Mn, Ni, Sc, Ti, V)

tričnih rjavih tleh na ozemlju metamorfnih kamnin na Strojni, Kozjaku in Pohorju. Prvi faktor ima najvišje negativne vrednosti na Pohorju, kjer izdanja granodiorit. V Julijskih Alpah so visoke negativne vrednosti v rendzinah, ki so nastale na nesprijeti moreni in grušču. Negativne vrednosti so še v distričnih rjavih tleh na permskih in permokarbonskih plasteh na Idrijsko-Škofjeloškem ozemlju in Posavskem hribovju. Faktor izraža prevladujočo podvrženost vremenskim vplivom z visoko stopnjo erozije in visoke hitrosti sedimentacije.

Geokemična združba K, Al, Ba in Na

Z drugim faktorjem je razloženo 13,8 % celotne variance. Obremenjen je s prvinami: K (0,83), Al (0,70), Ba (0,70) in Na (0,65). Visoke vrednosti faktorja so vezane zlasti na distrična rjava tla na različnih silikatnih kamninah in tla, ki jih občasno ali stalno zaliva površinska ali podzemna voda (oglejena tla in psevdogleji) (slika 2). Na Pohorju, Strojni in Kozjaku najdemo najvišje vrednosti drugega faktorja v tleh na granodioritu, muskovitno-biotitovem gnajsu in kremenovem sericitnem filitu. Visoke vrednosti so tudi v distričnih rjavih tleh na Idrijsko-Škofjeloškem



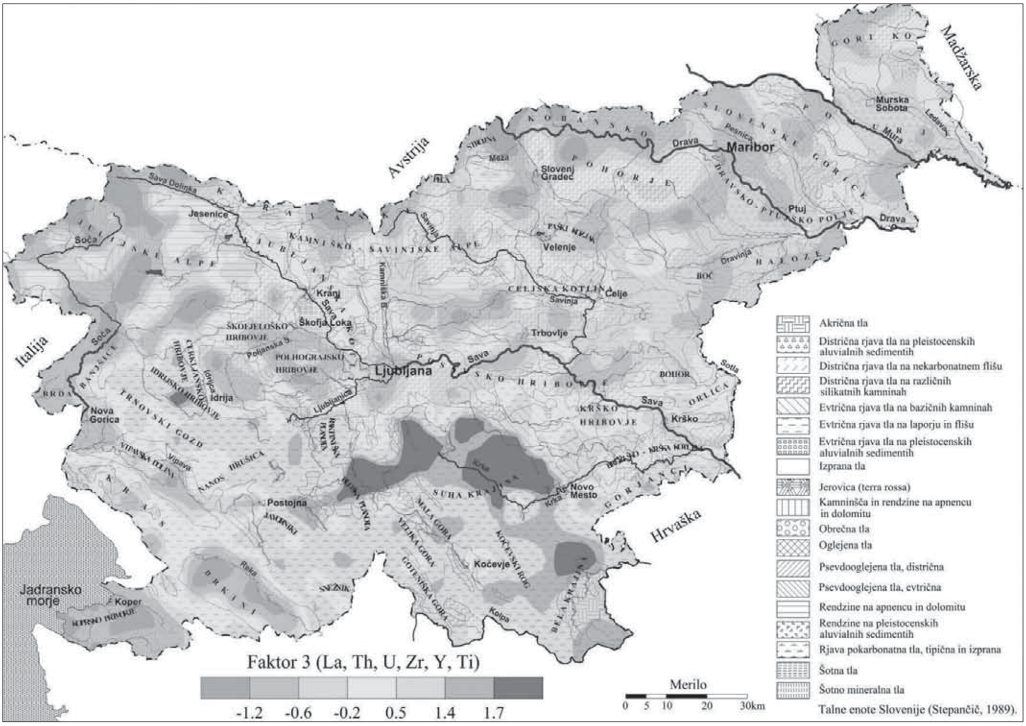
Slika 2. Prostorska porazdelitev drugega faktorja (Al, Ba, K, Na)

ozemlju in Posavskem hribovju na permokarbonskem kremenovem peščenjaku, skrilavem glinovcu in konglomeratu. V Dravski in Murski ravnini ter Slovenskih goricah so visoke vrednosti faktorja vezane na oglejena tla in psevdogleje ter na distrična in evtrična rjava tla, ki so nastala na peščenem laporju, pesku in produ.

Nizke vrednosti faktorja so na območju Zunanjih Dinaridov v rjavih pokarbonatnih tleh in rendzinah na triasnih, jurskih in krednih apnencih in dolomitih. Na območju Julijskih Alp so nizke vrednosti faktorja vezane za rendzine, nastale na morenah in pobočnem grušču. Prvine, ki nastopajo v tem faktorju, so vezane predvsem na glinaste komponente v tleh.

Geokemična združba La, Th, U, Zr, Y in Ti

Tretji faktor pojasni 15,2 % celotne variabilnosti. Pozitivno je obremenjen z: La (0,80), Th (0,79), U (0,77), Zr (0,64), Y (0,59) in Ti (0,53). Tretji faktor je najmočneje izražen na ozemlju karbonatnih kamnin južne Slovenije. Ozemlje je zgrajeno iz apnencev in dolomitov triasne, jurske in kredne starosti. Tu nastopajo rendzine, rjava po-



Slika 3. Prostorska porazdelitev tretjega faktorja (La, Th, Ti, U, Y, Zr)

karbonatna tla in izprana tla. Najvišje vrednosti faktorja najdemo v Suhi Krajini, na Blokah in v Beli krajini (slika 3). Visoke vrednosti faktorja opazimo tudi v rdečih in rjavih glinah Dolenjskega podolja.

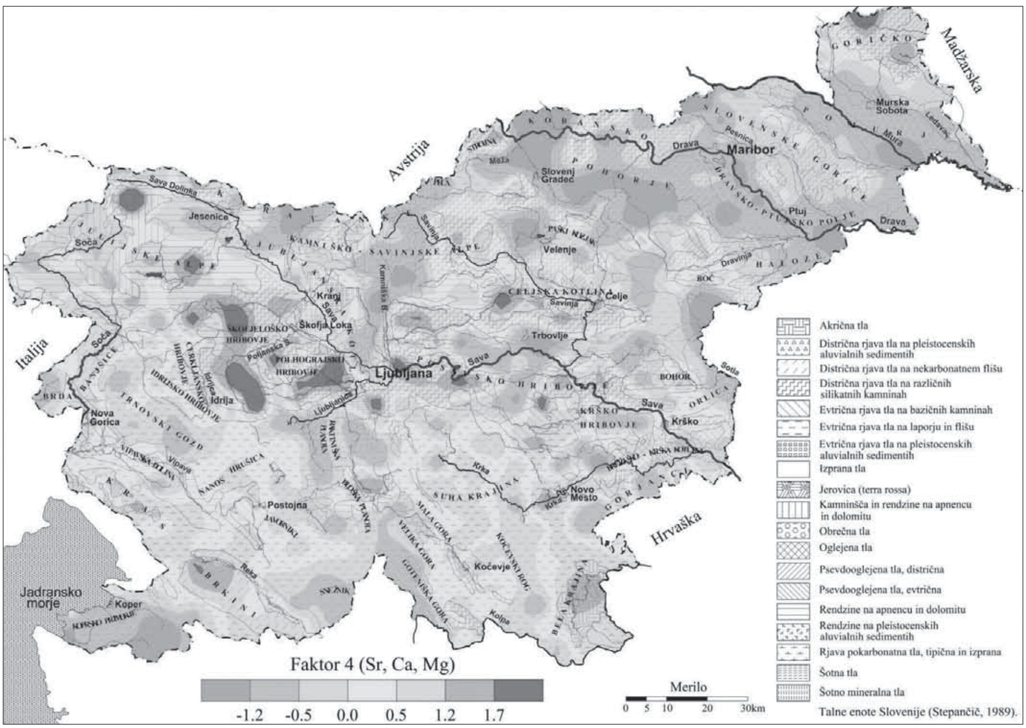
Negativne vrednosti faktorja v Koprskih brdih, Brkinih, Vipavski dolini in Banjšicah so vezane na distrična rjava tla na nekarbonatnih flišnih kamninah in evtrična rjava tla na laporju in flišnih kamninah. Negativne vrednosti faktorja na ozemlju Julijskih Alp nastopajo v rendzinah na morenah in grušču. Na Idrijsko-Škofjeloškem ozemlju in v Posavskem hribovju so negativne vrednosti faktorja v distričnih rjavih tleh na peščenjakih, skrilavih glinovcih in konglomeratih. Ravno tako so na ozemlju Pohorja, Strojne in Kozjaka negativne vrednosti faktorja vezane za distrična rjava tla na metamorfnih kamninah.

Med prvinami, združenimi v tem faktorju, je določena kristalno-kemijska podobnost (velikost iona, naboj, elektronegativnost itd.), zato pogosto prihaja do nadomeščanja med njimi. Uran je pogosto vezan kot zamenjava za itrij, cerij, cirkonij, torij, kalcij in barij v mineralih, kot so ksenotim, allanit, cirkon, torianit, fluorit, barit itd. Torij pa je vezan kot zamenjava za ione urana, cirkonija, cerija v uraninitu, cirkonu, monacitu, braneritu in allanitu.

Geokemična združba Sr, Ca in Mg

Četrti faktor pojasnjuje najmanj skupne variabilnosti, le 7,2 %. Izražen je predvsem njegov negativni krak, nanj so vezani: Sr (–0,74), Ca (–0,68) in Mg (–0,52). Visoke pozitivne vrednosti faktorja, ki pomenijo nizke vrednosti Sr, Ca in Mg, so vezane na distrična rjava tla na različnih silikatnih kamninah in nekarbonatnih flišnih kamninah (slika 4). Na Idrijsko-Škofjeloškem ozemlju in Posavskem hribovju so visoke vrednosti faktorja vezane na distrična rjava tla na skrilavem glinovcu, kremenovem peščenjaku in konglomeratu permske in permokarbonske starosti.

Visoke vrednosti faktorja opazimo tudi v tleh, ki so nastala na triasnih glinovcih in peščenjakih. V porečju Notranjske Reke in dolini Soče najdemo povišane vrednosti faktorja v distričnih rjavih tleh na flišnih plasteh. V Beli krajini so povišane vsebnosti faktorja v izpranih tleh. Povišane vsebnosti faktorja najdemo tudi na Pohorju, Strojni



Slika 4. Prostorska porazdelitev četrtega faktorja (Sr, Ca, Mg)

in Kozjaku v distričnih tleh, nastalih na kremenovem sericitnem filitu in filitoidnem skrilavcu. Na Goričkem so visoke vrednosti faktorja v tleh, nastalih na kremenovem produ.

Negativne vsebnosti tega faktorja so vezane na obrečna tla, ki nastajajo v ozkih poplavnih pasovih vzdolž rek in oglejena tla, za katera je značilno zadrževanje vode v tleh (Sava, Savinja, Drava, Mura). Na Dolenjskem in Notranjskem so negativne vrednosti v rjavih pokarbonatnih tleh in rendzinah na apnencih in dolomitih. Negativne vrednosti najdemo tudi v evtričnih rjavih tleh na flišnih plasteh Primorja. Na Pohorju, Strojni in Kozjaku so negativne vrednosti faktorja 4 vezane na predele, ki jih sestavljajo metamorfne kamnine, to so muskovitno-biotitov gnajs in kloritno-amfibolov skrilavec in globočnina pohorski granodiorit.

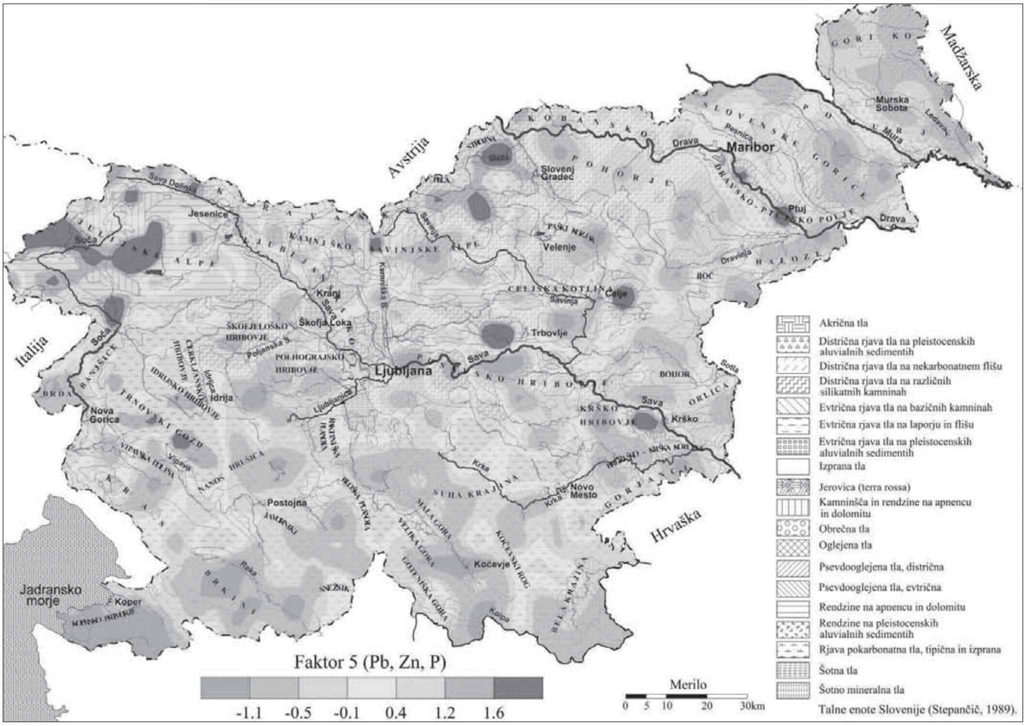
Na splošno lahko opazimo, da so vrednosti faktorja pozitivne na ozemljih silikatnih klastičnih kamnin, negativne vrednosti pa so na ozemljih karbonatnih kamnin. Ker je negativni krak bolj izražen, smo ga poimenovali negativni karbonatni faktor. Na ta faktor imajo domnevno velik vpliv klimatske variacije in izpiranje tal. Ugotovili so, da je vezava stroncija odvisna od vsebnosti glinenih komponent in topnih kationov v raztopini. Vezava stroncija v tleh upada, če narašča vsebnost Mg in Ca v talni raztopini.

Geokemična združba Pb, Zn in P

Peti faktor pojasni 8 % celotne variabilnosti. Ta faktor bremenijo: Pb (0,78), Zn (0,75) in P (0,66). Najvišje vrednosti faktorja so v rendzini na triasnem apnencu na Peci in v širši okolici, kjer so zelo pomembna orudenja svinca in cinka (slike 5). V Posavskem hribovju so visoke vrednosti faktorja v distričnih rjavih tleh na permokarbonskem skrilavem glinovcu, peščenjaku in konglomeratu. Na omenjenem ozemlju so v širši okolici Litije pomembna svinčevo cinkova rudišča. V podobnih kamninah so visoke vsebnosti faktorja v tleh na Idrijsko-Škofjeloškem ozemlju.

Visoke vsebnosti faktorja opazimo tudi v Julijskih Alpah v rendzinah na dolomitu in apnencu, moreni in pobočnem grušču. Pojave svinčevo-cinkove rude na tem območju najdemo v Planici pri Ratečah ter na jugozahodnem pobočju Mangarta in so v zvezi z rudiščem v Rablju (Drovenik et al., 1980). V zahodnih Karavankah so v distričnih rjavih tleh na glinovcu in peščenjaku povišane vrednosti faktorja pod Golico. Povišane vrednosti faktorja so tudi v evtričnih rjavih tleh na savskem prodnem zasipu v Ljubljanski kotlini.

Negativne vrednosti faktorja najdemo v tleh na flišu v Koprskih brdih, Brkinih in Vipavski dolini. Nizke vrednosti faktorja so vezane tudi za rendzine in rjava pokarbonatna tla na apnencih



Slika 5. Prostorska porazdelitev petega faktorja (Pb, Zn, P)

in dolomitih Notranjske in Dolenjske. V Murski ravnini in na Goričkem so negativne vrednosti faktorja vezane na distrična in evtrična rjava tla na peščenem laporju, pesku in produ. Faktor kaže naravno porazdelitev naštetih prvin v tleh, kot tudi domnevne vplive industrijskih onesnaževalcev. Peti faktor bremenita predvsem težki kovini.

Združba W in Co

Šesti faktor opredeljuje 10,9 % celotne variance. Ta faktor bremenita predvsem W (0,87) in Co (0,80). Glede na ti prvini lahko šesti faktor interpretiramo kot faktor onesnaženja vzorcev z mletjem v mlinu iz volfram-kobaltovega karbida. Faktor dejansko pomeni vsebnosti abrazivnih mineralov v vzorcih. Višje vrednosti faktorja imamo predvsem v bolj abrazivnih tleh severovzhoda Slovenije na magmatskih in metamorfnih kamninah Pohorja in na kremenovem pesku, produ in glinah v Dravski ravnini, Slovenskih goricah, Murski ravnini in na Goričkem.

Sklepi

S statistično obdelavo multielementnih kemičnih analiz tal, vzorčevanih v mreži 5 km × 5 km, in z geokemičnimi kartami smo prišli do sklepa, da obstaja najmanj pet geokemičnih združb prvin, ki so prostorsko vezane na različne tipe tal. Združba Cr-Cu-Fe-Mn-Ni-Sc-Ti-V je značilna za tla na flišu v zahodni Sloveniji, jerovice na Krasu, rjava pokarbonatna tla na Dolenjskem in distrična tla na metamorfnih kamninah v severovzhodni Sloveniji. Združba Al-Ba-K--Na je vezana na distrična rjava tla na različnih silikatnih kamninah, glejna tla in psevdogleje. Združba La-Th-Ti-U-Y--Zr je najmočneje izražena na ozemlju karbonatnih kamnin južne Slovenije, kjer nastopajo rendzine, rjava pokarbonatna tla in izprana tla. Za združbo Ca--Mg-Sr so značilne negativne vrednosti, ki so vezane na obrečna in oglejena tla (Sava, Savinja, Drava in Mura), na tla na metamorfnih kamninah (Pohorje, Strojna in Kozjak) in na evtrična rjava tla Primorja. Združba P-Pb-Zn je značilna za tla v okolici svinčevo-cinkovih rudišč (Mežica, Litija, Mangart), distrična rjava tla v Posavskih gubah in rendzine na dolomitu in apnencu, moreni in pobočnem grušču Julijskih Alp.

Glede na raziskovalne ugotovitve lahko sklenemo, da ocene naravnega ozadja vsebnosti kemičnih prvin v tleh niso odvisne le od geokemične sestave matičnih kamnin, ampak izražajo tudi obstoj znanih metalogenetskih anomalij, kar nakazuje na pomembno vlogo poznavanja regionalne geologije pri izbiri vzorčnega načrta za ugotavljanje naravnega ozadja tal.

Zahvale

Delo je rezultat naloge Karta naravne radioaktivnosti Slovenije. Podatki teh raziskav so bili podrobneje obdelani v doktorski disertaciji z naslovom Radioaktivne prvine v tleh Slovenije pod mentorstvom prof. dr. Simona Pirca. Za vso pomoč, nasvete in podporo pri nastajanju se mu iskreno zahvaljujem. Moja zahvala velja tudi sodelavcem Geološkega zavoda Ljubljana, še posebej pokojnemu Zoranu Klaiću za pomoč pri meritvah in vzorčevanju, kar je omogočilo zaključek tega obsežnega raziskovalnega dela.

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Mercury enrichments in soils influenced by Idrija mercury mine, Slovenia

Živo srebro v tleh na širšem vplivnem območju rudnika v Idriji, Slovenija

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Abstract: Presented investigations confirmed that soils in the wider Idrija surroundings are highly enriched with mercury. The most important sources of mercury in soils for wider Idrija area were atmospheric emissions from the roasting plant. Hg gasses and dust particles have spread far into the Idrija environs. Mercury is therefore present in soils at localities far from the outcrops of ore-rich rocks. Some other small but extremely contaminated areas were identified in the woods of the Idrija environs, where ore roasting was performed in the 16th and 17th century. In the Idrija urban area there are mutual mercury impacts on the environment from the atmosphere and the soil parent material. Mercury-rich parent material in the city of Idrija is the bedrock of Pront-area, where ore-bearing rocks containing native mercury and cinnabar crop out. Additionally, mercury is present in soils developed on ore and roasting wastes dumped along the banks of the Idrijca River in the city area. In the lower Idrijca Valley the floodplain soils are contaminated with Hg because most roasted ore residues were dumped into the Idrijca riverbed and washed away because of the torrential nature of the Idrijca River and some of this mercury enriched material was deposited on the floodplains.

Izvleček: Predstavljene raziskave potrjujejo, da so tla v širši okolici Idrije močno obremenjena z živim srebrom. Najpomembnejši vir živega srebra so bile med predelovanjem rude atmosferske emisije. Pri žganju rude je nastajalo veliko prašnih delcev in plinov, ki so obremenjevali širšo okolico pražarne rude in povzročili nastanek izjemno velike avreole živega srebra. Ugotovljena so bila tudi številna majhna, toda izjemno onesnažena mesta v gozdovih v okolici Idrije, kjer so v 16. in 17. stoletju žgali rudo v lončenih žgalnih posodah. Ugotavljamo, da so bila žgalniška območja pomemben vir onesnaženja okoliških ekosistemov z živim srebrom. V urbanem okolju Idrije so delovali na okolje vzajemni vplivi zračnega nanosa in talne podlage. Vir živega srebra na območju Pronta, kjer izdanjajo kamnine, ki vsebujejo samorodno živo srebro in cinabarit, je kamninska podlaga. Nadalje so v mestnem jedru tla razvita na deponijah prežgane rude vzdolž brežin reke Idrijce. Ker so med največjo proizvodnjo večino žgalniških ostankov vsipavali v strugo Idrijce in je bil ta material zaradi hudourniške narave reke prenesen v nižje predele, pa so vsebnosti živega srebra povišane tudi na poplavnih ravnicah v spodnjem toku Idrijce.

Ključne besede: soil, mercury, mining, Idrija, pollution
Key words: tla, živo srebro, rudarstvo, Idrija, onesnaženje

Introduction

Contamination of the Earth's ecosystems by potentially toxic metals is a global problem. It will probably grow with our planet's increasing population and their requirements for natural resources (Siegel, 2002). There are several sources of metals in the environment, both natural and manmade. The natural sources of metals in environment lie with the rocks and processes by which they formed and which affected them after lithification. High values of metals are found, for example, in mineralized areas and in areas where the dominant bedrock is rich in metals as, for example, in black shale. The presence of elevated levels of organic matter in an anoxic environment at the time of sediment deposition was responsible for concentrating anomalous amounts of metals. Volcanic emissions and forest fires are natural springs of some metals in the atmosphere (gases, aerosols, particulates) and after they precipitate they become part of the near-surface ecosystems. There are many anthropogenic sources in the environment: coal combustion residues, mining, metal-smelting industries, car emissions, military actions (Pirc & Budkovič, 1996; Greičiute et al., 2007; Idzelis et al., 2006) and primary input sources in agro-ecosystems (fertilizers, liming materials, sewage sludges, pesticides, irrigation water) (Adriano, 1986).

The mining and metal industry can be an important source of trace elements in the environment from (a) the mining and milling operations with problems of grinding, concentrating and transporting ores, and disposal of tails along with mine and mill waste water and (b) the smelter-refinery process with problems of concentrate, haulage, storage, sintering, atmospheric discharges and blowing dust (Adriano, 1986; Dudka & Adriano, 1997; Jordan, 2009). The proportion of trace elements releases into environment depends on ores being processed. Mining itself affects relatively small areas. It is the tailings and waste rock deposits close to the mining area that are the source of the metals (Hoskin et al., 2000). The impacts of atmospheric discharges (gaseous and particulate matter emissions) from smelters can be detected within several kilometres from the point of release. Depending on the efficiency of the recycling of metals, metals initially released by mining activities, end up after a number of years in the various compartments of the surface layer of the Earth (Kesler, 1994).

In many areas worldwide present and historical mining and smelting activities are causing a variety of environmental problems such as elevated metal concentrations in soils/sediments, dispersion of toxic metals in soil and water and ecological damage caused by extensive metal pollution. Because ore is only a small fraction of the total volume of mined material, ore extraction, beneficiation processes and further processing of ores produce large amounts of waste which can contain metals or chemicals from manufacturing processes (Siegel, 2002). The environmental concern in mining areas is primarily related to mechanical damage of the landscape and acid mine drainage (AMD). The trace element uptake from contaminated soils and direct deposition of contaminants from the atmosphere onto plant surfaces can lead to plant contamination by trace elements. These results in plant toxicity and a potential transfer of contaminating elements along the food chain exist (Dudka & Adraiano, 1997).

In context of long and intensive history of metal mining in Slovenia, it is clear that many older mining operations started at a time when there was little concern for the surrounding environment. The impact of long history of mining and metallurgy was intensively investigated in the last decade. It was established that, in Slovenia, mining and ore processing represent one of the major modes for anthropogenic input of metals into the environment. One of the most important districts influenced by metal mining and ore processing in Slovenia is the area around Idrija mercury mine, where half a millennium of mercury production is reflected in increased mercury contents in all of its environmental segments.

Mercury with its unique physicochemical properties is highly toxic and more

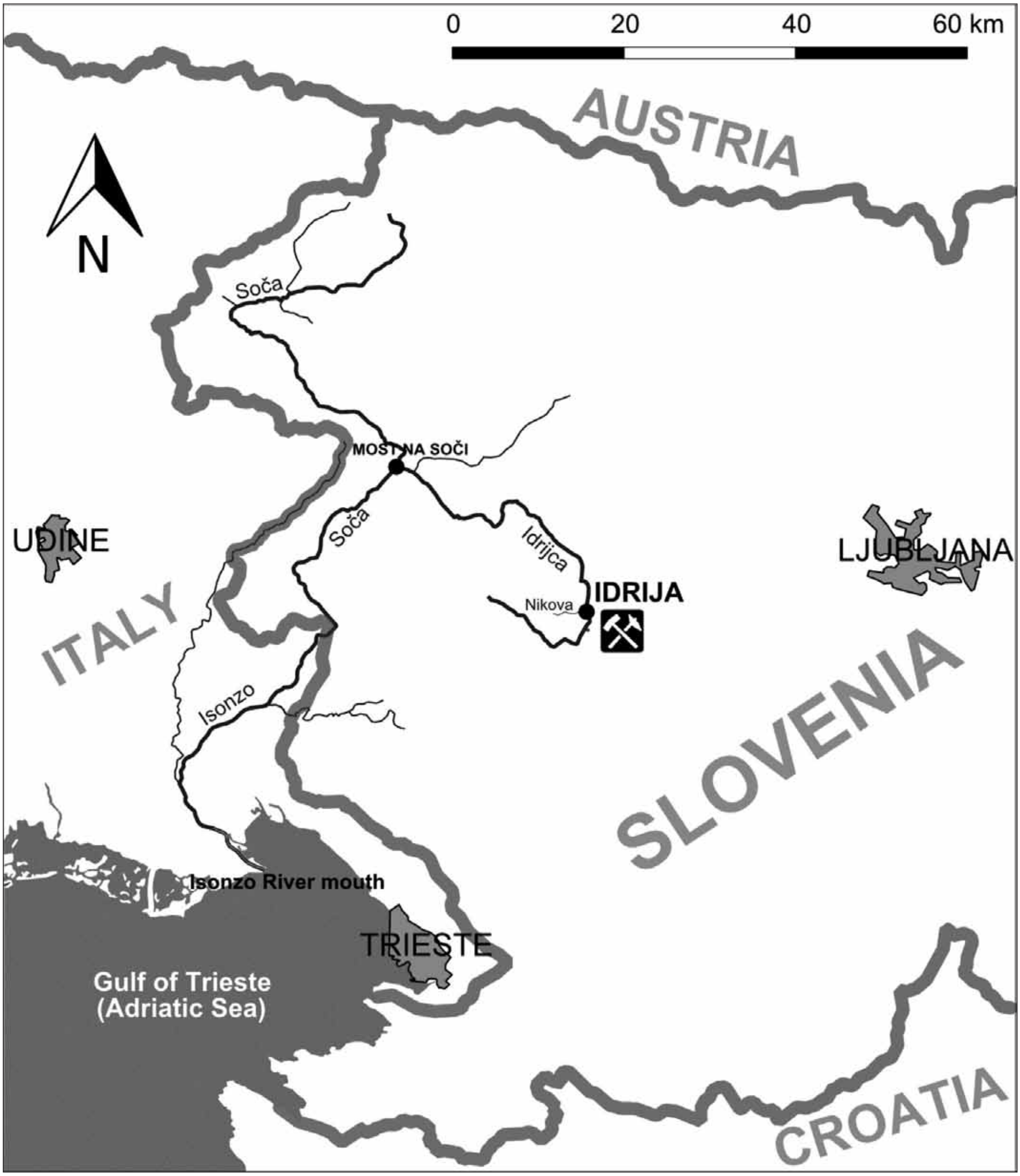

Figure 1. Map of study area

dangerous for living organisms than most other trace elements. It is regarded as a global pollutant. The outbreak of mass poisoning with this metal in the second half of 20th century (Minamata and Niagata in Japan, Iraq) warned the world about the danger of intoxication and mercury came into the focus of environmental investigations all around the world. Interest also arose at Idrija area, and pioneer's investigations on influence of mercury production on the environment were conducted (Byrne & Kosta, 1970; Kosta et al., 1974; Dermelj, 1974; Kavčič, 1974). After that investigations at Idrija area ceased for about 20 years.

In the last two decades numerous extensive and detailed investigations on mercury emissions, distribution, deposition, speciation and pollution in general were performed in Idrija region determining an unprecedented legacy of mercury contamination (Gnamuš, 1992, 2002; Hess, 1993; Palinkaš et al., 1995; Gosar, 1997; Gosar et al., 1997a, 1997b, 2006; Biester et al., 1999, 2000; Horvat et al., 1999, 2003; Dizdarević, 2001; Gnamuš et al., 2000; Gosar & Šajn, 2001, 2003; Gosar & Žibret, 2011; Kocman et al., 2004, 2011a, 2011b; Gosar & Čar, 2006; Hines et al., 2006; Žibret & Gosar, 2006; Gosar, 2008; Kocman & Horvat, 2010; Teršič et al., 2011a; Teršič et al., 2011b; Gosar & Žibret, 2011; Gosar & Teršič, 2012). Idrija and its surroundings are heavily polluted with Hg due to naturally increased mercury contents in mineralized rocks, mining and ore processing. During the operation period of the mine 107 692 t of mercury were produced. Taking into account the losses during mining and inefficient roasting process, the total amount of mercury mined is estimated to be at least 144 725 t (Mlakar, 1974; Miklavčič, 1999; Cigale, 2006). It has been estimated that 37 033 t of mercury were emitted into the environment during the operation period of the mine that ceased production in 1995 (Cigale, 2006).

In this paper environmental geochemistry studies of soils in the area of Idrija (Figure 1) which were performed at the Geological survey of Slovenia together with collaborating partners in the last 20 years are presented. This paper is dedicated to our honoured professor dr. Simon Pirc, who taught us geochemistry and to professor dr. Jože Čar who gave us basic knowledge and the idea of studying old roasting sites in Idrija area.

Materials and methods

The soil samples were air-dried, afterwards gently crushed in a ceramic mortar and passed through a sieve with 2 mm openings. The soil fraction smaller than 2 mm was pulverised before chemical analyses. The powdered soil samples were submitted for chemical analysis to ACME Analytical Laboratories in Vancouver (Canada) accredited under ISO 9001:2000. After aqua-regia digestion (1 hour, 95 °C) mercury was analysed eighter with Cold Vapor Atomic Absorption Spectrometry (CVAAS) (up to year 2008) or with inductively coupled plasma mass spectrometry (ICP-MS). Samples with more than 50 mg/kg Hg were analyzed with ICP emission spectrometry (ICP-ES).

The accuracy and analytical precision of the analytical methods were verified against standard reference materials (standards GXR-2 (Park City, Summit Co., Utah), GXR-5 (Somerset Co., Maine), GXR-6 (Davidson Co., North Carolina) and SJS-1 (San Joaquin Soil)) and duplicate samples in each analytical set. The shipment of samples, duplicates and geological standards to the laboratory was carried out in a random succession to distribute evenly any errors due to laboratory performance. This procedure ensured an unbiased treatment of samples and a random distribution of possible drift of analytical conditions for all samples. Objectivity was assured through the use of neutral laboratory numbers.

Geochemical mapping

Geochemical soil mapping was performed during summer months of the years 2000 and 2001. In the most polluted areas, such as Idrija and Spodnja Idrija, an average of samples 4/km^2 were taken, whereas in more distant areas sampling density was approximately 1/km^2. There were 100 soil samples collected (0–15 cm) in an area of 160 km^2 (GOSAR & ŠAJN, 2001, 2003; GOSAR et al., 2006). The results revealed the highest median (47 mg/kg) in Area 1, which includes the towns of Idrija and Spodnja Idrija, and the Idrijca River valley between them. Median in the intermediate Area 2 was 3.2 mg/kg and in the most distant Area 3 1 mg/kg (GOSAR et al., 2006). It was established that on 19 km^2 Hg contents in soil exceed the The New Dutchlist action value for Hg (10 mg/kg; MHSPE, 1994) which is also the critical values according to Slovenian legislation (Uradni list RS – Official Gazette RS, 1996). Spatial distributions of mercury contents in soil depended very much upon the morphology of terrain (GOSAR & ŠAJN, 2001, 2003; GOSAR et al., 2006). We can come to the conclusion that the pollution is primarily related to the River Idrijca Valley, while the effect on the farther surroundings is less significant, but still important. It is of most interest to compare the Hg contents in samples taken higher or lower than the main exhaust stack of the roasting factory. The average of Hg in soil, which lies in lower altitudes than the main exhaust stack is 42 mg/kg. In higher altitudes the average is 2.8 mg/kg. High values occur in the Idrijca River valley and at the base of slopes, while lower values prevail at higher elevations and at margins of the investigated area (GOSAR et al., 2006). Strong relationship between the Hg contents in soil and between height above sea level and the distance from the smokestack of the roasting plant, which was the main anthropogenic source of mercury, was determined. Also Hg contents in soils along the Idrijca River depend mostly on the distance from the source of pollution, shape of the valley and local winds blowing along the valley. The highest concentrations were found near the source of pollution, i.e. the smokestack of the roasting plant and they decrease exponentially down the valley. Exceptions are alluvial soils which will be presented in paragraph "Contaminated floodplain soil". With geochemical mapping results we proved that the influence of atmospheric emissions caused by the Idrija roasting plant resulted in impacts on the environment on a regional scale (Gosar et al., 2006).

The results of Hg thermo-desorption measurements showed the presence of the cinnabar- and non-cinnabar-bound Hg. Metallic mercury was not detected (Gosar et al., 2002; Gosar et al., 2006). In the total researched area the weighted average of total cinnabar-bound Hg in soils was 18 %. The highest median (49 %) was identified in Area 1. The portions of non-cinnabar compounds increased with the distance from the mercury source. It has been assumed that there were two different transport mechanisms of dust particles and gaseous Hg^0 during the mercury production period. Coarse-grained particles with mostly cinnabar-bound Hg settled in the immediate vicinity of the smokestack of the roasting plant, whereas the fine grained fraction could be dispersed further ahead. As a consequence, fine grained material with Hg^{2+} and Hg^0 prevails in remote localities and is bound to soils with matrix and organic matter (Gosar et al., 2006).

Contaminated floodplain soil

Besides soil pollution by atmospherically derived mercury, considerable areas with polluted floodplain soils were identified in the areas of the Idrijca and Soča River Valleys. During mining history of the area, considerable amounts of mercury-bearing ore residues and roasting residues were spilled into the River Idrijca. This mercury-rich material was washed away because of the torrential nature of the Idrijca River and some of this material was deposited on the floodplains in the lower part of the Idrijca and Soča River valleys, thus building a large accumulation of mercury-enriched floodplain soils (Gosar et al., 1997b; Gosar, 2008; Žibret & Gosar, 2006: Gosar & Žibret, 2011).

Studies of mercury speciation in sediments and soils from floodplains (Biester et al., 2000) indicated the occurrence of cinnabar and matrix-bound Hg compounds. Accumulation of cinnabar predominately occurred in coarse grained river sediments. In contrast, non-cinnabar Hg was found enriched in areas where fine grained material was deposited reaching up to 40 % of Hg_{tot} (1–60 mg/kg) in floodplain soils (Biester et al., 2000).

In continuation the influence of geomorphological factors on the Hg contamination of the Idrijca River alluvial sediments was studied (Žibret & Gosar, 2006; Gosar & Žibret, 2011). According to our expectations, floodplains were found to be the most contaminated unit (mean Hg content 335 mg/kg). On the first terrace the identified mean Hg concentration was 155 mg/kg. The least contaminated material was found in the higher terraces (3.8 mg/kg), which most probably reflect only atmospheric influences of the Idrija mercury mine area. Mapping of the Idrijca River terraces was performed in order to estimate the volume of the identified geomorphological units. For the determination of mercury concentrations, the alluvial sediments on different levels were sampled and the analysis of variance was performed. The results showed that the concentration of Hg varies the most between the floodplain and terraces inside the same alluvial plain, but does not change significantly in relation to the distance from the source of pollution, neither in relation to the position inside one terrace or floodplain nor the depth. It was estimated that about 2000 tons of mercury have been stored in the Idrijca River alluvial sediments (Žibret & Gosar, 2006).

Historical mercury-ore roasting sites

In last couple of years interesting historical small-scale mercury-processing sites, which are non-uniformly distributed in the surroundings of Idrija, have become the subject of our investigations. In 2005 Čar and Terpin published interesting paper about different ways of ore roasting techniques in the first 150 years (16th and first half of 17th century) of mercury production in Idrija. They found numerous localities of historical ore roasting sites in the woods around Idrija, where large quantities of broken pottery in which Hg ore was roasted, can be found. Up to now, 21 localities of ancient roasting sites were established on the neighbouring hills and in more distant localities. They also found very interesting and old literature (Grund, 1911) reporting mercury contamination at the Pšenk ancient ore roasting area that was discovered during cutting down old spruce-trees in the beginning of the 20^{th} century. Grund (1911) reported that 0.6 m thick layer of roasting vessels fragments was found, which was investigated in detail. In three of the reduced grouped samples, 0.7 %, 0.45 % and 2.09 % of mercury was found. A fragment of a certain earthen vessel contained 0.06 % of Hg, a small piece of recipient 4.92 % of Hg, and soil from one of the earthen vessels 0.52 % of Hg. It was calculated that more than 1850 kg was present at the Pšenk locality (Grund, 1911).

At the beginning of mercury production in Idrija the technology of excavation and ore processing were very simple. The excavated ore was roasted similar as charcoal in piles and later in earthen vessels at various sites in the woods around Idrija (Valentinitsch, 1981; Čar & Terpin, 2005; Kavčič, 1993, 2008). The ore roasting in earthen vessels lasted without any fundamental changes from 1510 to 1652. The major modification was done merely in 1580, when distilled lime began to be added to the ore in order to prevent the exhaled mercury to re-bind to HgS. At this method a suit of two earthen roasting vessels was used – the bigger upper, in the shape of longish gourd (*earthen vessel*), and smaller lower vessel (*receptacle*). The ore was transported to roasting sites which, due to felling large quantities of trees, were being set up at increasingly greater distances from mine pits. In this procedure, 1.5 kg of rich ore mixed with quicklime was placed in small clay vessels; the vessels were stopped with moss, placed neck downwards onto a receptacle, and their contacts smudged with clay. About 1000 vessels prepared in this way were placed on a piece of treaden ground encircled with stones, covered with sand or ash up to a height of 10 cm above the contact of lower and upper vessels, stacked with wood and ignited. As it grew hotter, the mercury evaporated from the upper vessel and accumulated in the lower, cooler vessel. After one day of burning and several days of cooling, the vessels were separated and the mercury was collected from the bottom vessel. As well as roasting in piles also roasting in earthen vessels gave a very poor yield and resulted in considerable losses. Because of the high temperatures usually a third of earthen vessels cracked during burning and mercury escaped from the vessels (Kavčič, 2008).

Our preliminary investigation of mercury contents in soils at old roasting site locations (Gosar & Čar, 2006) revealed that mercury contents in soils at these sites are very high, surpassing all up to that time described localities at Idrija and surroundings. It was estimated that there are about 40 t of mercury still present at ancient roasting sites (Gosar & Čar, 2006). We started detailed investigations on mercury contents in soils at 2 historical roasting site locations (Gosar & Čar, 2006; Teršič & Gosar, 2009; Teršič et al., 2008; Teršič, 2010, 2011; Teršič et al. 2011a; Teršič et al. 2011b). The main aims were to find out the extension of mercury pollution at old roasting sites and their significance for mercury dispersion locally and also in the wider Idrija area, to determine the contents and vertical distribution of mercury in soils and sediments and to establish the changes in mercury speciation with depth in the soil profile. As several anomalies were discovered during geochemical soil survey (Gosar et al., 2006) where increased mercury contents could not be the consequence of main Hg sources such as atmospheric emissions, mineralized rock dumps and roasting residues or their use in construction, we wanted to find out if old roasting sites could be the reason for these anomalies.

At Frbejžene trate roasting site the organic matter-rich surface soil layer (SOM) and underlying mineral soil were sampled at 63 sampling locations on an approximately 300 m × 250 m area. The results indicate extremely high Hg concentrations with a maximum of 37 000 mg/kg in SOM and 19 900 mg/kg in mineral soil. The established Hg median in soil was 370 mg/kg and in SOM 96.3 mg/kg. Spatial distributions of Hg in SOM and soil showed very high Hg contents in the central investigated area which decrease rapidly with the distance from this area. The New Dutchlist action value for Hg in soil (10 mg/kg; MHSPE, 1994) was exceeded in soil (5–20 cm) on approximately 95 % of the investigated area. The highest Hg contents were determined at a depth of 5–20 cm, and they decreased with depth in the soil profile. Mercury speciation was performed using Hg thermo-desorption-AAS to distinguish cinnabar from potentially bioavailable forms. The results of Hg thermo-desorption measurements indicated the presence of cinnabar (HgS) and Hg bound to organic or mineral soil matter. A significant portion (35–40 %) of Hg in the investigated soil and SOM samples was comprised of non-cinnabar compounds, which are potentially bioavailable. It has been shown that soils contain high amounts of potentially transformable non-cinnabar Hg, which is available for surface leaching and runoff into the surrounding environment. Therefore, contaminated soils and roasted residues at the studied area are important for the wider spatial contamination of soils and other environmental compartments (Teršič et al., 2011a).

The other investigated ancient roasting site was the Pšenk site, where similar results were obtained. Detailed soil sampling was performed on 210 m × 180 m area to establish the extension of Hg pollution and to investigate Hg transformations and transport characteristics through the 400 year-long period. A total of 156 soil (0–15 cm and 15–30 cm) and SOM (soil organic matter) samples were collected from 73 sampling points. Three soil profiles were sampled to determine vertical distribution of Hg. The main Hg phases were determined by the Hg-thermo-desorption technique. The measured Hg contents in soil samples in the study area vary from 5.5 mg/kg to almost 9 000 mg/kg with a median of 200 mg/kg. In SOM, Hg contents are ranging from 1.4 mg/kg to 4 200 mg/kg with a median of 20 mg/kg. The New Dutchlist action value for Hg (10 mg/kg; MHSPE, 1994) is exceeded on approximately 82 % of the investigated area. Extremely high Hg contents were found in soil profiles where the metal reaches 37 020 mg/kg. In general, Hg concentrations in all three profiles show a gradual decrease with depth with the minimum values between 140 mg/kg and 1 080 mg/kg. The Hg-thermo-desorption curves indicate the presence of Hg in the form of cinnabar and that of Hg bound to organic or mineral soil matter. The distribution of Hg species in soil and SOM samples shows almost equal distribution of cinnabar and non-cinnabar Hg compounds. The non-cinnabar fraction shows a little increase with depth, however, cinnabar represents a high portion of total Hg (about 40 %). Large amounts of potentially mobile and transformable non-cinnabar Hg compounds exist at the roasting site, which are potentially bioavailable (Teršič et al., 2011b).

At roasting site Pšenk we also studied the applicability of earthworm casts as a sampling media for determining soil contamination (Teršič & Gosar, 2012). Earthworm casts were sampled at the same locations as soil and SOM samples. In general the Hg values determined in casts are slightly higher compared to the values in SOM and somewhat lower compared to the Hg contents in soil. Strong correlation between Hg contents in casts and soil was found. Spatial distribution of Hg in earthworm casts is similar to the Hg distribution in soil with somewhat smaller anomaly. For most of the analyzed elements, the determined contents were in the order of soil > cast > SOM, indicating that the material from casts is a mixture of material from soil and SOM. Only Ca, Mg, P, Sr, Cu and Zn contents were higher in earthworm casts compared to soil. Beside Hg, strong correlations between concentrations in casts and soil were found also for U, Cr, Ni and Mo. Earthworm casts proved to be an appropriate sampling media for determining soil contamination at this particular area (Teršič & Gosar, 2012).

Regarding the investigation of Hg distribution in soils of the wider Idrija area (Gosar et al., 2006), the determined Hg values of the studied roasting site areas are much higher. Compared to the established Hg median (3.2 mg/kg) and maximum (75 mg/kg) values for soils in the surroundings of Idrija town (Gosar et al., 2006), the Hg median in soils of the studied areas are about 100-fold higher and the maximum value was almost 300-fold higher (Teršič, 2010). However, it should be taken into account that the roasting sites are of a small size and that Hg contents in soils and SOM decrease rapidly with the distance from the source of pollution.

Microanalysis of contaminated soils and roasting vessels fragments using scanning electron microscope coupled with energy dispersive spectrometer (SEM/EDS) has been applied to better characterize the Hg-bearing species in investigated materials (TERŠIČ, 2011). Mercuric sulphide (HgS) was found to be the main mercury compound present in the samples. Analysis of earthen vessels fragments showed abundant HgS coatings on the surface of ceramics, forming either crust-like aggregates on matrix or isolated grains. Some well-shaped grains with indicated structure and the size of up to 200 μm could also be observed. In soil HgS was present as powder-like concentrations scattered in soil samples, frequently coating silicate and quartz crystals and clay-minerals. Polycristalline, mercury- and sulphur- rich particles comprising silica, clay minerals and Al-, Fe- and Mg-oxides that were also observed in the samples were interpreted as soil aggregates infiltrated by mercuric and sulphur vapours and by liquid mercury spilled during roasting. These particles suggest a possible presence of mercury-sulphur associations other than HgS (TERŠIČ, 2011).

Detailed geochemical surveys carried out at these two ancient roasting sites proved that the unique way of historical ore processing in the surroundings of Idrija resulted in extremely polluted sites which influence today's extension and spatial distribution of mercury in the Idrija area. Several Hg anomalies in sediments which were discovered in upper Idrijca River Valley (GOSAR, 2008; GOSAR & ŽIBRET, 2011) and in the soils on the hills around Idrija (HESS, 1993; GOSAR & ŠAJN, 2001; GOSAR et al., 2006), where increased mercury contents could not be the consequence of main anthropogenic Hg sources, are now interpreted as a consequence of ancient ore roasting sites impacts.

COMPARISON OF MERCURY CONTENTS IN SOILS OF THE IDRIJA AREA TO OTHER MERCURY MINING SITES

The Idrija mine was the second largest mercury mine in the world being surpassed only by the Almadén mine in central Spain that has produced one-third of the total world production of mercury. As it was presented in this paper, five hundred years of intensive mercury mining activities in Idrija left a legacy of highly polluted environment. Idrija area can be compared to the Almadén area which is regarded as the largest geochemical anomaly of mercury on Earth. The district includes a series of mercury mineral deposits, having in common a simple mineralogy (dominant cinnabar, minor pyrite). The ore deposits have been mined for more than 2000 years, and the main mine of the district (Almadén), has been active from Roman times to pre-

Table 1. Hg concentrations in soils from mining contaminated areas worldwide

Location	Hg (mg/kg)	Reference
Idrija: historical mercury-ore roasting sites	3.4–19 900	Teršič, 2010, Teršič et al., 2011a; 2011b
Idrija: soil survey 160 km^2	0.3–973	Gosar et al., 2006
Idrija: alluvial soils in the Idrijca Valley	0.595– 1 970	Gosar & Žibret, 2011
Almadén district	6–8 889	Higueras et al., 2006
Mieres mining sites (N Spain)	1.7–2 224	Loredo et al., 1999
Mieres mining sites (N Spain)	54–29 304	Fernandéz-Martinez et al., 2006
Azogue Valley mining sites (SE Spain)	6–1 400	Viladevall et al., 1999
Andacollo Cu-Au-Hg mining district (Chile)	2.5–47	Higueras et al., 2004
Punitaqui Cu-Au-Hg mining district (Chile)	3.2–16	Higueras et al., 2004
Tongren district, Guizhou Province (China)	0.18–47	Li et al., 2008

sent day with almost no interruptions. The mercury distribution in soils of the Almadén district revealed the existence of high, and extremely high mercury values (6–8 889 mg/kg) (Higueras et al., 2003, 2006; Table 1). The soil contents in both districts are in the same range, but the contaminated area in the case of Idrija is much smaller. In both areas extremely contaminated areas of historical ore roasting are due to low recovery rate.

Highly elevated mercury contents were reported also from Mieres (northern Spain) by Loredo et al. (1999), who determined in soil samples near spoil heaps Hg values of up to 2 224 mg/kg. In continuation, extremely high Hg content (29 304 mg/kg) was reported from La Peña-El Terronal site (Mieres, N Spain) (Fernandéz-Martinez et al., 2006). Viladeval et al. (1999) report the contents of 6–1 400 mg/kg Hg in soils and overburden from a mineralized area in Azogue Valley (SE Spain) (Table 2).

Conclusions

Idrija certainly represents one of the areas where natural elevated mercury concentrations are technologically enhanced due to the 500 years long Hg mining, and therefore requires special attention. Presented studies have shown that Hg mining in Idrija caused intense pollution of local and regional soils. Although numerous studies have already been performed at Idrija mercury mining area, which have shown on complexity of mercury contamination problem, they also open new scientific questions and challenges for future work.

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Cooperation of GeoZS in geochemical investigation in former Yugoslavia

Vključenost GeoZS v geokemične raziskave v nekdanji Jugoslaviji

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Abstract: The main purpose of this paper is to present geochemical investigations in former Yugoslavia. Intensively, in the last decade Geological Survey of Slovenia (GeoZS) spread the geochemical researches to Bosnia and Herzegovina, Macedonia, Croatia, Kosovo and Serbia through many bilateral projects. The main mines, smelters and ironworks were the main target of investigation. According to fact that Slovenia is very rich with mines, and consequently with numerous ironworks and smelters, the GeoZS has a long tradition in this kind of researches. Successful cooperation between GeoZS and institutions from other countries resulted by numerous publications, especially with Macedonia. Some of our results are already published, but still some remains unpublished. For determination of contamination, various sampling materials such as soil, alluvial sediments, river sediments, attic dust, lichen and moss were collected. In data processing various techniques of statistical approach have been used, but for their visualization also for the preparation of predictive maps of contamination we used universal kriging method, double kriging method and artificial neural network (ANN).

Izvleček: Glavni namen prispevka je predstaviti geokemične raziskave v nekdanji Jugoslaviji. V zadnjem desetletju Geološki zavod Slovenije (GeoZS) uspešno sodeluje pri številnih geokemičnih raziskavah v Bosni in Hercegovini, Makedoniji, na Hrvaškem, Kosovu in v Srbiji na osnovi številnih bilateralnih in evropskih projektov. Glavno cilj raziskav je bilo stanje okolja v okolici večjih rudnikov, topilnic kovin

Review paper

in železarn. Glede na dejstvo, da je v Sloveniji delovalo večje število rudnikov ter posledično številne železarne in topilnice kovin, ima GeoZS dolgo tradicijo tovrstnih raziskav. Uspešno sodelovanje med GeoZS in ustanovami iz drugih držav je rezultiralo s številnimi objavami, kar posebej velja za sodelovanje z Makedonijo. Za določitev obremenjenosti okolja so bili zbrani različni vzorčni materiali, kot so tla, aluvialni in rečni sedimenti, podstrešni prah, lišaji in mahovi. V postopku obdelave podatkov so bile uporabljene napredne multivariantne statistične metode, za napoved razširjanja onesnaženja in vizualizacijo pa metode univerzalnega in segmentnega krigiranja, kakor tudi metode umetne inteligence (ANN – večslojni perceptron).

Key words: atmospheric contamination; river transport; heavy metals, former Yugoslavia
Ključne besede: težke kovine, onesnaženje, nekdanja Jugoslavija

INTRODUCTION

This study represents a summary of environmental geochemical researches in the countries formed by breakup of Yugoslavia. Our researches are mainly focused on mining and metallurgical processes which are obviously the biggest destructors of environment: B&H (Ironworks Zenica; Ironworks Vareš and Fe mines - Smreka, Droškovac, Brezik, Pb-Zn-Ba mine Veovača); Croatia (the Drava valley; Experimental geochemical map of Slovenia and Croatia); Kosovo (Pb- Zn mine Trepča and Pb smelter Zvečan–Kosovska Mitrovica); Macedonia (Cu mine Bučim, Pb-Zn mines SASA and Toranica, As-Sb-Tl mine Alšar), Pb smelter Veles; FeNi – Kavadarci; thermoelectric power plants (Kičevo and Bitola), alluvial deposits of the Vardar river, Skopje); Srbija (Mine and flotation Bor). After mineral extraction a big amount of waste has been exposed to oxidation conditions on the surface which lead to mobilisation of toxic material and formation of acidic water. Consequences of smelting and metallurgic processes are gaseous and atmospheric particles emission, waste water and waste mineral deposits.

The results help us to determine local and regional geochemical conditions, allowing us to understand a main processes and causes of the environmental changes and finally their contribution to the sustainable spatial planning. Obtaining and interpreting utilization data about chemical composition can be used in environmental protection and sustainable development of particular country, as well as for determination of pollution impacts to the human health, agriculture, forestry and future land use. Comprehensive approaches in investigation, understanding environmental issues, natural background and human impact on the environment is very important for development in earth and environmental sciences.

Basically, the major goals are strengthening an international scientific cooperation network and partnership between GeoZS and other former Yugoslav countries, improvement of material research standards, exploiting the research and technological demonstration results as well promoting the GeoZS to regional centres of excellence.

The results of numerous geochemical studies of natural distribution and proportion of anthropogenic heavy metals in the environment, especially in areas of former mining and smelting in Slovenia and the region can be used as guiding principles for the future environmental remedial actions.

Specifically, the results from the entire study will complement our knowledge about a complexity of chemical compounds in the environment. Special emphasis is given to the further development of advanced data processing techniques and methods of linear and nonlinear mathematical models, based on the application of modern mathematical analysis such as PCA (Principal Component Analysis), and ANN (Artificial Neural Network) at the distribution and transport of heavy metals in the environment.

Drava valley (Slovenia and Croatia)

The Drava watershed, including its tributaries, has been an important mining and smelting region since antiquity. The industry underwent significant development during the middle Ages, and achieved its peak in the middle of the last century. Numerous mines and smelters such as Bleiberg-Kreuth in Austria, Cave del Predil in Italy and Mežica in Slovenia have had a significant impact on the chemical composition of the alluvial sediments of the Drava. It is widely known that the broader Drava valley is rich with heavy metals (Pb, Zn, Cu, As, Cd).

The study area covers the course of the Drava from the Slovenian-Austrian border which can be divided into two regions: Alpine and Pannonian. The Alpine region occupies the Drava canyon from the Slovenian-Austrian border up to the town of Maribor (about 78 km) where the Alpine landscape is dominant. The Pannonian region occupies an area from the town of Maribor downstrem to the confluence of the Mura and Drava rivers, where the river valley is wide and exhibits the mor-

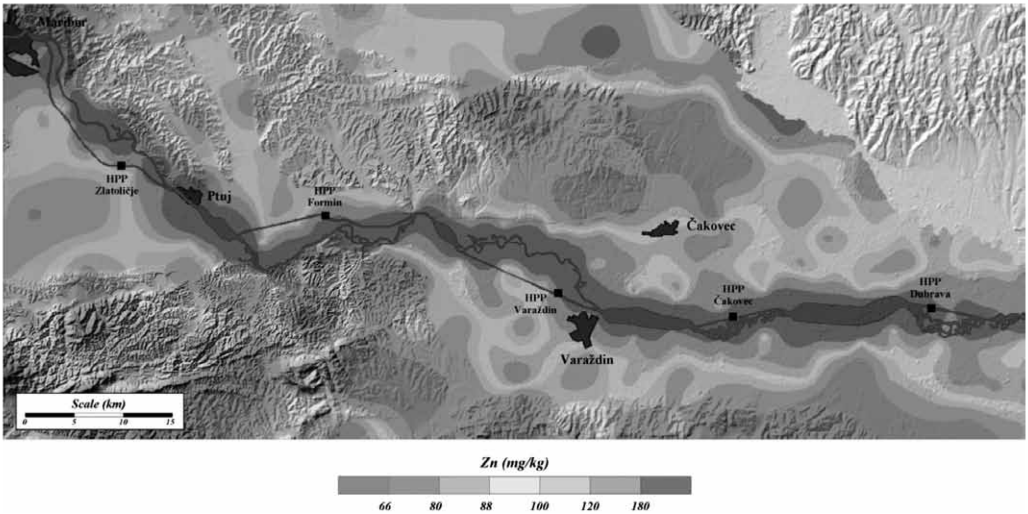

Figure 1. Spatial distribution of zinc in the Drava valley - Pannonian area (Croatia and Slovenia)

phological characteristics of the Pannonian basin. The Pannonian section of the study area covers about 123 km of the river flow. Throughout the study area, extensive deposits of alluvial sediments are found: in currently flooded zones (at present mainly behind the bank systems) covering about 55 km^2 in historically or periodically flooded areas (in recent times protected by the bulks, where agriculture production is intensive) covering about 100 km^2; and sediments of alluvial terraces comprising an area of 930 km^2 (PEH et al., 2008; ŠAJN et al., 2011).

Across the Alpine region, the 16 sampling locations are defined at places along the river course where alluvial plains and river terraces occur. Simultaneously, samples of stream sediment were collected at 8 points in the river. In the Pannonian part of the study area, where extensive alluvial plane and river terraces occur, 118 sampling locations at 25 profile lines were placed perpendicular to the river course. Analysis of 41 chemical elements was performed.

Based on a comparison of statistical parameters, spatial distribution of particular elements and the results of factor analysis, three natural and one anthropogenic geochemical associations were identified. The natural geochemical associations (Al-Fe-K-Co-Cr-Cu-Li-Ni-Rb-Sc-Th, Ti-Ce-La-Nb-Ta and Ca-Mg-Sr) were influenced mainly by lithology. The anthropogenic association (As-Ba-Cd-Mo-Pb-Sb-Zn) is mostly the result of historical zinc and lead mining and smelting in the Drava river watershed.

The entire assessed area of about 133 km^2 is, according to Slovenian and Croatian legislation, critically polluted with heavy metals, especially zinc. Based research of all forms of environmental pollution, including mines, smelters and ironworks in Slovenia at the present time, we have found that 88 km^2 of the total surface of the country is critically polluted with heavy metals. This means that alluvial sediments of the Drava River represent a wider source of pollution in both Slovenia and Croatia (Peh et al., 2008; Šajn et al., 2011).

Experimental geochemical map (Slovenia and Croatia)

Geochemical research of soil, stream and overbank sediments, as well as rocks in Slovenia and Croatia has been carried out continuously within the last two decades. The experimental geochemical map of Croatia and Slovenia is crated as a result of successful international cooperation in the field of environmental geochemistry. Regarding the fact that strategy and methodology in producing our national geochemical maps have hitherto much in common we decided to produce the joint geochemical map explaining the geochemical trends of the wider area in a more comprehensive way (Šajn at al., 2006; Šajn at al., 2008)

The high contents of Fe, Ni, Cr, Sc, V, Mn, Al and Cu, have found in the areas covered by Pg and Cretaceous flysch, and in the areas of Neogene postorogenic sedimentary formations as well as by metamorphic rocks of the Pohorje Mt. and its environs. Nb, La, Th, As, Y and Zr are characteristic for brown carbonate soils, or terra rossa on carbonate platforms, as well as for the areas of eastern Slavonia. Ba, K and Na are typical for areas covered by igneous rocks. Ca, Sr, Mg and P are the most poorly differentiated and are associated either with rendzinas and similar soil types in the mountainous areas or, again, with the carbonate contents in immature alluvial soils in the Sava and Drava river valleys. Pb, Zn, Hg and Cd represents a typical heavy metal association originated either as a consequence of natural erosion of ore-bearing rocks or, again, of mining activity and smelting industry in the past. Their highest concentrations can be found in Slovenia in the vicinity of mines and metallurgic centers (Idrija, Mežica, Litija, Jesenice and Celje). Mining activity left its traces as well, which is reflected in the higher concentrations of heavy metals in recent sediments of the Sava and Drava rivers. Increased values in the areas of Gorski kotar, Velebit and Dalmatia derive their origin mostly from atmospheric deposition (Figure 2).

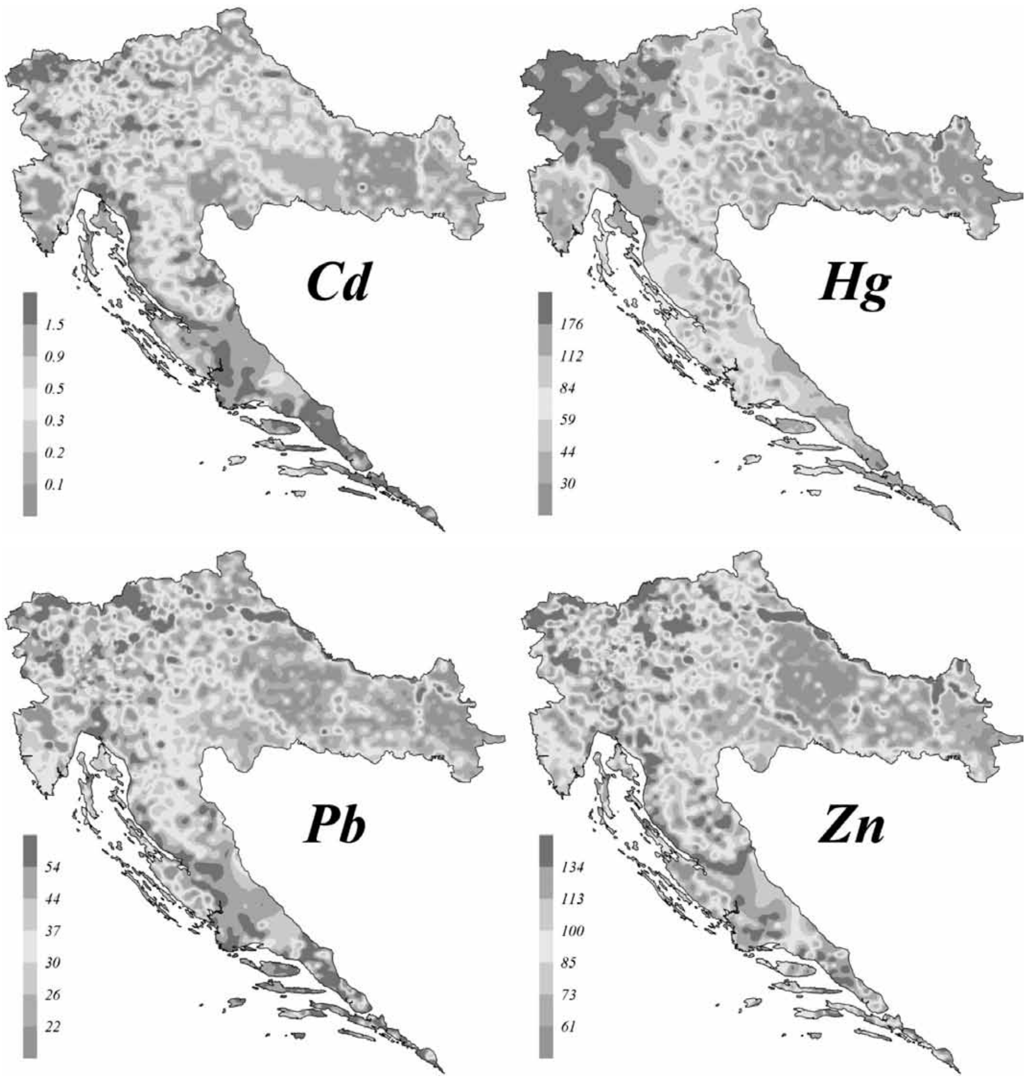

Figure 2. Spatial distribution of Cd, Hg, Pb and Zn in topsoil (Croatia and Slovenia)

Zenica (Bosnia and Herzegovina)

Zenica, 170 000 inhabitants, is located in the valley of river Bosna, about 70 km north from Sarajevo. Construction of the iron and steel works started in 1892, during Austro-Hungarian period, and until the end of 50's, becomes the biggest construction site in the former Yugoslavia. Expansion of production reached the record of 1.72 Mt of pig iron and 1.91 million tons of crude

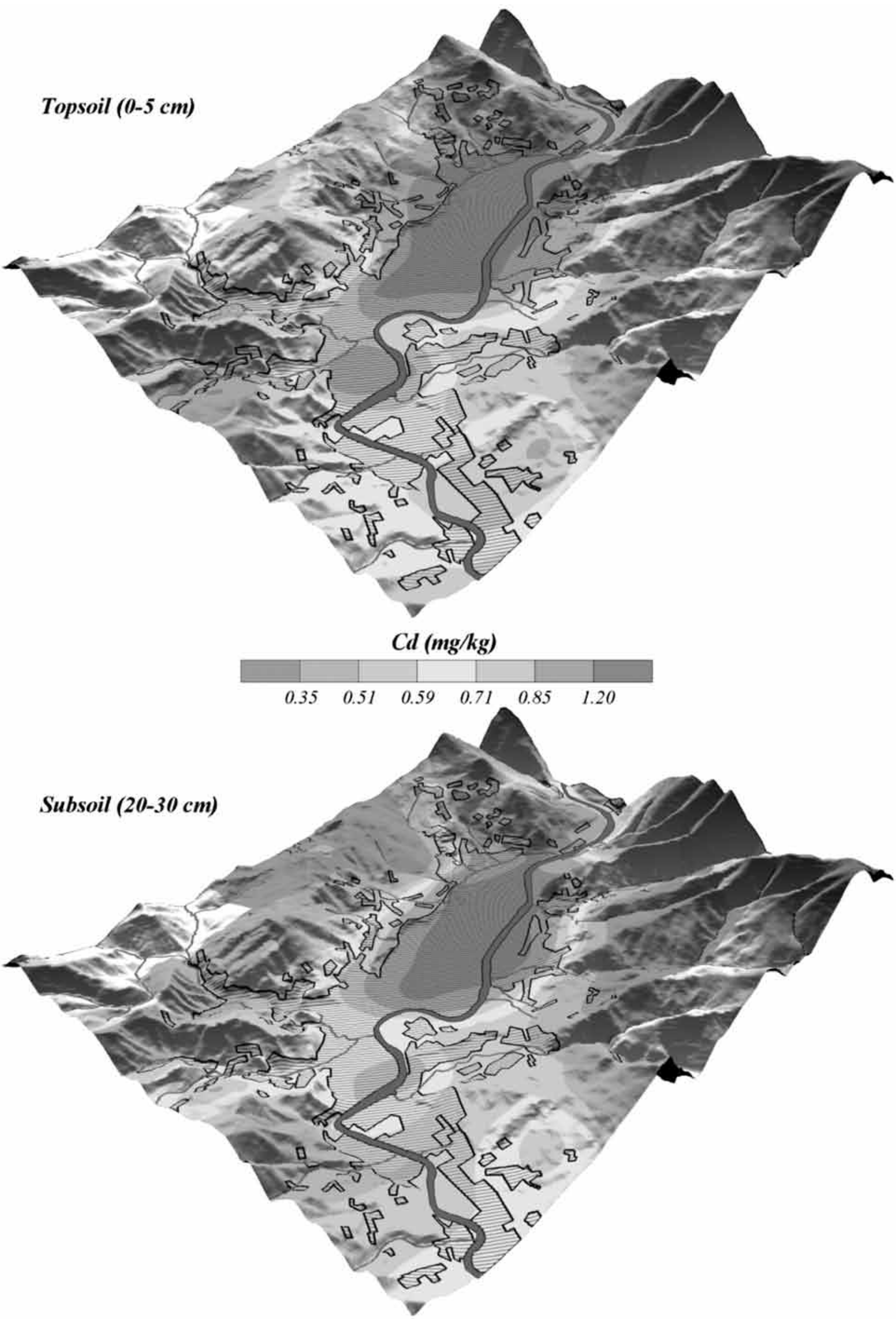

Figure 3. Spatial distribution of cadmium in the topsoil and the subsoil (Zenica, B&H)

steel in 1986. At the beginning of 90's production was completely stopped but production was continued with less capacity at the end of last century.

Area of 52 km^2 is covered with sampling grid that includes: urban zone, industrial zone and wider valley of the River Bosna. The entire area is separated into cells by the sampling grid with a density of sample per square kilometer but in the urban zone, sampling density is increased. At 62 different sites, 124 samples of topsoil (0–5 cm) and subsoil (20–30 cm) were collected

Two geogenic and one anthropogenic geochemical association are established on the basis of: visually indicated similarity of geographic distribution of elemental patterns in the topsoil and bottom soil, comparisons of basic statistics, correlation coefficient matrices, results of cluster and factor analyses and comparisons of enrichment ratios (Alijagić & Šajn, 2006; Alijagić, 2008; Alijagić & Šajn, 2010).

Two natural geochemical associations (Al, Ca, Ce, K, La, Li, Nb, Rb, Sc, Ta, Ti Th, V and Y) and (Co, Cr, Na, Ni and Mg) are influenced mainly by lithology, but the third anthropogenic association (Ag, Bi, Cd, Cu, Hg, Mo, Pb, Sb and Zn) is result of historical activities of the ironworks Zenica, but also coal mining and other anthropogenic influences in the past.

High concentrations of Co, Cr and Ni are result of weathering processes and critical level of the mentioned elements is found on c. 2 km^2 in topsoil and c. 3.3 km^2 in bottom soil. Natural critically polluted area is located on surrounding hills, outside from the urban zone and main share in total natural pollution is principally with Ni and Cr. Anthropogenic pollution that associate high concentrations of As, Cd, Cu, Hg, Pb and Zn, exceed critical level on c. 2 km^2 in both soil horizons. For the mentioned association is significant that polluted area is situated in the Zenica basin and area among the river. Critically polluted area is mainly situated on the Miocene coal layers on the NW side of the study area and refers to As distribution.

Stavnja Valley (Bosnia and Herzegovina)

Vareš is situated in the valley of the river Stavnja with 20 000 inhabitants. In this region, iron ore mined and smelted from Antique period but with arrival Austrians to Bosnia, Vareš admire revival in economy aspect. Construction of the ironworks and metal foundry in Vareš started in 1891, and until 1991. Three Fe ore deposits Smreka, Droškovac, and Brezik are situated in municipality of Vareš. Open pit's reserves and resources in the mentioned three Fe ore deposits are approximately 169 million tones, in 1991. Apart the Fe in hematite and siderite there are present another oligoelements such as Cu, Pb, Zn, As, Sb and Sn.

Lead, zinc and barite Veovača open pit is situated about 10 km of the town. Sulphide mineralization is associated with layers of barite and have volcanogenic – sedimentary genesis. Pb – Zn mineralization is associated with Droškovac Fe deposits. From the abandoned open pit and waste deposit "Veovača" is significant leeching of trace elements that have great influence on environmental pollution around the open pit and along the river Stavnja.

The main goals of the study have been: Identification of optimal methodology for geochemical research in the areas of former military operations (with remain minefields and/or suspected mined areas), according to the sampling material, sampling density, data processing and interpretation of results; Determination of concentration levels and spatial distribution of chemical elements in the secondary materials (soil, river sediments and attic dust) along the Stavnja valley; Assessment of the natural background according to lithology and the proportion of influence of mining and metallurgy activities on distribution of chemical elements in the secondary materials (soil, river sediments and attic dust) along the Stavnja valley; Identification of main geochemical associations and their spatial distribution using multivariate statistical approach (PCA) and Artificial Neural Network (ANN); Design models of heavy metal dispersion around the major emitters, using multivariate statistical approach (PCA) and Artificial Neural Network – ANN (Figure 4).

At 153 sampling locations, 265 samples of soil, stream sediment and attic dust were collected. Analysis of 36 chemical elements was performed. One anthropogenic and four geogenic geochemical associations were establish on the basis of visually indicated similarity of geographic distribution of elemental patterns in the topsoil and subsoil; comparisons of basic statistics, correlation coefficient matrices; results of cluster and factor analyses and comparisons of enrichment ratios (Alijagić & Šajn, unpublished data).

The geogenic geochemical associations (Cr, Ni, Co, Fe, V, Sc and Cu), (Th, La, As, K, Sc and Tl), (Al, Ga and V) and (K and P) are influenced mainly by lithology, but anthropogenic geochemical association (Pb, Zn, Ag, Sb, Hg, Cd, W, Bi, U, Mo, Mn, Ba, Sr, Ca, Cu, Tl, Fe and As) links elements that are result of historical activities of the ironworks Vareš, mining activities as well as other anthropogenic influences of metallurgical

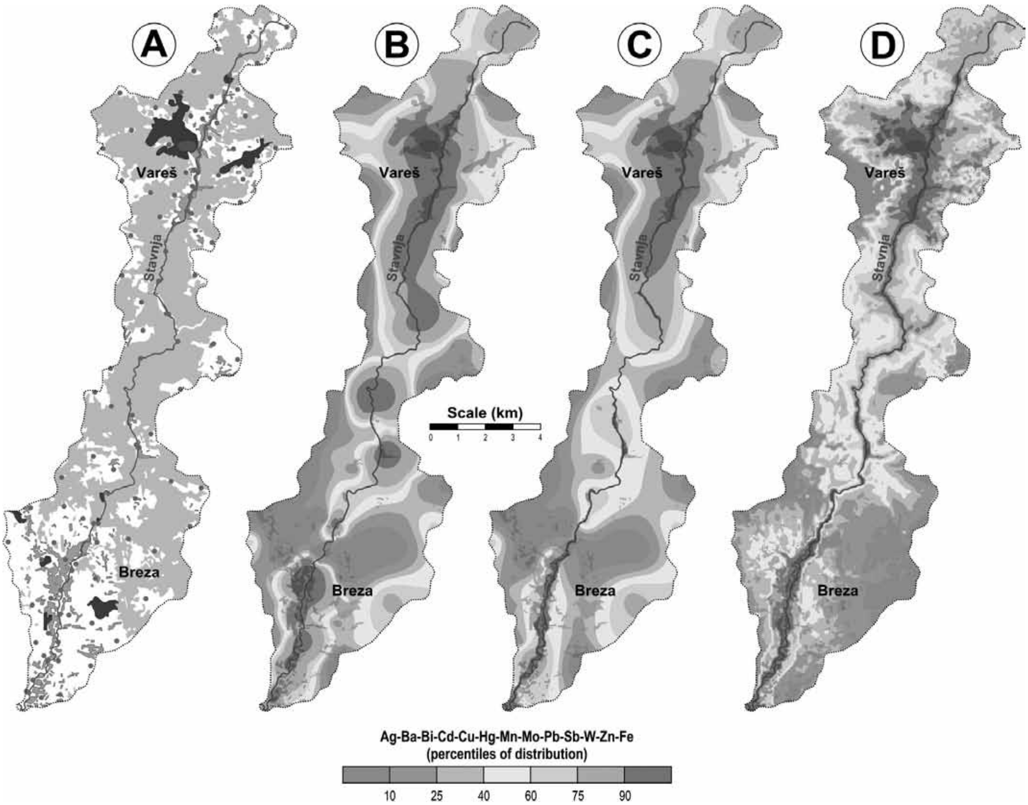

Figure 4. A – Landuse map with the sampling grid (Vareš, B&H); B - spatial distribution of Ag, Ba, Bi, Cd, Cu, Hg, Mn, Mo, Pb, Sb, W, Zn and Fe using standard kriging method; C – using segment (multiple) kriging; D – using ANN (multilayer perceptron neural networks)

factors in the past. The main polluted zones are found in the city Vareš and their surroundings, where are located two Fe open pits and the Veovača, Pb-Zn-Ba mine and ironworks. Another zone with high concentration of aforementioned heavy metals has been found downstream of the river Stavnja, in alluvial sediments suitable for agricultural activities (ALIJAGIĆ & ŠAJN, unpublished data).

INVESTIGATION IN MACEDONIA

Cooperation GeoZS with Macedonia is basically the strongest one at the moment, which can be proved by many already published materials. We focused our geochemical researches to most polluted locations such as the mines (Cu Bučim, Pb-Zn SASA and Toranica, As-Sb-Tl Alšar), Pb-Zn smelter Veles; FeNi – Kavadarci; thermoelectric power plants (Kičevo and Bitola), alluvial deposits of the Vardar river, Skopje. Here we want to present several study cases (Veles, Kavadarci and Bučim) but several other very interesting studies are: identification of heavy metals in honey samples (Stankovska et al., 2007; 2008), and moss samples (Barandovski et al., 2012) in R. Macedonia; determination of chemical composition of soil around the thermoelectric plant Oslomej, in Kičevo (Stafilov et al., 2011).

Veles (Macedonia)

Veles (50 000 inhabitants) is the most polluted city in Macedonia. In the centre of town lead and zinc smelter located. The Macedonian Institute for Health Protection reported in 2003, when the factory still operated, that Veles was absorbing 62 000 t of zinc, 47 300 t of lead and 120 000 t of sulphur dioxide annually. Plans for the cleanup include ridding the city of heavy metals and decontaminating soil in the 45 ha area around the smelter.

As, Cd, Cu, Hg, In, Pb, Sb and Zn are chemical elements introduced into the environment through anthropogenic activities. Typical for this elemental assemblage is the enrichment of the elements in topsoil versus European topsoil, from 2.2-times for the Sb to 27-times for the Cd. High concentrations and as well the enrichments of mentioned elements, especially Cd in topsoil is noticeable close to Zn smelter in Veles and in urban zone. In area of the main polluted area average concentration of Cd exceed European Cd average more than 110-times!

The shape of the dispersion halo has been strongly influenced by local winds and the shape of the Veles basin. Cd average in topsoil for the all study area amount 7.7 mg/kg in range 0.30–600 mg/kg. Considering land use, the average of Cd in cultivable area amount to 6.1 mg/kg, in uncultivable area 4.8 mg/kg, in urban area 12 mg/kg and in main polluted area 32 mg/kg. The most of highest values is in the industrial part of the region with the maximal Cd content from 76 mg/kg to 600 mg/kg, and in the part of the city which is close to the smelter plant (104 mg/kg and 105 mg/kg). In this region several topsoil samples with extremely high content of cadmium are present 420 mg/kg (3500-times higher that European topsoil average. According to experimental results, the area critically polluted with Cd is about 6.6 km^2, with Pb 4.2 km^2 and Zn 3.8 km^2. Materials for the study case are collected from the following articles: Stafilov et al., 2008; Stafilov et al., 2010. Radionuclides in soil were studied in Dimovska et al., 2010a. This work has awarded with The State Prize of the Government of Republic of Macedonia »Goce Delčev« for the scientific achievement in 2008.

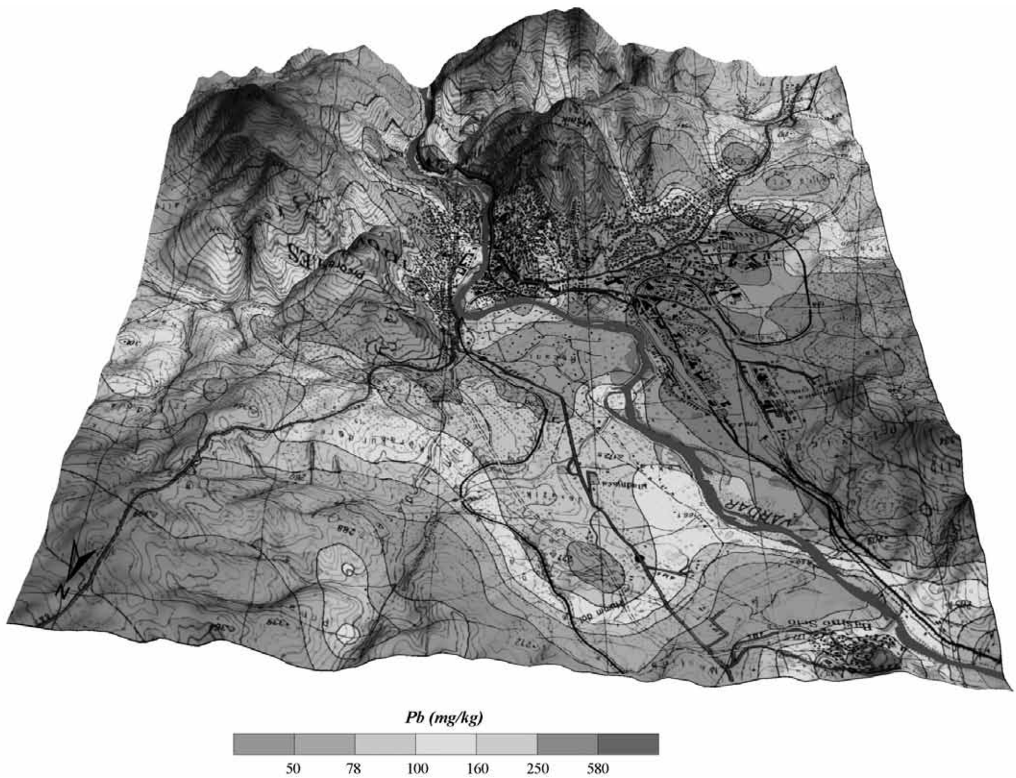

Figure 5. Spatial distribution of lead in topsoil (Veles, Macedonia)

Kavadarci (Macedonia)

Materials for the study case are collected from the following articles: Stafilov et al., 2008b; 2009a; 2009b; 2010b. But also several other interesting studies in this area are: Bačeva et al., 2009; 2011; 2012a; 2012b concern atmospheric pollution; Dimovska et al., 2012b represent radioactivity in soil; Žibret et al., 2012 applied artificial neural network in determination of contamination; Stafilov et al., 2012 provide an interesting study of As-Sb-Tl in this region.

Town Kavadarci is located in Tikveš valley, about 100 km south from the capital Skopje (Figure 1). The city is well known and famous by its vineyards and it is main vine production region in Macedonia. The urban area is located on 200–300 m altitude, surrounded with hills from east and south sides of the valley (with height difference between 300 m and 770 m). The climate in Kavadarci is of a continental type of climate with a reduced Mediterranean climate and with hot summer and cold winter. The major wind direc-

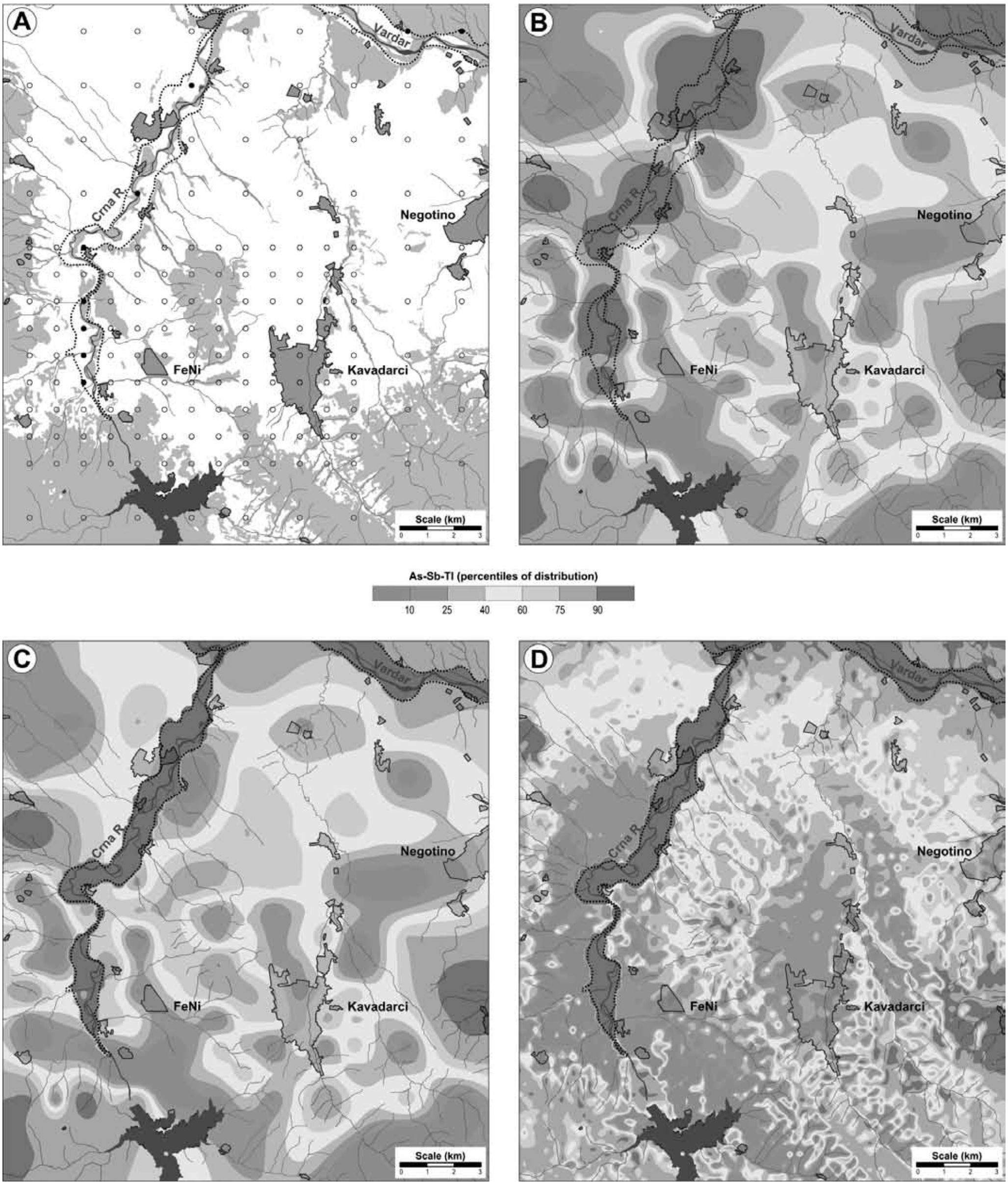

Figure 6. A – Landuse map of Kavadarci area with the sampling grid (Kavadarci, Macedonia) B – spatial distribution of As-Sb-Tl using standard kriging method; C – using segment (multiple) kriging; D – using ANN (radial basis function neural networks)

tion is from the north and northwest. The complete investigated region (360 km^2) was covered by 172 sampling location. 344 soil samples of topsoil and subsoil were collected.

The highest concentrations of Cr and Ni are are located on the outcropping Paleozoic serpentinites (inner parts of the Vardar zone). High, sometimes critically content of Cr and Ni in the zone of Eocene flysch is already proven in numerous researches from Macedonia and other Balkan countries. The ferronickel smelter plant "FENI", in spite of the obvious environmental pollution has not contributed significantly to the measured amount of these elements, which occur in high concentrations in the background.

High concentrations of Cd, Hg, Pb and Zn are also found on the SW and W, hilly part of the study area as a consequence of the high concentrations of heavy metals in organic material of topsoil or the long distance transportations. High concentrations of the mentioned heavy metals were also found as a result of urban activities in the city of Kavadarci, but they are very low. The highest concentrations of As, Sb and Tl are found on the Holocene alluvium of Crna Reka. Enrichment of the Holocene alluvium of the Crna Reka is consequence of natural erosion from the mine deposits (As and Sb) of Alšar on the Kožuf Mountain, but also from mine activities in the past. High concentrations are determined in the river sediments of Vardar River. This enrichments with As, Sb and Tl in the Holocene alluvium of the rivers Crna Reka and Vardar should be studied in the future because it is a rare example of enrichment of alluvial sediments (Fig 6). Principally, the natural enrichment is related especially to Ni. Pollution with As, Cd, Co, Cr, Cu, Hg, Mo, Pb and Zn is basically insignificant.

Construction of geochemical maps using universal kriging methods is quite useful in determination of distribution patterns, but in such a maps are present mistakes called Bull's eye effect because in the isotropic space appears elongated division, that is possible solve only with denser sampling grid. Applying the multilayer perceptron (MLP) avoiding this problem and we constructed much better maps of contamination, especially from the geological point of view (Figure 6.).

Bučim (Macedonia)
Materials for the study case are collected from the following articles: BALABANOVA et al., 2009, 2010; 2011a; 2011b; 2012a; 2012b; STAFILOV et al., 2010b.

The Bučim copper mine is located in the eastern part of the Republic of Macedonia. The mine is in function from 1980 and processes 4 Mt of ore annu-

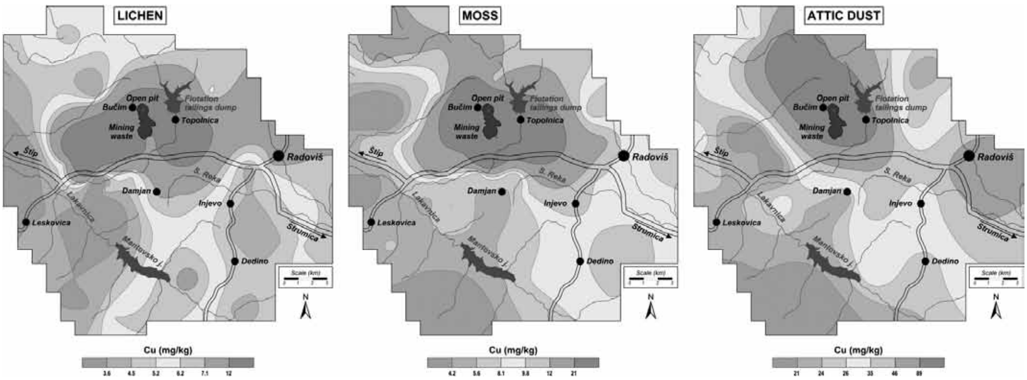

Figure 7. Spatial distribution of cooper in lichen, moss and attic dust (Bučim, Macedonia)

ally. The ore reserves are estimated to total about 85 Mt. The deposit is a porphyry copper type deposit and mineralization is related to Tertiary sub-volcanic intrusions of andesite and latite in a host of Pre-Cambrian gneisses and amphibolites. The main ore body is approximately 500 m in diameter and 250 m in vertical and has been worked in a large open pit, which actually allows direct exposure of ore particles to the atmosphere. The igneous rocks have been altered into clays and micas. The basic ore proceeding process includes: drilling and blasting, than blasted ore is transported towards primary crushing while the tailings on the mine disposal.

Different sampling media: moss, epiphytic lichens and attic dust were used for comparative analysis due to monitoring air pollution and distribution of 15 elements including certain heavy metals. Thus, attic dust, moss and lichen have the potential for collecting complementary information on present and historical air pollution trends.

For the geogenic geochemical association Ni-Cr-Cd-Fe-Al-K-Mn-Zn is significant a similar distribution pattern, with minor variations, especially in the biogenic samples. In all observed materials, the higher concentrations are observed in the area of predominant Pliocene sediments, with fact that both patterns, in attic dust and moss are much more similar. Significant deviation from that fact represents high values in moss and lichen in the area where occur Palaeozoic rocks, mainly schist. Spatial distribution pattern of anthropogenic association As, Cu and Pb is very similar for all three sampled materials. The association presents distribution of high contents of potentially risk elements close to the anthropogenic sources.

All three treated materials are shown to be useful in determining an anthropogenic impact as well as the chemical properties or geological background on orographic diverse terrain in the presence of complex geological structure. With fact that attic dust is the most stable and responsive to environmental changes and lichen is the worst.

Based on the research results, the combinations of attic dust and moss give the best results in the determination of anthropogenic impact on the environment as well as the natural enrichment. Attic dust shows very stable historical reconstruction of contamination, moss a current state, related to a period of growth and to period of accumulation of chemical elements.

Kosovska Mitrovica (Kosovo)

Materials for the study case are collected from the following articles: Aliu et al., 2009 2010; Stafilov et al., 2020a; Šajn et al., 2012;

Mining and metallurgic activities in Kosovo have a long history. The Trepča Mine Limited in K. Mitrovica was built in 1927 and produced lead, arsenic and cadmium from the 1930s until 2000. The smelter close to Zvečan commenced work in 1939. Because of the smelter and three huge tailing dams, environmental pollution in K. Mitrovica increased dramatically. The smelter has been working sporadically since the 1999 conflict between Kosovo's Albanian and Serb population in Kosovo.

The total production of mine Trepča from 1931 to 1998 has been estimated at 34 350 000 t run-of-mine ore at grades of 6 % Pb and 4 % Zn. The ore was beneficiated in the flotation plants. The Pb concentrates were brought to the lead smelter of Zvečan (capacity 80 000 t per year) and the Zn concentrates were brought to the zinc smelter of K. Mitrovica (capacity 50 000 t per year); there was also a unit for the production of fertilisers and batteries. The amount of metal produced was 2 066 000 t Pb, 1 371 000 t Zn as well as Ag, Bi and Cd.

The investigated region (300 km^2) was covered by a sampling grid of 1.4 km × 1.4 km. In total, 159 soil samples from 149 locations were collected. Inductively coupled plasma-mass spectrometry (ICP-MS) was applied for the determination of 36 elements. For data evaluation, parametric and non-parametric statistics methods were used.

The obtained results show that the content of Ag, Pb, Sb, Bi, Zn, Cd, As, Cu, Hg, Au, Tl and Mo appeared as an anthropogenic association, which contents mainly depend on mining and processing activities. In vicinity of cities Zvečan and K. Mitrovica their content is even higher than the corresponding intervention values ac-

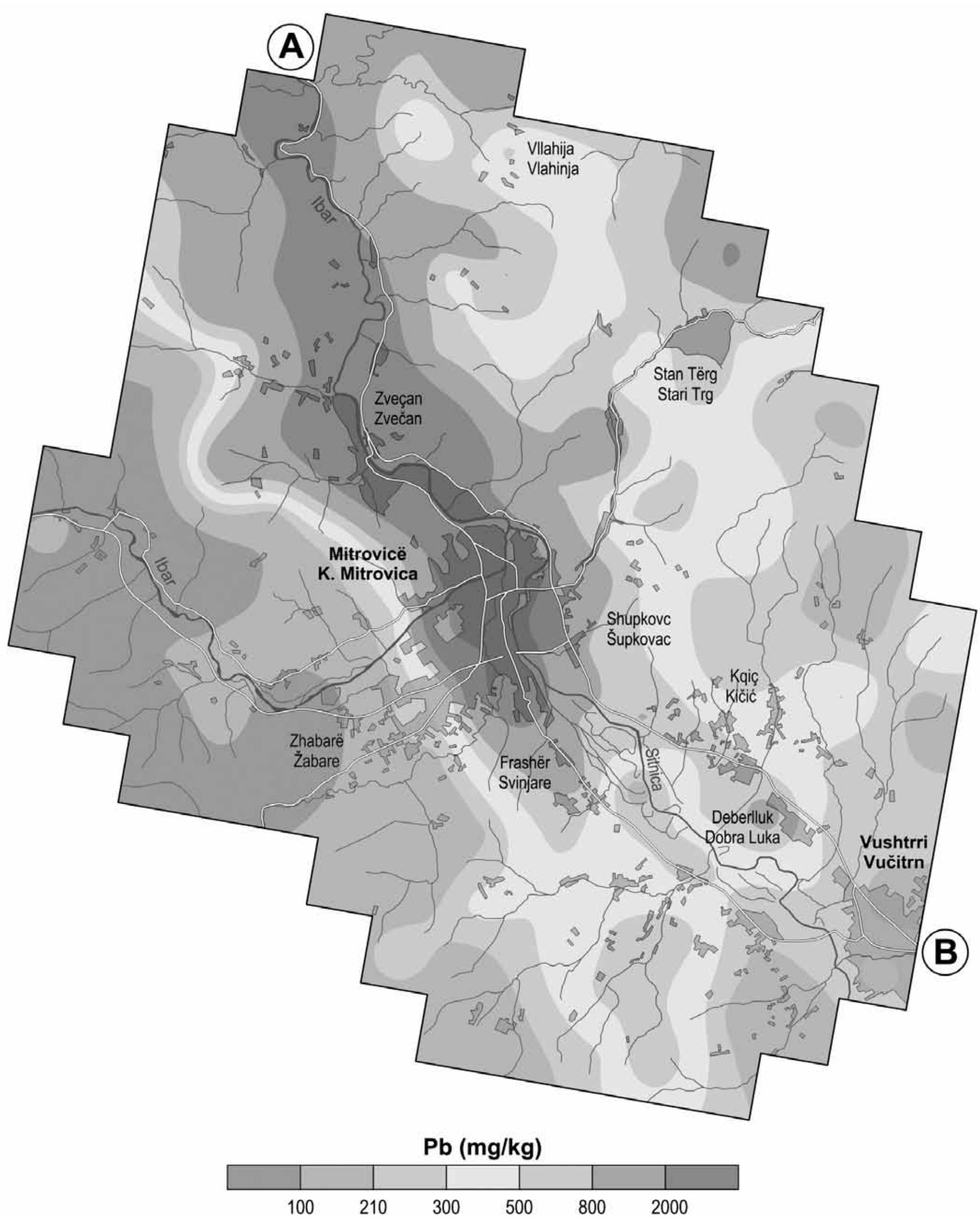

Figure 8. Spatial distribution of lead in topsoil (K. Mitrovica, Kosovo)

cording to The New Duch List exceed in 152 km^2 of the investigated area. The pollution is involving several extremely high elements such as Pb, Zn, Cd, Cu, Ag, and Hg. Their average contents are: Pb 450 mg/kg with a range of 34–35 000 mg/kg, Zn 30 mg/kg in the range of 32–12000 mg/kg, Cd 1.6 mg/kg with a range of 0.10–47 mg/kg, Cu 42 mg/kg in range 9.0–1600 mg/kg, Ag 30 mg/kg in range 0.05–58 mg/kg and Hg 0.20 mg/kg in range 0.02–11 mg/kg.

There is no doubt that the mining and smelting activities left huge consequences on environment in urban zones of K. Mitrovica and Zvečan, the Trepča mines in Stari Trg, but also in alluvial sediments of the Ibar River, where intensive agriculture activities are present.

Investigation in Serbia

Geochemical researches in Serbia begun in 2011 and finish 2012, we focused our study on the alluvial sediments of river Ibar (environmental impact of mine Trepča and Pb smelter Zvečan), river sediments and river terraces of the river Timok, and the copper mine Bor where we collected the soil samples and attic dust (Šajn et al., 2012, unpublished data).

Bor is a town located in eastern Serbia, with one of the largest copper mines in Europe. The population of municipality has about 50 000. Basic economic activities in Bor are copper mining and metallurgy. The mine was opened in 1903 and 1905 started the copper-smelting work. The factory, in which is now melting the copper concentrate was built from 1961 to 1968. Every year, it emits 4.86 kg to 7.99 kg of zinc, 6.27 kg to 25.11 kg of lead and 5.3 kg to 19.6 kg of arsenic per capita, which depends on the emission volume of production and content of these metals in raw materials.

Bor and surrounding is cover by 96 soil sampling sites (topsoil and bottom soil), 10 sites of urban soil and 86 sites of attic dust. First, preliminary results show that the mining and metallurgical activities in Bor and its surroundings caused numerous environmental problems, and left catastrophic consequences for the entire environment.

The river Timok with its tributaries represents a drainage water system from the copper mine Krivelj (Bor), and heavy metal industry in Bor. Hazardous waste is transported by this river to the Danube, consequently polluted by heavy metals. Sampling grid is constructed on the way that we cover the main polluted part from town Zaječar till its confluence with Dunav, but also a two main tributaries from the Krivelj mine. Altogether, 15 samples of river sediments and 15 soil samples from alluvial plains and 10 soil samples from river terraces were collected.

After the high concentrations of heavy metals especially Pb, Zn, Cd, Ag, Hg and Cu were discovered in Kosovska Mitrovica and Zvečan, we decided to continue a sampling along the river till its confluence with the river Zapadna Morava. Total, 14 samples of river sediments, 14 alluvial sediments (top and bottom soil), 14 river terraces (top and bottom soil) and 4 soil samples on second river terraces (top and bottom soil).

Conclusion

The major goals are strengthening an international scientific cooperation network and partnership between GeoZS and other former Yugoslav countries, improvement of material research standards, exploiting the research and technological demonstration results as well promoting the GeoZS to regional centres of excellence. The results of numerous geochemical studies of natural distribution and proportion of anthropogenic heavy metals in the environment, especially in areas of former mining and smelting in Slovenia and the region can be used as guiding principles for the future environmental remedial actions.

Specifically, the results from the entire study will complement our knowledge about a complexity of chemical compounds in the environment. Special emphasis is given to the further development of advanced data processing techniques and methods of linear and nonlinear mathematical models, based on the application of modern mathematical analysis such as PCA (Principal Component Analysis), and ANN (Artificial Neural Network) at the distribution and transport of heavy metals in the environment.

Soil is together with water and air, one of the most important natural resource of country. Apart of food production, soil is a natural filter for hazardous and noxious substances that can run out to system of drinkable water and groundwater respectively. Because of that soil care, as natural treasure, represent very important priority in environmental protection. For better soil treatment, is necessary to know all soil characteristic, their concentration of chemicals and concentration of potential toxic elements as well.

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Sustainable Aggregates Resource Management: experience learnt and shared within South East Europe

Trajnostno gospodarjenje z mineralnimi surovinami za gradbeništvo – izkušnje, pridobljene v jugovzhodni Evropi

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Abstract: The purpose of this paper is to describe sustainable mineral resources management and its application to aggregates management. First the theoretical foundations of sustainable resource management are introduced in the context of the characteristics of aggregates that differentiate them from most other mineral commodities. The environmental, economic and social aspects are reviewed and well as the challenges of implementation and the necessity of adaptation. The remainder of the paper discusses the SARMa project, which implemented sustainable aggregates resource management (SARM) and sustainable supply mix (SSM) in South East Europe (SEE). SARMa had 14 partners in 10 nations who worked together to develop a common approach to SARM and SSM in SEE. The project produced 3 manuals addressing such issues as environmentally friendly quarrying, decision-making for SARM and SSM at the regional, national, and transnational scales, and construction and demolition waste management. These results built on numerous case studies, analyses and recommendations that led to common

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methods and knowledge management tools. SARMa contributed to the SEE Programme's overall objectives by integrating environmental, social, and economic aspects of sustainability with respect to aggregates, capacity building, and fostering transnational territorial cooperation.

Izvleček: Namen članka je predstaviti trajnostno gospodarjenje z mineralnimi surovinami s poudarkom na gospodarjenju s kamenimi agregati. V prvem delu so predstavljene teoretične osnove trajnostnega gospodarjenja z viri glede na značilnosti kamenih agregatov, ki se razlikujejo od večine drugih mineralnih surovin. Prdstavljeni so tako okoljski, ekonomski in družbeni vidiki, kot tudi izzivi izvajanja trajnostnega gospodarjenja in potrebe po prilagajanju sprejetih politik. V drugem delu članka je predstavljen projekt SARMa, ki je apliciral koncepta trajnostnega upravljanja z mineralnimi surovinami (SARM – Sustainable Aggregates Resource Management) in trajnostne oskrbe (SSM – Sustainable Supply Mix) v jugovzhodni Evropi (JVE). Pri projektu je sodelovalo 14 organizacij iz 10 držav, ki so razvile skupen način obravnave SARM in SSM v JVE. Nastali so trije priročniki, ki obravnavajo teme, kot so: preprečevanje ali zmanjševanje površinskega pridobivanja na okolje, sprejemanje odločitev o SARM in SSM na regionalni, nacionalni in mednarodni ravni ter pridobivanje recikliranih kamenih agregatov iz inertnih odpadkov. Nastali rezultati temeljijo na številnih študijah primerov, analizah in priporočilih, ki so vodili k skupnim metodam in orodjem za povečanje znanja vključenih ciljnih skupin. Projekt SARMa je prispeval k ciljem programa Jugovzhodna Evropa, saj je povezal okoljski, ekonomski in družbeni vidik trajnosti na področju kamenih agregatov, pripomogel k izboljšanju kapacitet ter spodbudil mednarodno teritorialno sodelovanje.

Key words: Mineral resource management, Sustainable development, Policy, Sustainable supply mix, Slovenia

Ključne besede: trajnostno gospodarjenje z mineralnimi surovinami za gradbeništvo, trajnostni razvoj, politike, trajnostna oskrba, Slovenija

Introduction

In the second half of the twentieth century, societies began to realize that new approaches to development were needed. Human activities were having impacts that exceeded the Earth's carrying capacity on global, and in many places on regional and local, scales. This was particularly true with regard to environmental pollution and the consequences of natural resource extraction and consumption. Minerals are resources that are both essential for modern existence and future development, and whose extraction, use and disposal can cause negative social and environmental impacts. Societies cannot be expected to forego the stream of benefits coming from the use of mineral resource products, and by extension from mining. Therefore, it is crucial to encourage both the mitigation of cumulative negative impacts, which were in most cases the consequences of past practices, and the implementation of new, better practices.

Recognizing that past activities are no longer acceptable, a new development framework has emerged. The framework, called sustainable development, has four overarching goals: economic prosperity, environmental health, social equity for the present generation, and equal opportunities for future generations. In the past decade, the goals of sustainable development have been embraced by most countries in the world, and are now being applied to decision making at global, local, and individual scales, including those decisions related to mining.

The foundations for sustainable mineral resource management were laid through a review of sustainable development concepts, their links to mineral resources, national mineral policies and management programs. The likelihood of improved choices from among possible development options is increased when those decisions are informed by knowledge and science. Scientific and technical expertise can be applied to monitoring socio-economic and bio-physical processes and, in so doing, provide information and data to every stage of the policy cycle, including to sustainability policies.

Earth scientists, geologists and others are involved not only in fundamental research projects, but also in applied projects. Most applied projects are multidisciplinary and have as their goal the solution of different open and ongoing challenges that society faces. An important set of these projects deals with the provision of an adequate and secure supply of raw materials. This paper describes a Southeast Europe project "Sustainable Aggregates Resource Management". The main objectives of the project are to develop a common approach to sustainable aggregate resource management (SARM) and sustainable supply mix (SSM) planning at three scales (local, regional/national, transnational) to ensure efficient and secure supply in South East Europe.

Sustainable aggregates resource management

There has been an inappropriate tendency to focus exclusively on metals when minerals are used as an engine of development. As a result, the potential positive contributions of mineral development are often overlooked in countries with limited endowment of metals.

Under- or over-emphasis on the minerals sector can be lessened by addressing mineral development within the context of sustainable development. Each country identifies sustainability goals, with respect to social equity, environmental health, and economic growth that are appropriate to its circumstances. The contribution of mineral resources to the achievement of those goals will be similarly context dependent.

Natural aggregate is an essential commodity in modern society. Developing nations need stable, adequate and secure supplies of construction materials to build the infrastructure needed to achieve the Millennium Development Goals (Baird & Shetty, 2003). This includes highways, roads, bridges, railroads, airports, seaports, water and waste treatment facilities, and energy generation facilities. Construction materials are also essential to the provision of sustainable housing and the expansion of industrial capacity (CIB & UNEP, 2002). These large volume materials will need to be provided in a rational integrated manner that maximizes their societal contributions and minimizes environmental impacts.

Natural aggregate is a material composed of rock fragments, which may be used in their natural state or after mechanical processing such as crushing, washing, and sizing (Langer & Tucker, 2003). There are two categories of aggregates, gravel and crushed stone. Gravel generally is considered to be material whose particles are about 2.0 mm to 63.0 mm in diameter. Its edges tend to be rounded. Crushed stone is of the same size range, but is artificially crushed rock, boulders, or large cobbles. Most or all of the surfaces of crushed stone are produced by the act of crushing, and the edges tend to be sharp and angular. Natural aggregate has hundreds of uses, from chicken grit to the granules on roofing shingles (tiles). However, most aggregate is used in cement concrete, asphalt, and for other construction purposes. The average per capita consumption of aggregate generally ranges from 5 t to 15 t per year (Langer & Šolar, 2002).

While aggregate is a non-renewable resource, supplies are nearly inexhaustible on a global scale. They have characteristics that differentiate them from most other mineral commodities:

- a high number of potential extraction sites;
- a high volume to value ratio;
- significantly different set of potential environmental impacts; and
- regional importance combined with a narrow economic transportation radius.

In most cases, aggregate demand is met by local or in-country suppliers. This occurs because most aggregate transportation is carried out on roads and transportation short distances to different locations by road is economically viable. Moreover, constructing and maintaining a dense road network is less expensive than constructing rail or channel networks.

In many countries, aggregates have simplified legal frameworks (local level competence, licensing, taxation, control) compared to other minerals due to the above mentioned characteristics. In some countries aggregates are the landowner's property even if most of other minerals are state owned.

Aggregates are very often overlooked in minerals sustainability debates due to the fact that they are seldom export products of national importance like metals or energy resources.

Aggregates typically do become part of sustainability debate in countries with organized environmental protection groups that have active individual members. These are mostly developed countries where mining is a declining economic activity and most other types of mineral extraction have ended. In developing countries, the negative and positive effects of quarrying are not important issues in the development debate because the negative impacts of aggregate extraction that are passed on as burdens for future generations cannot be compared with the present desire for faster economic development and poverty alleviation. The fact that the costs of remediating negative social and environmental impacts of aggregate quarrying and use will be higher in the future than they are today is neither a priority nor a point of discussion in most developing countries.

Nonetheless, aggregates should be an integral part of any country's overall sustainability plans. Geological settings, and economic and social conditions, are influential factors in determining how aggregates are supplied. But because the manner in which aggregates are supplied affects the ability of developing nations to achieve a sustainable future, it is important that a country's strategic and operational policy guidelines are based on sustainable development principles.

Construction materials and aggregates present a very clear example of the transition from natural to human-made (manufactured / physical) capital. In order to optimize this transition, the positive impacts of quarrying should be maximized and negative ones minimized.

Lack of understanding about the links among different types of impacts of quarrying is a source of time consuming disagreements between stakeholder groups, including the general public, industry, environmental, social and expert groups on local and national levels. One of the most effective ways to identify the full range of positive and negative impacts, as well as system interactions, is to examine the entire quarry and product life cycle. Societal, value based, objectives expressed in policies emphasize certain parts of life cycle and bring those issues to the attention of stakeholders. One of the tools that can be used to ensure that mineral resources (aggregates) are provided in a manner that contributes to sustainability over the full life cycle is Sustainable Aggregate Resource Management (SARM).

Environmental Aspects – SARM requires developing aggregate resources in an environmentally responsible manner that does not result in long-term environmental harm, even if short-term environmental impacts are unavoidable. Two main environmental categories should be considered in SARM: reducing negative environmental impacts and resource protection / conservation. These goals are very achievable because the aggregate industry has made, and continues to make, great strides in environmental management.

Most destructive environmental impacts of aggregates are on the landscape (visual intrusions), air (noise, dust), water (surface, underground water), soil (erosion, pollution), and on biota (loss of biodiversity). Besides type, the nature of impacts (range, timing, duration, ability to prevent /control) should also be considered (Langer & Arbogast, 2002). There are many regulatory and voluntary tools that can be used to identify, reduce and control negative environmental impacts. These include environmental impact assessment, environmental management systems, environmental accounting, environmental reporting, life cycle analysis, ISO 14000 standards, all of which can be applied both on-site (quarry & processing facility) and to transportation routes.

SARM, however, is not just about protecting the environment from the potential negative impacts of aggregate extraction. Reclaiming aggregate operations or orphaned sites has tremendous potential to improve our quality of life, create additional wealth, increase biodiversity, and restore the environment. In the expanding suburban areas of today, mined-out aggregate pits and quarries are converted into second uses that range from home sites to wildlife refuges, from golf courses to watercourses, and from botanical gardens to natural wetlands. Reclamation should be a major consideration in sustaining the environment and in creating biodiversity (Langer, 2003).

Mineral resource (aggregate) protection includes: (a) minimal exploitation of primary aggregates with rational production by introducing the recycling and reuse of construction materials as secondary aggregates; (b) exploitation of renewable aggregate and substitute resources; (c) increasing the knowledge about aggregate potential, and (d) preserving the land access to aggregates in designated areas. The first two of these protection measures are intended to reduce the demand for aggregate that is newly mined or from newly developed sites. The latter two address the long-term need for primary materials (Šolar, 2003).

Economic aspects of SARM – There are four main economic aspects to SARM: (a) ensuring that the material requirements of society are provided for; (b) maintaining a viable business environment; (c) encouraging value-added production and employment; and (d) embracing full cost accounting while remaining competitive. The first three of these are the responsibility of government. The fourth is the responsibility of the firm.

All societies utilize a stream of material inputs for manufacturing and construction. In the case of transition and post-conflict economies, there is particular need for construction materials to support development and rebuilding of infrastructure, industrial capacity, and housing. One aspect of SARM involves ensuring that these resources are available to the marketplace. This is sometimes referred to as secure supply. The main elements of secure supply are creation or maintenance of production capacity, identification of sufficient reserves and resources, provision of land access (extraction and exploration sites / areas), and development of the country's or region's infrastructure capacity (roads, railroads, power). All the foregoing issues are interlinked and need to be balanced by policy makers and resource managers. Secure supply can also take the form of importation in cases where the full cost of domestic supply would be higher than the full cost of imported materials.

A viable business environment exhibits the following characteristics: (a) a stable and feasible permitting regime; (b) consistent application of rules and regulations; (c) functioning capital markets; (d) reasonable levels of taxation; and (e) well defined property rights. Underemployment and unemployment are serious problems in many parts of the world. Therefore, governments should also consider setting policies that support the availability of a trained workforce and promote employment in the extractive industries. Development of value-added manufacturing is another important issue. Existence of a value-added sector can reduce the need for imported materials while allowing the domestic economy to capture the economic benefits (employment, tax revenues) that would otherwise accrue in another country.

Economic realities drive industry activity. Firms need to remain competitive if they are to stay in business. Nonetheless, firms have a responsibility to accept the full cost of doing business, including costs of preventing or remediating environmental damage. Industry must be willing to accept the fact that in some cases, when all the costs are taken into consideration, a quarry will not be a viable economic enterprise and must be either shut down or not developed. Firms can, however, increase competitiveness by modifying production processes, upgrading product quality, and maintaining a well trained workforce. Production process and product quality can be achieved through voluntary quality control procedures such as adherence to ISO 9000 requirements. Quality is an important market element that can be labeled and traded. Research and development (R&D) is another issue that increases the enterprise's overall performance and has a great impact on increasing the added value.

Some of R&D's goals include new products, and using BAT (best available technology) in the field. Finally, maintaining or increasing employment is not only governmental issue, because human resources are one of most important driving forces of every enterprise. Corporate culture, knowledge and skills need to be created, maintained, reviewed and revised (if necessary). Special attention with regard to human resources should be put on health and safety of employees.

Social aspects – Identifying stakeholders' values, interests, goals and the scale at which they apply is the first step in resolving the complex situations that impact a country's ability to maintain a secure material supply and achieve other policy goals. As an example, there may be abundant sites in a region that have suitable aggregate, but the existence of conflicting land uses, zoning, regulations, or citizen opposition can lead to insufficient or more costly supply. Scale of interest is a consideration in such situations due to fact that benefits and costs accrue to different parties in different regions. A third important issue is intra-generational equity, fairness to those living near or impacted by quarrying. Equity implies a need for transparency and public participation in decision making, as well as access to information within democratic process (Šolar, 2003).

Broader societal aspects can be described in terms of the legal framework, communication and education. The legal framework should protect the interests not only of country or region, but also investors and all other stakeholders. An effective legal framework needs balance between administrative requirements and flexible, time efficient, inexpensive procedures of licensing. Further, a country or region needs to have the institutional capacity to implement and enforce the legislation (monitoring and control components in particular), to develop and maintain resource information infrastructure, to foster research and development, to use funds from mineral rents (taxes) for the benefit of current and future generations, and facilitate cooperation with other sectors.

In addition to the legal framework, voluntary initiatives from different stakeholders (industry, non-governmental organizations) enrich dialogue and facilitate agreements. Voluntary initiatives include communication, education, partnership, and participation. All stakeholders should have access because increased awareness of the costs and benefits of supplying materials to society will lead to more timely agreements about how to (re)distribute costs and benefits of aggregate extraction and use. (Šolar, 2003).

Implementation – To ensure that aggregate resources are managed in a sustainable manner, each of the primary stakeholders – government, industry, public, and other non-governmental organizations – must accept certain responsibilities. The government is responsible for developing the policies and climate that provide conditions for success. The industry must work to be recognized as a responsible corporate and environmental member of the community. The public and non-governmental organizations have the responsibility to become informed about natural resource management issues, take personal responsibility for their consumption patterns, and to constructively contribute to a process that addresses not only their own, but a range of objectives and interests. All stakeholders have the responsibility to identify and resolve legitimate concerns, and the government, industry, and the public must cooperate at the regional and local levels in planning for sustainable aggregate extraction (Langer, 2003a).

To be effective, SARM must be a pragmatic pursuit, not an ideological exercise. It is an iterative process and government, citizens, and industry should all be involved in the pursuit. The process consists of a number of steps, including issuance of policy statements, elaboration of objectives, establishment of actions, identification of indicators, and monitoring:

- Policy statements issued by governments commonly identify the aggregate industry as a key industry contributing to jobs, wealth, and a high quality of life for their citizens, and commit the government to the protection of critical resources and protection of citizens from the unwanted impacts from aggregate extraction. Industry policy statements commonly identify environmental and societal concerns and commit the company to environmental stewardship and interaction with the community.
- Objectives describe what is to be accomplished and commonly are subsets of the social, economic and environmental components of SARM. Typically objectives will include, but not be limited to: (a) ensuring future supplies of aggregate; (b) reducing the demand for newly mined aggregate; and (c) protecting and restoring the environment.
- Actions are associated with each objective and describe the steps to reach the objective.
- Indicators deserve special mention. They measure progress as well as the effects of efforts to protect and enhance natural and human systems and will be discussed in more detail below.
- Monitoring, feedback, and the regular reconsideration of requirements as events develop to the SARM process. The establishment of a joint monitoring process presents an excellent opportunity to forge partnerships with communities and involve citizen groups.

Measurement – Progress toward the policy goals that have been described in detail within a resource management plan need to be measured over time. Measurement can be described in terms of the hierarchical model of principles, criteria, and indicators.

Adaptation – It is useful to think of policy making as a continuous process. Sustainable aggregate management has a place in all these stages. Over time societal goals, governmental policy, laws and acts, public and corporate management plans, regulatory regimes, and data sets can change. SARM should be seen as an adaptive process that responds to changes in social, economic and environmental system and to changing public preferences as well.

There are a range of potential problems associated with adoption, including: (a) unrealistically high expectations, (b) lack of commitment, and (c) inappropriate past practices. Therefore, a very clear roadmap of the management plan, and also a plan to address disappointment, is needed. In order to strengthen stakeholder commitment, all open issues should be discussed in a way that promotes consensus on the outcomes. Building trust and confidence during the process of creating a management plan can help overcome the distrust that has been created by past bad practices.

Given the impacts of the global recession, current aggregates production levels are now dependent to some degree on economic stimulus expenditures and on public infrastructure projects. This circumstance provides an opportunity for governments to encourage producers to practice SARM and also to coordinate their mineral policies with other public policies so as to minimize conflicts and costs and optimize benefits. Recognition of the need for SARM that fulfills present demand and planning for supplies to meet future demand is present within modern society, although stringent SARM policies do not exist in most countries. Nonetheless, the multiple aspects and goals of SARM are not being achieved in many regions or countries, including the region of South East Europe (SEE). SEE countries are rich in aggregates, but neither management nor supply is coordinated within or across the area. At the site level, the issues are high environmental impacts, a need for stakeholder consultation and capacity, a lack of social license to operate, and limited recycling. At the regional/national level, the issues are policies and regulations affecting aggregates that: do not address resource and energy efficiency or EU guidelines, preclude the use of recycled materials and industrial by-products, and fail to address aggregate consumption in long-term sustainable development and spatial planning. The transnational issues are lack of capacity and lack of coordination on aggregates production and transport. Taken together these issues demonstrate the need to shift to sustainable aggregate resource management (SARM) and sustainable supply mix (SSM) policies. As noted above, efficient, low socio-environmental impact quarrying and waste management is SARM. A SSM comprises materials from multiple sources, including recycled wastes and industrial by-products (slag), that together maximize net benefits of aggregate supply across generations.

SARMa PROJECT 2009–2011

In 2009, the EU Commission approved a project titled "Sustainable Aggregates Resource Management"

(SEE/A/151/2.4/X – SARMa) under the South East Europe Transnational Cooperation Programme. The SARMa project focused on implementing sustainable aggregates resource management (SARM) across SEE and identifying the components of a sustainable supply mix (SSM) of aggregates for SEE. It should be noted that the South East Europe Programme does not fund research, but rather is a framework intended to foster transnational partnerships and enhance the integration of new and candidate countries into the European Union through the application and distribution of existing knowledge.

Partnership – In selecting the project team, there was a need for: (a) broad geographical coverage, and (b) the inclusion of partners from old member states, new member states, and candidate countries. This assured knowledge transfer and best practices transmission to zones with less experience in SARM and SSM, which will enable better cohesion of SEE countries in aggregates management and supply. Other aspects of the partnership were: (c) competence and expertise of partners, not only in resources, but also with environmental issues, (d) vertical coverage in different countries of activities at different scales (i.e., different zones for field work, model development, and pilot implementation), which facilitated transnational activities, and knowledge transfer from experts to stakeholders at the policy and implementation levels in different countries, and (e) continuing partnership among project members and observers representing ministries in charge of mining, regional authorities, chambers of commerce, and industry. The 14 partners in 10 countries of SEE area are listed below:

1. Geological Survey of Slovenia, SI
2. University of Leoben, AT
3. Ministry of Economy, Labour, and Entrepreneurship, Directorate for Mining, HR
4. Prefectural Authority of Pella, GR
5. Institute of Geology and Mineral Exploration, GR
6. Technical University of Crete, GR
7. Hungarian Office for Mining and Geology, HU
8. Emilia-Romagna Region - Environment, Soil and Coast Defense Department, IT
9. Parma Province, IT
10. National Institute for Research-Development in domain of Geology, Geophysics, Geochemistry and Remote Sensing, RO
11. University of Bucharest, Faculty of Geology and Geophysics, RO
12. Ministry of Economy Herzegbosnian Canton, BH
13. University of Belgrade, Faculty of Mining and Geology, SR
14. Ministry of Economy, Trade and Energy, AL

Scientists and experts formed a major part of the project team of the SARMa SEE project. They were selected to ensure that the necessary expertise would be available to achieve the expected objectives and implement the expected results. Geological surveys, institutes and faculties work regularly as experts and policy advisers with government and industry and combine up-to-date knowledge and expertise in the area of aggregates. All have continuing, long-term relationships with decision making bodies in their countries and prepare strategic documents for authorities. Partners have the experience in major projects and public awareness-raising activities in order to manage the SARMa project and disseminate outputs and results. Also, 8 decision making bodies were included that have aggregates sector extraction areas under their rule and expressed a desire to participate actively in seeking solutions to the challenges of aggregates production and supply. In addition, emphasis was being placed on public/stakeholder capacity building activities (Šolar & Shields, 2011).

Project goals – The two main project objectives were to: develop a common approach to SARM across SEE, and ensure a SSM in SEE based on fair distribution of costs and benefits of aggregate production, use, waste disposal and recycling, so as to enhance resource and energy efficiency and quality of life. Other supporting objectives included: coordination in managing aggregate resources, increasing the transfer of know-how, and supporting capacity building in firms, government and civil society; development of a unified information infrastructure and common understanding of aggregates based on EU guidelines and directives, including those on protected areas, potential secondary supply, and transnational transportation networks; and prepare for a Regional Centre on SARM & SSM.

Project activities were intended to connect institutional actors, decision makers, policy implementers, economic sector, quarry operators, civil society, and NGOs through data collection activities, workshops, and targeted results at 3 spatial scales because, as previously noted issues differ by scale. Each scale was handled as a separate Work Package having its own specific goals: those being Local, Regional/National, and Transnational. Local goals: (a) optimize the efficiency of primary aggregates production, (b) prevent or minimize environmental impacts of quarrying and improve reclamation, (c) minimize illegal quarrying by improving knowledge, (d) promote recycling (construction, demolition & quarry waste), and (e) increase interested and affected groups' capacity. Regional/national goals: (a) assess and quantify aggregate resources and relevant transportation links, (b) develop strategies for sustainably managing aggregate resources, including in protected areas, considering aggregate resources in land management and use planning, and harmonizing policies across regions, and (c) develop guidelines and procedures for SSM planning. Transnational goals: (a) recommend methods for harmonizing SARM & SMM transregionally and transnationally, and (b) design a multi-purpose and multi-scale Aggregates Intelligence System (AIS) as a long-term tool for know-how transfer. Planning has also begun for a Regional Centre on SARM & SSM, the purpose of which will be to increase capacity of all interested and affected groups through additional studies, workshops, and educational materials.

Final results – The Sustainable Aggregates Resource Management (SARMa) project contributed a transnational bottom-up approach by developing a common approach to Sustainable Aggregates Resource Management (SARM) and ensuring a Sustainable Supply Mix (SSM) in 10 participating SEE countries.

At the local level, the main findings for local authorities, industry representatives and communities are presented in the manual "How to achieve aggregates resource efficiency in local communities", emphasizing environmentally friendly quarrying, reduction of illegal extraction, and increased recycling.

At the regional, national and transnational level, the recommendations are presented in the manual "SARM and SSM at the Regional, National and Transnational Level", which is targeted at decision-making authorities. An additional contribution on the pathway to a more sustainable society was the "Construction and Demolition Waste Management Manual", which illustrates activities related to inert waste recycling.

As the base of these manuals (in the bottom-up approach) 50 case study reports, 10 studies/analyses, 9 different recommendations and other documents were prepared as the supporting materials. Additionally (not planned in the AF), the two specific manuals were prepared: "Guidelines for the environmental recovery of quarries in near river areas" and "Concise planning manual for the recovery of aggregate quarries". The following results should also be emphasized:

- 9 common guidelines covering recommendations for environmentally friendly quarrying, recycling and preventing illegal quarrying for industry and authorities; on implementation of (EU) legislation; for aggregate policy and management; and for development and land use

planners; on transnational level for decision-makers on SARM and on SSM;
- common methodologies adopted among partners on database framework on illegal quarrying and Lifecycle Assessment scheme, and on GIS and Aggregate Intelligence System (AIS);
- advanced tools adopted to improve knowledge management within the partnership: SARM, SSM and GIS.

Over 9 500 copies of the manuals were printed in 11 languages to facilitate dissemination to the end-users. Moreover, the messages were directly promoted to more than 1 300 representatives of public authorities and 2 100 representatives of the industry, at the 19 different regional, national or transnational workshops, aiming at increasing awareness, knowledge and capacity of the target groups. Additionally the project was presented at a number of events (over 20) organized outside the project, in SEE and EU. Thirteen press conferences were organized and 54 articles were published. Counting magazine and journal articles, over 900 000 people were reached.

On the basis of these methodologies, regional or national policies on SARM and SSM were improved in 11 participating countries or regions: Slovenia, Austria, Greece, Region of Central Macedonia, Hungary, Emilia-Romagna Region, Parma Province, Romania, Herzeg-Bosnian Canton, Serbia, Albania and Croatia. The benefits of the harmonised transnational approach are confirmed and will contribute to increased aggregates resource efficiency in participating countries. The 23 participating partners and observers intensively promoted the project outcomes to target groups in their territories.

At the policy level, important achievements have been accomplished at the national, regional and local level of 10 participating countries by contributing to the improved policies on aggregates management and supply, as well as the waste management, recycling and protection of the environment related to quarrying activities. The outcomes of the recommendations in the SEE area were also contributing to the EU policies and initiative related to these topics. Please see next point for details.

At the policy level, an important contribution was imposed in 12 participating territories (Zelič, 2012):
- At the national level:
    - Greece: the SARMa project is referenced twice in the working document for the New Greek National Minerals Policy – it was also referenced several time in the public forum presenting the work on the Greek National Minerals Policy;
    - Austria: contribution to Austri-

an Mineral Resources Plan development;
    - o Hungary: the transposition of the Community law and policy was impacted by the SARMa outcome on the national level, its conclusions are built into the national mineral strategy in preparation;
    - o Slovenia: SARMa activities coincided with the drafting of National Mining Strategy and evaluation of Mining Act;
    - o Romania: Mineral resources Department at the Ministry of Economy, Commerce and Business Environment of Romania has realized the need of drawing up a national mineral policy (inclusively aggregates) based (also) on promotion of SARMa outcomes and is trying to obtain financing for this project;
    - o Albania: SARMa Project has been implemented within the same period in which the reviewing and the improvement of the Albanian Law on Mining have been carried out as well as its approval.
    - o Serbia: SARMa activities had an impact on the national policies and regulations – there were some changes in the structure of Ministries related to aggregates production, new Law on Mining and Geological Exploration (end 2011), and the new Minerals Policy of Serbia is being prepared.
    - o Croatia: SARMa activities are positively influencing the national policy on aggregates management.
- At the regional level:
    - o Emilia-Romagna Region: SARMa recommendations will be integrated into the new law on soil defence and quarrying activities, at time of writing in an early phase of development.
    - o Herzeg-Bosnian Canton: public authorities in this and other Bosnian structures increased awareness, knowledge and capacity about the aggregates policy and its reference with other areas, which will influence their decision-making in the future.
- At the local level:
    - o Parma Province: will apply new law about soil defence and quarrying activities that will be issued by the ER Region in the future on the basis of SARM practices and recommendations;
    - o Pella Prefecture/Region of Central Macedonia: SARMa activities positively influenced the local policy on aggregates management.

The 3 dimensions of sustainability were realised in the following way, including the steps after the project end:

- Institutional sustainability is assured since partners incorporated the recommendations and new methods in their daily work, at the level of public authorities or expert organisations;

- Additionally, partners are taking a lot of effort to promote and disseminate the project outputs (manuals) and the described methods also in their networks in each country or region;
- The political sustainability was is parallel assured since the recommendations addressed directly the local, regional and national policies and were promoted at the level of public authorities directly or by the expert organisations providing the expert support for these institutions;
- The financial sustainability was partially assured by financing the regular operations of the mentioned organisations in which the developed approaches will be used;
- Additionally, it was estimated that the developed recommendations are generally applicable, while especially the public authorities are still lacking capacity to incorporate them in the new or improved regulations. Therefore a new SEE project proposal SNAP-SEE – Sustainable aggregates supply in SEE was applied at the SEE programme 4th call;
- There are initiatives also for upgrading the developed topics at other levels, e.g. at the EU level in the Interreg IVc or at more scientific level in FP7, or the successors of these programmes.

The project had a significant impact on territorial cohesion of 10 SEE countries in the tackled field by harmonising their approach to aggregates management and related policies, and to transferring efficiently the related EU guidelines to the national or regional level. These policies are also contributing to the environmental dimension by promoting the environmentally friendly quarrying, promoting recycling and preventing illegal quarrying. These activities are contributing to the social dialogue with affected stakeholders. Economic activities of private sector operators (large and small ones) are influenced by promoting the positive sides of more socially and environmentally acceptable quarrying activities, leading to positive impacts for the society.

At the EU level SARMa activities coincided with the implementation of the EU new waste management legislation, mine waste management legislation and mineral policy issues. In this way SARMa had a reinforcement effect on the above EU policies by producing practical manuals and recommendations on the best practice measures in the SEE region. Within the networks of the SARMa partners the recommendations were promoted during the events of the Hungarian and Polish presidency of the EU.

Conclusions

The SARMa project's impact is noticeable at the level of national, regional and local public authorities, where different policies regulating aggregates management and supply from the economic or environmental perspectives are being developed or improved. There are proposals for follow-up projects further increasing capacity of the public authorities and enhancing the involvement of stakeholders in these processes. The project also contributed to the improvement of the EC Raw Materials Initiative, waste management legislation.

Finally, SARMa contributed to the SEE Programme overall objectives by integrating environmental, social and economic aspects of sustainability with respect to aggregates management and supply, capacity building, and fostering transnational territorial cooperation among local, regional, national and transnational authorities.

All SARMa manuals, recommendations and other reports are available at http://www.sarmaproject.eu

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Data-driven modelling of groundwater vulnerability to nitrate pollution in Slovenia

Podatkovno vodeno modeliranje ranljivosti podzemne vode na nitratno onesnaženje v Sloveniji

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Abstract: This paper describes the case study of statistical data-driven models implementation to assess groundwater vulnerability to nitrate pollution of alluvial aquifers in Slovenia. The aim of the research was spatial prediction of the relative probability for increased groundwater nitrate concentration in order to plan the groundwater nitrate reduction measures and optimize the programme for monitoring the effects of these measures. For the selection of possibly optimal statistical model and comparison with the one of point count system methods PCSM, receiver operating characteristic method ROC was used. Results of the probabilistic classifier from the weights-of-evidence model WofE and neuro-fuzzy model NEFCLASS has in the case of groundwater nitrate pollution a significant better average performance than the widespread used SINTACS parametric point count relative rating as groundwater contamination potential.

Izvleček: Članek opisuje študijski primer uporabe statističnih podatkovno vodenih modelov za ocenjevanje ranljivosti podzemne vode na nitratno onesnaženje v aluvialnih vodonosnikih Slovenije. Namen raziskave je bil prostorsko napovedati relativno verjetnost zvišane vsebnosti nitrata v podzemni vodi za potrebe načrtovanja ukrepov za zmanšanje nitratnega onesnaženja in optimiranja programov merilnega nadzora učinkov teh ukrepov. Za izbor optimalnega statističnega modela in primerjavo z rezultati večparametrske metode razvrščanja in tehtanja je bil uporabljen pokazatelj karakteristike delovanja klasifikacijskih metod ROC. Verjetnostni klasifikatorji modela teže evidenc WofE in nevronske mehke logike NEFCLASS izkazujejo v primeru nitratnega onesnaženja podzemne vode značilno boljše povprečne klasifikacijske lastnosti kot sicer zelo razširjena metoda razvrščanja in tehtanja parametrov SINTACS.

Key words: groundwater vulnerability, nitrate, data-driven modelling, Slovenia

Ključne besede: ranljivost podzemne vode, nitrat, podatkovno vodeno modeliranje, Slovenija

Introduction

Groundwater nitrate pollution in Slovenian shallow alluvial aquifers has been a major concern in recent years, and more than a third of the groundwater in these aquifers has poor chemical status according to Water Framework Directive (Directive 2000/60/ES) criteria, most frequently due to a high concentration of nitrate (Uhan et al., 2010). The operative programme of measures requires identification of the potentially vulnerable priority areas within groundwater bodies for cost-effective measures planning. Groundwater vulnerability maps are an important tool of the water management decision-making process. Most of the previous groundwater vulnerability assessments of shallow alluvial aquifers in Slovenia (Janža & Prestor, 2002; Bračič Železnik et al., 2005; Mali & Janža, 2005; Uhan et al., 2008) used a variety of parametric point count methods with a relative rating for the potential of groundwater contamination, e.g. the SINTACS index, adapted to conditions in the Mediterranean region (Civita, 1990). These methods require validation with field measurements, such as a tracer test, groundwater residence studies or investigation of pollution processes, e.g. denitrification. Gogu & Dassargues (2000) identified the integration of results from process-based models in vulnerability mapping techniques as a new research challenge in groundwater vulnerability assessment. Data-driven modelling offer the possibility of analysing the relevant data about a groundwater system, in fact, learning from available data, which incorporates the so far unknown dependencies between a system's inputs and outputs (Mitchell, 1997; Price & Solomatine, 2000).

Materials in methods

Modelling of the groundwater vulnerability to pollution is generally understood as probability modelling or a mathematical representation of a random phenomenon. Most commonly used methods of the classification modelling are neural networks and fuzzy logic methods, statistical method of logistic regression and closely related Bayesian approaches to classification. In the Lower Savinja Valley case study, we have used the neuro-fuzzy approach for the data classification NEFCLASS-J (Nauck & Kruse, 1995), and weights-of-evidence method for combining evidence in support of a hypothesis Arc-WofE (Kemp et al., 1999). The results of these two data-driven methods were compared with the results of the SINTACS parametric point count relative rating as groundwater contamination potential (Uhan et al., 2008), coupling with the results of the agricultural nitrate hazard index IPNOA (Pehan, 2008).

The SINTACS scheme of aquifer pollution vulnerability mapping incorporates seven parameters, relevant for the contaminant attenuation and vertical flow capacity (Table 1). The grid square cell structure of the SINTACS input data has been designed in order to use several weight strings in order to satisfactorily describe the effective hydrogeological and impacting situation as set up by the sum of data (Civita & De Maio, 2000). For each grid squares, element normalized SINTACS index was calculated and coupled with the agricultural nitrate hazard index (IPNOA). The IPNOA method integrates two categories of parameters (Table 1): the hazard factors representing farming activities and the control factors which adapt the hazard factors to the characteristics of the site (Padovani & Trevisan, 2002).

Neuro-fuzzy system is an identification method that combines the methods of neural networks and fuzzy logic. The neural networks classify among the »black box« methods, where the model is set solely on the basis of measured data without an insight into the dynamics of the process. Fuzzy logic on the other hand classifies among the »grey box« methods, where the model structure is given as a parameterized mathematical function that is at least partially based on the laws of physics. Both systems have been developed independently, and only later great advantages have been recognised in their joint use, especially for the classificatory purposes (Nauck & Kruse, 1995), as well as in the area of groundwater vulnerability to pollution (Dixon, 2001).

Bayesian classifier uses attribute independence assumption and estimates the conditional probabilities (coefficients in the model) on the basis of counting the cases in a particular class. Although the Bayesian classifier probabilistic model is based on the assumption, which the practice does not support, the empirical evidence shows that this has no major impact on its classificatory accuracy (Domingos & Pazzani,

Table 1. List of used evidential themes in groundwater nitrate pollution vulnerability assessment case study

SINTACS	IPNOA	NEFCLASS	WofE
Deep to the groundwater	Use of fertilizers	Hydrogeological homogeneous units	Hydrogeological homogeneous units
Effective infiltration	Application of livestock and poultry manure	Irrigation and drainage areas	Irrigation and drainage areas
Unsaturated zone attenuation capacity	Food industry wastewater and urban sludge	Development of the river networks	Development of the river networks
Soil/overburden attenuation capacity	Topographic slope	Long-term groundwater recharge	Long-term groundwater recharge
Hydrogeological characteristics of the aquifer	Climatic conditions	Nitrogen load in seepage water	Nitrogen load in seepage water
Coefficient of hydraulic conductivity	Agronomic practices	Groundwater flow velocity in saturated zone	Groundwater flow velocity in saturated zone
Topographic slope			

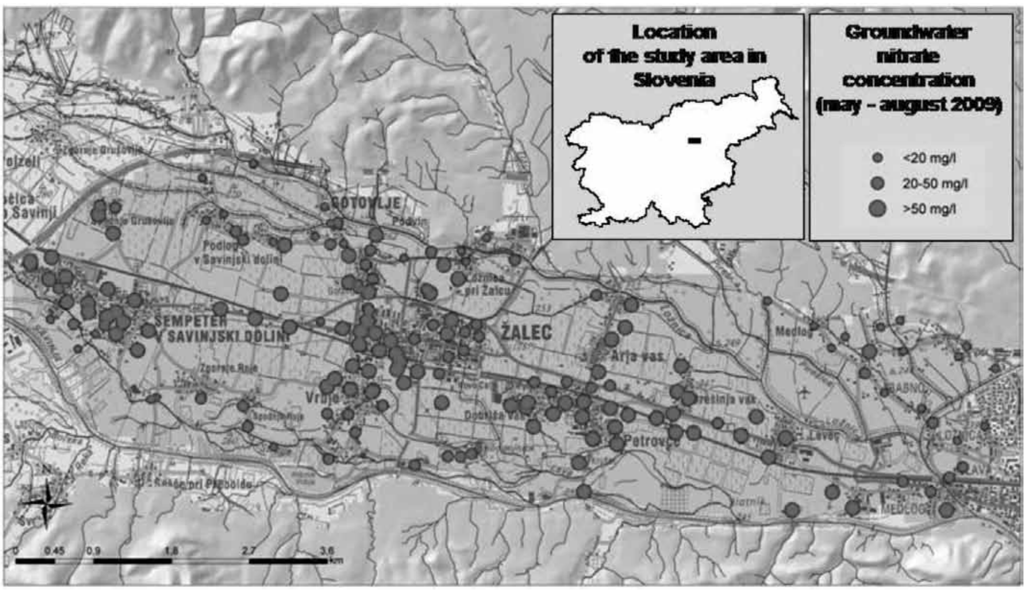

Figure 1. Groundwater nitrate measurements in central part of Lower Savinja Valley, used as a training dataset

1997; Kononenko, 2001). Advantages of this method are in better response for problems with a small number of training points and missing attribute values, and in greater clarity of the resulting model. Mainly due to an easier interpretation of the results, the weights-of-evidence method, which is based on the Bayesian theorem, has been successfully used also for the assessment of groundwater vulnerability to pollution (Arthur et al., 2005; Baker et al., 2006; Masetti et al., 2007; Sorichetta et al., 2008).

In both cases of data-driven modelling of groundwater vulnerability to nitrate pollution, NEFCLASS-J modelling and Arc-WofE modelling, we have used the same evidential themes, including also process-based modelling outputs of groundwater recharge, groundwater flow velocity and nitrate leached from the soil profile (Table 1). In the vulnerability assessment procedure, the central part of the Lower Savinja Valley (30.8 km^2) was discretised with a regular mesh grid of 100 m × 100 m. Randomly chosen 173 groundwater nitrate in-situ measurements have been used as a training points dataset. Monitoring sites have been classified for further analysis into two or three groups on the basis of distribution of groundwater nitrate concentration with 20 mg/l as antopogenic impact concentration or 50 mg/l as EU threshold value.

Results and discussion

Groundwater intrinsic vulnerability assessment of Lower Savinja Valley shallow aquifer using SINTACS parametric method (Uhan et al., 2008) identified two classes with different vulnerability degrees. The first zone with higher vulnerability is characterised mainly by the lower terrace with shallow groundwater, high surface/groundwater interaction and a thin protective soil layer. The second zone with medium vulnerability is characterised mainly by the upper terraces with deeper groundwater and thick soil layer with increased clay component. The most sensitive parameters are depth to the groundwater and effective infiltration action. The results of single-parameter sensitivity analysis enable better understanding of the vulnerability model results, enable consistent evaluation of the analytical result and give a new orientation for further methodological contamination research by using statistical and numerical model results with selected SINTACS groundwater vulnerability parameters. It is pointed out that detailed vulnerability mapping, including analysis of hydrochemical data, especially nitrate concentration in groundwater, linked to the assessment of pressures and impacts, is a very good basis for establishing detailed monitoring programmes and programmes of measurement to achieve the WFD objectives of good groundwater status for groundwater bodies at risk.

The intrinsic nitrate contamination risk from agricultural sources, assessed using the IPNOA methodology, is high for the 87 % of the study area, whereas the 11 % of the southern parts of the area indicate a diffuse and extremely high potential risk. The greatest discrepancies between the estimates of the potential risk of groundwater contamination by nitrates from agricultural activities and the results of groundwater nitrate field measurements have been identified on the northern part of the study area. Here the nitrate levels in groundwater are in many places markedly below the expectations, given the high level of potential risk for groundwater contamination by nitrates from agricultural activities (PEHAN, 2008). These findings have highlighted the need for further study of spatial variability in conditions of nitrogen cycle processes, which affect the reduction processes in groundwater.

In the Lower Savinja Valley groundwater vulnerability model, we have, in light of the results of an extensive sensitivity analysis of the NEFCLASS-J model (DIXON, 2004), used the triangular membership function and three fuzzy sets structure. The model discovered a total of 36 possible learning rules, of which five of the best rules for a particular classificatory range were used for the grid. Additional optimization of the network resulted in the 93.02 % accuracy for the classification of the learning data patterns, 75.58 % accuracy for the validation, and 84.30 % accuracy for the classification of the entire data series into two classes of groundwater nitrate level. When modelling the three-class fuzzy grid (<20 mg/l, 20–50 mg/l, >50 mg/l), the model accuracy was somewhat lowered, yet the classificatory accuracy improved. The model classified all of the 3,079 spatial cells, namely: 978 in the first group (31.76 %), 689 in the second group (22.38 %), and 1412 in the third group (45.86 %) of the spatial cells. The hydrogeological boundary between the middle and the highest terrace markedly stood out at this classification (Figure 2).

WofE modelling technique combines known occurrences of phenomenon (training points) with available spatial data (predictor evidence) in a predictive response (phenomena occurrences conditional probability map). Six evidential themes were applied to generate the response theme with posterior probability values ranging from 0 to 0.312 (Figure 3). The response theme values describe the relative probability that a 100 m × 100 m spatial unit will have a groundwater nitrate concentration higher than the training points threshold values with regard to the prior probability value of 0.057. Based on the definition of the training point, higher posterior probability values correspond with more ground-

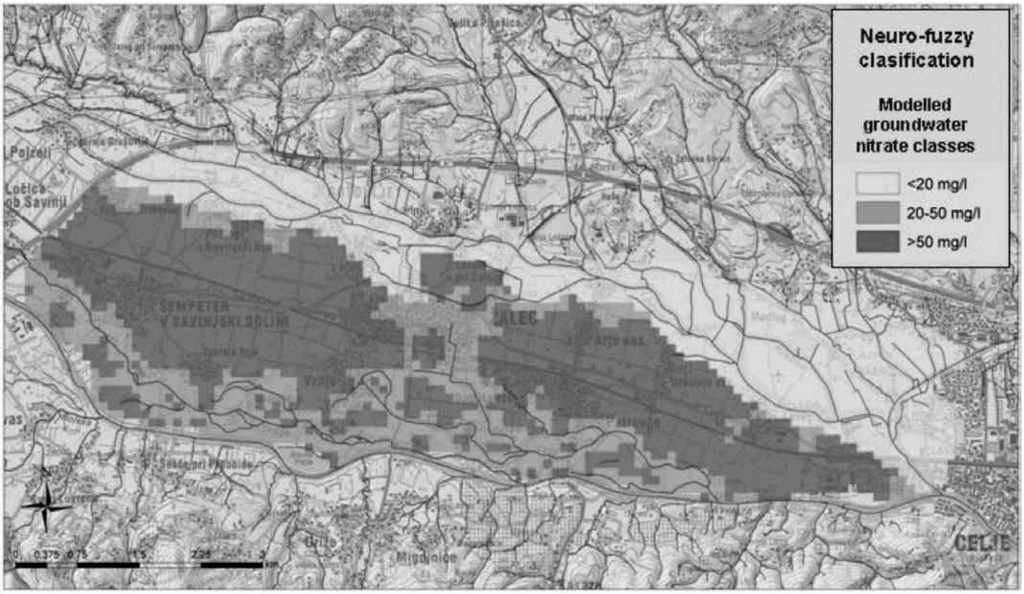

Figure 2. Neuro-fuzzy prediction of groundwater nitrate pollution in central part of Lower Savinja Valley (threshold values: <20 mg/l, 20–50 mg/l and >50 mg/l)

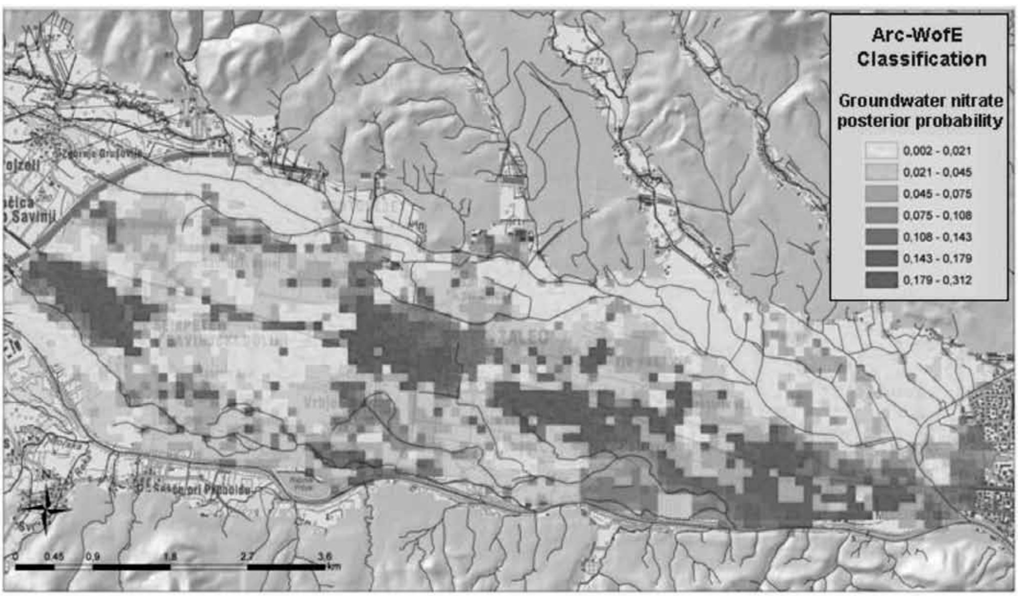

Figure 3. WofE posterior probability prediction of groundwater nitrate pollution in central part of Lower Savinja Valley (threshold value: 20 mg/l; prior probability = 0.057)

Table 2. Statistics of ROC analysis

Model output	Area under the ROC curve (%)	Standard error	95 % confidence interval
SINTACS x IPNOA	75.7	0.041	0.685–0.820
WofE	82.9	0.034	0.756–0.877
NEFCLASS (3 classes)	84.4	0.031	0.779–0.895

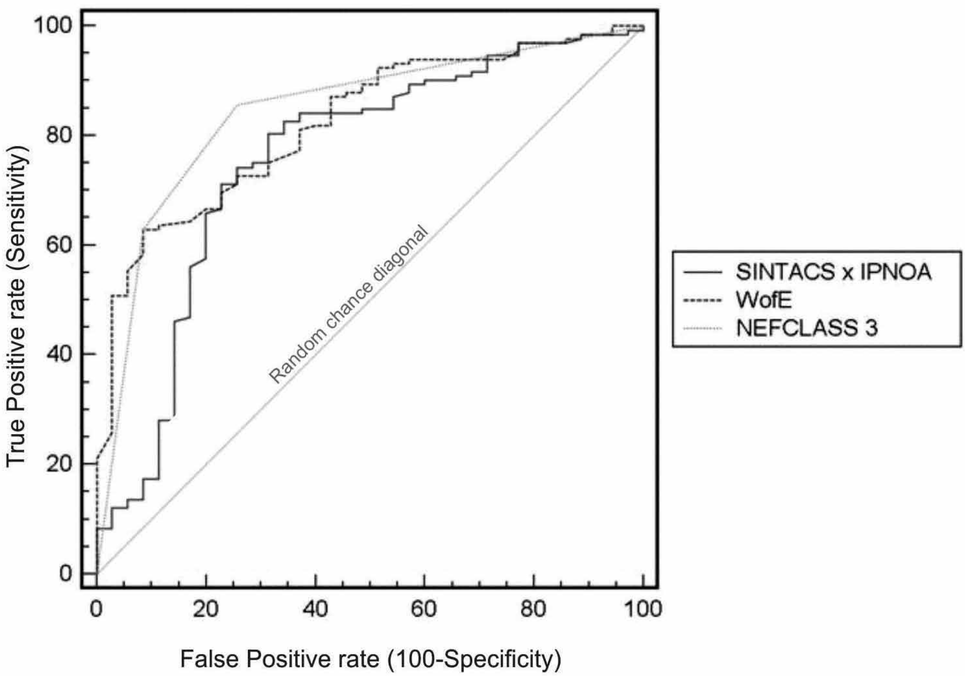

Figure 4. Predictive reliability of different classification schemes in ROC diagram

water vulnerable cells and lower posterior probability values correspond to less vulnerable areas. The highest probability of groundwater nitrate vulnerability zones has been found to be generally in the central part of the study area. According to the calculated confidence value, the most important contribution to the final response theme was assessed for the groundwater flow velocity evidential theme, followed by the groundwater recharge evidential theme. Conditional independence as an important assumption of the WofE model was within the range that generally indicates no dependence amongst evidential themes (BAKER et al., 2007).

The predictive reliability of the applied models has been verified by the receiver operating characteristic analysis (Metz, 1978), which through the sensitivity and specificity assessment provides the area under curve (AUC) in receiver operating characteristic diagram (ROC). Receiver operating characteristic curves were developed in the field of statistical decision theory and assess the value of diagnostic/prediction tests by providing a standard measure of the ability of a test to correctly classify subjects or phenomena. The ROC curve reflects the probability of correct and incorrect positive findings of the phenomenon and can be illustrated in space with the coordinates for sensitivity and specificity. Sensitivity is defined as the probability that the highly vulnerable spatial aquifer cell is correctly classified, whereas specificity is defined as the probability of the correct classification of the moderately vulnerable spatial cell. The rate of false negative value is given by 1-specificity. The discrete three-class classification of the model of neuro-fuzzy network NEFCLASS-J and the linear distribution of the WofE posterior probability of increased groundwater nitrate levels in the studied area of Lower Savinja Valley has been compared also with the results of the SINTACS and IPNOA analysis (Figure 4). The area under ROC curve (AUC) was the lowest for SINTACS x IPNOA prediction model (75.7). According to the ROC analysis, the best results were achieved by the neuro-fuzzy model, within which the highest value of the parameter AUC (84.4) was achieved (Table 2). When comparing it to the weights-of-evidence model through the κ statistical comparison of matching between the measured and the predicted categories (Jenness & Wynne, 2007), the differences were, however, very small.

Conclusion

When comparing the results of classification schemes, the neuro-fuzzy method was proven somewhat more effective for predicting the groundwater nitrate concentration and thereby predicting the groundwater vulnerability in Lower Savinja Valley. However, the discrete character of this model result has to be emphasised, whereas the weights-of-evidence method enables the assessment of the probability of groundwater nitrate pollution while not sacrificing much the quality of the results. The assessment of the probability of groundwater nitrate pollution can be of great service for mapping the groundwater vulnerability to nitrate pollution. Data-driven models cover the relationships between the relevant input and output variables and are very effective if it is difficult or not possible to build knowledge-driven simulation models. Case study in Lower Savinja Valley aquifer indicates the possibilities and the directions of incorporation of data-driven models into the decision support frameworks.

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Hydrochemical characteristics of groundwater from the Kamniškobistriško polje aquifer

Hidrokemijske značilnosti podzemne vode vodonosnika Kamniškobistriškega polja

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Abstract: The article describes basic chemical properties of the Kamniškobistriško polje aquifer groundwater. The aquifer is composed of the upper aquifer in sand and gravel deposits of the Kamniška Bistrica river and of the lower, dolomite aquifer. The water of both aquifers differs significantly as to its chemical composition. Compared to the lower aquifer, the water of the upper aquifer is more mineralized, which is reflected in a higher electrical conductivity and concentrations of HCO_3, calcium and magnesium. The water from the upper aquifer is also more loaded with pollutants originating from agricultural activities. On the basis of chemical properties of groundwater from both aquifers it can be concluded that the recharge area of both aquifers is different; the upper aquifer is recharged mainly by precipitation and infiltration of the Kamniška Bistrica river, while the larger quantity of water from the lower aquifer is estimated to originate from carbonate rocks on the western fringes of the Kamniškobistriško polje.

Izvleček: V članku so prikazane osnovne značilnosti kemijske sestave podzemnih vod vodonosnika Kamniškobistriškega polja. Ta vodonosnik sestavljata zgornji vodonosnik v peščeno-prodnih sedimentih reke Kamniške Bistrice ter spodnji dolomitni vodonosnik. Po kemijski sestavi se vode obeh vodonosnikov občutno razlikujejo. V primer-

Original scientific paper

javi s spodnjim vodonosnikom je voda zgornjega bolj mineralizirana, kar se izraža v večji elektroprevodnosti ter koncentraciji HCO_3, kalcija in magnezija. Prav tako je voda zgornjega vodonosnika bolj obremenjena z onesnaževali, ki večinoma izhajajo iz kmetijske dejavnosti. Na osnovi kemijskih značilnosti podzemnih vod iz obeh vodonosnikov ocenjujemo, da je napajalno območje obeh vodonosnikov različno; zgornji vodonosnik se napaja pretežno iz padavin ter infiltracije reke Kamniške Bistrice, medtem ko ocenjujemo, da je v spodnjem vodonosniku večji delež vode iz karbonatnih kamnin zahodnega obrobja Kamniškobistriškega polja.

Key words: Kamniškobistriško polje, aquifer, groundwater, chemical composition
Ključne besede: Kamniškobistriško polje, vodonosnik, podzemna voda, kemijska sestava

Introduction

Our research was aimed at determining the basic chemical properties of groundwater of the Kamniškobistriško polje aquifer. The aquifer is composed of two parts: the upper, intergranular aquifer, and the lower, fissured aquifer in dolomite rocks. It is recharged by precipitation, by the Kamniška Bistrica river, flowing into the aquifer from the east, and by inflows from the hills along the aquifer's western border. Chemical analyses of groundwater from different parts of the aquifer were used for a more detailed determination of the influence of recharge, lithological factors and anthropogenic pollution on the chemical composition of groundwater.

Description of the Kamniškobistriško polje aquifer

The Kamniškobistriško polje alluvial plain extends on the gravel fan of the Kamniška Bistrica river between cities Kamnik, Mengeš and Domžale. Its surface is inclined in the north-south direction, with an altitude of 340 m at Šmarca in the north, and 285 m at Dragomelj in the south. The Kamniška Bistrica river flows along the eastern edge of the Kamniškobistriško polje approximately in direction north-south. At Jarše, the Pšata stream, originating outside the research area at the foot of the Kamnik Alps, flows into the Kamniška Bistrica from the west. The Radomlja stream flows into the Kamniška Bistrica from the east.

The surface of the gravel fan of the Kamniška Bistrica is formed by an 8–12 m thick layer of pure gravel. South of the road Trzin–Domžale the gravel is partly covered by a several meter-thick layer of sand and silt, deposited by the Pšata stream.

The upper gravel layer is underlain with older Pleistocene gravel deposits with inlays of conglomerate and clay. These deposits reach a depth from 35 m to over 70 m in the central part of the plain between the factory Lek and the Depala vas. Along the southern edge of the plain, Pleistocene gravel deposits are 35 m to 45 m deep, while they are less massive on the eastern outskirts, reaching 15 m to 40 m depth.

The base of the sand-gravel deposits contains dolomite which represents a carbonate aquifer with fissure porosity. Deep wells located between Mengeš and Domžale reach the carbonate aquifer at a depth of 50 m to 80 m, and the impermeable base composed of Carboniferous and Permean clayey shales and sandstones lies 160 m below surface in this area (Rogelj & Petauer, 1993, Rogelj, 1998, 1993, Harahodžič, 2011).

The groundwater table in the northern part of the plain is relatively deep under the surface –22 m to 31 m at low-water conditions. In the central part of the plain between Jarše and Mengeš the table at low-water conditions is about 22 m deep. In the area between Trzin and Domžale the groundwater table at low water is at 7 m to 12 m, while it is at 2.5 m to 6.5 m in the southern part of the plain near Pšata. The fluctuation range of groundwater in the area of Kamniškobistriško polje gradually decreases from north to south, amounting to about 7 m in the north and only to about 1 m in the southern part of the area.

The water-bearing gravel layer in the Kamniškobistriško polje is quite thick, amounting to between 32 m and 42 m in the northern part, and to approximately 80 m in the central part between Mengeš and Jarše. The thickness of the water-bearing layer in the Trzin–Domžale profile is about 40 m, decreasing to about 8–40 m in the south between Dragomelj, Pšata and Ihan.

Groundwater balance calculation in the upper aquifer shows an inflow of about 140 l/s of groundwater from Kranjsko polje into the Kamniškobistriško polje at medium-water conditions (Mencej, 1991). The groundwater flow in the central part at the intersection with the Trzin–Domžale aquifer is estimated at 170 l/s, and at about 400 l/s in the southern part of the plain, in the Dragomelj–Ihan profile.

Materials and Methods

Chemical and isotopic properties of groundwater from the Kamniškobistriško polje were observed at the following monitoring points:

Monitoring point	Type of object	Aquifer
DG-1	pumping well	lower
VDG-2	observation well	lower
VDG-3	observation well	lower
VDG-4	observation well	lower
C-2	pumping well	upper
C-3	pumping well	upper
C-4	pumping well	upper
Lek pumping station	pumping well	upper
DG-3	observation well	upper
K-1	observation well	upper
L-6	observation well	upper
L-9	observation well	upper
M-1	pumping well	dolomite

Locations of monitoring points are evident from the map in Figure 1.

The groundwater samples were obtained by sampling pump Grundfos MP1. Two groundwater sampling campaigns were carried out in April and May 2011 in the Kamniškobistriško polje aquifer. A graphical presentation of average values from both samplings is given below in this article. Chemical analyses of groundwater samples were carried out in the laboratory of JP Vodovod-Kanalizacija, d. o. o., Ljubljana.

Results and discussion

Electrical conductivity

Electrical conductivity of groundwater in unpolluted groundwater is usually in correlation with the concentration of dissolved carbonates in water, i.e. with carbonate hardness of water. Measurement results of electrical conductivity of groundwater of the Kamniškobistriško polje are presented in Figure 2.

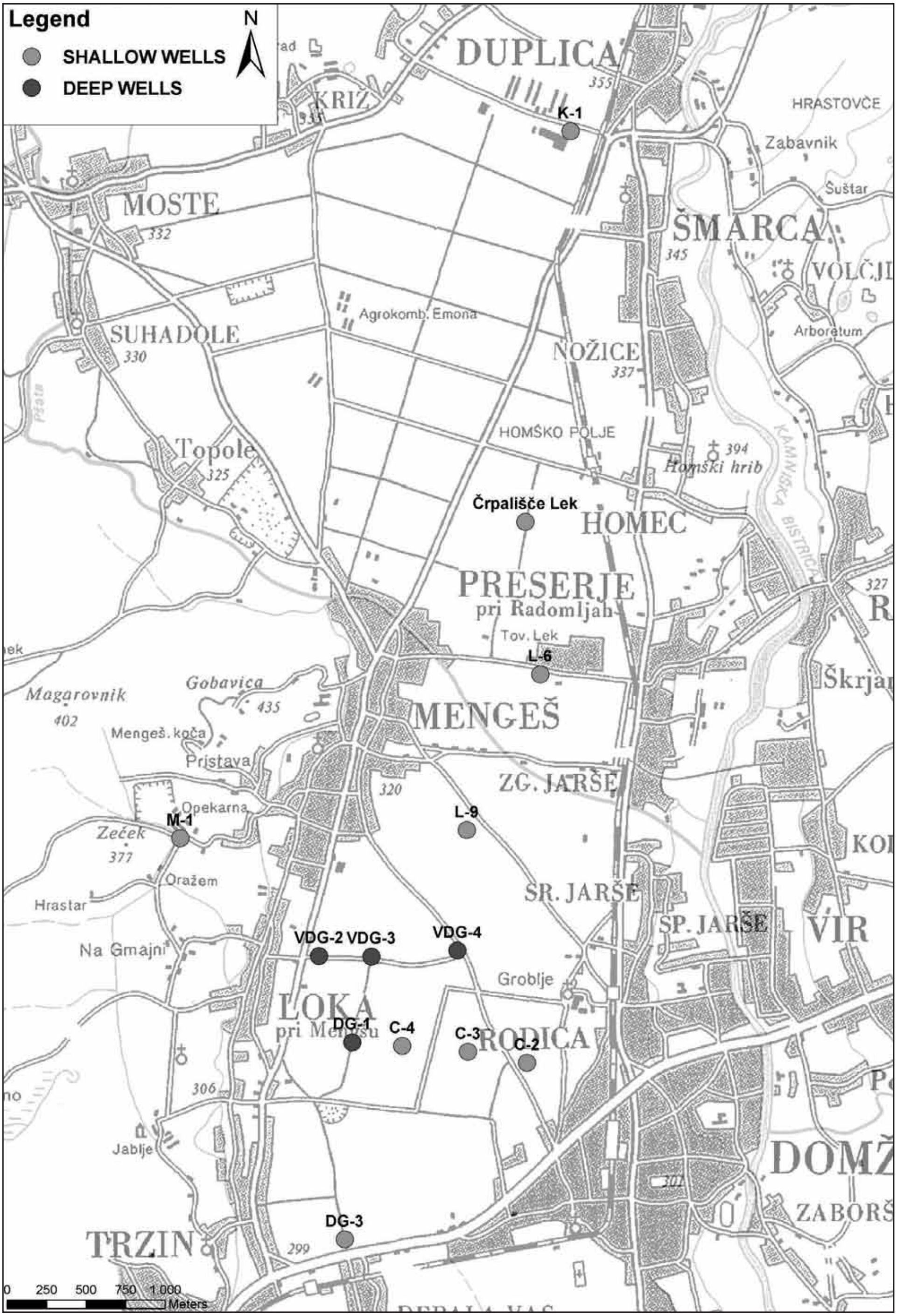

Figure 1. Monitoring point locations in the Kamniškobistriško polje

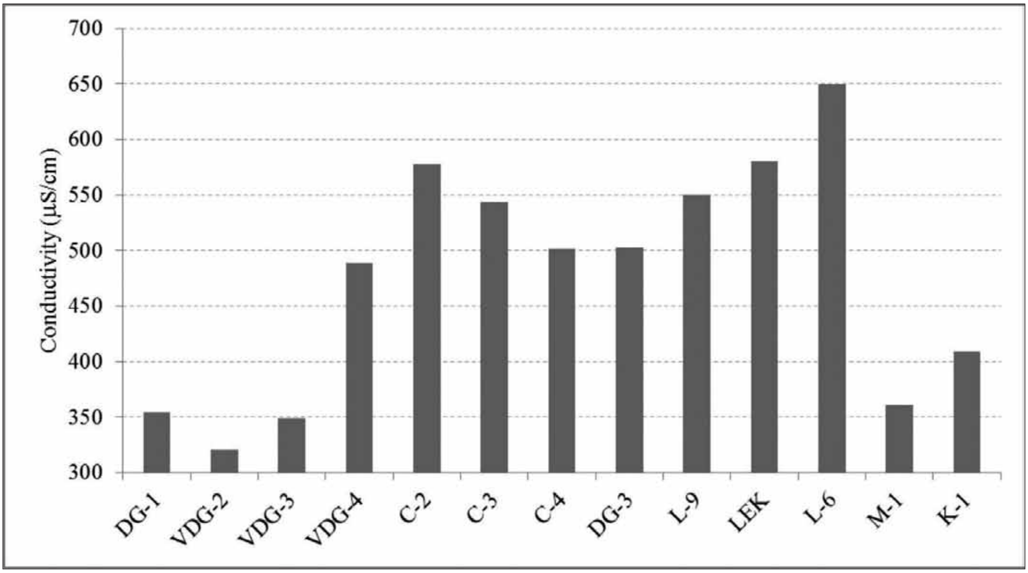

Figure 2. Electrical conductivity of groundwater of the Kamniškobistriško polje aquifer

Most values of electrical conductivity in the groundwater of the Kamniškobistriško polje range between 500 μS/cm and 600 μS/cm. Significantly lower values between 300 μS/cm and 350 μS/cm were measured in water from the deep dolomite aquifer, in well M-1, which also comprises the dolomite on the western fringes of the Kamniškobistriško polje, and in piezometer K-1, which is located in the northern part of the Kamniškobistriško polje near Duplica.

The lower values of electrical conductivity in the wells from the lower dolomite aquifer reflect a lesser quantity of dissolved carbonates in groundwater, which indicates that the hydrochemical properties of both aquifers are distinctly different due to their different recharge areas of precipitation.

A deviation from the typical values of electrical conductivity in the lower dolomite aquifer is observed only in the deep well VDG-4, which has a slightly lower value than water from other observation points in the upper Kamniškobistriško polje aquifer, and higher than water from the lower aquifer. Similar characteristics of well VDG-4 are observed also with regard to other hydrochemical and isotope parameters, which are presented further in this report. Thus it can be concluded that water from the lower and upper aquifer of the Kamniškobistriško polje is mixed in this well.

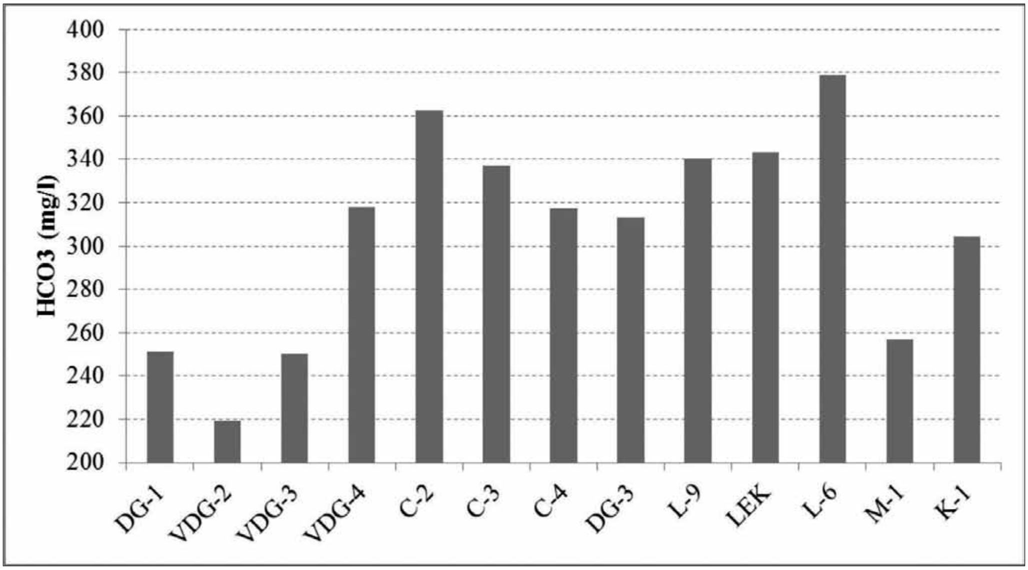

Figure 3. Concentration of HCO_3 in groundwater from the Kamniškobistriško polje aquifer

HCO_3 in groundwater

It is evident from Figure 3 that a higher concentration of HCO_3 is observed in groundwater from the upper Kamniškobistriško polje aquifer, where HCO_3 concentrations range between 300 mg/l and 380 mg/l, whereas water from deep wells in the lower dolomite aquifer shows lower concentrations of HCO_3, between 220 mg/l and 250 mg/l. A higher concentration of HCO_3 reflects a low-altitude aquifer recharge area in the Kamniškobistriško polje, where the production of soil CO_2 is bigger due to a higher average soil temperature. This in turn results also in a higher mineralization of groundwater.

Map on Figure 4 shows spatial characteristics of the HCO_3 parameter in groundwater from the Kamniškobistriško polje aquifer.

Because the HCO_3 parameter, similar as electrical conductivity, reflects the quantity of dissolved carbonate in water, a considerable degree of correlation between the two parameters may be expected. Figure 5 shows the relation between electrical conductivity and the concentration of HCO_3 in groundwater from the Kamniškobistriško polje. The chart also clearly shows the substantial difference between the carbonate chemistry of water from the upper and lower aquifer of the Kamniškobistriško polje.

Calcium and magnesium

Figure 6 presents the characteristics of calcium and magnesium distribution in

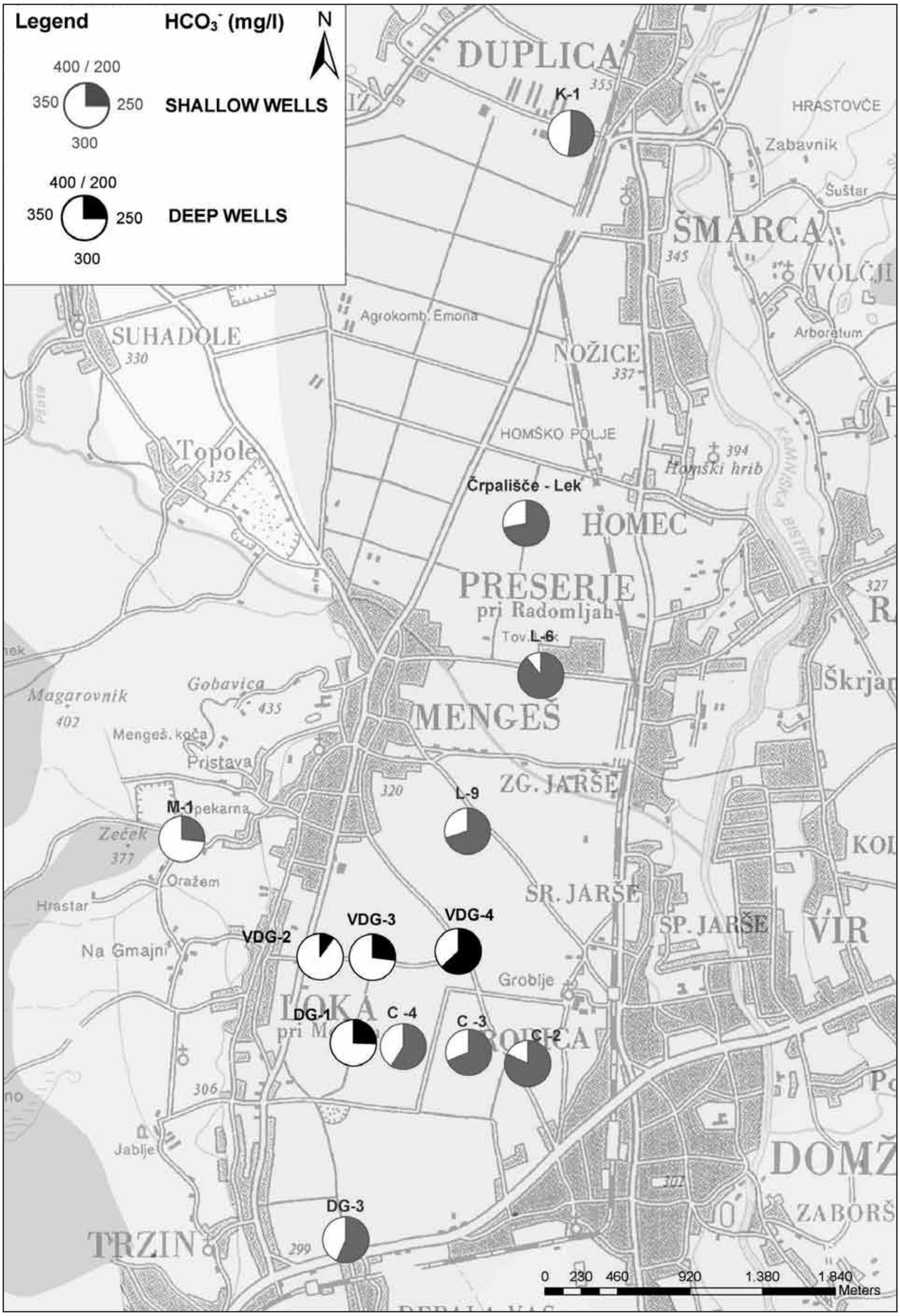

Figure 4. Spatial characteristics of HCO_3 concentration in groundwater from the Kamniškobistriško polje aquifer

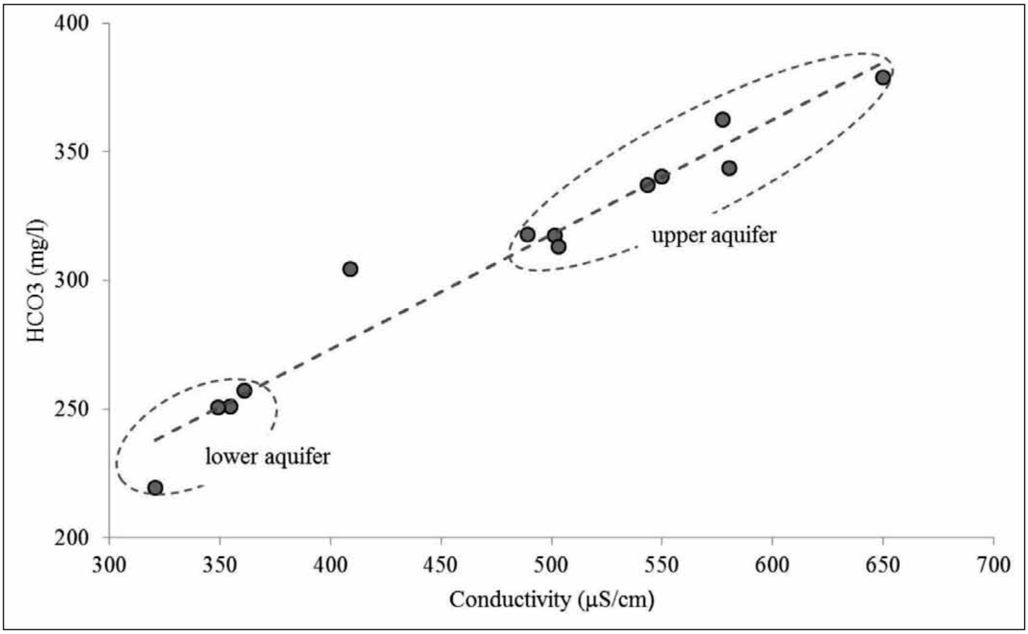

Figure 5. Relation between electrical conductivity and HCO_3 content in groundwater from the Kamniškobistriško polje

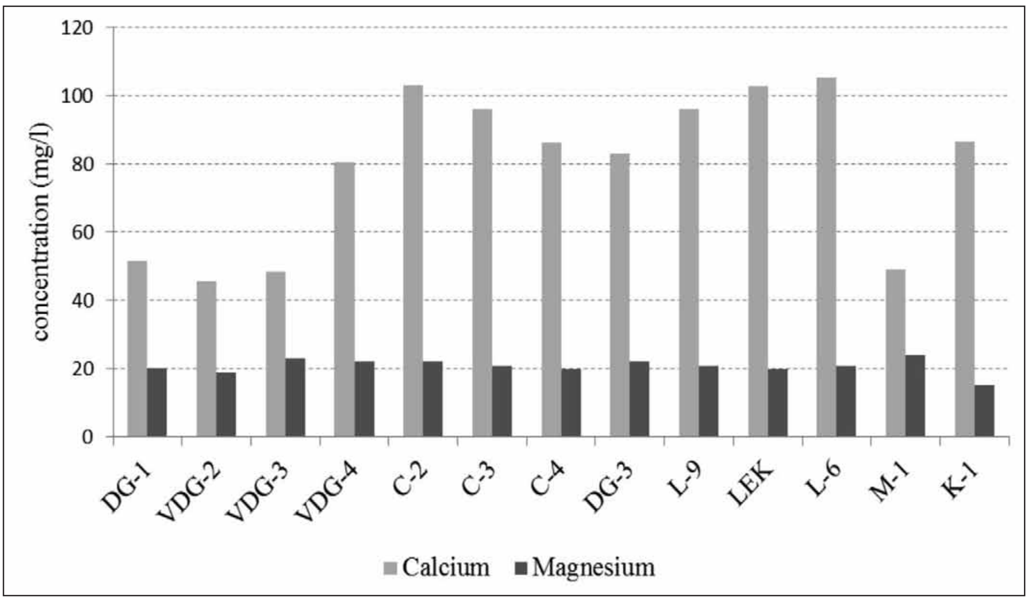

Figure 6. Calcium and magnesium content in the Kamniškobistriško polje groundwater

the Kamniškobistriško polje groundwater.

Values of calcium content in groundwater from the lower aquifer are about 50 mg/l, whereas they are considerably higher in the upper aquifer, approximately between 80 mg/l and 110 mg/l.

Compared to calcium, magnesium concentration in groundwater from the Kamniškobistriško polje show a substantially smaller span, from 19 mg/l to 24 mg/l. In this case the difference between groundwater from the upper and lower aquifer is not as pronounced.

The characteristics of the molar ratio between calcium and magnesium in the groundwater of the Kamniškobistriško polje are shown in Figure 7. Most values of the Ca/Mg molar ratio in the upper aquifer lie in the interval between 2.5 and 3.5, which means a marked predominence of calcium from limestone in the aquifer's recharge area. In the lower aquifer the molar ratio is between 1.3 and 1.6, which is close to the theoretical ratio typical of dolomites.

On the basis of these facts it can be concluded that dolomites prevail in the recharge area of the lower aquifer, while the upper aquifer's recharge area is composed of considerably more limestone rocks. We can assume that the lower aquifer mainly recharges in the dolomites outcropping on the western border of the Kamniškobistriško polje in the area of Dobeno, Debeli Vrh and Šinkov Turn.

Groundwater nitrate

Nitrates in groundwater usually originate from the use of fertilizers on agricultural areas or from the influence of waste water on the aquifer. Because waste water drainage is regulated in this area, we assume that nitrates in the Kamniškobistriško polje aquifer mostly originate from agricultural activities.

Figure 8 shows average nitrate concentrations in individual monitoring facilities in the area of the Kamniškobistriško polje.

Most nitrate concentrations in the upper Kamniškobistriško polje aquifer lie within the interval between 25 mg/l and 40 mg/l. Markedly lower nitrate concentrations are observed in the lower Kamniškobistriško polje aquifer, where they average at 6 mg/l at the most.

Sodium and chlorides

The average concentration of sodium and chlorides in the groundwater of the Kamniškobistriško polje is presented in Figure 10.

The lowest sodium and chloride contents are found in groundwater from the lower Kamniškobistriško polje

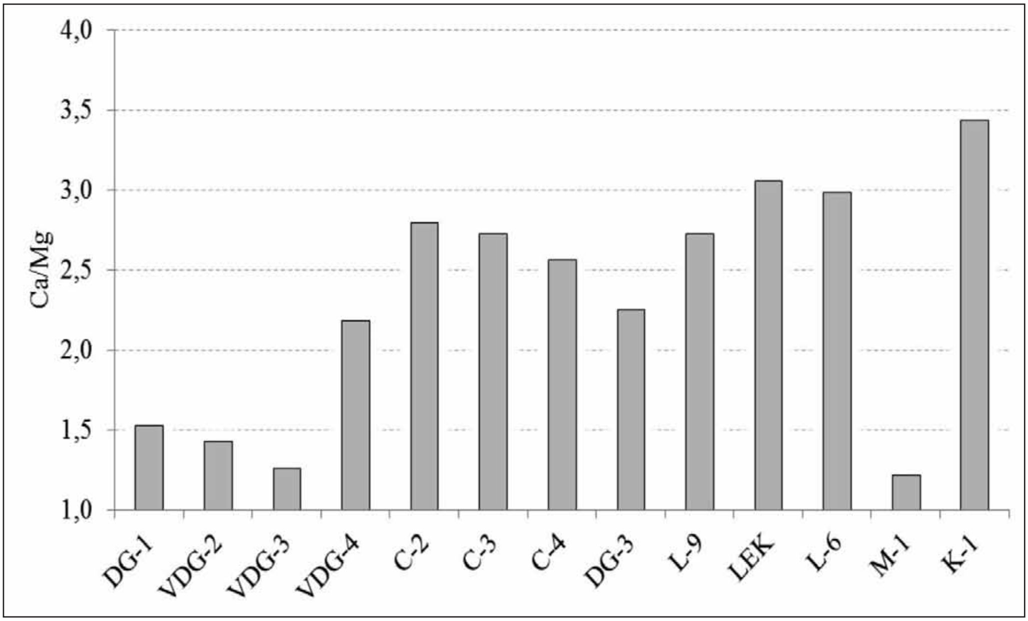

Figure 7. Molar ratio between calcium and magnesium in the groundwater of the Kamniškobistriško polje

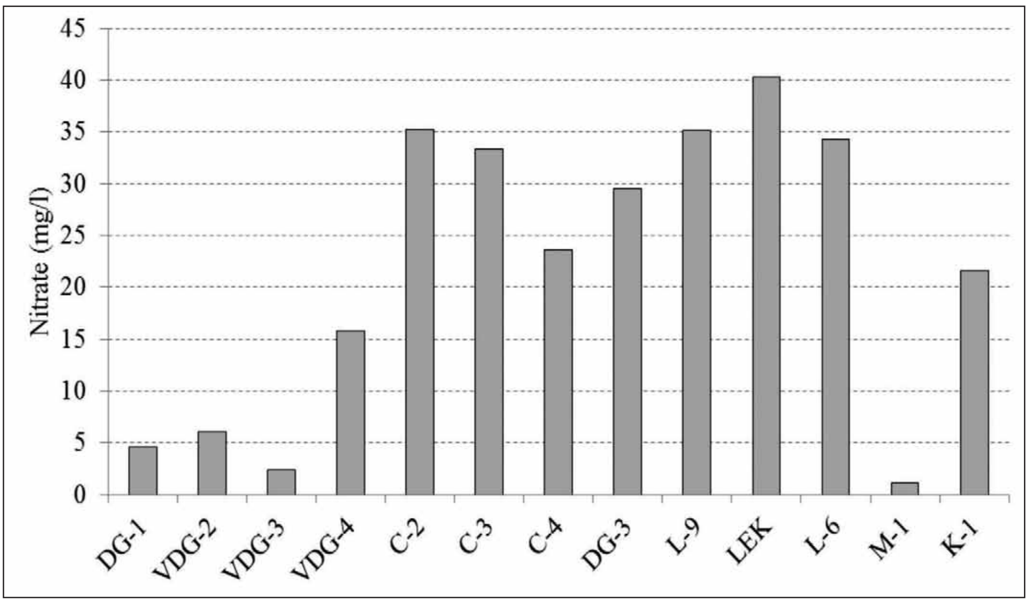

Figure 8. Average nitrate concentrations in the groundwater of the Kamniškobistriško polje

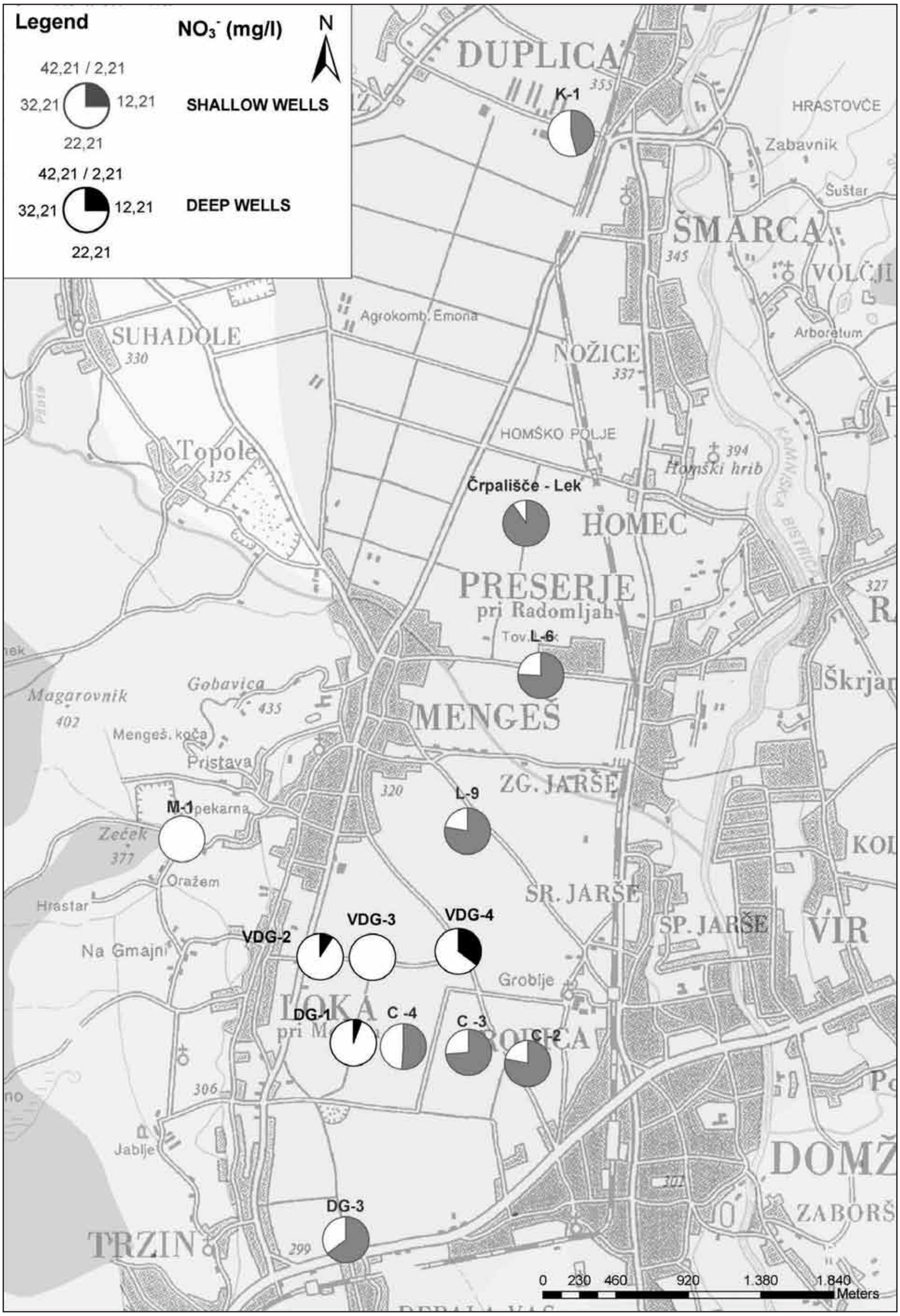

Figure 9. Characteristics of spatial distribution of nitrates in the groundwater of the Kamniškobistriško polje

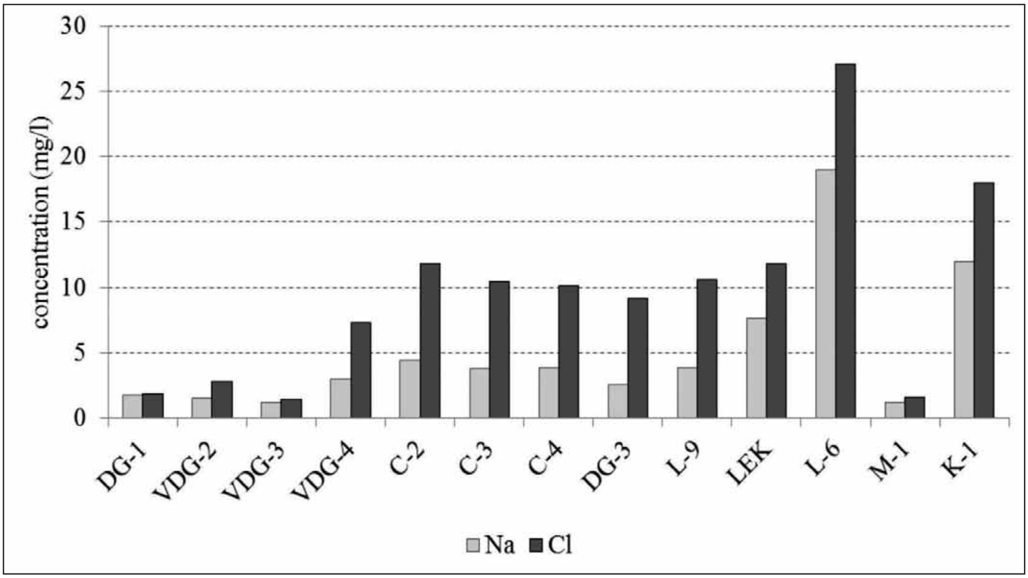

Figure 10. Average concentration of sodium and chlorides in the Kamniškobistriško polje aquifer

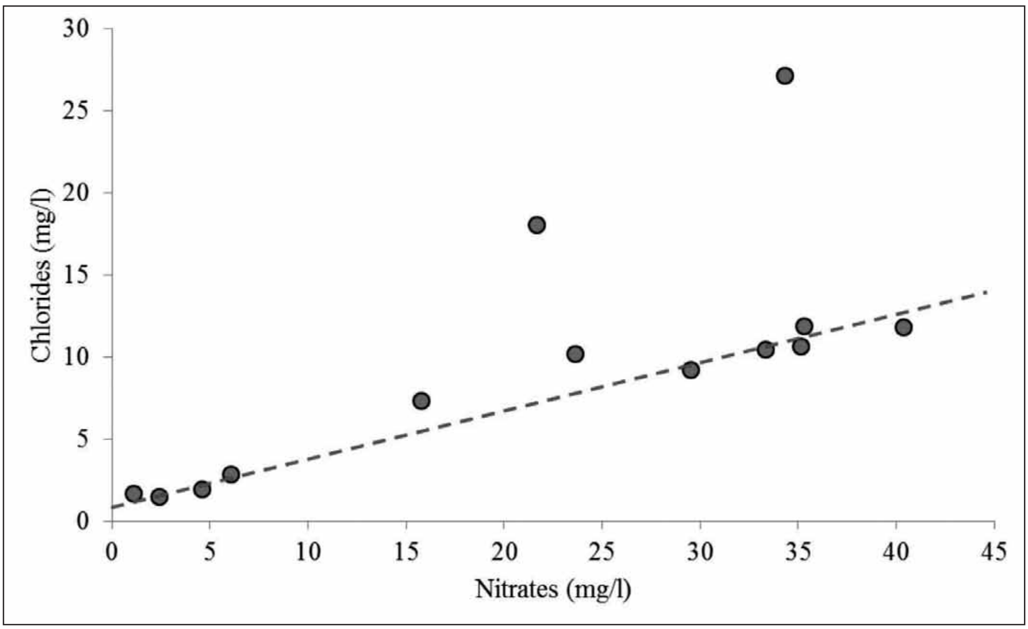

Figure 11. Correlation between chlorides and nitrates in groundwater from the Kamniškobistriško polje aquifer

aquifer, the values never exceeding 5 mg/l. A typical chloride concentration is about 10 mg/l.

In some cases also higher chloride concentrations were measured. The highest concentration of chlorides, 27 mg/l, was measured in well L-6 in the central part of the Kamniškobistriško polje. Because the well is located near traffic or parking areas, we suppose that chlorides in this area are mainly a result of salting of roads against frost.

This interpretation is confirmed also by Figure 11 which shows the correlation between chlorides and nitrates in groundwater. On the chart, only the two monitoring points (K-1 and L-6) located in proximity to roads deviate from the regression line in the direction of relatively higher chloride concentration.

Conclusions

Hydrochemical investigations of groundwater in the area of the Kamniškobistriško polje show that groundwater of the upper gravel aquifer has a fairly different chemical composition than that of the lower dolomite aquifer, which is a result of different recharge areas of both aquifers. The groundwater of the upper aquifer in sands and gravels is more mineralised than groundwater of the lower, dolomite aquifer. This is reflected in a higher electrical conductivity of the water and in the concentrations of HCO_3, calcium and magnesium.

The molar ratio between calcium and magnesium in the upper aquifer is higher, which indicates the predominance of limestone over dolomite in the aquifer's recharge area. The molar ratio between calcium and magnesium in the lower aquifer is close to 1, which is typical of pure dolomite recharge areas. We assume that the main recharge area of the lower aquifer is the western border of the Kamniškobistriško polje aquifer in the area of Dobeno, Debeli Vrh and Šinkov Turn, where triasic dolomite prevails.

Also the concentrations of pollutants, such as nitrates and chlorides, are significantly higher in the upper, intergranular, than in the lower, dolomite aquifer. It is assumed that nitrates enter groundwater mostly through agricultural activity, while the application of road salt is the main source of chlorides.

Acknowledgements

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The influence of vegetation type on metal content in soils

Vpliv vrste vegatacije na vsebnost težkih kovin v tleh

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Abstract: Human influence on soil contamination with metals can only be established when the real background values are known. Besides parent rock type and climate, vegetation cover can be one of the factors influencing soil properties. Fifty samples of soils developed on Upper Triassic dolomite at an elevation of around 600 m and on slopes with SW insulation were collected. At each of the five locations, four samples and one replicate were taken from forest-covered area and from area covered by grass. The Co, Cr, Cu, Ni, Pb and Zn content was analysed by emission spectroscopy. Very high Co, Cr and Ni values are natural, typical for karstic soils in Slovenia. An analysis of variance showed a high analytical error for Pb and Zn, and high variability at small distances (1 m, 10 m, and 100 m) for Co, Cr, Cu and Ni. This is the reason why vegetation influence on the metal content was only proven for Cu. On the contrary, a t-test indicates lower values of all elements in the forest soils, except Pb, where there seems to be no difference between soils covered by grass or forest. The reason for the higher metal content in the meadow soils could be the application of manures. Vegetation cover should be considered when designing the sampling and interpreting the data.

Izvleček: Vpliv človeka na onesnaženost tal s kovinami lahko ugotovimo le, če poznamo prave vrednosti ozadja. Poleg matične podlage in podnebja je eden od dejavnikov, ki vplivajo na lastnosti tal, lahko tudi vegetacijski pokrov. Na nadmorski višini 600 m smo na pobočjih vzorčili 50 vzorcev tal, razvitih na zgornjetriasnem dolomitu. Na vsakem od petih področij smo odvzeli štiri vzorce in eno ponovitev na delu, pora-

Original scientific paper

ščenem z gozdom, in delu, poraščenem s traviščem. Vsebnost Co, Cr, Cu, Ni, Pb in Zn je bila določena z emisijsko spektroskopijo. Izredno visoke vsebnosti Co, Cr in Ni so naravne in značilne za kraška tla v Sloveniji. Analiza variance je pokazala visoko analitsko napako Pb in Zn ter veliko spremenljivost Co, Cr, Cu in Ni na majhni razdalji (1 m, 10 m in 100 m). Zato je vpliv vegetacije na vsebnost težkih kovin z analizo variance potrjen le za Cu. Nasprotno, t-test kaže v gozdnih tleh nižje vsebnosti vseh prvin, razen Pb, kjer je videti, da ni razlik med tlemi, poraščenimi z gozdom ali traviščem. Razlog za višje vsebnosti kovin v tleh bi lahko bilo gnojenje. Pri načrtovanju vzorčenja in interpretaciji rezultatov bi morali upoštevati vrsto rastlinske poraščenosti.

Key words: soil, metals, vegetation
Ključne besede: tla, težke kovine, vegetacija

Introduction

The distribution of most elements in soils shows a pattern related to geology. Geochemical surveys reveal patterns of a geochemical signature on the scale of the selected area, and indicate the different factors influencing these patterns, notably bedrock geology, climate and human influences (De Vos & Tarvainen, 2006). With time, soil-forming processes modify the basic geochemical composition and redistribute the content of metals within the soil profile (Bini et al., 2011). In their study of the FOREGS database, Imrie et al. (2008) reported that the overall distribution of geochemical elements in European topsoils follows diverse patterns that can be explained by various processes occurring on different spatial scales. They concluded that the geochemical variation on short scales chiefly depends on local variations of lithology, land use, weathering processes and organic matter content.

Vegetation is a well-known key factor governing soil-forming processes. A diversity of vegetation can lead to different stages of soil formation, soil profiles and soil types (Küfmann, 2003). In certain climatic conditions, vegetation influences the status of trace elements by affecting their release, migration, transformation and transportation (Zhang et al., 2002). Some authors try to eliminate at least some effects of pedogenic processes by, for example, sampling just forest soils (De Vos & Tarvainen, 2006; Bini et al., 2011), which is not always possible. Others seek to establish how different land use and/or vegetation cover may influence metal accumulation in soils (Bai et al., 2010; Baize & Sterckeman, 2001; Zhang et al., 2002; Xia et al., 2011). Zhao et al. (2007) even proposed that vegetation would best proxy the delineation of the single attribute of urban soils and can be used as a basis for soil regionalisation in urban and peri-urban environments.

To establish anthropogenic soil pollution it is necessary to know what the real background values are. It is therefore very important to evaluate not only the geologic and climatic effect on soil geochemistry, but also the biologic one. The presented study was part of a project to geochemically map Slovenia which was designed and conceptually guided by Prof. Dr. Simon Pirc. The aim of this paper is to present possible differences in the content of six metals (Co, Cr, Cu, Ni, Pb, and Zn) in soils developed on the same parent rock but covered by forest or grassland in Slovenia.

Materials and methods

As the main purpose of the study was to establish the influence of vegetation cover on metal contents in soils, we tried to minimise all other possible factors which could affect their content. Slovenia is prevailingly a carbonate country so we decided to sample on Upper Triassic dolomite, which is supposed to be spatially quite uniform. The sampling locations were selected from five different parts of Slovenia (Postojna, Zaplana, Stična, Dole pri Litiji, Dolič pri Mislinji) representing variations of climatic conditions in terms of distance from the sea, but always at approximately the same elevation (600 m) and the same inclination of the slope (SW).

At each sampling location, four soil samples were taken from the grassland and four from the forest. At Postojna, the vegetation type was *Carici humilis – Centaureetum rupestris* for grassland and *Querco – Carpinetum* for the forest. At Zaplana, the meadows were mainly cultivated (*Brometalia erecti*) and the forest type was *Ostryo – Fagetum*. At Stična, the grassland was covered with *Arrehno – thetrtum medioeuropeum* and the woods with *Fagetum submontanum praedinaricum*. The same forest type prevails at Dole pri Litiji, where the grassland is *Bromo – brachypodietum*. Dolič was vegetated with *Arrehno – theretum medioeuropeum* on the meadows and with the only type of coniferous forest – *Genisto – Pinetum*. At all of the grassland locations contamination due to agriculture was possible to some extent.

Four samples at each location were arranged in randomly positioned 100 m long profiles, with samples taken at

0 m, 1 m, 10 m and 100 m from the starting point. Each sample from the starting location was split into two to provide replicate samples to serve as a control over the accuracy of the analyses. This sampling strategy enabled a hierarchical nested analysis of variance (ANOVA) design to be used along with an estimation of the variability source and its significance.

A total of 50 soil samples weighing 1.5–2 kg were collected. All organic soil horizons were removed, and soil down to a depth of 15 cm was taken. The soil samples were air dried. About 1 kg of every sample was ground, split and sieved to produce a 20 g sample with a grain size of less than 0.063 mm. The chemical composition of the samples was determined at the Kemijski inštitut (National Institute of Chemistry, Ljubljana, Slovenia) by emission spectroscopy.

To control the accuracy of the analysis five standard materials (GXR-2, GXR-5 (Allcot & Lakin, 1978), SO-1, SO-2, SO-3 (Abbey, 1983)) were added. The Co, Cr and Zn accuracy was established good, Cu, Ni, and Pb satisfactory. Precision was estimated from ANOVA of repeated soil samples and a calculation of the coefficients of variation (*CV*) for five replicate analyses of each standard material. Generally, analytical error is below 10 % for Co, Cr, Cu and Ni and close to 30 % for Pb and Zn. The interpretation of the last two elements requires some caution.

Results

Analytical results with the ANOVA scheme are presented in Table 1, whereas descriptive statistics of all samples and both vegetation groups are shown in Table 2.

Table 1. Analysis of variance (ANOVA) design and metal content (mg kg^{-1}) for 50 soil samples from Upper Triassic dolomite from Slovenia.

sample	vegetation	location	100 m	10 m	1 m	anaytics	Co	Cr	Cu	Ni	Pb	Zn
s1	forest	Postojna	1	1	1	1	14	75	17	40	33	51
s2	forest	Postojna	1	1	1	2	16	67	13	32	65	30
s3	forest	Postojna	1	1	2	1	12	117	117	7	40	49
s4	forest	Postojna	1	2	1	1	14	102	16	59	11	22
s5	forest	Postojna	2	1	1	1	37	135	32	102	22	65
s6	forest	Zaplana	1	1	1	1	20	98	17	59	30	52
s7	forest	Zaplana	1	1	1	2	23	100	22	76	49	60
s8	forest	Zaplana	1	1	2	1	34	165	27	117	39	64
s9	forest	Zaplana	1	2	1	1	26	132	22	103	35	34

s10	forest	Zaplana	2	1	1	1	43	170	34	133	36	84
s11	forest	Stična	1	1	1	1	16	70	21	47	25	35
s12	forest	Stična	1	1	1	2	10	82	21	48	34	53
s13	forest	Stična	1	1	2	1	12	85	85	9	41	123
s14	forest	Stična	1	2	1	1	16	87	18	43	65	74
s15	forest	Stična	2	1	1	1	24	62	18	39	35	70
s16	forest	Dole	1	1	1	1	33	190	22	70	29	49
s17	forest	Dole	1	1	1	2	25	170	25	75	39	43
s18	forest	Dole	1	1	2	1	33	167	25	90	2	40
s19	forest	Dole	1	2	1	1	29	190	36	93	48	90
s20	forest	Dole	2	1	1	1	21	114	20	61	13	18
s21	forest	Dolič	1	1	1	1	10	42	17	22	45	53
s22	forest	Dolič	1	1	1	2	9	42	18	20	52	12
s23	forest	Dolič	1	1	2	1	3	25	33	13	14	66
s24	forest	Dolič	1	2	1	1	15	50	10	26	37	47
s25	forest	Dolič	2	1	1	1	10	53	12	30	255	275
s26	meadow	Postojna	1	1	1	1	25	175	27	80	34	93
s27	meadow	Postojna	1	1	1	2	29	171	28	76	26	49
s28	meadow	Postojna	1	1	2	1	32	200	26	89	40	54
s29	meadow	Postojna	1	2	1	1	12	90	19	59	32	34
s30	meadow	Postojna	2	1	1	1	16	205	32	84	165	270
s31	meadow	Zaplana	1	1	1	1	28	140	33	99	16	33
s32	meadow	Zaplana	1	1	1	2	35	185	32	112	42	86
s33	meadow	Zaplana	1	1	2	1	28	140	24	102	13	31
s34	meadow	Zaplana	1	2	1	1	27	175	30	85	33	100
s35	meadow	Zaplana	2	1	1	1	48	230	31	119	20	21
s36	meadow	Stična	1	1	1	1	51	160	28	61	37	61
s37	meadow	Stična	1	1	1	2	46	175	24	60	37	49
s38	meadow	Stična	1	1	2	1	65	250	31	85	58	65
s39	meadow	Stična	1	2	1	1	60	175	38	70	62	100
s40	meadow	Stična	2	1	1	1	41	125	35	65	80	710
s41	meadow	Dole	1	1	1	1	43	193	32	74	34	66
s42	meadow	Dole	1	1	1	2	41	142	34	72	29	119
s43	meadow	Dole	1	1	2	1	52	202	50	79	58	89
s44	meadow	Dole	1	2	1	1	41	140	43	95	16	42
s45	meadow	Dole	2	1	1	1	32	130	29	74	18	63
s46	meadow	Dolič	1	1	1	1	18	75	28	34	35	58
s47	meadow	Dolič	1	1	1	2	19	95	27	37	24	66
s48	meadow	Dolič	1	1	2	1	19	89	29	41	28	155
s49	meadow	Dolič	1	2	1	1	25	83	27	42	21	56
s50	meadow	Dolič	2	1	1	1	10	57	17	26	20	50

Table 2. Descriptive statistics of metals (mg kg^{-1}) for all 50 soil samples, and for the forest and meadow subgroups. Corrected Mean – Mean of data where outliers were replaced by the average of the element, SD – Standard Deviation, CV – Coefficient of Variation, Skew. – Skewness, Kurt. – Kurtosis, S-W – normality according to Shapiro-Wilk's test.

All	Mean	Corrected Mean	Median	Min	Max	SD	CV	Skew.	Kurt.	S-W
Co	26.96	26.96	25	3	65	14.293	53.0	0.68	–0.05	yes
Cr	127.84	127.84	131	25	250	55.233	43.2	0.09	–0.93	yes
Cu	29.04	26.12	27	10	117	17.137	59.0	3.53	15.63	no
Ni	64.68	64.68	68	7	133	30.873	47.7	0.04	–0.69	yes
Pb	41.44	34.70	35	2	255	39.160	94.5	4.06	19.60	no
Zn	81.58	60.54	57	12	710	103.739	127.2	4.96	28.43	no
Forest										
Co	20.20	20.20	16	3	43	10.210	50.55	0.55	–0.47	yes
Cr	103.60	103.60	98	25	190	49.569	47.85	0.36	–1.01	yes
Cu	27.92	22.08	21	10	117	23.463	84.04	3.05	9.64	no
Ni	56.56	56.56	48	7	133	35.008	61.90	0.51	–0.58	yes
Pb	43.76	35.32	36	2	255	46.574	106.43	4.15	19.31	no
Zn	62.36	51.40	52	12	275	50.398	80.82	3.35	13.80	no
Meadow										
Co	33.72	33.72	32	10	65	14.752	43.75	0.36	–0.56	yes
Cr	152.08	152.08	160	57	250	50.470	33.19	–0.14	–0.65	yes
Cu	30.16	30.16	29	17	50	6.817	22.60	0.90	2.43	yes
Ni	72.80	72.80	74	26	119	24.145	33.17	–0.17	–0.39	yes
Pb	39.12	34.08	33	13	165	30.831	78.81	3.10	11.76	no
Zn	100.80	69.68	63	21	710	136.610	135.53	4.06	17.90	no

The metal abundance sequence varies somewhat regarding all the data or separate groups and also if we take mean or median values as a measure of it. Most commonly, it is Cr > Zn or Ni > Pb > Cu or Co. The highest values of Co, Cr and Zn are found in the Stična grasslands, Ni in the Zaplana forest and Pb in the Dolič forest. The lowest values of all elements are always found in forests – Co, Cr, Cu and Zn in Dolič, Ni in Postojna and Pb in Dole. The variation sequence according to CV also differs for all data, forest and grassland, but the values are very high in all cases. For all data, it is Zn > Pb > Cu > Co > Cr > Ni, for forest Pb > Cu > Zn > Ni > Co > Cr and for grassland Zn > Pb > Co > Cr > Ni > Cu.

Most statistical analyses demand a normal distribution of the data. The normality of the distribution was tested visually from histogram and normal probability plots, with comparisons of the mean, geometric mean and median, testing of skewness and kurtosis and with Shapiro-Wilk's test, as proposed by Madansky (1988). The distribution is not normal for Co, Cr and Ni and extremely positively skewed for Cu, Pb and Zn. For all three elements, the deviation from normality is mainly caused by five outliers (s3, s13, s25, s30 and s40), with three of them being in forests (Postojna, Stična, Dolič) and two in meadows (Postojna and Stična). Except in outlier s3 where only the Cu, and s40 where only the Zn content is very high, in the rest of them two elements exhibit extreme values – in s13 Cu and Zn, in s25 and s30 Pb and Zn. Omitting outliers from the datasets improves the distribution to normal. Coefficients of variation remain around 30 due to the very low values recorded for every analysed element. As it was uncertain if the extreme values are real or perhaps just the consequence of an error, we transformed all the data to a more symmetric distribution with a Box-Cox transformation (Box & Cox, 1964). This transformation improved the normality of the distribution of all variables except Pb, which remained a little skewed. If we replace the outliers of critical elements with mean values for the appropriate vegetation type (forest Cu 28, Pb 44, Zn 62, and meadow Pb 39, Zn 101), the distributions become normal for all elements except Zn. All of the statistical analyses were performed with parametric statistics for the Box-Cox transformed data and the data with outliers changed by mean values – so-called corrected data. The results with the original data are presented in the box-whisker diagrams.

The correlations were computed on raw data (Table 3), mean-replaced outliers data, and Box-Cox transformed data with a nonparametric Spearman correlation coefficient as proposed by Swan & Sandilands (1995). All three matrices are similar, showing a really good correlation among Co – Cr – Ni and a less persuasive one of Cu with this group of elements, and Zn and between Pb, and Zn.

Table 3. Nonparametric Spearman correlation coefficients of raw data ($n = 50$). The 95 % statistically significant values are in bold.

	Co				
Cr	**0.79**	Cr			
Cu	**0.54**	**0.54**	Cu		
Ni	**0.73**	**0.78**	**0.39**	Ni	
Pb	0.01	0.08	0.05	–0.12	Pb
Zn	0.18	0.18	0.**46**	0.01	**0.45**

The comparison of the metal content in soils covered with different types of vegetation was first assessed with a t-test. The Box-Cox transformed data results (Table 4) indicate statistically significant differences in Co, Cr, Cu and Ni content between the forest and grassland soils. Data with the replaced outliers (Table 4) give the same result for Co, Cr and Cu as the Box-Cox transformed data, but show no differences in Ni and in addition differences in Zn.

Raw data (Table 2, Figure 1) generally show a lower mean content of all elements, except Pb in the forest soils and the high variability of Cu and Pb in the forest and Zn in the meadow soils. Enrichment in meadow soils is most pronounced for Co (1.7-times), followed by Zn (1.6-times), Cr (1.5-times), Ni (1.3-times) and Cu (1.1-times). If we disregard the outliers, the sequence is Co (1. 7-times), Cr (1.5-times), Cu (1.4-times) = Zn (1.4-times) and Ni (1.3-times). In both cases, the Pb values are just a little higher in the forest soils.

Table 4. t-test and F-test results of Box-Cox transformed (first row) and corrected (second row) data. Statistically significant results are in bold.

	t	p	F	p
Co	**–3.76**	**0.00**	1.14	0.76
	–3.77	**0.00**	2.09	0.08
Cr	**–3.44**	**0.00**	1.16	0.72
	–3.43	**0.00**	1.04	0.93
Cu	**–2.55**	**0.01**	**5.53**	**0.00**
	–4.14	**0.00**	1.05	0.91
Ni	**–2.03**	**0.05**	2.26	0.05
	–1.91	0.06	2.10	0.07
Pb	0.04	0.97	1.90	0.12
	0.28	0.78	1.12	0.78
Zn	–1.73	0.09	1.08	0.85
	–2.47	**0.02**	**2.64**	**0.02**

The high variability of the data and/or the existence of outliers seem to hinder the interpretation so a hierarchical nested analysis of variance was performed taking the influence of not only vegetation into consideration, but also the geographical position of the sampling location, the place of the sample in each sampling profile and analytical replications. A method using the expected MS and a Type III calculation of SS was applied. The results for the Box-Cox transformed data and corrected data are presented in Table 5 and Figure 2. It is obvious that the vegetation type is never the main source of variation for any element. The influence of vegetation is highest for corrected values of Cu (28 %), where it is also statistically significant. For Co and Cr, the proportion for the vegetation level is around 15 %, but not significant, for corrected Zn around 10 %, and practically 0 for Ni, Pb and non-corrected Zn. The statistical significance of the corrected Zn is unreliable due to high analytical error. The same is true for the corrected Pb and non-corrected Zn results so any further statistical inference regarding these two elements is limited. A quite obvious feature of the data is the statistically significant variability at a small scale, i.e. comparison of 0 m and 1 m, for Co, Cr, Cu, Ni and it seems that it could also hold true for Pb and Zn. It is significant and within a range of between 10 % for Co to 75 % (50 % for corrected data) for Cu. For Co, the next statistically significant source of variance is variability on a 100 m scale, and for Cr and Ni it is location. For all of them, variance at the location level comprises 20–60 %.

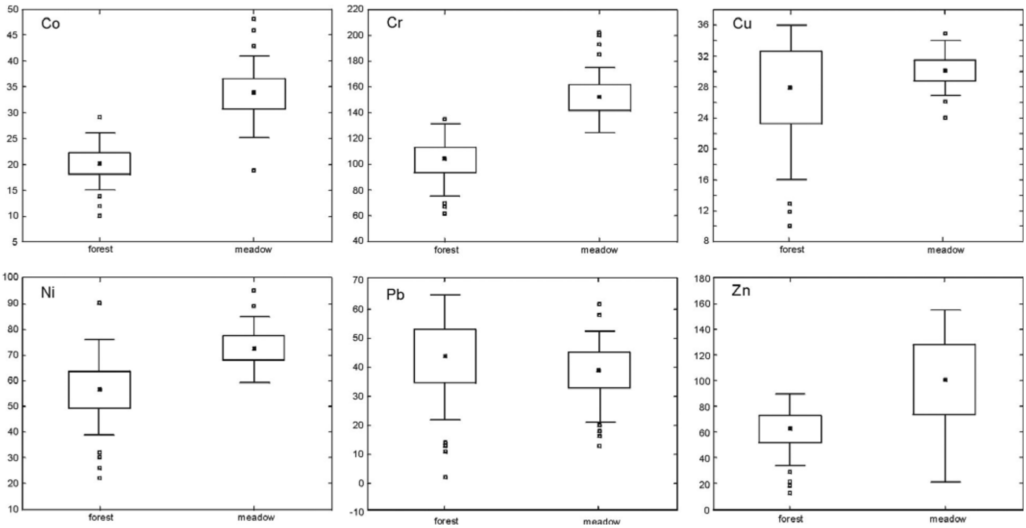

Figure 1. Box-whisker graphs of metals (mg kg^{-1}) in the forest and meadow soils. Entral dot – Mean, box – Mean ± Standard error, whisker – Non-Outlier Range, external dots – outliers.

Table 5. Hierarchical nested ANOVA results for Box-Cox (first row) and replaced outliers (second row) data. Statistically significant differences at 95 % probability are shown in bold.

	Vegetation	Location	100 m	10 m	1 m	Analytics
Co	13.8	41.4	**24.4**	5.6	**9.8**	5.0
	15.2	37.9	**32.2**	0.0	**10.2**	4.5
Cr	15.6	**47.6**	14.0	0.4	**15.1**	7.3
	16.3	**42.5**	16.0	0.0	**16.8**	8.4
Cu	8.6	12.2	0.0	0.0	**75.1**	3.7
	28.0	5.0	14.9	0.0	**47.9**	4.2
Ni	0.0	**57.1**	15.4	0.0	**25.3**	2.3
	0.0	**57.2**	17.7	0.0	**22.7**	2.4
Pb	0.0	8.5	29.4	0.0	**47.9**	14.2
	0.0	33.2	0.0	10.2	25.5	31.1
Zn	1.5	0.0	**56.0**	3.4	0.0	39.2
	9.7	0.0	0.0	19.4	18.9	52.0

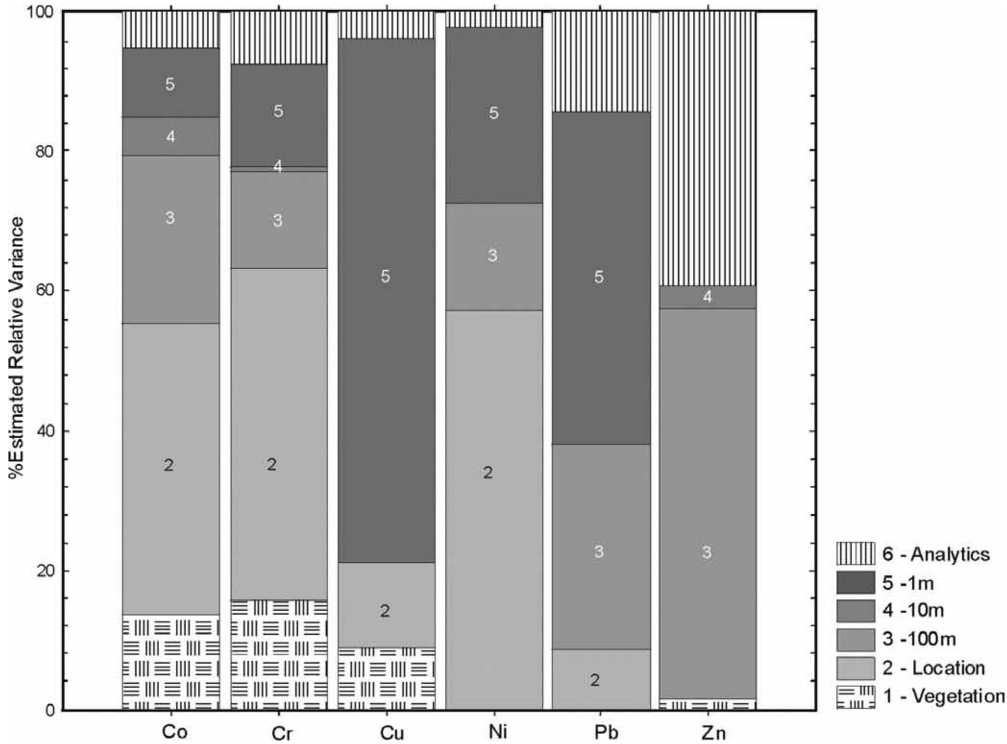

Figure 2. Estimated relative variance (%) the contributions of vegetation, location, 100 m, 10 m, 1 m and analytical error factors for metals in soils.

DISCUSSION

Before making any conclusions about the role of vegetation cover in metal content in soils, it is important to establish that we are dealing with natural values and that the soils are not polluted due to human activity.

The observed Co, Cr and Ni values are quite high. Their mean values for both vegetation types and even median values for the meadows are above the Slovenian legal limit (Uradni list RS, 1996) and in the case of Cr and Ni even above the action value (Table 6). They are also above the Slovenian (PIRC & ŠAJN, 1997) and European median values (DE VOS & TARVAINEN, 2006). For Cu, Pb and Zn the mean and median values are within the normal range for Slovenia and Europe (Table 6).

Only 19 individual Co values are below 20 mg kg^{-1}, with the majority of them being sampled in forest at the Dolič location. Four values higher than 50 mg kg^{-1} were all sampled in Stična (three) and Dole (one) grasslands. The high Co values in soil are very often geogene, related to mafic or ultramafic rocks, but they could also be the result of adsorption and coprecipitation processes with Fe and/or Mn from lithologies rich in these metals. Co may also bind to humic and fulvic acids and inorganic colloids (Qian et al., 1998). The karst soils of Slovenia exhibit a high Co content > 14.4 mg kg^{-1} that is probably related to the bauxite and Fe-Mn rich rocks (De Vos & Tarvainen, 2006).

Nearly the same 19 samples have Cr values above the limit value of 100 mg kg^{-1} and 19 samples, again mainly sampled in the meadows, have values above the action value of 150 mg kg^{-1}. In soils, Cr behaviour is governed by pH, Eh and organic matter. Its adsorption by clays is also highly dependent on pH. The dominant effect of organic matter is the stimulation of the reduction of Cr^{6+} to Cr^{3+}, the rate of which increases with soil acidity (Kabata-Pendias & Pendias, 2001). De Vos & Tarvainen (2006) reported that high Cr values in Slovenia are found over carbonate rocks so the observed contents seem to be natural.

Also for Ni, only 17 values below the limit (50 mg kg^{-1}) are observed mainly in the forest soils and at the Dolič location. Twenty-five values mainly from the Zaplana and Dole forests and grasslands are even above the action value (70 mg kg^{-1}). Organic matter can contain Ni concentrations in excess of 50 mg kg^{-1}, but high values of Ni (>37.4 mg kg^{-1}) are found in Slovenia in residual soils over carbonate rocks (De Vos & Tarvainen, 2006).

Several authors (De Vos & Tarvainen, 2006; Zhang et al., 2002) have established a strong correlation between Co, Ni, Cr and Cu, which is also the case in our study. Spearman's correlation coefficients above 0.7 support a similar geochemical behaviour and origin of Co, Cr and Ni. The observed high values seem to be natural and not influenced by human activity.

Cu content is above the limit value of 60 mg kg^{-1}only in one forest sample from Stična and one from Postojna. In both sampling areas no obvious pollution source was documented and the nearby samples also do not exhibit any Cu increase. The reason for the elevated Cu could be analytical error or natural local concentration due to one or a combination of reasons. In unmineralised sediments, Cu concentrations are principally determined by mafic detritus, secondary Fe and Mn oxides (Forbes et al., 1976), clay minerals (Heydeman, 1959) and organic matter (Stevenson & Ardakani, 1972). Further, the affinity of Cu for natural organic matter has been widely documented (Rashid, 1974; Rippey, 1982).

Table 6. A comparison of the forest and meadow soils' metal content (mg kg^{-1}) with other work. All values are rounded off to the nearest integer value: a – Uradni list RS, 68/96 (1996), b– Pirc & Šajn (1997), c – De Vos & Tarvainen (2006)

		Co	Cr	Cu	Ni	Pb	Zn
This study	Me forest	16	98	21	48	36	52
	Me meadow	32	160	29	74	33	63
This study	Mean forest	20	104	28	57	44	62
	Mean meadow	34	152	30	73	39	101
Slovene Law[a]	Limit Value	20	100	60	50	85	200
Slovene Law[a]	Action value	50	150	100	70	100	300
Slovene Law[a]	Critical Value	240	380	300	210	530	720
Slovenia[b]	Me		42	23	31	34	77
Europe[c]	Me	8	60	13	18	23	52

The quality of the Pb and Zn analytics is not sufficient to allow any serious interpretation. In spite of this, some comments are presented. Just two Pb values, one from a Postojna meadow and the other from a Dolič forest, are above the Slovenian legal action value. In both cases, this could be just an analytical error or a natural reason. Pb in soils is mainly associated with clay minerals, Mn oxides, Fe and Al hydroxides and organic matter. In some soil types, Pb may be highly concentrated in Ca carbonate particles (Kabata-Pendias & Pendias, 2001).

In the same two samples the Zn limit value is also exceeded. In one sample from the Stična meadows the Zn content is very close to the critical value. Zn content in soil depends on the nature of the parent rocks, texture, organic matter and pH, and ranges from 10 mg kg^{-1} to 300 mg kg^{-1} (Mihaljević, 1999). Since Zn is easily adsorbed by mineral and organic components in most soil types, it normally accumulates in the surface horizons (Kabata-Pendias & Pendias, 2001). High Zn values (>76 mg kg^{-1}) occur in karstic Slovenia (De Vos & Tarvainen, 2006). The three observed values are above this, but could still be just a coincidence and do not prove pollution. No possible contamination was established at the mentioned locations and the samples from very near positions have a normal Zn content.

In subsoil and topsoil Pb is strongly correlated with Zn (Baize & Sterckeman, 2001), which is also true for our data.

A simple comparison of the forest and meadow metal contents in the soils indicates lower values of Co, Cr, Cu, Ni and Zn in forest soils and the nearly equal content of Pb in both types. For the first four elements, the difference is statistically significant at a 95 % probability level. An analysis of variance was unable to confirm the result, except for Cu, due to the very high variability at lower levels, especially the location, 100 m and 1 m. Our results are in line with Bai et al. (2010) who established a relatively large difference in the effect of the accumulation of Cr, Ni, Cu, and Zn in soils under different land use patterns (i.e. greenhouse, vegetable field, maize field and forest field), except Pb, with less accumulation in the forest soils. The agricultural chemical compound and application of manures, especially the quantity and quality of the applied fertilisers, is a main factor leading to the different accumulation of metals in soils (Bai et al., 2010), which could at least also hold true for the meadows.

On the contrary, in their study Zhang et al. (2002) claimed that the total concentrations of trace elements followed the pattern: farmland ≈ shrub > forests > meadow > prairie > marsh and others. Also some other authors have found higher values of some elements in forest compared with grassland or agricultural soils, for example Baize & Sterckeman (2001) for Zn and Cd and Rusjan et al. (2006) for Cd and Co. In the latter case, the differences were not statistically significant. Baize & Sterckeman (2001) explain the difference as a consequence of unequal inheritance between the thinner very clayey soils below the wood, and the thicker less clayey soils of the cultivated part. It seems that to make a detailed interpretation of metals in soils a precise determination of the pedological and mineralogical characteristics should also be considered, i.e. the type and content of clay minerals, organic matter and soil pH.

Conclusions

The influence of vegetation cover, i.e. forest and meadow, on the Co, Cr, Cu, Ni, Pb and Zn content in soils was tested at five locations where four samples were taken at different distances from the starting point. According to the added standard materials and replicate samples, the analytics proved satisfactory for Co, Cr, Cu, and Ni, but was less good for Pb and Zn.

The metal abundance sequence is in most cases Cr > Zn or Ni > Pb > Cu or Co. The data variation is quite high with extremely low and high values. When considering the whole dataset it is Zn > Pb > Cu > Co > Cr > Ni.

Due to the outliers, the distribution of no elements for all samples is normal. Normality was achieved by a Box-Cox transformation and by replacing extremely high values with mean values for selected elements in appropriate soils, i.e. grass or forest covered.

Although Co, Cr and Ni exhibit very high absolute values, which even exceed the limits permitted by Slovenian law in the majority of samples, one can be relatively confident that they are not caused by pollution. They are probably related to bauxite and Fe-Mn rich carbonates, which are typical for some karstic soils developed on carbonates. They are also highly correlated, which could support their common origin.

The Cu, Pb and Zn values are higher than expected just in a few cases. We could not establish any pollution source so we interpret these values as accidental. It is unsure if the observed values are some kind of analytical error or just natural variability in clay and/or organic matter content in soils.

The analysis of variance helped reveal very variable geochemical conditions on a small scale, i.e. the statistically different element content of samples from the same location and under the same vegetation cover in the profiles where samples were just 1 m, 10 m or 100 m apart. Moreover the variance component due to different sampling locations (Postojna, Zaplana, Stična, Dole and Dolič) is quite high (approximately 30 % to 60 %) for Co, Cr, Ni and Pb, but statistically significant only for Cr and Ni, as for the other three elements the high variability at lower levels (Co on 100 m, Cu on 1 m, Pb on 1 m or analytics and Zn on 100 m and analytics) prevented any statistically significant confirmation of higher factors.

The high variability at lower levels is also a reason why the analysis of variance did not prove the influence of vegetation cover on metal content in soil, except for Cu in the case of corrected data. The share of variance in the case of the corrected Cu data is nearly 30 %, but half of that for Co and Cr, practically zero for Ni and Pb, and around 10 % for the corrected Zn. In spite of this, a t-test managed to show statistically significantly higher values of all elements, except Pb, in the soils covered by grassland. The reason for the higher metal content in the meadow soils could be the application of manures. In our study, the meadow soils are 1.7-times enriched with Co, 1.6-times with Zn, 1.5-times with Cr, 1.3-times with Ni, and 1.1-times with Cu regarding the forest soil. If we disregard the outliers, the sequence is Co (1.7-times), Cr (1.5-times), Cu (1.4-times) = Zn (1.4-times) and Ni (1.3-times). In both cases, the Pb values are just a little higher in the forest soils. In the case of Pb and Zn, the results are merely indicative due to the low analytical quality. We can still conclude that, where possible, vegetation cover should be considered when designing the sampling and interpreting the data.

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Sedemdeset let življenja in dela profesorja geologije dr. Jožeta Čarja

Jože Čar se je rodil 23. aprila 1942 v Idriji. Po diplomi iz geologije leta 1968 se je zaposlil v rudniku živega srebra v Idriji. Kot rudniški geolog, na koncu tudi vodja rudniške geološke službe, je bil v zelo kompleksnih geoloških razmerah rudišča vrsto let odgovoren za reševanje operativnih problemov, ki so pogosto zahtevali sprotni odziv, predvsem pa izjemno geološko znanje, prostorsko predstavo in veliko natančnost, sistematičnost in profesionalnost pri geološkem delu. Ob Ivanu Mlakarju in Ladislavu Placerju je postal eden od nosilcev te neformalne idrijske geološke šole, ki ji slovenska geološka znanost zelo veliko dolguje. Njegova osnovna specializacija je bila sedimentologija; za to področje se je usposabljal tudi v Nemčiji. Leta 1985 je zagovarjal doktorsko disertacijo Razvoj srednjetriasnih sedimentov v idrijskem tektonskem jarku. Vmes je bil nekaj časa, sledeč svojemu drugemu velikemu zanimanju, geologiji krasa, zaposlen kot raziskovalec na Inštitutu za raziskovanje krasa v Postojni.

Leta 1989 je z nazivom izrednega profesorja na študiju geologije na takratni Fakulteti za naravoslovje in tehnologijo začel predavati predmeta Sedimentna petrologija in Facielna analiza, kasneje še predmet Tektonika. Njegova predavanja so bila vedno skrbno pripravljena in podajana, saj je imel pravo žilico in veliko veselje do pedagoškega dela, saj je pred zaposlitvijo na fakulteti ob opravljanju geološkega poklica celo 8 let poučeval geologijo na gimnaziji v Idriji. Zelo skrbno je pripravljal terenske vaje pri svojih predmetih, ki jih je najraje organiziral v območju Idrije in njene okolice, ki ga pač iz svoje prakse najbolje pozna, in kjer smo študenti tudi imeli kaj videti in spoznati. Njegove terenske vaje niso bile izleti, ampak trdo delo, pri katerem smo študenti pridobivali dragoceno praktično znanje in izkušnje. Gorje študentu, ki je na terenskih vajah »zabušaval« ali ki je oddal malomarno izdelano poročilo! Profesor je vložil veliko časa in truda, da je študentska poročila pregledal in popravil, tudi slovnično, in nas s tem navajal k doslednemu in profesionalnemu strokovnemu delu.

Kot mentor je kar najpogosteje poudarjal pomen natančnega terenskega dela, zlasti geološkega kartiranja, in je študente upravičeno opozarjal, da je to neobhodna podlaga kakršnega koli tehtnega raziskovalnega dela v geologiji. S svojimi študenti, pa tudi s študenti, ki so pri njem le opravljali kak podiplomski izpit, ali pa so ga preprosto prosili za pomoč, je na terenu preživel neštete ure in nanje prenašal svoje izjemno znanje in izkušnje iz kartiranja. Vedno je zelo zavzeto in brez zadržka podpiral svoje študente pri razvijanju novih idej in dopolnjevanju znanja v tujini. Na oddelku za geologijo, pa tudi v širši strokovni javnosti je imel veliko avtoriteto. Vedno je bil zelo takten in diplomatski, vendar pa je nepopustljivo zagovarjal strokovna in etična načela, ki se jih je trudil vzpostaviti v pedagoškem in raziskovalnem delovanju na fakulteti in v geološki stroki.

Po našem mnenju se je vse prehitro upokojil konec leta 1998, ker so mu to omogočala leta zaposlitve v rudniku. A tudi pri tem je sledil svoji trezni življenjski modrosti, saj se je želel ukvarjati še s čim drugim kot z vse bolj stresnim profesorskim delom na fakulteti. Profesor spada v krog uglednih idrijskih intelektualcev in se je vse življenje udejstvoval tudi na kuturnem področju, med drugim je denimo urejal Idrijske razglede in revijo Kaplje. Veliko deluje na področju popularizacije geologije v širši javnosti, precejšen je tudi njegov prispevek pri raziskavah zgodovine geoloških in naravoslovnih raziskav, zlasti seveda v območju njegove Idrije. Vseeno se tudi po upokojitvi občasno ukvarja z raziskovalnimi nalogami in ekspertizami in, kot prostodušno prizna, »kartira, ker ga veseli in da ostane v formi«. Še dolgo časa po upokojitvi se je zavzeto angažiral pri izvedbi terenskih vaj za študente na »njegovih« terenih.

Njegov znanstveni prispevek je največji na področju triasne sedimentologije in tektonike, posebej iz območja srednjetriasnega Idrijskega tektonskega jarka. Na tem prodročju je prispeval nekaj ključnih del. Bil je pionir, v svetovnem merilu, pri preučevanju vpliva geoloških struktur na oblikovanje kraških jam in vrtač. Njegovo zadnje veliko delo je geološka karta idrijsko-cerkljanskega ozemlja v merilu 1 : 25 000, ki je po eni strani spomenik idrijski geološki šoli, po drugi strani pa zakladnica geoloških podatkov, ki bo še dolgo časa navdihovala nadaljnje raziskave tega zanimivega in geološko pomembnega dela Dinaridov.

Še na mnoga leta, Jože!

Marko Vrabec

Geophysical evidence of recent activity of the Idrija fault, Kanomlja, NW Slovenia

Geofizikalni dokazi za recentno aktivnost Idrijskega preloma v dolini Kanomlje

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Abstract: In the Kanomlja valley NW of Idrija, previous geomorphological survey indicated a site where (sub)recent activity of the Idrija fault may be best preserved in relatively young succession of terrestrial deposits. In 2011 a set of geophysical investigations followed geological reconnaissance of the narrowest area of interest. A small alluvial plain of the Kanomlja tributary was surveyed by electrical resistivity tomography and seismic refraction tomography. The results showed remarkably clear and converging evidence of potential activity of the fault in (sub)recent time. A paleoseismological trench is foreseen at the site in late 2012 to further investigate this phenomenon.

Izvleček: V Srednji Kanomlji so predhodne geomorfološke raziskave nakazale lokacijo, kjer bi se lahko v sorazmerno mladih terestričnih sedimentih ohranila sled (sub)recentne aktivnosti Idrijskega preloma. V letu 2011 smo zato v okolici sistema teras Kanomljinega pritoka Bratuševa grapa izvedli geološki in geomorfološki pregled, ki so mu sledile geofizikalne raziskave z metodama električ-

Original scientific paper

ne upornostne tomografije in refrakcijske seizmične tomografije. Rezultati nakazujejo relativno mlado aktivnost Idrijskega preloma na tem območju. S preiskavo smo omejili območje največjih deformacij in nakazali območje verjetno najmlajše deformacije, kjer bomo pred koncem leta 2012 naredili paleoseizmološki jarek.

Key words: Idrija fault, paleoseismology, active tectonics, Kanomlja
Ključne besede: Idrijski prelom, paleoseizmologija, aktivna tektonika, Kanomlja

Introduction

The Idrija fault is one of the most, if not the most, prominent NW-SE oriented ("Dinaric-trending") structural features in W Slovenia. It enters the country at its NW tip, passes the town of Idrija, the Planina and Cerknica karst poljes, after which its trace seemingly disappears within the Dinaric thrust structures further to the south. The Idrija fault was first described by Lipold (1857), and its tectonic importance and its significance in seismotectonics have been investigated ever since. In the neighborhood of Idrija, the fault plane dips 65° to 75° toward the NE (Čar, 2010). The estimated average dip along the full length of the fault is 77.5° and its maximum depth is estimated to 14 km (Kastelic & Carafa, 2012). The fault formed during the Miocene as an oblique-normal fault, and was reactivated as a dextral strike slip fault at the transition from the Miocene to the Pliocene (Vrabec & Fodor, 2006; Čar, 2010). Its activity has been quantified by several methods. From the cumulative displacement of the mercury ore body in the Idrija mine, amounting to 480 m in vertical direction and 2414 m in horizontal direction (Placer, 1982), a long-term slip-rate at around 0.5 mm per year can be postulated. 8-year continuous measurements of recent displacements with a TM-71 extensometer in the Učja valley in NW Slovenia yield average slip-rates at 0.26 mm per year with extreme values up to 0.54 mm per year (Gosar et al., 2011; Čar & Gosar, 2011). By modeling active fault displacements in the eastern Adriatic region using a thin-shell finite element method Kastelic & Carafa (2012) calculated slip-rates between 0.06 mm and 0.22 mm per year for the Idrija fault with 0.10 mm per year on the average.

The strongest historic seismic event on the Idrija fault might be the destructive W Slovenia earthquake in 1511 (estimated magnitude 6.8 and maximum intesity X EMS-98; Cecić, 2011). It has to be noted that the historic data does not allow univocal allocation of this particular event to the fault itself (Živčić et al., 2011) and that alternative interpretations of the seismic source are also proposed for the 1511 event (Camassi et al., 2011; Košir & Cecić, 2011).

In the Kanomlja valley, 5 km NW of the town of Idrija, airborne LiDAR survey disclosed several geomorphic indicators of Idrija fault recent activity, such as displaced streams, truncated fluvial terraces, dry valleys, bent ridges, etc. (Cunningham et al., 2006). This was the first application of airborne laser scanning for the purpose of mapping active faults in Europe. Detailed geomorphic field surveying confirmed the suggestion of Cunningham et al. (2006) to focus paleoseismological study to the area south of Kapa hill (Figure 1). We conducted a geophysical survey in this area in order to investigate indications of recent activity and to find an appropriate location for paleoseismological trenching.

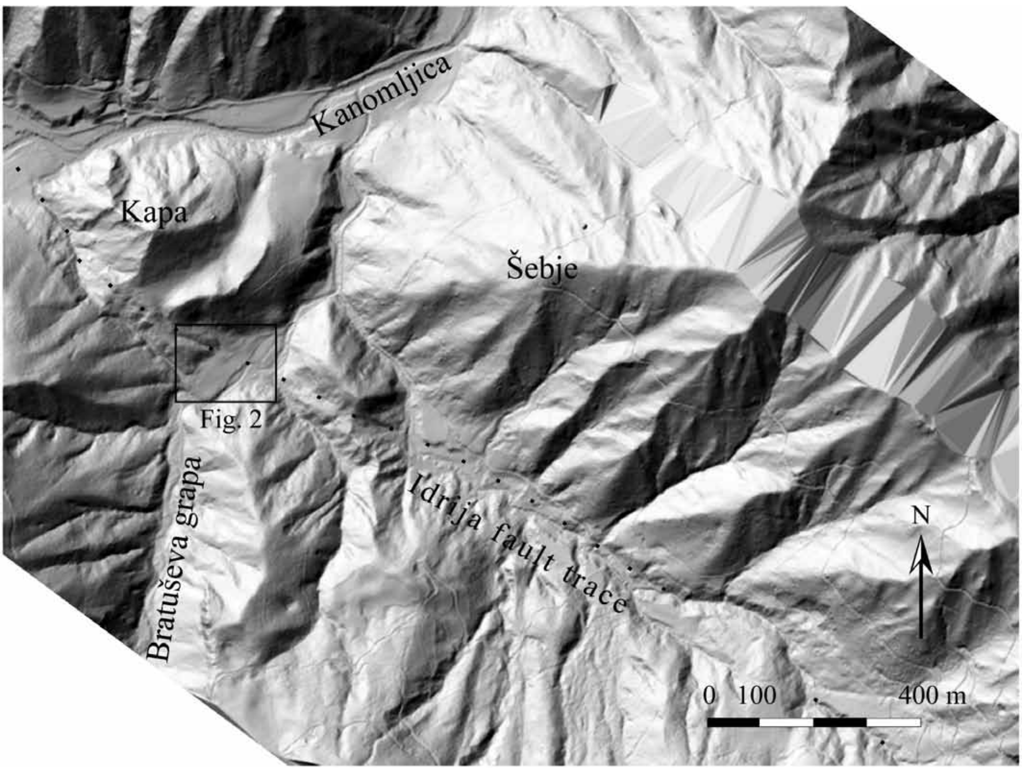

Figure 1. Location map on the 2 m grid Digital Elevation Model of bare ground from the LiDAR survey (Cunningham et al., 2006).

Geologic setting

By detailed geomorphological and geological mapping of the near vicinity of the target area proposed by Cunningham et al. (2006), we first defined an approximate location such that the fault trace is well expressed and where young sediments are available, for paleoseismological investigations fault deformations must be investigated in young and datable sediments. Both demands were met in the Bratuševa grapa system of fluvial terraces and its near vicinity (Figure 2 and 3). In the W part of the terrace system the Mesozoic carbonate rocks (pre-Quaternary bedrock) outcrop along the stream channel and are covered by a thin veneer of loose terrestrial deposits of fluvial and slope mass wasting origin (young deposits). Toward the E, the bedrock does not outcrop along the stream anymore; instead the whole outcrop consists of young deposits. We infer that the fault is located where the thickness of young deposits changes from negligible to significant (Figure 4 and 5). At the same locality, the topographically best expressed fault trace crosses the system of fluvial terraces (Figure 3) and the fault probably affects their for-

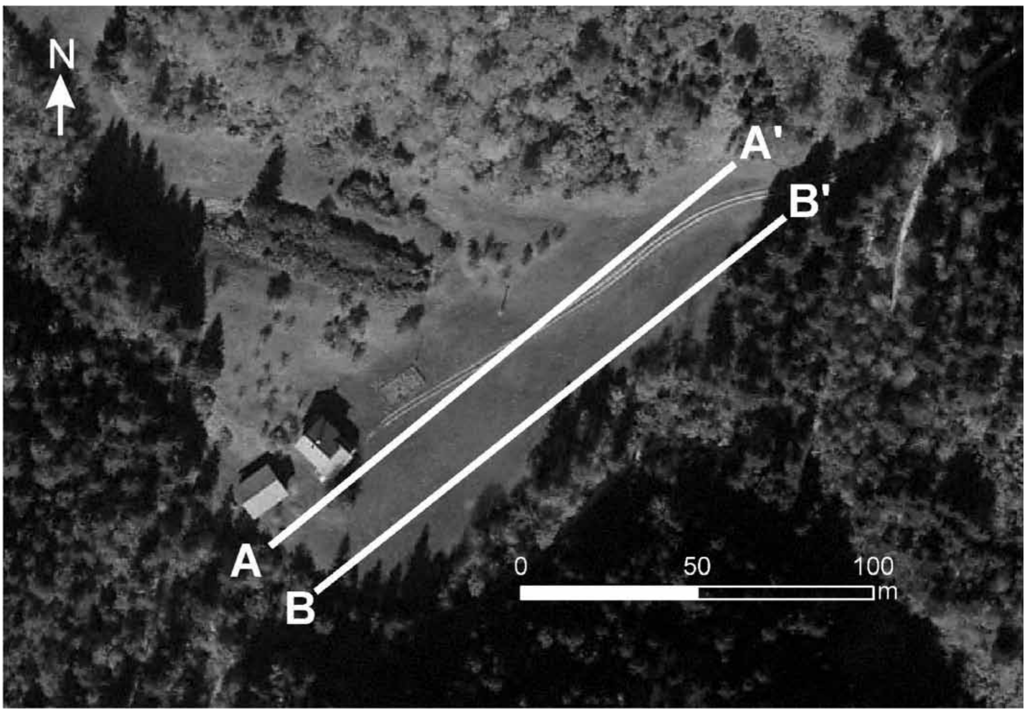

Figure 2. Location of geophysical sections A-A’ and B-B’. Location of this map is shown as an inset in Figure 1.

mation. Additionally, a stream channel bend, suggesting a dextral offset of approx. 40 m, is located immediately to the SE of the locality (Figure 3). All these observations lead us to focus geophysical investigations to this area.

Methods

In an attempt to better constrain the area of maximum and/or most recent deformation along the selected segment of the Idrija fault, we applied four geophysical methods along two sections crossing the inferred fault trace: electrical resistivity tomography (ERT), seismic refraction tomography (SRT), ground penetrating radar (GPR) and active multichannel analysis of surface waves (MASW). In lack of borehole data, vertical electrical sounding (VES) was also conducted in order to estimate typical resistivity of hard rock and young deposits for further use in ERT. Due to field conditions (presence of low velocity layers, clay content, ground water), GPR and MASW did not yield consistent results, therefore we describe here only results of VES ERT and SRT methods.

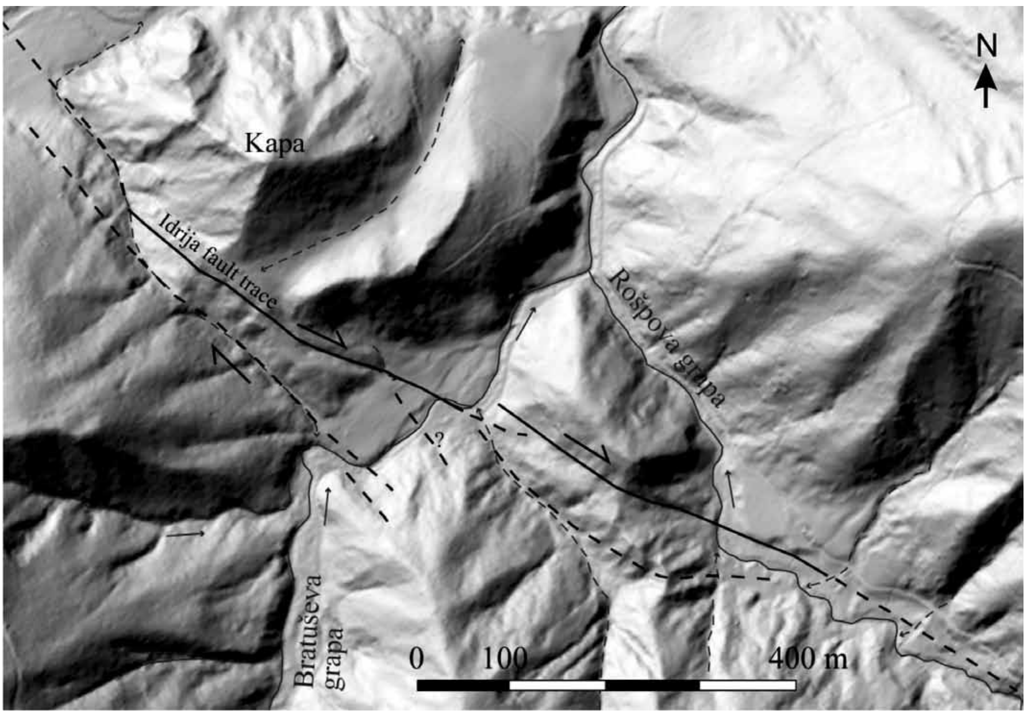

Figure 3. Outline of main geomorphic features within the Bratuševa grapa terrace system on the 2 m grid Digital Elevation Model of bare ground from the LiDAR survey (Cunningham et al., 2006).

Vertical electrical sounding (VES) was conducted using the Schlumberger array with maximum half-distance of probes AB/2 at 10–100 m. Seven VES were performed along the ERT sections and on the outcropping carbonate in the near vicinity of these sections. The measured data were inverted by using RESIXPlus software (Interpex Ltd.).

Two methodologically identical ERT sections were measured using the Wenner array. The unit probe spacing was set at 2 m and the total number of levels accomplished was 15. Each section was 190 m long (lines A and B, Figure 2). In this way we believe to achieve the requested depth penetration of 10–12 m. SYSCAL-R2 resistivity meter and compatible Multinode system (both BRGM) were used. Measurements were conducted in stable weather after a long dry period. Data were modeled by applying various 2D algorithm techniques available in RESIX2DI (Interpex Ltd.) software.

Along the same trace as the ERT, SRT sections A and B were measured (Figure 2). Geophone spacing was 2 m; shot points were selected at every 3rd geophone. An 8 kg sledgehammer with metal plate was used as a seismic source and two 24-channel ABEM Terraloc VI seismographs were used to record the signal from 4.5 Hz vertical geophones. Relatively good signal-to-noise ratio lead to very accurate first arrival picking and consequently to reliable results. The elevation of each geophone was measured in the field with a leveling instrument for later topographic correction. A three-layer seismic model and velocities were computed by Wayfront method using Rayfract 3.19 software from Intelligent Resources Inc. Same application was further used to compute the final velocity model by 2D WET (Wavepath Eikonal Traveltime) tomography.

Geophysical observations

ERT- electrical resistivity tomography

Electrical resistivity of sediments along both sections varies from few tens ohm-meters to over 1000 Ω m (Figure 4). Given the geological context and VES data, we relate modeled resistivities to three lithological equivalents: 1) 40–100 Ω m: topsoil, clay and silt with gravel; 2) 100–400 Ω m: gravel, clayey/silty gravel, sand and possibly also carbonate bedrock with more terrigenous component; and 3) >400 Ω m: relatively highly-resistive carbonate bedrock with minor terrigenous component.

Resistivity model (Figure 4) shows four distinctive units that appear in both sections:

- The surface layer (up to 2 m thick) with low specific electrical resistivity (40–100 Ω m) is interpreted as overbank deposit of the Bratuševa grapa creek and organic-rich topsoil.
- Relatively homogenous high-resistivity unit (>800 Ω m) underlying the surface layer in the SW part of both sections and exceeding the surveying target depth of 12 m is interpreted as Mesozoic (carbonate) bedrock.
- Heterogeneous unit with patchy distribution of subunits of very low resistivity (few tens ohm-meters) and subunits of resistivity between 100 Ω m and 250 Ω m is interpreted as a sequence of mass wasting events (landslides, sedimentary mass flows), potentially interfingered with fluvial sediments of Bratuševa grapa creek.
- Heterogeneous unit at 60–95 m in section A (missing in section B) that may resemble a faulted zone (marked as transition zone in Figure 4) within the bedrock.

SRT- seismic refraction tomography

The final result of SRT is presented on Figure 5. Atop the sections is a thin (1–1.5 m) low-velocity layer (veloc-

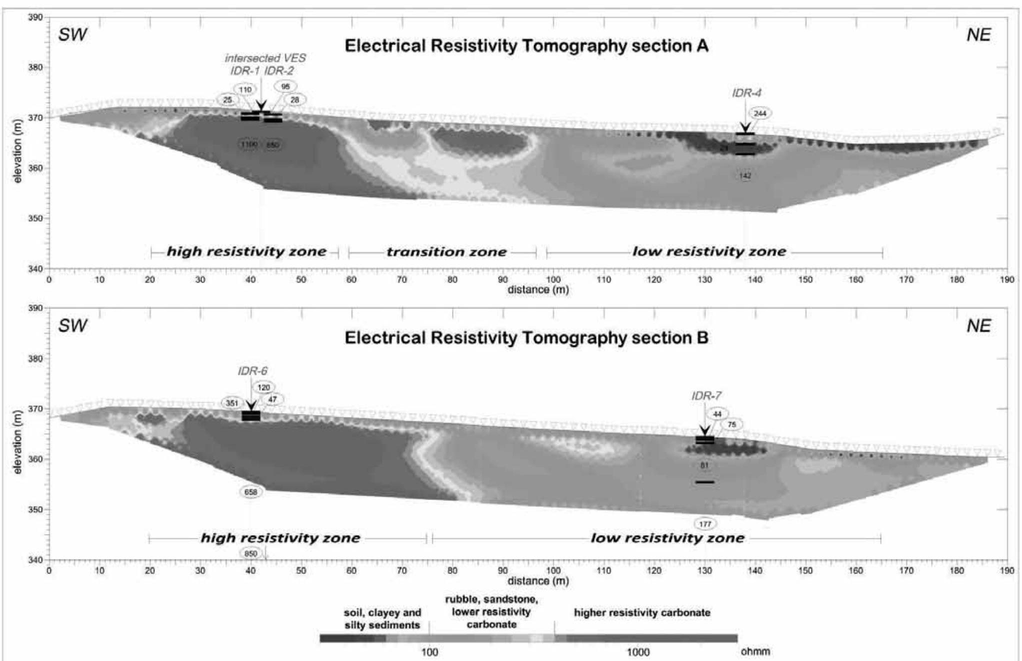

Figure 4. Electrical resistivity tomography sections A and B. (Stopar & Car, 2011). The main trace of the Idrija fault is inferred at between 60 m and 95 m in section A and between 70 m and 80 m in section B.

ity at around 500 m/s) that stretches along the full length of both sections. It is interpreted as overbank deposit of the Bratuševa grapa creek and organic topsoil. Underneath this low-velocity layer, the velocity increases to above 1000 m/s in a layer that stretches along the full length of both sections. The reason for this could be lithological as well as the increase in groundwater content. Below these two layers lies a layer with a significantly higher velocity (above 3000 m/s). This high-velocity layer appears close to the surface (approx. 5 m deep) in the SW parts of both sections, but is much deeper towards the NE. A sharp change in depth of the high-velocity layer is observed between 80 m and 100 m distance in section A, and between 70 m and 80 m distance in section B. The lateral decrease in velocity observed within the layer could be interpreted as a presence of tectonically crushed bedrock, or as juxtaposition of two different bedrock lithologies. Both interpretations are consistent with the fault crossing the sections.

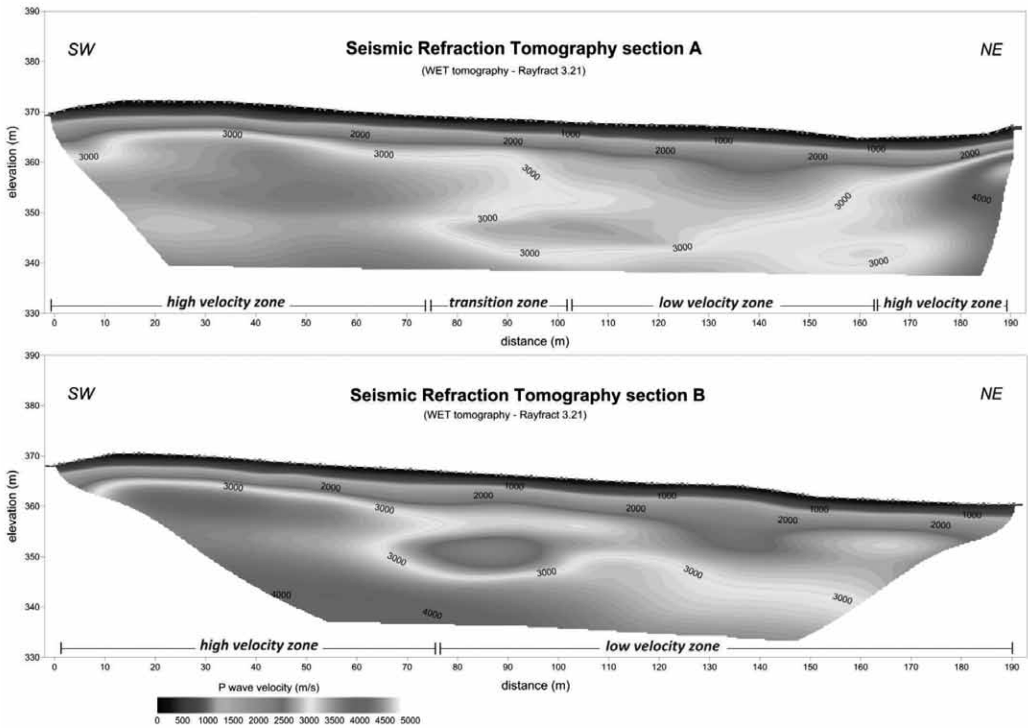

Figure 5. Seismic refraction tomography sections A and B. (Stopar & Car, 2011). The main trace of the Idrija fault is inferred at between 80 m and 100 m in section A and between 70 m and 80 m in section B.

Interpretation and conclusions

Joint interpretation of the two independent geophysical methods is fully consistent with geological and geomorphological observations, that indicate the presence of a recently active fault. Both methods show a significant change in geophysical properties underneath the surface layer at a depth between 1 m and 5 m. A drastic drop in electrical resistivity coincides with a drop in seismic velocities within that zone, which is only few meters to tens of meters (at most) wide. SW of this zone both sections are interpreted to consist of relatively solid bedrock covered by a veneer of gravel and overbank deposits. NE of the zone the geophysical signature is much more heterogeneous compared to the SW parts. We attribute this geophysical heterogeneity to heterogeneous lithology within the upper few meters of section. Given the geologic setting, we interpret the NW part to consist of deposits of mass wasting (consecutive landslides and/or mass flow events) that are possibly interfingered with gravely deposits of the Bratuševa grapa creek.

Geophysical surveying indicated a contact between the Mesozoic bedrock and relatively young terrestrial deposits in the area of Bratuševa grapa terrace system, which we attribute to (sub)recent activity of the Idrija fault. However, the amount of displacement can not be inferred from these data. Given the promising result we aim to continue the study by paleoseismological trenching in late 2012. According to geophysical observations, a paleoseismological trench should be located between 70 m and 100 m distance along the section A, and between 70 m and 80 m distance along the section B. A potential trenching target is also the area of low resistivity between 55 m and 75 m in the section A. However, for the final decision on a trench site, geomorphic and geologic indicators will also be taken into account in search for the youngest (and not necessarily most prominent) deformation.

Acknowledgements

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and the importance of including basic research results in applied geology.

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Characteristics of the Predjama fault near Postojna, SW Slovenia

Značilnosti Predjamskega preloma pri Postojni, JZ Slovenija

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Abstract: The course of the Dinaric oriented (NW-SE) Predjama fault in the area of the northern Pivka valley and through Javorniki mountain is not well determined. The position of the Predjama fault through the Pivka flysch valley is mostly determined hypothetically. In the area of Javorniki hills the fault is divided into several parallel strands and accompanied by mostly cross-Dinaric (NE–SW) oriented faults. Predjama fault in the area of Postojna was probably not the seismogenic source of Postojna M_{LV} = 3.7 earthquake in 2010. Micro-tectonic deformations detected by TM 71 extensiometers in Postojna cave system on the other hand show minor ongoing aseismic displacements in northern NW-SE oriented fault, which is parallel to the Predjama fault.

Izvleček: Potek dinarsko usmerjenega (SZ–JV) Predjamskega preloma na območju severnega dela Pivške kotline in čez Javornike ni dobro ugotovljen. Položaj Predjamskega preloma skozi flišno Pivško kotlino je večinoma določen hipotetično. Na območju Javornikov je prelom razdeljen na več ločenih vzporednih prelomov, ki jih spremljajo predvsem prečno dinarsko (SV–JZ) usmerjeni prelomi. Predjamski prelom na ozemlju Postojne verjetno ni bil izvir potresa M_{LV} = 3.7 v Postojni leta 2010. Mikrotektonske deformacije, ugotovljene z ekstenziometri TM 71 v Postojnskem jamskem sistemu, pa kažejo manjše tektonske aseizmične premike na severnem SZ–JV usmerjenem prelomu, ki je vzporeden Predjamskemu.

Review paper

Key words: Predjama fault, Postojna, Slovenia
Ključne besede: Predjamski prelom, Postojna, Slovenija

Introduction

Recent tectonic activity of Slovenia is driven by northward movement of the Adria microplate and its counter-clockwise rotation (e.g. Vrabec & Fodor, 2006). The NW–SE trending Predjama fault is generally not considered as important as the Raša or the Idrija fault. It is treated as a continuation of Avče fault (Janež et al., 1997). Its position east from Col, through Trnovski Gozd is clearly visible. The continuation of the fault to northern Pivka valley between Predjama and Postojna and further into Javorniki hills is less clear.

The January 15, 2010 M_{LV} = 3.7 earthquake in the area of Postojna town called attention to the fact that recently not only the area around Pivka or Snežnik Mountain is seismically active, but also the northern part of the Pivka valley at Postojna can generate strong motions. The January 1, 1926 M = 5.6 Cerknica earthquake was strongly felt inside the Postojna cave system, with reported stalagmite collapse inside the cave (Šebela, 2010).

Preliminary geological interpretation of the 2010 Postojna earthquake attributed the event to slip on the regional Predjama fault, which runs in the NW–SE orientation south of Postojna. However, the subsequently derived fault plane solutions of the event (Živčić et al., 2011) did not confirm this idea. Therefore we review the existing geological literature with respect to the position of Predjama fault in the northern part of the Pivka valley. In this area, the precise location of the fault zone was mostly infered, resulting in mismatch from 200 m to 1500 m between the existing interpretations of the Predjama fault location. The most unclear is the SE-ward continuation of the Predjama fault towards Javorniki hills, where the fault is complicated by NE–SW oriented faults and is probably separated into several segments.

Predjama fault geometry in the vicinity of Postojna

A compilation of structural data, discussed in this section, is shown on the geological map in Figure 1.

On the Postojna sheet of the 1 : 100 000 Basic geological map of SFRJ (Buser et al., 1967) the Predjama fault is terminated about 500 m west from Predjama and does not continue through the northern part of Pivka valley and through Javorniki hills.

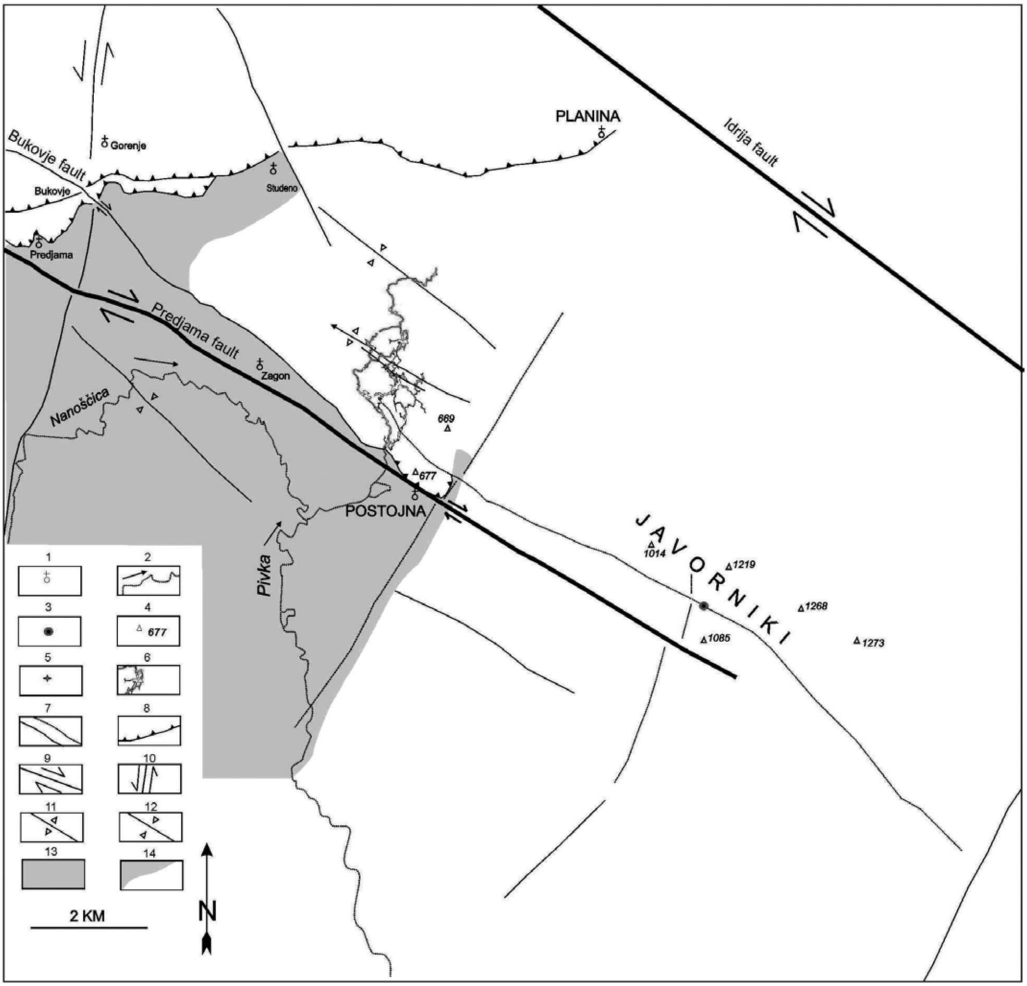

Figure 1. The basic structural-geological map of the Postojna area and position of Predjama fault. 1- town or village, 2- river and its flow direction, 3- Javorniška Koliševka, 4- hill with above sea level in metres, 5- TM 71 extensiometer in Postojna cave system, 6- ground-plan of Postojna cave system, 7- fault/hypothetic fault, 8- thrust fault, 9- dextral horizontal strike-slip movement, 10- sinistral horizontal strike-slip movement, 11- anticline, 12- syncline, 13- Eocene flysch rocks, 14- discordant contact between flysch and limestone.

The eastward continuation of the Predjama fault, from Avče fault into Javorniki was first documented by Placer (1981 and 1996).

On the sketch of geological structure of Postojna the Predjama fault is marked as a hypothetic subvertical fault (Placer, 1996). The fault is visible in the highway road-cut close to the Postojna railway station about 190 m north from the railway bridge. The inner fault zone is 18 m wide. Its northeastern fault plane has orientation of 25/70, with slickensides dipping 295/12. In the Hrušica area the Predjama fault shows dextral horizontal movement. In the vicinity of Postojna the NE block of Predjama fault moved towards right and slightly up with respect to the SW block. The apparent displacement on Predjama fault near Postojna is insignificant (Placer, 1996).

The morphologically well-expressed contact between Upper Cretaceous limestone and Eocene flysch is, according to Placer (1996), a fault, which is running nearly parallel to the southern Predjama fault. This fault is geologically better determined in the field than the principal Predjama fault, which runs through the Pivka flysch valley.

On the 1 : 500 000 geological map of Slovenia (Buser, 1989) the Predjama fault runs about 1 km south of the Nanoščica stream, and continues along the southern edge of Javorniki hills towards the Babno Polje where it approaches the Idrija fault zone.

The investigations of Janež et al. (1997) and Rižnar (1997) agree with Placer's (1996) interpretation of the position of Predjama fault. According to Janež et al. (1997) the fault runs about 200 m northward of the position shown on the map of Buser (1989). They trace the Predjama fault along the southern edge of Sovič hill (677 m) near the town of Postojna and argue that the morphologicaly well-expressed scarp dividing Upper Cretaceous limestone from Eocene flysch, which runs NW-ward from Postojna towards Predjama, is controlled by a fault zone parallel to the Predjama fault. Further to the NW, west of the town of Col, the Predjama fault continues into the Avče fault (Janež et al., 1997). There, the trace of fault is much better visible both in morphological and geological sense than in the northern Pivka valley and eastward in the southern parts of Javorniki hills.

The Bukovje fault, which is situated north from Predjama fault near Bukovje was determined by Čar & Šebela (2001). The fault is displacing a morphologically well expressed approx. N–S oriented sinistral strike-slip fault, which runs north from Gorenje towards Hrušica. The Bukovje fault shows insignificant dextral horizontal displacement (Čar & Šebela, 2001).

The structural-tectonic map of Slovenia (Poljak, 2000) traces the Predjama fault similarly to Buser et al. (1967). The fault is traced in the area NW from Postojna, where it separates Hrušica structure from Nanos structure, whereas the eastward fault continuation in the Eocene flysch of the northern Postojna valley and at the southern foot of Javorniki hills is left undefined.

The detailed structural map of the area between Postojna, Planina and Cerknica (Čar & Gospodarič, 1984) was a major contribution towards understanding the tectonic structure of the area. After almost 30 years this is still the most important structural-geological map of the region. Unfortunately, the Predjama fault zone is outside the mapped territory.

Active tectonics and seismicity near Postojna

On January 15, 2010 at 14:20 (UTC) an earthquake occurred in the area of Postojna town. Its local magnitude was 3.7 and the highest intensity V EMS-98. The earthquake was felt in the territory of SW Slovenia and also in Jesenice, Velenje and Celje (Jesenko et al., 2011).

405 shocks occurred before and after the main earthquake. The fault plane solutions obtained from the first motion data for the main earthquake event and its strongest aftershock on March 6 2010, $M_{LV} = 2.4$, constrain a nearly vertical fault plane, which is either a SSE trending (N165° E) dextral strike-slip fault, or a WSW trending sinistral strike-slip fault (Živčić et al., 2011). Seismological data therefore suggest that the 2010 Postojna earthquake was not related to slip on the Predjama fault, but to some so far unidentified geological structure.

Faults in suitable SSE-NNW orientation were mapped by Čar & Šebela (1997) around the Pivka and Črna Jama, but were at the time not interpreted as active or potentially active. Fissures and faults-orientation data from the Postojna cave system (Šebela, 1998), presented in Figure 2, also demonstrate a prominent cluster of structures with NNW–SSE orientation, which is nearly as abundant as the one in the Dinaric NW-SE orientation. The major geological structures in the cave, mostly fault zones, have a Dinaric NW–SE orientation (Šebela, 2012). Significant fissured to broken zones (in sense of Čar & Gospodarič, 1984) are mostly SSE–NNW orientated and exhibit no slickensides. Significant displacements in the Postojna cave system are visible on NW–SE and NE–SW oriented faults, whereas the SSE-NNW oriented geological structures are generally cut by NW–SE and NE–SW oriented faults and thus represent secondary structures to those with Dinaric orientation.

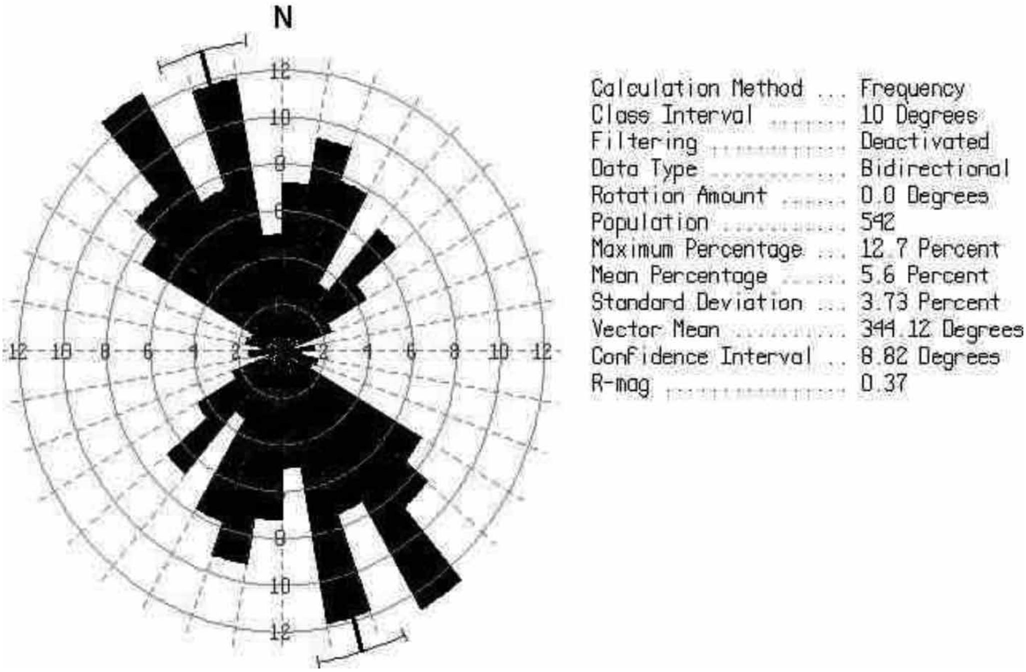

Figure 2. Orientations of faults and fractures in the Postojna cave system (Šebela, 1998).

From the 25 m resolution Digital terrain model of the wider Postojna town area (Podobnikar, Arhiv ZRC SAZU) we infer the existence of morphologically well-expressed fault zone east from Studeno (Figure 1), which could be the NNW continuation of N165° E trending fault that was seismogenically active during the January 15, 2010 earthquake (Živčić et al., 2011). This fault could be the connective fault between the Idrija and Predjama faults, or a shorter fault connecting the southern Predjama fault and the parallel northern fault in the outer zone of the Predjama fault. General direction of the fault running east from Studeno is 10–20° towards the north deviated from the Dinaric NW–SE orientation. The fault is morphologically very clearly expressed, similarly to the nearly N–S oriented fault north from Gorenje (Figure 1). Basic geological map (Buset et al., 1967) does not indicate a fault or a lithological contact at this location.

Otherwise, micro-tectonic deformations detected by TM 71 extensiometers in Postojna cave system since 2004 (Figure 1) show measurable aseismic displacements on the fault, which is parallel to the Predjama fault (Gosar et al., 2011). Two instruments are placed on a Dinaric-trending NW-

SE fault that builds the NE wall of the Velika gora collapse chamber. Southern instrument is situated between the cave wall and the collapse block. Generally dextral horizontal diplacement of 0.05 mm since 2004 indicates tectonic deformation and not movements due to cave collapse processes. Additionally, the down-slip movement of the NE block for 0.01 mm since 2004 suggests tectonic movements.

Javorniška Koliševka

Morphologically the best expressed collapse doline in the area of Javorniki hills is Javorniška Koliševka (Figure 1). It is a closed depression of underground origin. The big volume of the depression is due to rocks being sapped away. Closed depressions are karstic, unflooded morphological forms that are results of karst processes and removal of the rocks.

Javorniška Koliševka is situated along a Dinaric-trending fault that has already been detected by Placer (1996), which is parallel to the main Predjama fault. The bottom of the collapse doline is at 847.80 m. The southern edge of the doline is at 905 m and the northern at 953 m. Javorniška Koliševka is at least 57.20 m deep and has a volume of about 800 000 m^3. The position of Javorniška Koliševka on one of the northern faults parallel to the main Predjama fault indicates that the wider Predjama fault zone continues into Javorniki hills and that favourable rock conditions (tectonically crushed zone) are present for development of deep karst collapsed doline.

Conclusions

The position of the Predjama fault through the Pivka valley was mostly determined hypothetically (Placer, 1981 and 1996). In some cases (Buser, 1989; Janež et al., 1997; Rižnar, 1997; Šebela, 2005) the position is more deterministic, but there is between 200 m to 1500 m of difference between the interpretations of the fault position.

Between Postojna and Javorniki hills the Predjama fault is probably dissected into separate parallel faults. One such segment runs through Javorniška Koliševka collapse doline and has probably controlled the origin of this deep karst depression. In the area SE of Javorniki hills this Dinaric oriented (NW-SE) fault parallel to Predjama fault is complicated by a prominent, mainly NE-SW oriented fault. The continuation of Predjama fault towards SE is clear at least into the area of southern slope of Javorniki hills.

Regarding the seismological analyses of the Postojna M_{LV} = 3.7 earthquake in 2010 (Živčić et al., 2011) the Predjama fault in the area of Postojna was probably not the seismogenic source for the earthquake. Micro-tectonic deformations detected by TM 71 extensiometers in Postojna cave system (Gosar et al., 2011) on the other hand show recent small tectonic aseismic displacements in one of the northern NW–SE faults parallel to the main Predjama fault.

To find the seismogenic source for Postojna M_{LV} = 3.7 earthquake in 2010 detailed structural-lithological mapping should be the best answer.

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Middle to Upper Jurassic succession at Mt Kobariški Stol (NW Slovenia)

Srednje- do zgornjejursko zaporedje na Kobariškem Stolu (SZ Slovenija)

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Abstract: The Slovenian Basin represents a deeper-water paleogeographic unit that today extends approximately in E–W direction from Kobarid towards east. However, westward from Kobarid the successions of the Slovenian Basin are not present. Mt Kobariški Stol is located directly westward from the last outcrops of Slovenian Basin rocks. This area is in the Middle and Upper Jurassic represented by a unique facies association of nodular limestones, and abundant shallow-water carbonate resediments and corresponds to the transitional zone between the Dinaric Carbonate Platform located southeastward and northeastward located deeper marine sedimentary environments of the either Slovenian Basin or even more likely the submarine plateau named the Julian High. The Kobariški Stol area at that time represented a deeper-water current-swept plateau that was well connected to the adjacent shallow-water Dinaric Carbonate Platform. This proves the early idea that the Slovenian Basin in this part pinched out.

Izvleček: Slovenski bazen je globljevodna paleogeografska enota, ki se danes od območja Kobarida razširja proti vzhodu. Zahodno od Kobarida izdanki Slovenskega bazena niso znani. Kobariški Stol se nahaja neposredno zahodno od Kobarida in bi lahko bil nadaljevanje Slovenskega bazena. Zgrajen je iz kamnin, ki tvorijo posebno faciesno združbo nodularnih apnencev in številnih presedimentiranih karbonatnih gravitacijskih tokov, ki jih gradijo plitvovodni klasti Dinarske karbonate platforme. Območje Kobariškega Stola je bilo tako v srednji in zgornji juri globljevodni podmorski plato, ki je bil dobro povezan z

Original scientific paper

Dinarsko karbonatno platformo. Območje Kobariškega Stola zatorej ne pripada bazenu, marveč prehodnemu območju med plitvovodno Dinarsko karbonatno platformo na jugu ter globljevodnim območjem Slovenskega bazena ali Julijskega platoja na severovzhodu oziroma severu. To dokazuje hipotezo prejšnjih raziskav, da se je Slovenski bazen vzhodno od območja Kobarida izklinil.

Key words: Slovenian Basin, Julian High, palaeogeography, Jurassic, deeper-water, transitional zone

Ključne besede: Slovenski bazen, Julijski plato, paleogeografija, jura, prehodno območje

Introduction

Slovenian Basin (SB) represents a Mesozoic deep-water paleogeographic unit surrounded by shallow-water carbonate platforms until Middle Jurassic and later by pelagic plateau on its northern side. Today it stands for a narrow facies belt of Late Triassic to Late Cretaceous deeper-water strata extending approximately in E–W direction from Kobarid towards east (Cousin, 1970; Buser, 1989, 1996; Rožič, 2005; Rožič & Popit, 2006; Buser et al., 2008; Buser & Ogorelec, 2008; Rožič, 2009; Rožič et al., 2009; Gale, 2010; Rožič & Šmuc, 2011; Goričan et al., 2012; Gale et al., in press). Westward from Kobarid the successions of the Slovenian Basin are not present. According to Buser (1996), Buser & Debeljak (1996), and Miklavič & Rožič (2008) the reason for this absence of SB deposits west of Kobarid area is that Slovenian Basin in this part pinched out (see also paleogeographic reconstruction in Rožič & Šmuc, 2011). These previous studies were however based on the study of Dinaric and Julian Carbonate Platform rocks of Lower Jurassic (Buser, 1996; Buser & Debeljak 1996) or Upper Cretaceous rocks formed after the disintegration of Dinaric Carbonate Platform (Miklavič & Rožič, 2008) that outcrop north or south from the area of possible eastward continuation of the Slovenian Basin. Kobariški Stol succession, on a contrary, is located directly eastward from the last outcrops of Slovenian Basin rocks on Ozben hill (Buser, 1986, 1987), is composed of different Upper Triassic to Cretaceous shallow and deeper-water strata (Cousin, 1981) and thus represents a site of possible continuation of the Slovenian Basin.

The aims of this study are to present a detailed sedimentologic and biostratigraphic study of the Middle and Upper Jurassic rocks that outcrops at the Kobariški Stol, to interpret the sedimentary environment in which they were formed, and shed a light on the Jurassic spatial distribution of the Slovenian Basin westward of Kobarid area.

Geological Setting

The studied succession is located in NW Slovenia on Mt Kobariški Stol that represents the southernmost part of the Julian Alps (Figure 1). The succession outcrops at the 1350 m of altitude, along the road that leads from Kobariški Stol peak towards the town of Kobarid. Structurally the area belongs to the Southern Alps, more exactly to the lowermost Tolmin Nappe (Buser, 1986, Placer, 2008) (Figure 1). Paleogeographically the area in the

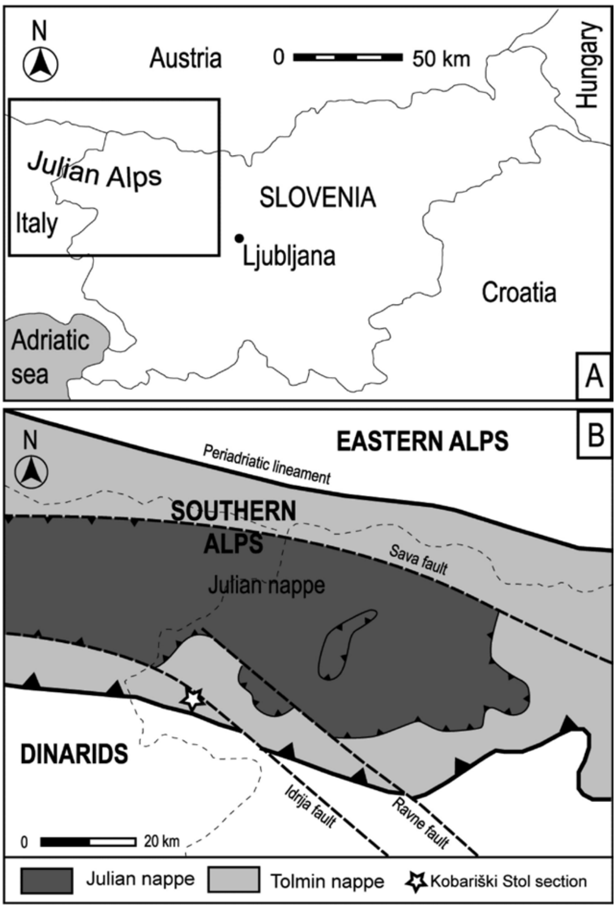

Figure 1A. Location of the Julian Alps. Insert in A represents the location of B. B: Main structural elements of the region and location of the investigated sections.

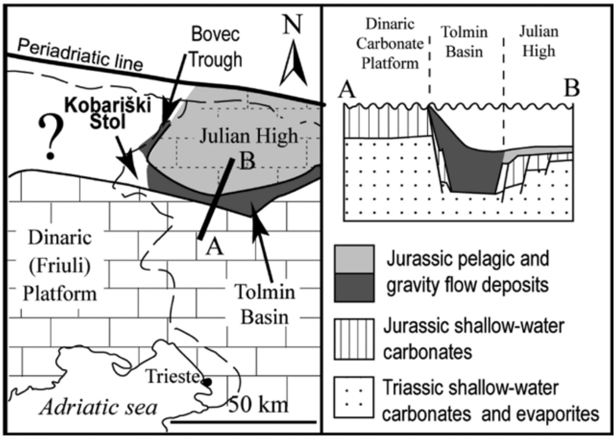

Figure. 2. Present-day position of paleogeographic units (compiled from Bosellini et al. 1981, Martire 1992, Buser 1989, Placer 2008) and schematic palaeogeographic cross-sections at the end of the Jurassic (Bernoulli et al. 1979).

Middle and Upper Jurassic belonged to a transitional area between Dinaric Carbonate Platform to the South, Slovenian Basin to the East and Julian Plateau to the North (Miklavič & Rožič, 2008, and this study) (Figure 2).

The area was investigated by Cousin (1981) who distinguished following Middle and Upper Jurassic beds in Kobariški Stol: 1) upper Middle Jurassic (upper Dogger) to lower Upper Jurassic (lower Malmian) alternation of oolitic and crinoidal limestones, carbonate microbreccias and nodular limestones that are at places silicified; 2) Kimmeridgian to lower Tithonian Rosso Ammonitico facies; 3) Upper Tithonian/Berriasian to Valanginian micritic limestone of Biancone type. The Kobariški Stol area was also mapped for the Basic Geological Map of Yugoslavia, at a scale of 1: 100 000 by Buser (1986) (the Tolmin and Videm sheet).

Kobariški Stol section: description of lithostratigraphic units

The Kobariški Stol section was divided into three lithostratigraphic units named Unit 1, Unit 2, and Unit 3, respectively (Figure 3). Unit1 (U1) represents the base of the investigated succession and consists of Bathonian or Callovian to lower Kimmeridgian gray, fine-grained limestones (packstone/wackestone to mudstone) with intercalated fine- to coarse-grained

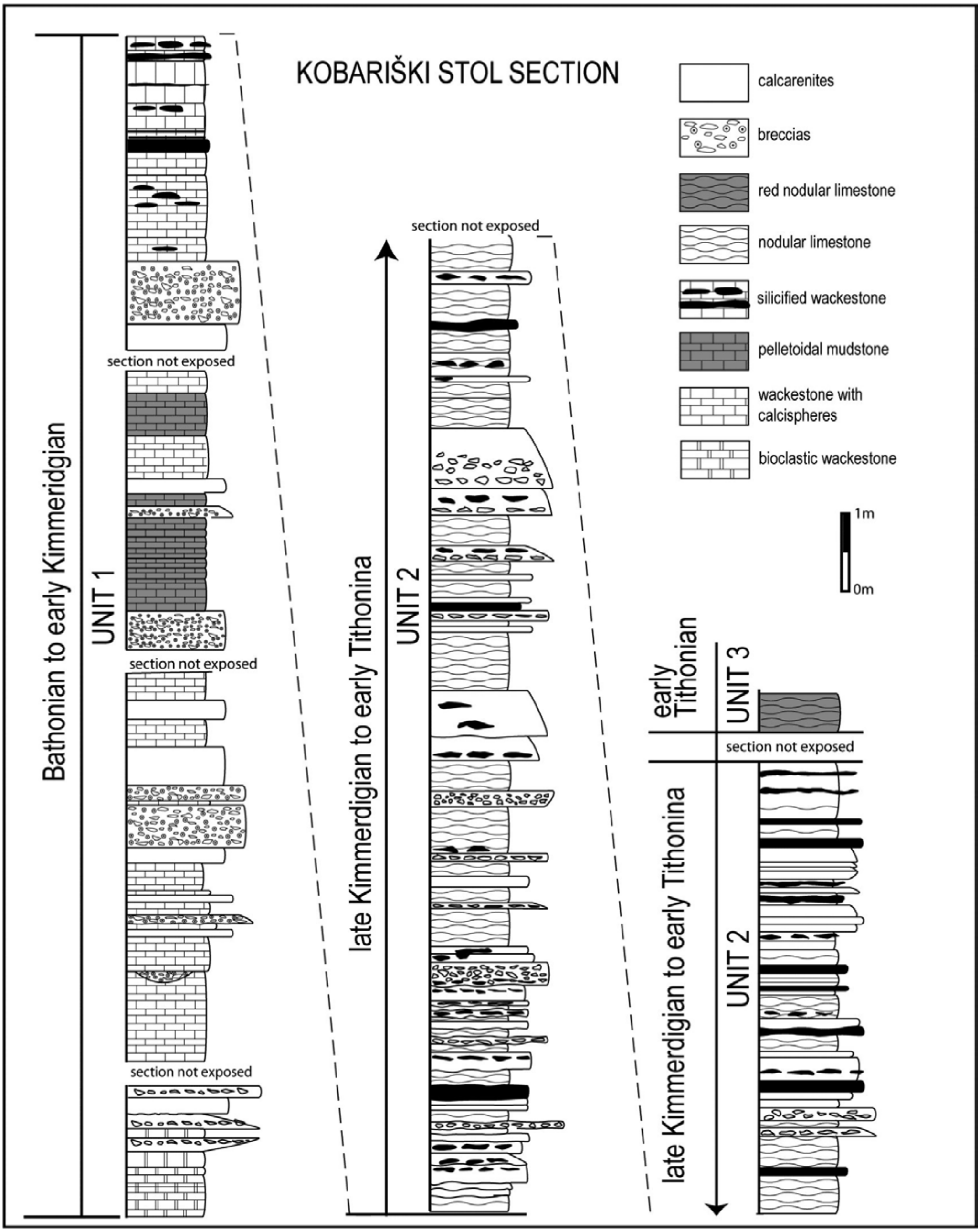

Figure 3. Kobariški Stol section (please note that unexposed intervals between logged sections span usually for only few meters)

calcarenites and fine-grained carbonate breccias. Unit 2 (U2) is represented by a gray distinctly nodular limestones with intercalated fine- to coarse-grained calcarenites and breccias of Late Kimmeridgian to early Tithonian age. Unit 3 (U3) corresponds to red nodular limestone of Rosso Ammonitico type of early Tithonian in age.

3.1 Unit 1 (U1):

The Unit 1 represents the base of the studied succession; the contact with underlying formations is not visible. The unit is at least 15 m thick and consists of 10 cm to 1 m thick beds of fine-grained limestones (mudstone to packstone) with intercalated 15 cm to 50 cm thick beds of diverse carbonate gravity-flows (Figure 3).

Fine-grained limestones

The fine-grained limestones include following facies types: bioclastic wackestone, wackestone with calcispheres, pelletoidal mudstone to packstone and silicified wackestone.

Bioclastic wackestone

Bioclastic wackestone to packstone is gray, thin bedded and at places nodular. Elongated grains are often oriented parallel to the bedding. It consists mainly of bioclasts of disarticulated valves of thin-shelled bivalves (*Bositra* sp.), echinoderm fragments, gastropod protoconch, juvenile ammonites, ammonite fragments, planktic foraminifera (protoglobigerinids), benthic foraminifera (*Lenticulina* sp., *Textularidae*), and unidentified sparitic bioclast fragments (Pl. 1, Figs.1, 2). Small peloids, ooids, pellets and rare micritic intraclasts are rare. At places, where the wackestone exhibit nodular aspect, the matrix between the nodules consists of *Bositra sp.* rich packstone. Also common are irregular fields where peloids and filaments predominate.

Wackestone with calcispheres

This facies is represented by a thin to thick bedded wackestone to packstone. At places beds exhibit horizontal parallel lamination. Lamination is defined by alternation of thicker packstone to wackestone laminae composed mostly of calcispheres and thinner laminae of packstone to wackestone where thin shelled-bivalves (filaments) predominate (Pl. 1, Fig. 3). Other grains are echinoderm fragments, benthic foraminifera (*Lenticulina* sp., Textulariidae) and planktic foraminifera (protoglobigerinids). Aptychi and partly recrystallized ooids are rare.

Pelletoidal mudstone to packstone

Pelletoidal mudstone to packstone is thin to medium-bedded (10 cm to 70 cm), at places laminated, grains are oriented parallel to the bedding. Laminas are represented by an alternation of thin microsparitic mudstone (Pl. 1, Fig. 4) with thicker pelletoidal mudstone to

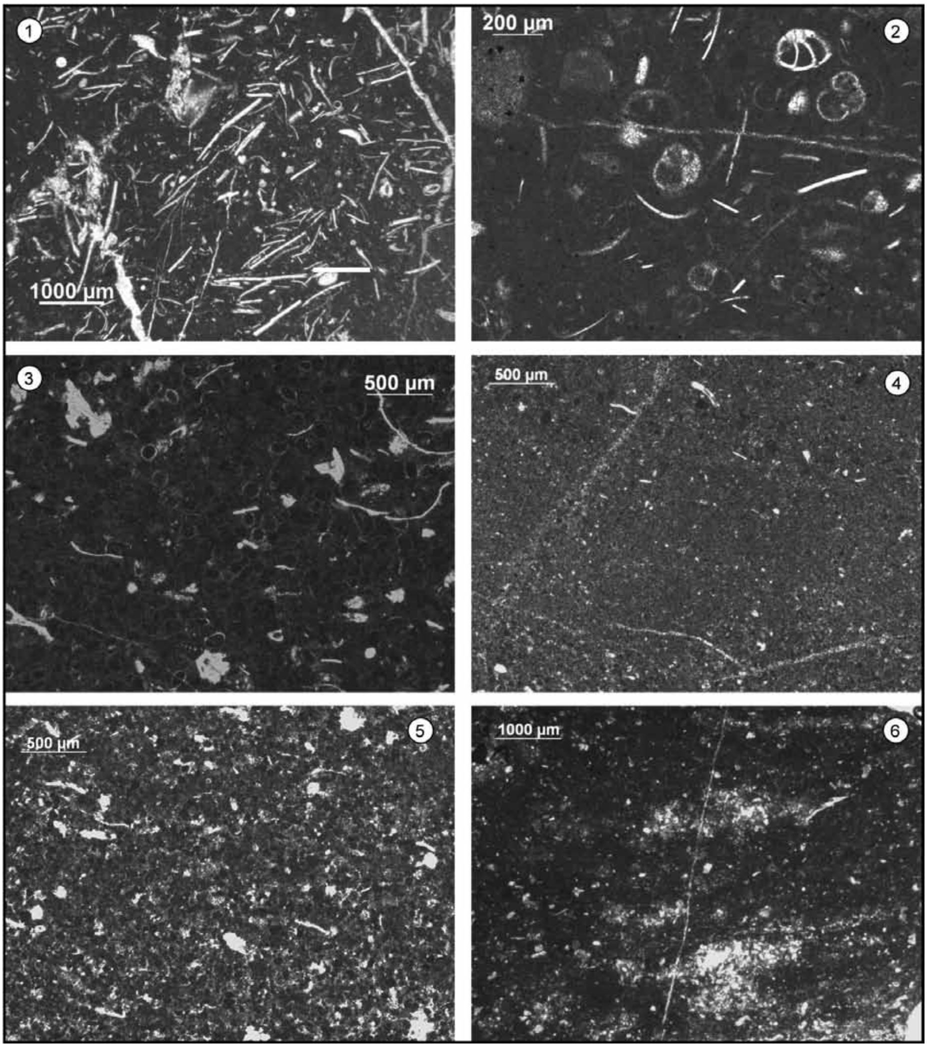

Plate 1.
Figure 1. Unit 1, fine-grained limestone; bioclastic wackestone with filaments and small echinoderm fragments.
Figure 2. Unit 1, fine-grained limestone; bioclastic wackestone with small benthic foraminifera, planktic foraminifera (protoglobigerinids) and filaments.
Figure 3. Unit 1, fine-grained limestone; wackestone/packstone with calcispheres and filaments.
Figure 4. Unit 1, fine-grained limestone; pelletoidal mudstone to packstone. Laminae of microsparitic mudstone.
Figure 5. Unit 1, fine-grained limestone; pelletoidal packstone with abundant pellets and rare echinoderm fragments
Figure 6. Unit 1, fine-grained limestone; silicified wackestone with rare calcified radiolarian moulds.

packstone (Pl. 1, Fig. 5). Mudstone to packstone are composed mainly of pellets (at places cannot be distinguished from matrix) and rare echinoderm fragments and filaments.

Silicified wackestone

Silicified wackestone exhibits parallel, wavy parallel and wavy nonparallel laminations. Silification occurs as beds and nodules of replacement chert. At places also wackestone matrix is partly silicified. Laminae are thinner mudstone to wackestone with rare radiolarian moulds, calcispheres and echinoderm fragments (Pl. 1, Fig. 6) and thicker wackestone/packstone to grainstone with small echinoderm fragments and pellets. Matrix is microsparite to sparite and at places syntaxial overgrows around echinoderm fragments.

Breccias and calcarenites

Intercalated breccias and calcarenites are thin to medium bedded and range from fine-grained breccias to fine-grained calcarenites.

Breccia beds

Thickness of breccia beds is up to 50 cm. The contact with underlying beds deposits is erosional. Additionally; at places breccias fill small channels up to 1 m wide and 20 cm deep. Breccias are poorly to medium-sorted, clast-supported and at places show inverse and normal grading. Clasts are sometimes oriented parallel to the bedding. Grains are up to few cm large and include clasts of underlying bioclastic wackestone, mudstone with calcispheres; and also shallow-water clasts of A) grainstone to packstone with Microproblematica, B) grainstone to packstone with peloids, echinoderm fragments, ooids, and filaments, C) pelletoidal packstone with rare benthic foraminifera, and D) oodial packstone to grainstone. Other grains in breccia are Microproblematica, partly recrystallized large ooids, echinoderm fragments, rare fragments of corals, and sparitic bioclast fragments (Pl. 2, Figs. 1, 2). The matrix of the breccia consists of packstone at places also grainstone mainly with individual partly recrystallized ooids, peloids, echinoderm, algae and coral fragments, benthic foraminifera (*Lenticulina* sp., Textulariidae*, Protopeneroplis striata* Weynschenk), unidentified bioclasts, and thin-shelled bivalve fragments (Pl. 2, Figs. 1, 2). Grains are embedded in a micritic and microsparitic matrix, at places also cemented with syntaxial cements around echinoderm grains.

Fine to coarse-grained calcarenites

Fine to medium-grained calcarenites are medium bedded. Elongated grains are usually oriented parallel to the bedding. Normal and inverse grading and parallel laminations are sometimes present. At places also grading from breccia to calcarenites is observed. The

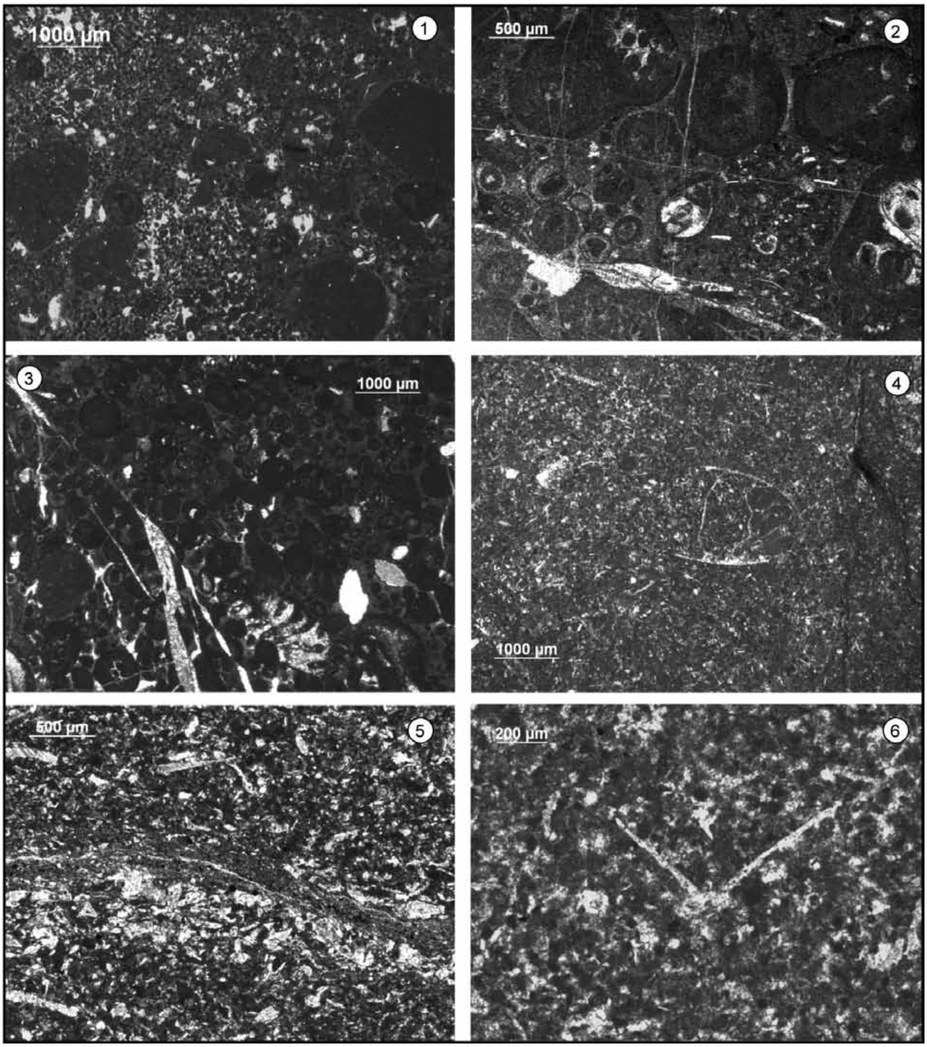

Plate 2.

Figure 1. Unit 1, limestone breccia; larger Microproblematica and partly recrystallized ooids in a packstone matrix composed of peloids, ooids, and echinoderm fragments.

Figure 2. Unit 1, limestone breccia; larger clasts of Microproblematica, lithoclasts, aggregate grains, partly recrystallized ooids and *Protopeneroplis striata* Weynschenk in a microsparitic matrix.

Figure 3. Unit 1, coarse-grained calcarenite; packstone with peloids, recrystallized ooids, echinoderm fragments and bioclasts.

Figure 4. Unit 2, nodular limestone; wackestone with pellets, calcispheres, echinoderm fragments and fragmented ammonite moulds.

Figure 5. Unit 2, nodular limestone; middle part of the photo is thin gray clay film between the nodules and around a packstone with echinoderms.

Figure 6. Unit 2, nodular limestone; packstone with pellets, echinoderm fragments and *Saccocoma* sp.

calcarenites are packstone to grainstone and have the same composition as breccia, but are devoid of larger lithoclasts (Pl. 2, Fig. 3).

Age of Unit 1

Based on the presence of planktic foraminifera (protoglobigerinids) and of individual tests of *Protopeneroplis striata* Weynschenk the age of the Unit 1 most probably ranges from Bathonian to early Kimmeridgian (cf. Caron & Homewood, 1983; Sartorio & Venturini, 1988; Tappan & Loeblich, 1988; Darling et al., 1997). Due to relatively small thickness of Unit 1 (15 m), it possibly records only upper part (Early Kimmeridgian) within this interval or contains hiatuses. The latter is also indicated by presence of nodular structure in fine-grained limestones.

Sedimentary environment of Unit 1

Fine-grained limestones (bioclastic wackestone, wackestone with calcispheres, pelletoidal mudstone to packstone and silicified wackestone) represent background pelagic and hemipelagic deposits in relatively deep-water environment as evidenced by a presence of mainly pelagic bioclasts (calcispheres, thin shelled-bivalves, radiolarians, planktic foraminifera, aptychi). Minor input from shallow-water environment is however indicated by rare shallow-water grains (ooids and also benthic foraminifera, echinoderm fragments). Presence of different laminations (parallel, wavy parallel and wavy nonparallel) present almost in all fine-grained facies suggest some sort of hydrodynamic sorting, most probably by contour currents or redeposition of the material by fine-grained turbidites. Beds at places also exhibit nodular bedding that also indicates influence of bottom-currents that caused slower sedimentation rates and early selective cementation.

Sedimentary structures of breccias suggest deposition by debris flows or gravelly-high density turbidity currents. Different intraclasts (mud-chips) and also shallow-water lithoclasts indicate exhumation and partial erosion of underlying deposits. The fine-to medium grained calcarenites were deposited by sandy high-density turbidity currents. Presence of individual grains of ooids, Microproblematica, benthic foraminifera, corals and algal fragments indicates input from shallow-water areas.

Unit 2 (U2)

Unit 2 is up to 20 m thick and represented by gray nodular limestone with intercalated fine to coarse-grained calcarenites and breccias. The contact with the underlying Unit 1 is covered.

Nodular limestone

This facies usually occur in up to 70 cm thick packages that exhibit distinct internal nodular bedding. Individual nodules are 3–7 cm thick, bedding surfaces are marked by thin brown to gray clay films. The nodules are wackestones to packstones composed of pellets, *Saccocoma sp.* and other echinoderm fragments, *Bositra* sp., calcispheres, and calcified radiolarian moulds (Pl. 2, Figs. 4, 5, 6). Benthic foraminifera, algal fragments, aptychi and poorly preserved ammonites are rare. The calcispheres at places exhibit geopetal infillings. Towards the edge of individual nodule the structure becomes tightly packed packstone with predominant echinoderm fragments (Pl. 2, Fig. 5). This facies is frequently silicified and contain beds and lenses of replacement cherts. Common diagenetic feature is also the presence of pyrite that is usually concentrated between the borders of the nodules, but occurs also within the nodules.

Breccias and calcarenites

Intercalated breccias and calcarenites are thin to medium bedded and represented by a fine-grained breccias and fine-to coarse-grained calcarenites.

Fine-grained breccias

Intercalated breccias are fine-grained, matrix to clast supported, and exhibit normal and inverse grading (from medium-breccia to medium-grained calcarenite). It contains also lenses and beds of replacement cherts. Individual breccia beds are up to 70 cm thick and usually have an erosional contact with underlying deposits. Clasts are up to 3 cm large and are embedded in a matrix represented by a medium-grained calcarenite. Larger grains are composed exclusively of eroded underlying nodular limestones (mud-chips) or fragments of ammonite moulds filled with mudstone (Pl. 3, Fig. 1).Calcarenite matrix is composed mainly of individual grains of Microproblematica, small peloids, pellets, micritic and microsparitic lithoclasts and various bioclastic debris represented by fragments of corals and stromatoporoids, larger sparitic bioclasts, fragments of mollusks, brachiopods, echinoderms, benthic foraminifera, belemnites and aptychi (Pl. 3, Figs. 2, 3). Matrix is microsparite or fine-grained sparitic and syntaxial cement.

Fine to coarse-grained calcarenites

Beds of calcarenites are up to 25 cm thick, elongated grains are oriented parallel to the bedding. Beds and lenses of replacement chert are present. Calcarenites are packstone with echinoderm fragments, small peloids, and rare benthic foraminifera (*Lenticulina* sp., multichambered with micritic walls), *Bositra* sp., bioclastic sparitic fragments, algal fragments, and also larger clay clasts (Pl. 3, Figs. 4, 5). Grains are embedded in a microsparitic matrix or cemented by fine-grained sparitic and syntaxial cement.

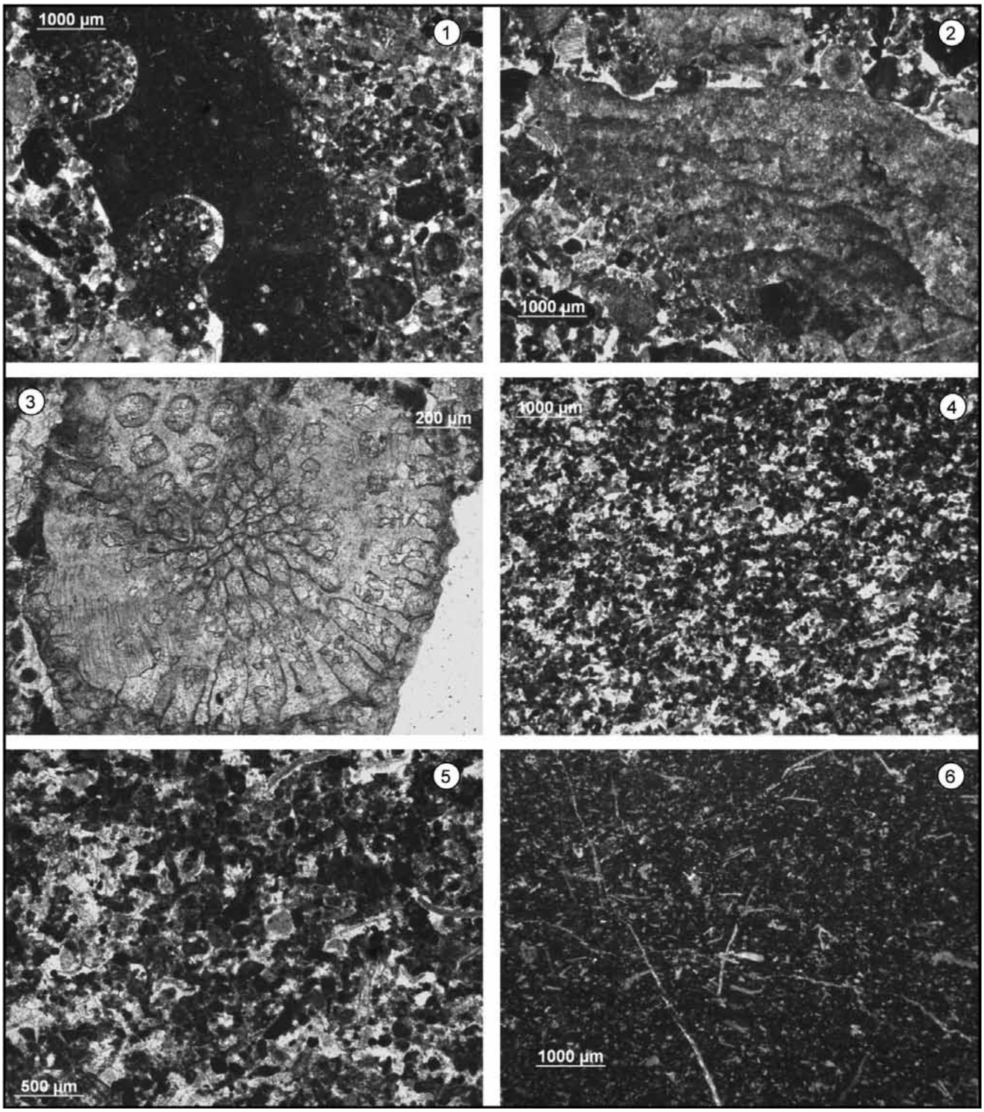

Plate 3
Figure 1. Unit 2, breccia; large clasts of micrite filled ammonite mould in a calcarenite matrix with peloids, echinoderm fragments, and other bioclastic fragments
Figure 2. Unit 2, breccia; stromatoporoid fragment in a calcarenite matrix with peloids, echinoderm fragments, and other bioclastic fragments.
Figure 3. Unit 2, breccia with coral
Figure 4. Unit 2, calcarenite; packstone with echinoderm fragments, peloids and rare filaments.
Figure 5. Unit 2, calcarenite; packstone/grainstone composed of echinoderm fragments, peloids and rare filaments.
Figure 6. Unit 3, red nodular limestone; wackestone with fragments of *Saccocoma* sp.

Age of Unit 2

Late Kimmeridgian to early Tithonian age for Unit 2 was determined on the basis of the presence of *Saccocoma* sp. (according to Sartorio & Venturini, 1988).

Sedimentary environment of Unit 2

Nodular limestone represents deeper-water sediment as evidenced by presence of mainly pelagic bioclasts. Nodular structure however indicates early selective cementation on a current swept sea bottom.

Sedimentary structures of breccias suggest deposition by mud to debris flows. Lithoclasts of the nodular limestones indicates erosion of the underlying strata by over-riding flows. The fine-to coarse grained calcarenites were deposited by sandy high-density turbidity currents and represents top-cut-of Bouma sequences. The composition of shallow-water grains within the breccias and calcarenites indicate provenance area from adjacent contemporaneous shallow-water coral reef areas.

Unit 3: Red nodular limestone of Rosso Ammonitico type

The Unit 3 is at least 5 m thick; however the lower and upper contact is not visible, so the exact thickness of the Unit 3 is not known.

Nodular limestones

Nodular limestones are of wackestone to packstone type. Individual nodules are 3–7 cm thick, bedding surfaces are marked by thin red clay films. They are composed almost exclusively of fragments of *Saccocoma* sp., while other grains (aptychi, calcified radiolarian moulds, and benthic foraminifera) are extremely rare (Pl. 3, Fig. 6).

Age

On the basis of the stratigraphic position and abundant presence of *Saccocoma* sp. the age of this unit is early Tithonian (cf. Sartorio & Venturini, 1988).

Sedimentary environment

The red nodular lime-stones represent condensed sedimentation and are typical of sedimentation on isolated pelagic plateau. Nodules indicate presence of bottom currents that allowed micrite accumulation followed by long and repeated phases of cementation, bioturbation and current reworking (cf. Martire, 1996). The higher clay content is most probably a secondary enrichment due to the pressure dissolution of micrite (cf. Clari & Martire, 1996).

Middle and Upper Jurassic sedimentary evolution of the Kobariški Stol area

Callovian to Kimmeridgian deposits of Unit 1 were deposited in a deeper-water environment and are dominated by carbonate background sediments (bioclastic wackestone, wackestone with calcispheres, pelletoidal mudstone to packstone and silicified wackestone). Nodular structure that is present at places indicates that this depositional area was episodically current-swept. Unit 1 also contains abundant beds composed of shallow-water calcareous material that was resedimented by debris flows and turbidity currents. The redeposition into deeper environment was from the adjacent south lying Dinaric Carbonate Platform that at that time represented the only known shallow-water environment in the area. Additionally, the breccias also contain reworked clasts of the underlying deposits and also older shallow-water lithoclasts. This indicates an important submarine erosional event cutting into older substratum, which was probably exposed due to the normal faulting. This normal faulting could be attributed to the extensional tectonic event in Callovian, that is well documented westward in Trento plateau (see Martire, 1996).

In the Kimmeridgian and early Tithonian the nodular limestones and carbonate resediments of Unit 2 were deposited. The Unit 2 represents quite unique facies association of nodular limestones that are usually distinctive for a current-swept isolated pelagic plateau (cf. Martire, 1989, 1992, 1996) and abundant carbonate resediments containing numerous reworked shallow-water elements (algae, coral fragments, benthic foraminifera etc.). Therefore the Kobariški Stol area at that time represented a current-swept plateau that was nevertheless connected to adjacent shallow-water carbonate platform as evidenced by frequent carbonate gravity flows. The composition of the resedimented carbonates indicates an onset of coral-reef sedimentation in a provenance area and probably also progradation of reef margin, over deeper-water areas. Namely, the breccias composed mainly of coral reef fragments that are interpreted as a fore-reef facies, are well documented in Mija-Matajur Anticline (Buser, 1987) located southward of the investigated area.

In early Tithonian the sedimentation of red nodular Rosso Ammonitico facies of Unit 3 started. It represents typical sediment of a current-swept pelagic plateau. It is devoid of shallow-water elements and most probably indicates a change in the mode of the deposition in Dinaric Carbonate Platform from highly productive reefs to the sedimentation of algal limestones of Tithonian age (cf. Buser, 1965; Turnšek, 1966, 1969, 1972, 1997; Strohmenger & Dozet, 1991).

Correlation with the Slovenian Basin and Julian Plateau

The investigated area show similarities and also differences to both: Slovenian Basin and Julian High paleogeographic domains. The correlation with the Slovenian Basin successions revealed that Unit 1 and 2 of the Kobariški Stol section are time and to some degree also facies equivalent to the Tolmin Formation of Slovenian Basin (Rožič, 2006, 2009, Goričan et al., 2012). The Tolmin Formation contains mainly siliceous limestones and thin-bedded radiolarian cherts with intercalated two intervals of carbonate resediments. Carbonate resediments of the Unit 1, especially ooidal packstone corresponds to the lower resedimented limestone of the Tolmin Formation, while carbonate resediments of Unit 2 correspond to the upper resedimented limestone of the Tolmin Formation (Rožič & Popit, 2006, Rožič, 2009). The main difference between Slovenian Basin and Kobariški Stol area is absence of abundant siliceous limestones and radiolarian rich cherts in the Kobariški Stol succession. This indicates that the Slovenian Basin at that time represented deeper sedimentary environment with comparison of Kobariški Stol area.

On the other hand, when correlating solely the background sediments, the Units 1, 2, and 3 represent time and facies equivalent of the Prehodavci Formation of the Julian Plateau (Šmuc, 2005; Šmuc & Rožič, 2011). In both areas condensed nodular limestones are presents and indicate sediment-starved bottom current-swept deeper-water environment. The Julian Plateau however was an isolated plateau completely devoid of any shallow-water carbonate resediments, while Kobariški Stol area contains abundant calciturbidites and debris flow with shallow-water grains. This indicate that Kobariški Stol area was a site of condensed background sedimentation, but was well connected to the adjacent Dinaric Carbonate Platform and received relatively large amount of shallow-water resedimented material.

Conclusion

The Kobariški Stol area in the Middle and Upper Jurassic represents a unique facies association of nodular limestones, and abundant shallow-water carbonate resediments. At that time it represented a deeper-water current-swept plateau that was nevertheless well connected to the adjacent shallow-water Dinaric Carbonate Platform. Compared to the contemporary, eastward lying successions of the Slovenian Basin, the Kobariški Stol clearly represents shallower-water environment, that was however still located well below photic zone. In that sense Kobariški Stol area represents a transitional zone between the Dinaric Carbonate Platform located south, the Julian High towards north and the Slovenian Basin to the east. This study thus confirms the idea that the Slovenian Basin in this part wedged out (Buser, 1996; Buser & Debeljak, 1996; Miklavič & Rožič, 2008).

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Evidence of Quaternary faulting in the Idrija fault zone, Učja canyon, NW Slovenia

Znaki kvartarne tektonske aktivnosti v coni Idrijskega preloma pri Učji

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Abstract: Above the Učja river canyon, NW Slovenia, an outcrop of poorly sorted monomict Quaternary breccia, located in the fault zone of the dextral Idrija fault, is dissected by several NW–SE oriented subvertical faults and associated fault-parallel fractures. Orientation and position of the observed faults match perfectly with one of the strands of the Idrija fault that is exposed in Mesozoic rocks on the other side of the river valley. Brittle structures in Quaternary and Mesozoic rocks are consistent with N–S directed maximum horizontal compression that is believed to prevail in the region since the early Pliocene. This is the first direct evidence of Quaternary to recent deformation along the Idrija fault. Activity of the fault is further indicated by dextral offsets of the Učja river course coinciding with the strands of the Idrija fault zone.

Izvleček: V prelomni coni desnozmičnega Idrijskega preloma nad kanjonom reke Učje v severozahodnem Posočju smo našli izdanek slabo sortirane monomiktne kvartarne breče, ki ga sekajo SZ–JV orientirani subvertikalni prelomi in vzporedne spremljajoče razpoke. Opisani prelomi se po legi in orientaciji popolnoma ujemajo z enim od prelomov notranje cone Idrijskega preloma, ki je razgaljen v mezozojskih kamninah na nasprotni strani reke. Lomne strukture v kvartarnih in mezozojskih kamninah so skladne z maksimalno tlačno napetostjo v smeri S–J, ki v regiji verjetno deluje od začetka pliocena. To je prvi

Original scientific paper

neposredni dokaz za kvartarne do recentne deformacije ob Idrijskem prelomu. Aktivnost preloma dodatno kažejo tudi desni zamiki reke Učje ob sekundarnih prelomih cone Idrijskega preloma.

Key words: Idrija fault, active tectonics, Učja/Uccea river
Ključne besede: Idrijski prelom, aktivna tektonika, reka Učja

INTRODUCTION

The NW–SE trending Idrija fault is one of the most prominent faults in the territory of Slovenia. Along the 120 km of its trace, the fault is very clearly expressed both in topography and in geology by up to 15 km of dextral separation of geological units. Due to conspicuous geomorphic expression of the fault and its favourable orientation with respect to the regional N–S to NNW–SSE direction of principal shortening (e.g. VRABEC & FODOR, 2006; WEBER et al., 2010), the Idrija fault is generally considered to be currently active. For example, the 1511 earthquake with estimated M = 6.9, one of the most devastating seismic events recorded in the Eastern Alpine region, is attributed to dextral slip on the Idrija fault (e.g. FITZKO et al., 2005), though the source and mechanism of the earthquake remain controversial (CAMASSI et al., 2011; KOŠIR & CECIĆ, 2011). Adding to the controversy is the apparent lack of recorded instrumental seismicity along the fault trace both in map view and in cross-section (ŽIVČIĆ et al., 2011), implying no significant seismic slip on the fault at least for the last 50 years. Nevertheless, the 1998 and 2004 Posočje seismic sequences on the Ravne fault that runs parallel to the Idrija fault (e.g. KASTELIC et al., 2008) provided direct evidence that NW–SE oriented faults of western Slovenia can be dextrally activated in the current regional stress regime.

Due to the fact that the Idrija fault cuts almost exclusively through Mesozoic rock units, it is quite difficult to confirm its neotectonic activity with conventional geological methods. As a possible indicator of neotectonic deformation, the Quaternary karst poljes located along the fault were interpreted as pull-apart structures (VRABEC, 1994). A detailed LIDAR-based morphological study of a small section of the fault trace at Kanomlja in the Idrija region revealed several geomorphic features that are implying Quaternary displacements in the fault zone (CUNNINGHAM et al., 2006). The Kanomlja site was recently investigated by geophysical profiling, which provided strong indications of recent to sub-recent faulting along the fault zone (BAVEC et al., this volume).

In this paper we present field observations from the NW-most part of the Idrija fault zone, which for the first time confirm Quaternary to presumably recent faulting along the fault.

Geological setting

The roughly E–W trending, deeply incised valley of the Učja (Uccea) river is situated in NW Slovenia, close to the Bovec basin. Ther river canyon crosses the entire width of the Idrija fault zone, which makes it one of the few localities where direct observations of internal structure of the fault zone are possible. The Učja valley was mapped in detail by Čar & Pišljar (1993), who documented several fault strands and the accompanying fracture zones. In their map, the Idrija fault proper comprises three major NW–SE trending faults, which we name the Oslovo brdo strand, the Hlevišča strand, and the Žlebišče strand (Figure 1). Older fault sets, oriented predominately in E–W and N–S directions, also outcrop in the zone (Čar & Pišljar, 1993). Whereas the canyon mainly cuts through Late Triassic limestones and dolomites, two smaller blocks of Jurassic and Creta-

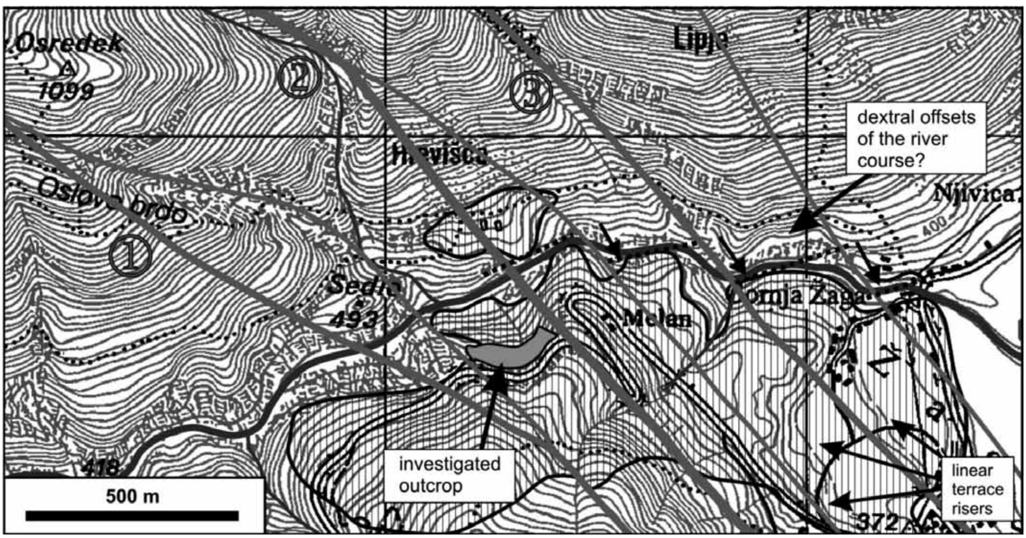

Figure 1. Geographical and structural position of the investigated outcrop in the lower Učja canyon in the central part of the Idrija fault zone. Geological data after Čar & Pišljar (1993). Hatchured areas show the extent of Quaternary sediments. 1) Oslovo brdo strand of the Idrija fault zone. 2) Hlevišča strand. 3) Žlebišče strand. Topographic map from The surveying and mapping authority of the Republic of Slovenia, National topographic map at 1 : 25 000 scale.

ceous rocks are wedged between the Oslovo brdo and Hlevišča strands (Buser, 1987; Čar & Pišljar, 1993), indicating significant (km-scale) displacement in this part of the Idrija fault zone. Further to the NW, the Oslovo brdo strand terminates eastward continuation of a low-angle thrust of Late Triassic limestone over the Cretaceous flyschoid formation (Buser, 1987).

In 2004, a permanent extensometer was installed on the fault plane of the Hlevišča strand exposed at the bottom of the Učja valley. The 8-year time series of measurements suggests a nearly horizontal slip with the average rate of 0.25 mm per year (Gosar et al., 2011), but the results are currently controversial since the measured slip sense is sinistral, which is in conflict with other geologic and geodetic indicators.

The southern side of Učja valley is predominately covered by Quaternary sediments (Buser, 1987; Čar & Pišljar, 1993; see also Figure 1). In the eastern part around Žaga village, several nested terraces in fluvial gravels and conglomerates occur. Linear terrace risers, generally following the NW–SE trend of the Idrija fault suggest possible influence of faulting on shaping of terraces. Between the Hlevišča fault strand and the Žaga village, the NW–SE oriented fault strands successively shift the E–W directed course of Učja river for 100–130 m in a dextral sense that is consistent with the Idrija fault kinematics (Figure 1). Towards the west, the steeper slopes above the terraces are covered by poorly sorted lithified breccias, interpreted as glacial drift (Buser, 1987; Čar & Pišljar, 1993). A small, terrace-like remnant of such sediments is preserved also on the northern side of Učja at Hlevišča location (Figure 1), and additional large accumulations occur further to the west along the Učja river (Čar & Pišljar, 1993).

We examined a large outcrop of Quaternary breccia, situated below the road that follows Učja valley from the Žaga village towards the border crossing with Italy (Figure 1). The outcrop is up to 10 m high and about 100 m in length (Figure 2), and consists of poorly sorted, partly blocky breccia, containing almost exclusively clasts of Late Triassic carbonates. The monomictic nature of the breccia and its large vertical extent along the valley slopes suggest that it may have originated from slope processes rather than from glacial deposition. At the base of the outcrop the breccia is only poorly lithified, which is manifested by a prominent erosional notch (see the right part of Figure 2). Currently we have no firm constraints on the age of the breccia.

Figure 2. View of the investigated outcrop in lithified Quaternary breccia from the north. Showed is the position of faults discussed in the text.

On its western side, the outcrop is bound by a small branch of the Oslovo brdo fault strand (Figure 1), which is manifested by several parallel fault planes in Late Triassic dolomite (see for example the fault plane exposed along the right border of Figure 2). Quaternary breccia is cut by several weakly-expressed fault planes that are parallel to the NW–SE trend of the Idrija fault zone (Figure 2). On its eastern side, the outcrop extends close to the Hlevišče fault strand, but due to poor exposure no faults in Quaternary deposits could be found there.

Structural observations

We recognized four faults cutting the Quaternary breccia (Figure 2).

Fault A (Figure 3) is located at the bottom of a small gully that probably originated along the fault (Figure 2). The core of the subverctical fault zone is up to 1 m wide and consists of (probably) cataclastically modified sedimentary breccia, which is less coherent and darker in color than the surrounding rock (Figure 3a). Along the core zone, prominent intragranular fractures parallel to the fault cut the breccia clasts

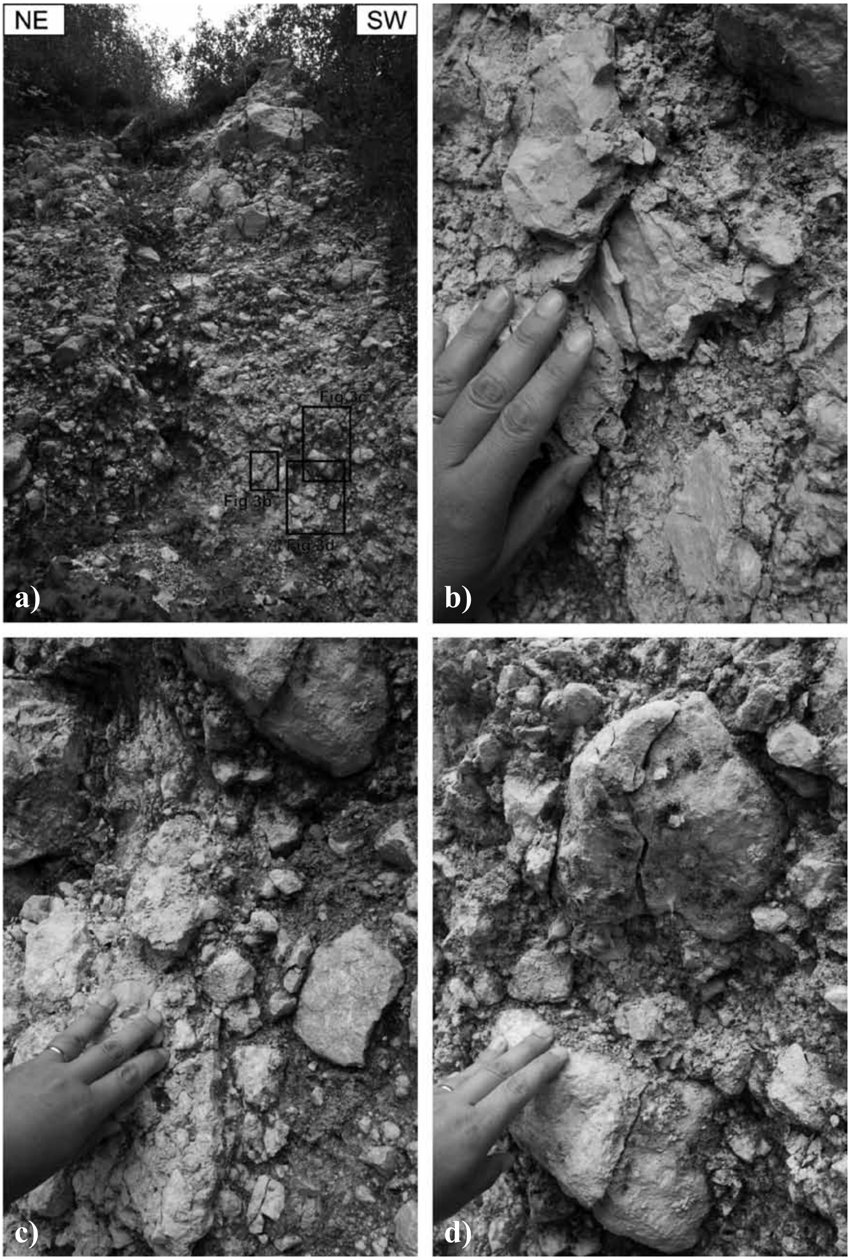

Figure 3. Fault A (refer to Fig. 2 for location). a) View of the core of the fault zone (darker part, up to 1 m wide in the center of the picture with accompanying fracture zone. b) Fractured clasts at the SW boundary of the core zone. c) Weakly developed fault-parallel fractures. d) Fault-parallel transgranular fractures cutting boulders in breccia.

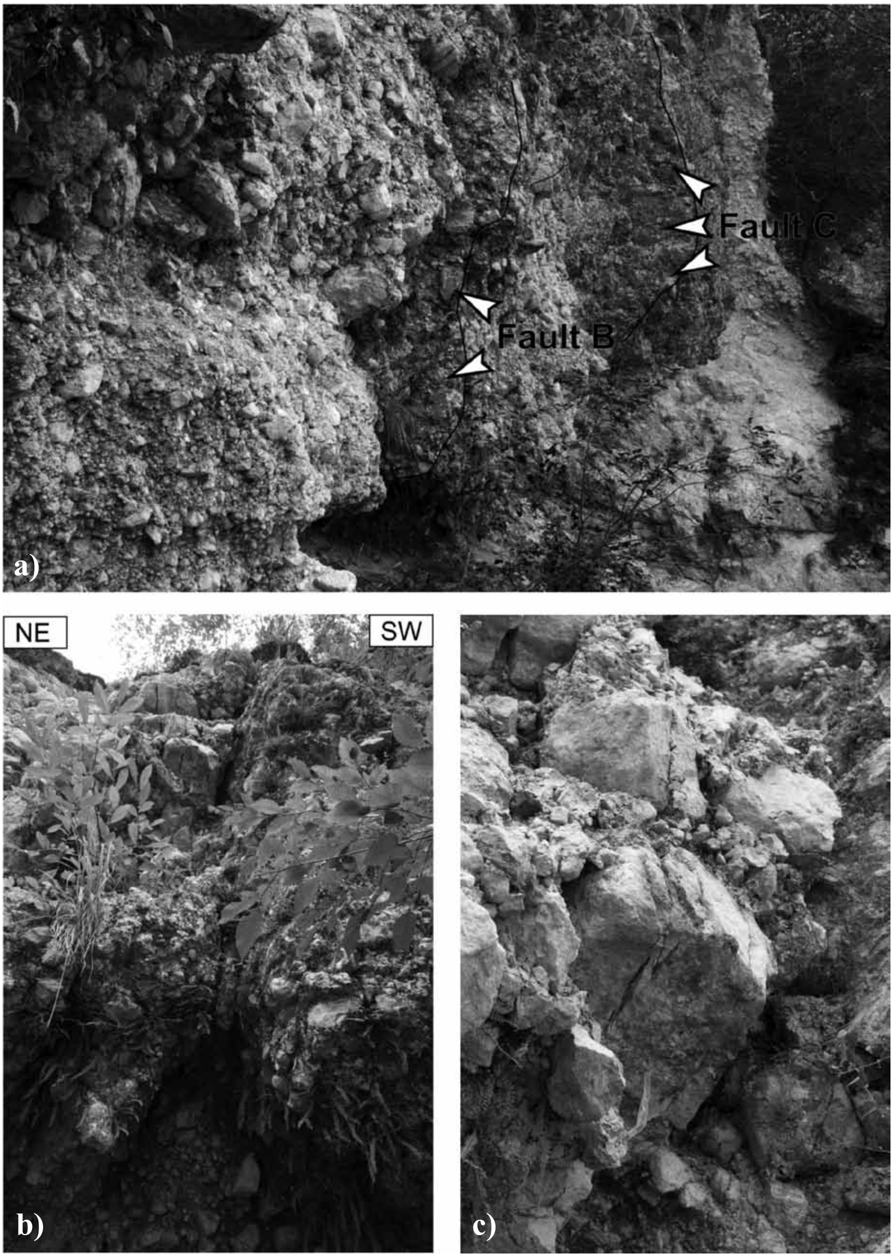

Figure 4. Faults B and C (refer to Fig. 2 for location). a) View towards the SW. Both faults apparently offset the vertical cliff face for ≈0.5 m in a dextral sense. b) Fault B, view from the bottom up. c) Fault B, view of the fault-parallel fractures in large clasts adjacent to the fault plane.

Figure 4. (continued) d) Weakly fractured zone adjacent to Fault B. Note the subvertical planar fabric which is subparallel to the fault plane.

and large boulders (Figures 3a, b, c). Along the entire length of the breccia outcrop such fractures were only found in close proximity to faults. Some of the fault-parallel fractures also cut through the whole rock (Figure 3d). An impression of weak vertical arrangement of clasts along the outer boundary of the core zone (Figures 3c, d) suggests partial modification of the original rock structure by intergranular flow.

Faults B and C (Figure 2, Figure 4a) are discrete subvertical fault planes with up to 0.5 m of apprent dextral shift of the vertical cliff face. Apart from a few very weak subhorizontal ornamentations we were not able to find any on-plane tectonic striations that would reliably constrain slip direction. Prominent subvertical fractures run parallel to the main plane, partly occuring as intragranular fractures in large boulders (Figure 4b, 4c). A weak subvertical planar fabric in breccia, manifested partly by arrangement of clasts and partly by short discrete fractures, was observed along the Fault B (Figure 4d).

Fault D is a prominent feature at the westernmost edge of the outcrop, at the contact of Quaternary breccia with Late Triassic dolomite (Figure 2, Figure 5a). The fault dips moderatly

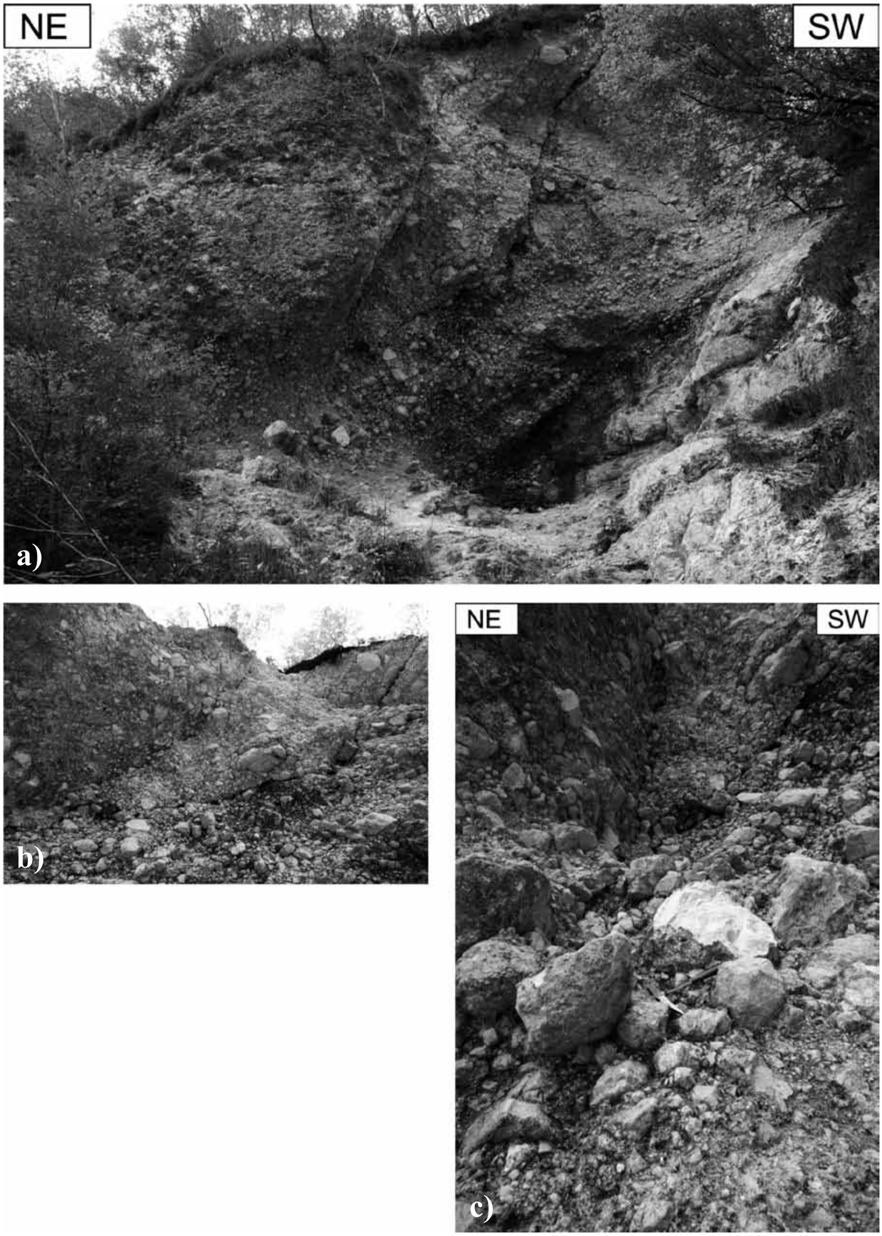

Figure 5. Fault D (refer to Fig. 2 for location). a) View from the north. Note the fault scarp in Late Triassic dolomite in the lower right corner of the photo, covered by inclined strata of Quaternary breccia. b) Fault D, view from the bottom up. c) Fault D. Note how the discrete fault plane, visible in the upper half of the photo, disappears in the lower part of the oucrop which is less strongly lithified.

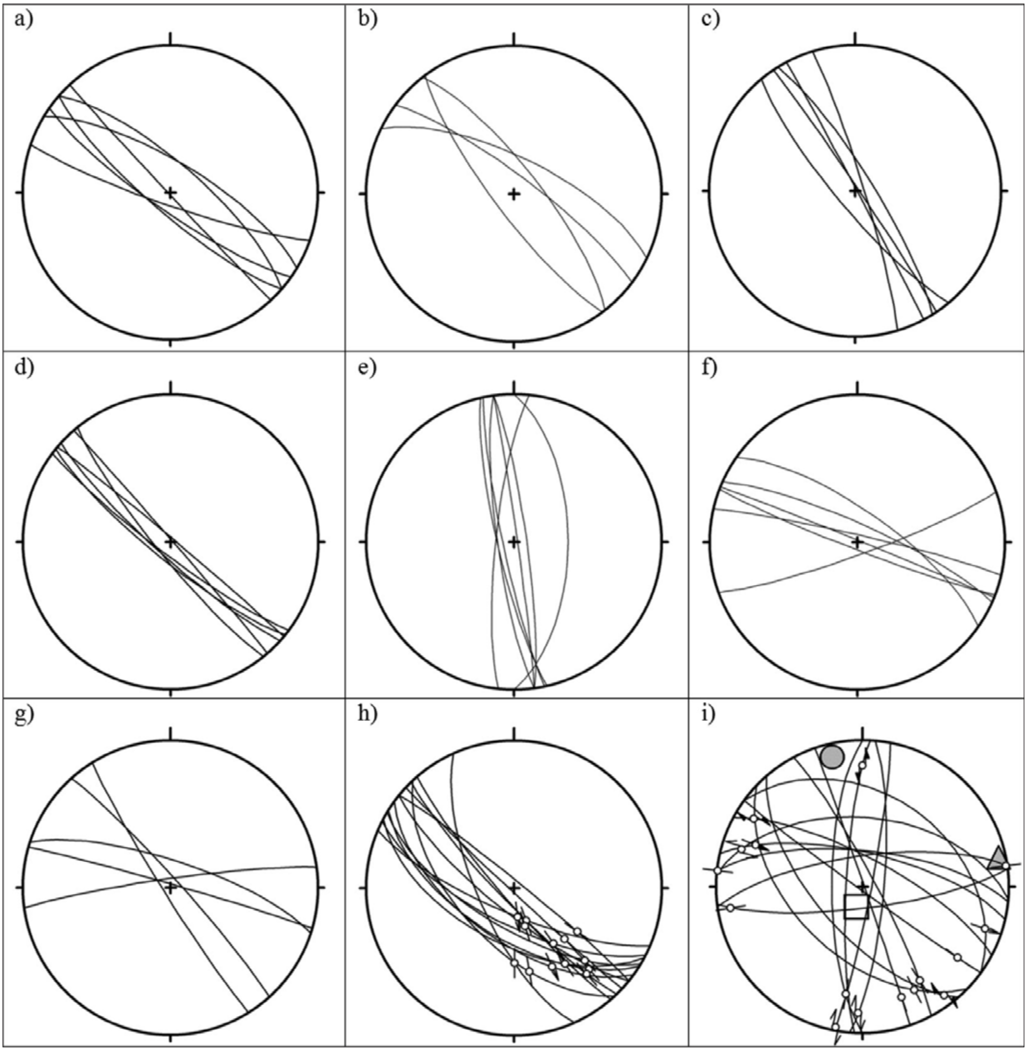

Figure 6. Measured orientations of faults and fractures in equal area projection, lower hemisphere plot. a) Fault A, fractures parallel to the fault. b) Fault A, intragranular fractures in large boulders. c) Fault B, principal fault plane. d) Fault B, fault-parallel fractures and small-scale faults. e) Fault B, intragranular fractures in large boulders. f) Fault D, fractures and intragranular fractures in Quaternary breccia. g) Fault D, fault planes in Late Triassic dolomite below the Quaternary breccia. h) Fault-slip data in Late Triassic dolomite from the Oslovo brdo fault strand, northern slope of Učja valley. i) Fault-slip data and derived paleostress axes orientations from the Drnohla fault zone in the western part of the Učja valley. Circle - σ_1 orientation. Triangle – σ_3 orientation. Square – σ_2 orientation.

steeply to the NE and forks into two branches. Apparent stratification of the breccia, manifested by weak planar structuration and by vertical changes in clast size, is dipping cca 30° towards the NE, and appears draped over the fault scarp in Triassic dolomite that is exposed below the breccia layers (Figure 5a). Otherwise, the stratification of breccia along the entire investigated outcrop, where recognized, is exclusively subhorizontal. The fault is expressed as a predominately planar, partly open fissure of the rock, without parallel fracture zones such as were observed at other faults (Figure 5b). We therefore cannot exclude that this fault originated due to gravitational mass-motion, but as the fault plane strikes nearly perpendicularly to the vertical face of the outctrop, we find this less likely. Downdip, at the foot of the outcrop, the fault plane apparently disappears in the non-lithified section of the breccia succession (Figure 5c), suggesting perhaps that here the displacement was absorbed entirely by intergranular flow. A few weak fractures parallel to the main fault plane, partly intragranular in character, were observed several meters away from the main plane.

The measured orientations of fractures and fault planes from all four sites are presented in Figure 6. Orientations of structures in Quaternary breccia (Figure 6 a–f) very clearly follow the NW–SE trend of the Idrija fault and of the immediately adjacent faults in Mesozoic rocks (Figure 6 g–h). Fault-slip data on the Oslovo brdo strand, measured in Late Triassic dolomite at a site accross the Učja valley in the direct NW-ward continuation of the faults A–D, demonstrates dextral to dextral-normal slip on subvertical to SW-ward dipping fault planes (Figure 6g).

For a sample paleostress inversion of fault slip data (Figure 6i), we used the data measured in Jurassic limestone in the NW–SE oriented Drnohla fault zone (Čar & Pišljar, 1993), which is located a few km west of the study area. Inversion results confirm that the measured dextral slip directions on NW–SE oriented faults are consistent with the N–S oriented compression with E–W oriented tension that is characteristic of the post-Miocene regional stress field (Vrabec & Fodor, 2006).

Discussion and conclusions

The brittle deformation structures, observed in Quaternary breccia that is covering the southern slopes of the Učja river valley, are clearly related to Quaternary – recent motion on the Oslovo brdo strand of the Idrija fault zone. The faults cutting the breccia outcrop are positioned in direct continuation of the well-exposed Oslovo brdo fault zone which dissects Late

Triassic dolomite on the other side of the Učja valley. The NW–SE trending subvertical orientation of fault and fracture planes measured in breccia is identical to orientations of fault planes measured on the Oslovo brdo fault and on other strands of the Idrija fault that are crossing the Učja valley.

The origin of subvertical NW–SE trending fractures and faults observed in this study is consistent with N–S compression in a strike-slip stress regime. A single exception to this are N–S oriented fractures in breccia boulders at the site of Fault B (Figure 6e), which deviate from the prevailing NW–SE orientation. Those fractures could have originated as tensile fractures in response to N–S oriented maximum horizontal compression (e.g. EIDELMAN & RECHES, 1992). The preferred mode of fracturing in Quaternary breccia may depend on local stress conditions, influenced perhaps by the degree of breccia cementation.

Our observations therefore provide for the first time the direct evidence for Quaternary – recent dextral slip in N–S compression along the Idrija fault zone. Due to the setting of the investigated outcrop, it will likely not be possible to constrain the fault slip rate, even with improved dating of the breccia. More favorable location for this could probably be found in the vicinity of the Žaga village, where the NW–SE trending faults apparently offset the Učja river course and shape the alluvial terraces south of Učja (e.g. Figure 1). These geomorphic features suggest that slip is distributed across the entire zone of the Idrija fault. According to mapping of ČAR & PIŠLJAR (1993) and our own geomorphological observations NW of Učja valley, the main fault of the Idrija zone is the Hlevišča strand, implying that the structures that we observed on the Oslovo brdo strand may be relatively minor with respect to the main strand. Further investigations along the strike of individual strands may provide better data on fault slip rates and, perhaps, on paleoseismic events.

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This paper was contributed to celebrate the life and work of prof. Jože Čar on the occasion of his 70th birthday. I am highly indebted to Jože for his guidance and mentorship all the way from my diploma work to the doctoral thesis, not to mention his kind and thoughtful advice and support in matters of life in general. Jože focused a lot of his research on the Idrija fault. Not surprisingly, this paper is only a small extension of the major mapping work he did in the Učja area, and would not have been possible without it.
I thank Erazem Dolžan for assistance

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Geomorfni indikatorji kvartarne aktivnosti Savskega preloma med Golnikom in Preddvorom

Geomorphic indicators of Quaternary activity of the Sava fault between Golnik and Preddvor

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Izvleček: Z metodami tektonske geomorfologije smo raziskovali geomorfne značilnosti vzdolž trase Savskega preloma, ki je med pomembnejšimi aktivnimi prelomi na območju Slovenije. Različni geomorfni indikatorji med Golnikom in Preddvorom potrjujejo kvartarno aktivnost preloma. Na podlagi zamika vršajnih vrhov Kokre ocenjujemo povprečno hitrost premikanja ob prelomu na 0,6–4,1 mm na leto za obdobje 365–1 750 tisoč let pred sedanjostjo. Ta ocena se v okviru natančnosti ujema z recentno hitrostjo premikov (1,0 ± 0,5) mm na leto, ki je bila izmerjena z GPS, naša ocena dolgoročne povprečne hitrost premikov na podlagi geoloških meril pa je 1,0–5,0 mm na leto v zadnjih 20–6 milijonov let pred sedanjostjo.

Abstract: We investigated geomorphic expression of the Sava fault, one of the most important active faults in Slovenia. Various geomorphic indicators along the section of the fault between Golnik and Preddvor confirm its Quaternary activity. We use offset apexes of the Kokra alluvial fan to estimate short-term slip-rate of the fault to 0.6–4.1 mm per year for the period 365–1 750 thousand years BP, which agrees with the GPS-derived recent slip-rate of (1.0 ± 0.5) mm per year, whereas the long-term slip-rate derived using geological criteria is estimated to (1.0–5.0) mm per year for the last 20–6 million years BP.

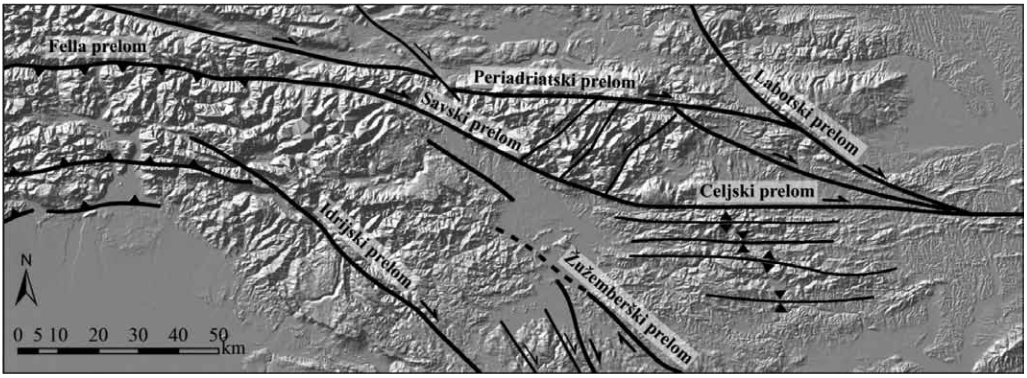
Ključne besede: Savski prelom, geomorfologija, kvartarna aktivnost
Key words: Sava fault, geomorphology, Quaternary activity

UVOD

Savski prelom je med pomembnejšimi prelomi na območju Slovenije, saj ozemlje države prečka po celotni dolžini (slika 1). Na Z vstopi iz Severne Italije, kjer je poznan kot Belski prelom (Fella fault) s slemenitvijo Z–V, v Zgornjesavsko dolino kot Savski prelom in poteka prek nje do Ljubljanske kotline, kjer je njen severni rob s slemenitvijo SZ–JV. Njegovo nadaljevanje proti vzhodu naj bi bil Celjski prelom s slemenitvijo Z–V, ki prečka Tuhinjsko sinklinalo na njenem severu, poteka po južnem robu Celjske kotline (KAZMER et al., 1996; PLACER, 1996; FODOR et al., 1998) in se po nekaterih interpretacijah nadaljuje do stika s Šoštanjskim in Labotskim prelomom pri Rogaški Slatini in dalje proti E (PLACER, 1996; VRABEC & FODOR, 2006). Tako kot njegova slemenitev se spreminja tudi njegov značaj, saj ima na območju Italije prelom reverzen do desno transpresiven značaj, ki postopoma prehaja v bolj desnozmičnega v Zgornjesavski dolini in med Jesenicami in Preddvorom, kjer slednjič preide nazaj v desno transpresivnega (VRABEC, 2001; VRABEC & FODOR, 2006). Glede na podatke geološkega kartiranja vpada Savski prelom strmo proti severu (BUSER, 1980; VRABEC, 2001; KASTELIC, 2007).

Savski prelom je najjužnejši prelom v Periadriatskem prelomnem sistemu (VRABEC & FODOR, 2006). Severno je med njim in Periadriatskim prelomom mega strižna leča z zapletenim mehanizmom notranje deformacije rotacije tektonskih lamel (FODOR et al., 1998), južno od njega pa pravokotna ravnica, zapolnjena s kvartarnimi sedimenti – Gorenjski bazen. Zadnje omenjeni je verjetno nastal kot »pull-apart« bazen v sproščujočem preskoku med Savskim in Žužemberškim prelomom na jugu (npr. VRABEC, 2001).

Ugotovljene kinematske faze aktivnosti Savskega preloma si sledijo v naslednjem zaporedju (VRABEC, 2001): desni zmik z glavno fazo premika, desna transpresija in nastanek stiskajočega prevoja med Preddvorom in Stahovico, tenzijske do transtenzijske deformacije ob ugrezanju Gorenjskega bazena ter ponovna transpresija, ki traja še danes. Dolžina skupnega horizontalnega premika ob prelomu je bila na podlagi korelacije različnih oligocenskih forma-



Slika 1. Potek Savskega preloma in poenostavljena tektonska karta območja (prirejeno po Vrabec & Fodor, 2006). Digitalni model reliefa je iz podatkov SRTM (Shuttle Radar Topography Mission), dostopnih prek Global Land Cover Facility (http://glcf.umiacs.umd.edu/index.shtml).

cij vzdolž preloma ocenjena na 25 km (Hinterlechner – Ravnik & Pleničar, 1967), 40 km (Kazmer et al., 1996) oziroma 65–70 km (Placer, 1996).

Savski prelom velja za aktiven prelom (Poljak et al., 2000, 2010; Vrabec & Fodor, 2006), vendar njegova kvartarna aktivnost še ni bila podrobneje raziskana. Kvartarno aktivnost sicer nakazujejo izrazita topografija in v reliefu jasno vidna trasa preloma (Vrabec, 2001; Kastelic, 2007) ter nekatere deformacije kvartarnih sedimentov (Vrabec, 2001). Potencialno recentno aktivnost preloma nakazujejo tudi hipocentri potresov, ki se pojavljajo na širšem območju (Poljak et al., 2000, 2010). Študija aktivnih premikov v Periadriatskem prelomnem sistemu v Sloveniji z uporabo GPS-tehnologije je ob zahodnem delu trase Savskega preloma ugotovila aktivne desne premike s hitrostjo okoli 1 mm na leto (Vrabec et al., 2006).

Kot aktiven prelom regionalnih razsežnosti je Savski prelom verjeten vir seizmičnih dogodkov, vendar iz zgodovinskih zapisov ne poznamo nobenega uničujočega potresa, ki bi mu ga lahko z gotovostjo pripisali. Iz kataloga potresov (Živčić, 2009) je v širšem območju Savskega preloma poznanih nekaj potresov z magnitudami med 3 in 4,9. Le-ti so se morda zgodili na Savskem, morda pa na katerem od spremljajočih prelomov, saj hipocentri niso določeni z natančnostjo, ki bi omogočala zanesljivo korelacijo potresov s posameznimi prelomi.

Da bi opredelili kvartarno aktivnost Savskega preloma in s tem pripomogli k boljšemu razumevanju njegove recentne aktivnosti in potencialne potresne nevarnosti, smo geomorfološko analizirali njegovo traso na odseku med Golnikom in Predvorom, iskali geomorfne indikatorje za kvartarno aktivnost preloma in poskusili kvantificirati hitrost premikov ob njem.

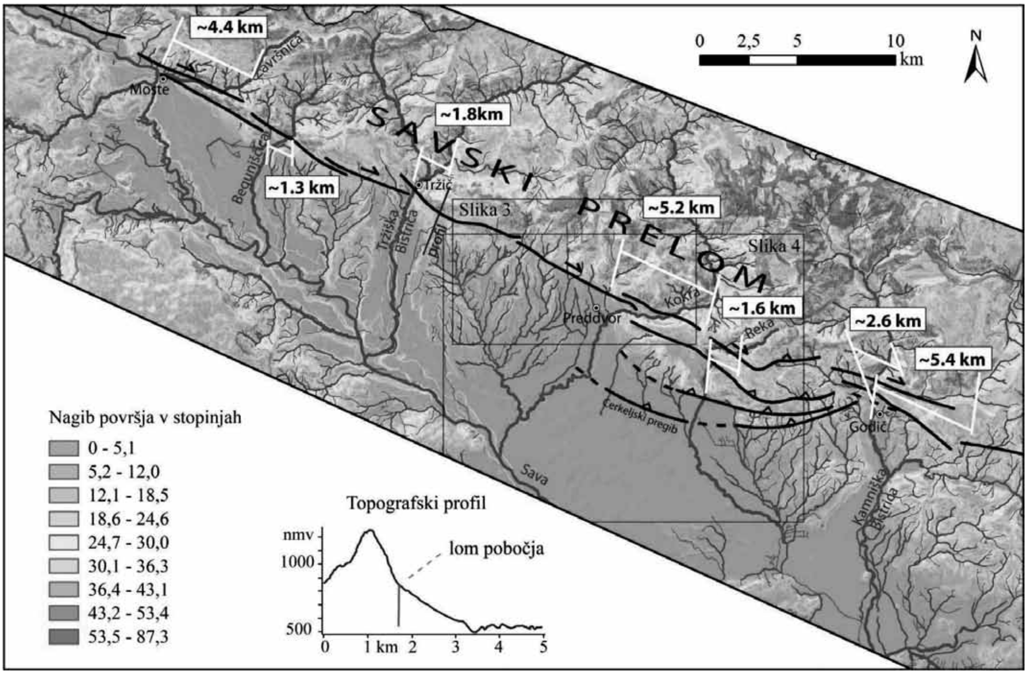
TEKTONSKO-GEOMORFOLOŠKA OPAZOVANJA

Geomorfološko kartiranje trase Savskega preloma in tektonsko-geomorfološka opazovanja deformacij ob njem smo izvedli z analizo Temeljnih topografskih načrtov meril 1 : 5 000 in 1 : 10 000 (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, TTN 5 in TTN 10, 1999), Topografskih podatkov merila 1 : 25 000 (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, GKB 25, 2005), digitalnega modela reliefa z ločljivostjo 5 m, izdelanega iz podatkov Digitalnega modela višin (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, DMV 5, 2006), letalskih posnetkov v stereo parih in satelitskih SPOT-posnetkov z ločljivostjo 2,5 m v stereo parih. Opravili smo tudi terenske oglede zanimivih lokacij. Iz podatkov DMV 5 so bili izdelani topografski profili in karta nagibov površja.

Regionalna geomorfološka izraženost Savskega preloma

Savski prelom je sicer med geomorfološko najbolj izraženimi prelomi na ozemlju Slovenije, vendar pa je tektonsko-geomorfološko kartiranje njegove trase pokazalo, da le-ta ni povsod jasno vidna. Vzdolž Zgornjesavske doline je trasa preloma slabše izražena, kar bi lahko nakazovalo manjšo aktivnost preloma na tem odseku, še bolj verjeten razlog pa tiči v poledenitvah, predvsem v zadnji ledeni dobi, ko je Savski ledenik lahko izbrisal ves geomorfni tektonski signal, čas po umiku ledenika pa ni bil dovolj dolg, da bi se kasnejši premiki jasno izrazili v površju. Trasa Savskega preloma je nato izjemno dobro geomorfološko izražena na območju med HE Moste pri Jesenicah in Preddvorom, kjer jo definira oster lom v naklonu površja (slika 2). Na tem odseku je prelom očitno segmentiran na posamezne desnozmične segmente. Vzhodno od Preddvora preide Savski prelom v transpresiven stiskajoči prevoj (iz angl. *restraining bend*, po VRABEC, 2001), ki ga sestavljajo od SZ–JV do ZSZ–VJV usmerjeni desnozmični do desnoreverzni prelomi in SV–JZ do V–Z usmerjeni reverzni prelomi in narivi (VRABEC, 2001). Trase teh prelomov so relativno jasno izražene v reliefu med Preddvorom in Godičem. Najjužnejši tak prelom je Cerkeljski pregib (po VRABEC, 2001), ki tvori do 5 m visoko stopnjo v Würmskem prodnem vršaju Kokre. Transpresivni sistem se konča pri Godiču severno od Kamnika, kjer preko doline Kamniške Bistrice poteka več vej Savskega preloma, ki so na tem območju še jasno vidne v površju, dalje proti vzhodu pa postane trasa preloma spet slabše geomorfološko izražena in jo zato tu ne bomo podrobneje obravnavali.

Lom v naklonu površja vzdolž prelomne trase je lahko posledica spremembe v litologiji preko preloma, vendar pa lom opažamo tudi tam, kjer litoloških sprememb ni. Zato lomljeno površje interpretiramo kot znak aktivnosti Savskega preloma v določenem časovnem obdobju. Določeno časovno obdobje pri tem razumemo kot čas, ki je dovolj dolg za obprelomno oblikovanje reliefa in obenem dovolj kratek, da se tektonski relief še ohrani. V tektonski geomorfologiji navadno privzamemo, da je to časovno obdobje kar obdobje kvartarja. Ker



Slika 2. Karta nagibov površja z označeno aktivno traso Savskega preloma na območju med Jesenicami in Tuhinjem, topografski profil preko Savskega preloma pri Tržiču ter ocenjeni desni zamiki tokov večjih rek. Na topografskem profilu je označeno mesto loma pobočja, kar je ena od značilnih geomorfoloških oblik na trasi aktivnih prelomov. Karta nagibov površja in topografski profil sta bila izdelana iz podatkov DMV 5 (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, DMV 5, 2006). Vir vodotokov so Topografski podatki merila 1 : 25 000, GKB 25, podatkovni sloj vode (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, GKB 25, 2005).

so kvartarno aktivni prelomi v večini primerov tudi recentno aktivni, lahko spoznanja o kvartarni aktivnosti uporabimo tudi kot indikacijo recentnih premikanj.

Desnozmična aktivnost Savskega preloma v daljšem časovnem obdobju je razvidna tudi iz povijanja tokov vseh večjih rek, ki ga prečkajo. Na območju med Jesenicami in Tuhinjem so to Završnica, Begunjščica, Tržiška Bistrica, Kokra, Reka in Kamniška Bistrica (slika 2). Zavoji teh rek nakazujejo med okoli 1,3 km do 5,4 km desnega zmika vzdolž slemenitve preloma. Reke ob prečkanju preloma tudi drastično spremenijo svoj režim iz vrezovanja severno od preloma v akumulacijo (nasipavanje) južno od preloma, zaradi česar je v kvartarju južno od preloma nastal sistem rečnih teras in vršajev. Danes so te reke sicer vrezane v svoje sedimente, kar pa je (najverjetneje) predvsem posledica klimatskih sprememb in z njimi povezanim padcem erozijske baze po zadnjem glacialnem maksimumu, ne moremo pa izključiti niti regionalnega dvigovanja ozemlja. Kljub temu je Savski prelom tudi danes izrazita geomorfološka meja med goratim reliefom Karavank in Kamniško-Savinjskih Alp severno od preloma in nižinskim reliefom Ljubljanske kotline južno od njega. Iz tega sklepamo, da ima Savski prelom tudi pomembno vertikalno komponento premika (ali pa jo je imel v preteklosti).

Geomorfološka analiza med Golnikom in Preddvorom

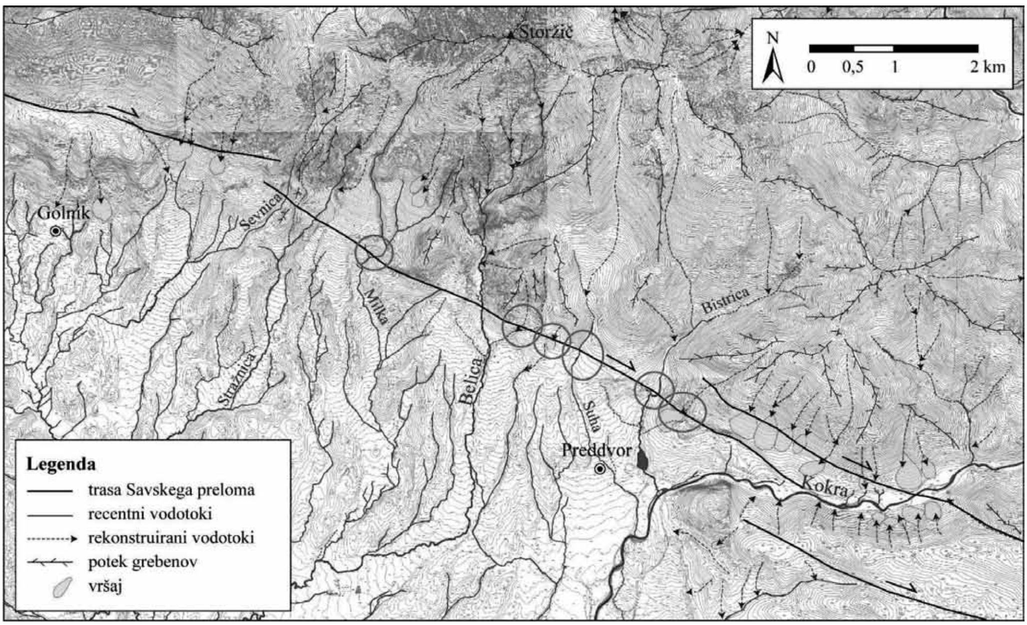
Na območju med Golnikom in Preddvorom je trasa Savskega preloma geomorfološko zelo dobro izražena. Geomorfološko kartiranje potek preloma postavlja na kontakt med goratim območjem, v katerega so vrezane številne doline različnih velikostnih razredov, ter pobočjem, ki ga prekrivajo vršaji aluvialnega in koluvialnega izvora. Na tem kontaktu se naklon površja izrazito lomi. Iz poteka grebenov in vodotokov je razvidno, da je hidrološki relief razvit prečno na aktivni prelom, kar je ugodneje za ugotavljanje deformacij površja kot v primeru drenaže, razvite vzporedno s prelomom (npr. Zgornjesavska dolina). Grebeni in doline severno od preloma so usmerjeni večinoma v smeri SV–JZ, nekaj jih ima orientacijo S–J, nekateri pa potekajo tudi v smeri V–Z. S slike 3 je razvidno, da je nekaj strug potokov ob prečkanju trase Savskega preloma rahlo povitih, kot bi bile desno zamaknjene ob prelomu z dolžino premika med 100 m in 200 m. Nekaj potokov sicer takega povijanja ne kaže. Takšen je denimo potok Belica; njegova nedeformiranost je morda posledica močnejšega pretoka, zaradi česar ima potok večjo moč uravnavanja struge sočasno s tektonskimi deformacijami, morda pa je drenažni sistem mlajši od drugih. Analiza vršajev in teras ob Belici bi lahko pokazala zgodovino deformacij ob tem potoku. Nedeformirana sta videti tudi potoka

Sevnica in Stražnica, ki prečkata segment Golnik–Preddvor na njegovem SZ koncu. Mislimo, da je tam desnozmična deformacija zaradi prenosa premika med prelomnimi segmenti manj lokalizirana in bi bilo potrebno daljše obdobje, da bi lahko tam nastale vidne deformacije površja.

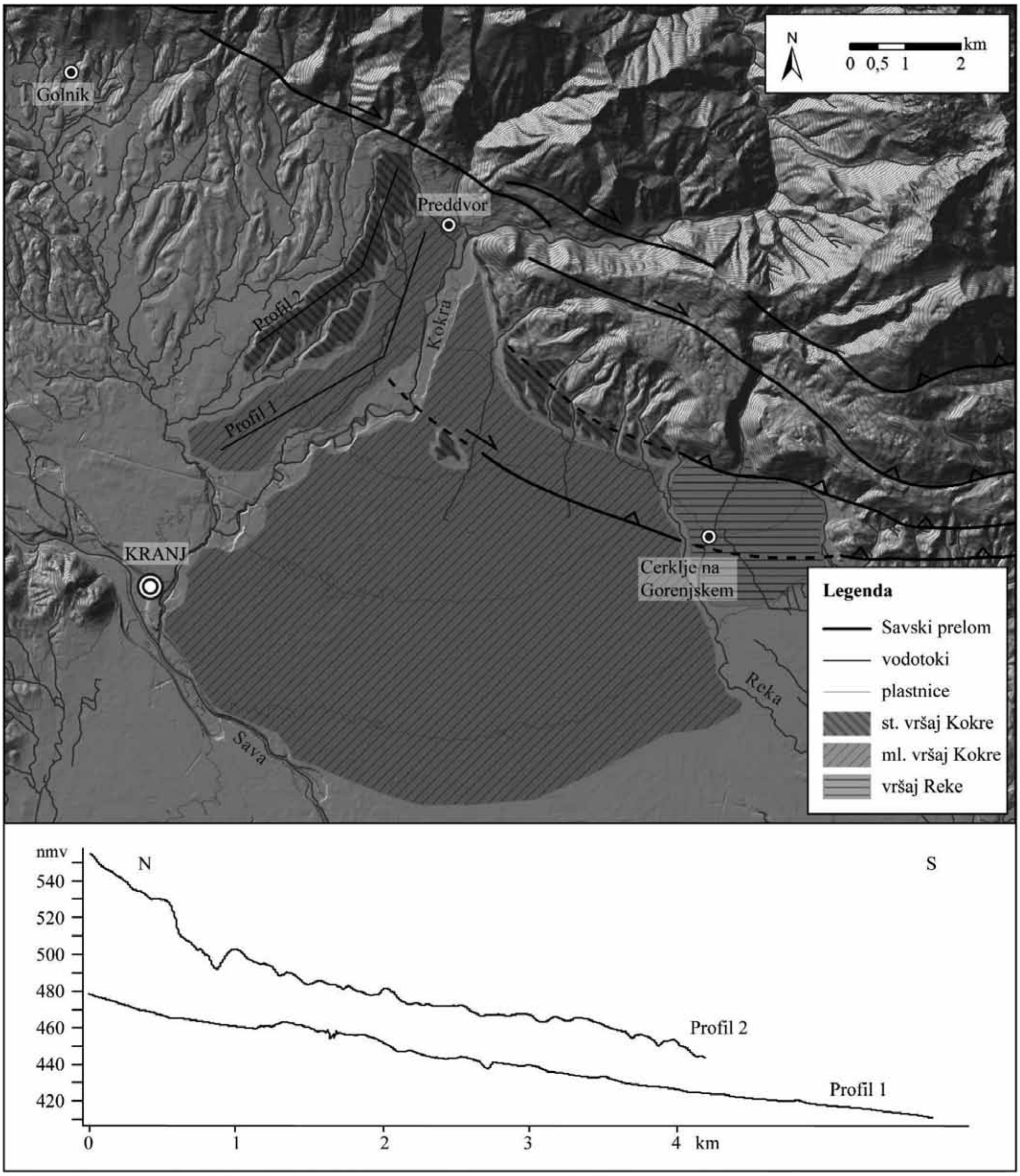
Iz oblike površja so bili rekonstruirani tudi občasni vodotoki, ki se večkrat končajo v vznožju pobočja v obliki manjšega vršaja (slika 3). Prehod iz grape v vršaj se pogosto nahaja na prelomnem kontaktu; enako kot pri stalnih vodotokih in njihovih kvartarnih vršajih. Geomorfološko kartiranje teh vršajev še poteka, vendar že njihov obstoj priča o vertikalni komponenti aktivnosti Savskega preloma v kvartarju.

Vršaj Kokre

Med številnimi vršaji, ki so jih ustvarile reke in potoki južno od Savskega preloma na območju Gorenjskega bazena, je vršaj Kokre daleč največji in tudi med najlepše ohranjenimi. Njegova oblika je lepo vidna iz poteka plastnic na dolžini okrog 10 km in širini dobrih 9 km (slika 4). Na površju ohra-



Slika 3. Zamiki strug manjših vodotokov med Golnikom in Preddvorom (označeni s krožnicami) ter manjši recentni vršaji, ki nastajajo ob zaključkih pobočnih grap, po katerih tečejo hudourniki. Vir plastnic in vodotokov so Temeljni topografski načrti meril 1 : 5 000 in 1 : 10 000 (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, TTN 5 in TTN 10, 1999).



Slika 4. Geomorfološka karta vršaja Kokre. Digitalni model reliefa in plastnice z ekvidistanco 25 m so izdelani iz podatkov DMV 5 (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, DMV 5, 2006). Vir vodotokov so Topografski podatki merila 1 : 25 000, GKB 25, podatkovni sloj vode (Javne informacije Slovenije, Geodetska uprava Republike Slovenije, GKB 25, 2005). Topografska profila 1 in 2 sta izdelana iz podatkov DMV 5.

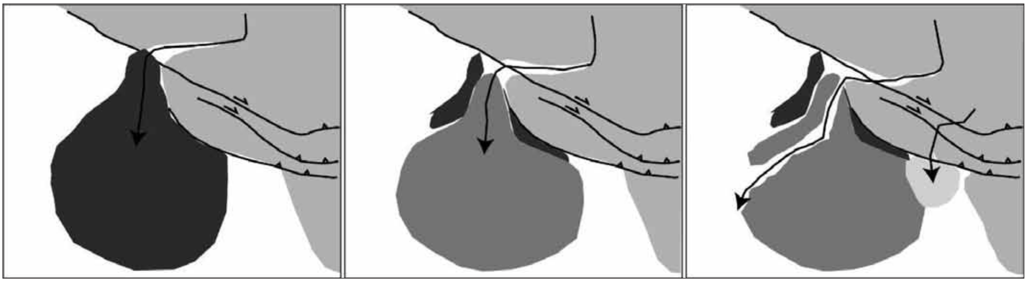
njena pahljačasta oblika vršaja je vidna na obeh straneh današnje reke Kokre, ki se vanj vrezuje. Na svojem V robu je vršaj Kokre prekrit z vršajem Reke, ki ima še lepše ohranjeno površje in je očitno mlajši. Geomorfološki pregled površja V in Z od vršaja Kokre nakazuje prisotnost podobno oblikovane površine tudi vzdolž njegovih bokov, le da ta površina leži približno 15 m nad njim in je manj ohranjena oziroma je močneje erodirana – torej starejša (slika 4). Podobno višje ležeče površje se nahaja tudi sredi vršaja Kokre in je erodirano z vseh strani. Domnevamo, da bi te površine lahko bile ostanek nekoč enotne površine starejšega vršaja Kokre. Rekonstruirana enotna površina je namreč podobnih razsežnosti kot mlajši vršaj Kokre, zaradi česar sklepamo, da jo je lahko odložila le Kokra, ki je edina dovolj velika reka na tem območju. Topografska profila v smeri padca obeh vršajev (slika 4) namreč kažeta, da imata obe površini enak sedimentacijski padec skoraj na celotni dolžini, le da ima starejši vršaj v zgornjem delu bolj strm profil, zaradi česar bi lahko sklepali, da ga tam dodatno prekriva mlajši koluvij in/ali potočni vršaj.

Starost sedimentacije opisanih vršajev je bila opredeljena z relativnimi metodami na podlagi kartiranja kvartarnih sedimentov, morfostratigrafskih značilnosti njihovih površin (Žlebnik, 1971) in značilnosti tal (Vidic et al., 1991). Mlajši vršaj Kokre in vršaj Reke sta bila pripisana morfostratigrafski enoti Würm I, medtem ko so bili deli starejšega vršaja Kokre pripisani enotam Riss, Mindel in Günz. Kasnejše absolutno datiranje površja s kozmogenim izotopom ^{10}Be in z analizami paleomagnetizma na različnih lokacijah v Gorenjskem bazenu (Pavich & Vidic, 1993; Vidic & Lobnik, 1997) uvršča enoto Würm I v časovno obdobje med 50 tisoč in 70 tisoč leti, Riss med 435 tisoč in 515 tisoč leti, Mindel med 780 tisoč in milijon leti ter Günz med milijon in 1 800 milijon leti. Z uporabo morfostratigrafske korelacije te starosti lahko uporabimo tudi za vršaje Kokre, kar povzemamo v tabeli 1.

Domnevamo, da je bila kronologija formiranja površja na območju vršajev Kokre in Reke naslednja (slika 5): a) sedimentacija starejšega vršaja Kokre, b) erozija starejšega vršaja Kokre, c) sedimentacija mlajšega vršaja Kokre, č) sedimentacija vršaja Reke, d) vrezovanje Kokre v mlajši vršaj. V več sto tisoč letih oblikovanja površja ob sočasni aktivnosti Savskega preloma se premik ob prelomu izraža v zamiku vrhov obeh vršajev Kokre. Rekonstruirani položaj vrha starejšega vršaja se nahaja SZ od vrha mlajšega vršaja. Iz njune današnje medsebojne razdalje ocenjujemo premik ob Savskem prelomu v času med odložitvijo starejšega in mlajšega vršaja na 1,0 km do 1,5 km v smeri slemenitve preloma.

Tabela 1. Starost vršajev Kokre in Reke

	Morfostratigrafska enota (VIDIC et al., 1991)	**Absolutna starost** (VIDIC & LOBNIK, 1997)
Starejši vršaj Kokre	Riss, Mindel ali Günz	435–1 800 · 10^3 let
Mlajši vršaj Kokre	Würm I	50–70 · 10^3 let
Vršaj Reke	Würm I	50–70 · 10^3 let



Slika 5. Kronologija sedimentacije vršajev Kokre pod vplivom Savskega preloma (zaporedje od leve proti desni).

HITROST PREMIKOV OB SAVSKEM PRELOMU

Aktivnost Savskega preloma je mogoče ovrednotiti z oceno hitrosti premikov ob njem, za kar je treba poznati dolžino premika in čas, v katerem je premik nastal. Povprečne hitrosti premikov (v nadaljevanju PHP) in recentne hitrosti premikov (v nadaljevanju RHP) ob prelomu lahko ocenimo na podlagi različnih metod. Izbira metode je odvisna od časovnega razpona, za katerega PHP oz. RHP določamo. S premiki, določenimi na podlagi geoloških meril, je praviloma mogoče oceniti PHP za daljše časovno obdobje (*long-term slip-rate*), z geomorfološko določenimi premiki za krajše časovno obdobje (*short-term slip-rate*), z geodetskimi metodami pa je mogoče določiti RHP. V literaturi so podane različne ocene za dolžino premika ob Savskem prelomu na podlagi zamika geoloških enot (Hinterlechner – RAVNIK & PLENIČAR, 1967; KAZMER et al., 1996; PLACER, 1996) in za RHP, ki je bila izmerjena z GPS (VRABEC et al., 2006). K tem podatkom dodajamo še oceno hitrosti premikov na podlagi geomorfoloških meril, ki jih predstavljamo v tem članku. Pregled vseh meril podajamo v tabeli 2.

Pri določitvi dolžine premika na podlagi geoloških meril avtorji uporabljajo zamik zgornjeoligocenskih vulkanoklastičnih kamnin, manj pa je jasno, kakšna je zgornja starostna meja začetka aktivnosti Savskega preloma.

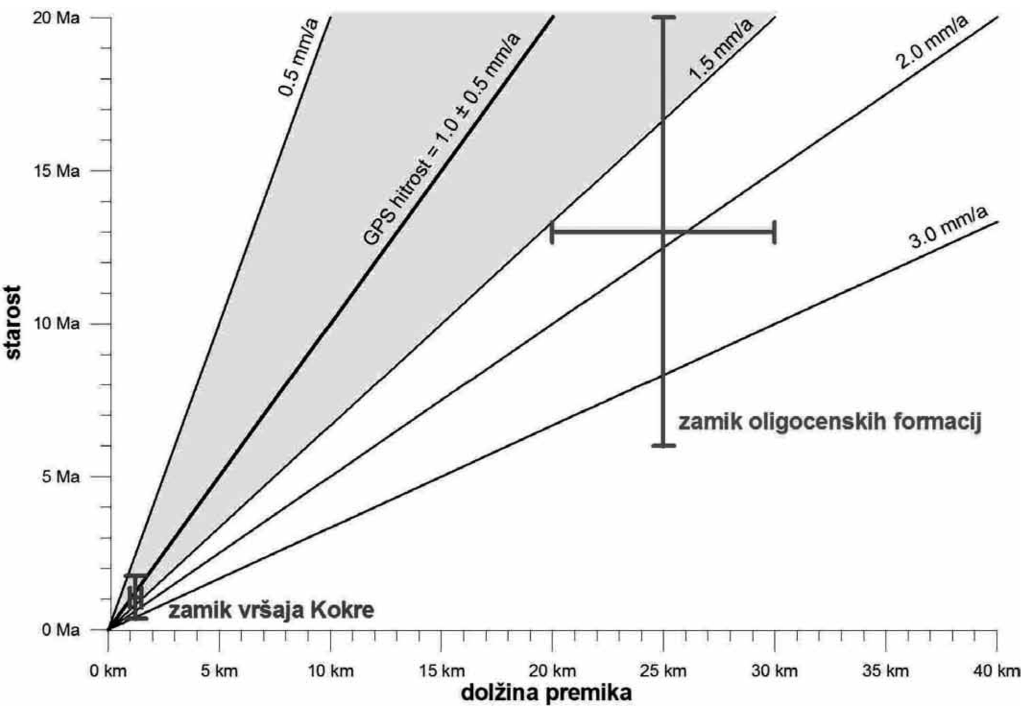
Do sarmatija (12 milijonov let) na območju osrednje Slovenije prevladuje morska sedimentacija, prevladujoče napetostno stanje pa je tenzija v smeri približno V–Z (npr. Fodor et al., 1998), kar ne omogoča desnih premikov ob Savskem prelomu, ki so vezani na kompresijo v smeri približno S–J (Vrabec, 2001). Tudi po podatkih OGK vzhodno od Kamniške Bistrice prelomi cone Savskega preloma jasno sekajo tam razgaljene srednjemiocenske plasti (Premru, 1983), kar postavlja aktivnost Savskega preloma v čas po približno 14 milijoni let. Ob regionalnih prelomih v vzhodnem delu Periadriatskega prelomnega sistema v Sloveniji deformirane srednjemiocenske plasti in veliki zamiki srednjemiocenskih tektonostratigrafskih enot kažejo, da so desnozmične transpresivne deformacije mlajše od srednjega miocena (Fodor et al., 1998). Vrabec (2001) povezuje nastanek velike prevrnjene gube v neogenskih plasteh Tunjiškega gričevja s transpresivnimi deformacijami v stiskajočem prevoju Savskega preloma pri Kamniku, kar bi glede na starost najmlajših nagubanih plasti omejilo aktivnost preloma na obdobje po sarmatiju. Na podlagi regionalne korelacije je bila glavna faza aktivnosti Savskega preloma vezana na nastop inverzijske faze v Panonskem bazenu in transpresivnega gubanja v Posavskih gubah južno od preloma pred približno 6 milijoni let na prehodu iz miocena v pliocen (Vrabec & Fodor, 2006). Vendar pa struktura prelomne cone v stiskajočem prevoju Savskega preloma severno od Kamnika kaže, da se je faza velikih premikov ob prelomu zgodila že pred nastopom transpresivnega povijanja ob prelomu (Vrabec, 2001), kar dopušča, da se je aktivnost preloma začela že pred 6 milijoni let.

V svoji oceni smo za skupno dolžino premika ob Savskem prelomu vzeli bolj konzervativno vrednost med 20 km in 30 km, ki je po našem mnenju bolj realna (Vrabec et al., v pripravi). Za časovno obdobje, v katerem se je ta premik zgodil, privzemamo glede na zgornjo diskusijo kot zgornjo mejo 20 milijonov let, kot spodnjo pa 6 milijonov let (tabela 2, slika 6). Ocena dolgoročne PHP za Savski prelom je tako od 1,0 mm do 5,0 mm na leto. Geomorfološko ocenjena kratkoročna PHP na podlagi naše ocene zamika vršaja Kokre je od 0,6 mm do 4,1 mm na leto, RHP, izmerjena z GPS, pa je okrog 1 mm na leto z natančnostjo okoli ±0,5 mm na leto.

Pri analizi ocenjenih vrednosti je treba upoštevati, da je na ozemlju Slovenije recentna hitrost konvergence med Jadransko mikroploščo in Evrazijo 2–4 mm na leto (npr. Weber et al., 2010). Ta deformacija je porazdeljena po vseh aktivnih strukturah ozemlja, tako da lahko pričakujemo, da so maksimalne hitrosti premikov ob posameznih prelomih v območju 0,1–1,0 mm na leto.

Tabela 2. Primerjava hitrosti premikov ob Savskem prelomu, pridobljenih z različnimi metodami

Metoda	Avtorji	Zamik	Starost (čas)	Povprečna hitrost premika
Geološko določen premik	Hinterlechner–RAVNIK & PLENIČAR (1967)	25 km	6–20 · 10^6 let	1,3–4,2 mm na leto
	KAZMER in sod. (1996)	40 km	6–20 · 10^6 let	2,0–6,7 mm na leto
	PLACER (1996)	65–70 km	6–20 · 10^6 let	3,25–11,7 mm na leto
	VRABEC (2001)	30–50 km	6–20 · 10^6 let	1,5–8,3 mm na leto
Geomorfološko določen premik	ocenjen zamik vršaja Kokre (ta prispevek)	1,0–1,5 km	(365–1 750 · 10^3 let)	0,6–4,1 mm na leto
GPS	VRABEC et al. (2006)		Recentno	(1,0 ± 0,5) mm na leto



Slika 6. Primerjava ocenjenih hitrosti premikov ob Savskem prelomu na podlagi podatkov, uporabljenih v tem članku

Palinspastične rekonstrukcije postkolizijskih deformacij v Alpskem orogenu za zadnjih 20 milijonov let ne kažejo bistveno povečanih hitrosti tektonskih procesov, zato hitrosti premikov ob Savskem prelomu, ki bi bile bistveno višje od današnjih, verjetno niso geološko realistične.

Geomorfološko določena kratkoročna PHP in geodetsko izmerjena RHP se v okviru natančnosti dobro ujemata (slika 6). Natančnejše opredelitve bodo mogoče, ko bomo podrobneje raziskali geomorfološke znake aktivnosti ob Savskem prelomu in jih ustrezno natančno datirali z absolutnimi metodami, prav tako je že v pripravi nov preračun z GPS izmerjenih hitrosti tektonskih deformacij v regiji.

Geološko ocenjena dolgoročna PHP kaže, da so bile hitrosti premikov ob Savskem prelomu v geološki preteklosti verjetno vsaj nekoliko večje kot danes, saj dobimo z RHP primerljivo hitrost le, če uporabimo minimalno dolžino premika 20 km in maksimalni časovni razpon 20 milijonov let (slika 6), če pa uporabimo po našem mnenju bolj realistične vrednosti do 25 km in do 14 milijonov let, dolgoročna PHP naraste na 1,5 mm do 2,0 mm na leto. Manj je verjetno, da je skupni desni premik ob Savskem prelomu 40 km ali več, saj bi v tem primeru dobili za dvakrat do petkrat večje hitrosti premikov, ki pa najbrž niso realistične (tabela 2).

Sklepi

Oblikovanost površja lahko razodene mnogo informacij o načinu nastanka in razvoja površja ter o dejavnikih, ki so vplivali na procese oblikovanja. Med drugim lahko iz oblikovanosti površja prepoznamo tudi vplive tektonskih procesov. Geomorfološke informacije so ključne pri ugotavljanju kvartarne oziroma recentne aktivnosti tektonskih struktur v regionalnem in tudi v bolj lokalnem merilu.

Na območju med HE Moste in Godičem je Savski prelom dobro geomorfološko izražen. Orientacija geomorfnih indikatorjev prečno na prelom in njihova kvartarna starost omogoča izvedbo tektonsko-geomorfoloških analiz, saj so indikatorji dovolj stari, da se na njih akumulirajo deformacije, hkrati pa so nastale geomorfne oblike ostale ohranjene in jih je mogoče datirati. Naše tektonsko-geomorfološke analize Savskega preloma so pokazale znake za njegovo kvartarno desnozmično aktivnost na območju med HE Moste in Preddvorom ter potrdile njegov desno transpresiven značaj med Preddvorom in Godičem. Večje reke so desno zamaknjene prek preloma za 1,3–5,4 km. Med Golnikom in Preddvorom smo ob prelomu ugotovili 100–200 m dolge desne zamike potokov, na območju kvartarne sedimentacije reke Kokre pa desni zamik vrhov njenih različno starih vršajev za 1,0–1,5 km.

Ocenili smo kratkoročno in dolgoročno povprečno hitrost premikov ob Savskem prelomu. Geološko ocenjena dolgoročna PHP je od 1,0 mm do 5,0 mm na leto za obdobje v zadnjih 20–6 milijonov let pred sedanjostjo, geomorfološko določena kratkoročna PHP pa od je od 0,6 mm do 4,1 mm na leto v obdobju 365–1 750 tisoč let pred sedanjostjo, kar je v okviru z GPS izmerjene recentne hitrosti premikov (1,0 ± 0,5) mm na leto. V prihodnje nameravamo z natančnim kartiranjem geomorfnih indikatorjev vzdolž celotne trase Savskega preloma med HE Moste in Godičem in z njihovo datacijo natančneje ovrednotiti kvartarno aktivnost preloma in s tem oceniti stopnjo potresne nevarnosti, ki jo pomeni prelom.

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