ГЕОЛОШКИ ЗАВОД УНИВЕРЗИТЕТА У БЕОГРАДУ
INSTITUT GÉOLOGIQUE DE L'UNIVERSITÉ A BELGRADE

ГЕОЛОШКИ АНАЛИ
БАЛКАНСКОГА ПОЛУОСТРВА

Година оснивања 1888.

КЊИГА LXXII

Уредник

ВЛАДАН РАДУЛОВИЋ

ANNALES GÉOLOGIQUES
DE LA PÉNINSULE BALKANIQUE

Fondée en 1888

TOME LXXII

Rédacteur

VLADAN RADULOVIĆ

БЕОГРАД 2011 BELGRADE

ISSN 0350-0608 **UDC 55+56 (1-924.64)**

Геолошки анали Балканскога полуострва
Annales Géologiques de la Péninsule Balkanique

Founded in 1888

For this volume, the following reviewers are gratefully acknowledged:

Alexey BENDAREV (Sofia, Bulgaria), Paola DE CAPOA (Naples, Italy), Nikolaos CARRAS (Athens, Greece), Stjepan ĆORIĆ (Vienna, Austria), Romeo EFTIMI (Tirana, Albania), Aleksandar GRUBIĆ (Belgrade, Serbia), Rade JELENKOVIĆ (Belgrade, Serbia), Elena KOLEVA–REKALOVA (Sofia, Bulgaria), Ruslan KOSTOV (Sofia, Bulgaria), Veselin KOVACHEV (Sofia, Bulgaria), Marcin MACHALSKI (Warszawa, Poland), Mira MILIĆ (Banja Luka, Bosnia and Herzegovina), Radoslav NAKOV (Sofia, Bulgaria), Todor NIKOLOV (Sofia, Bulgaria), Ladislav PALINKAŠ (Zagreb, Croatia), Platon TCHOUMATCHENCO (Sofia, Bulgaria), Hans ZOJER (Graz, Austria).

Managing Editor

Vladica CVETKOVIĆ, Dean

Technical Editor and computer work

Nenad MALEŠEVIĆ

Language review

Lynne KATSIKAS

Published by

Department of Geology and Department of Palaeontology,
Faculty of Mining and Geology, University of Belgrade,
Kamenička 6, 11000 Belgrade, Serbia.

Abbreviation

Geol. an. Balk. poluos. / Ann. Géol. Pénins. Balk.

Printed at

“Excelsior”, Belgrade

Impression

500 exemplares

The editing of the journal is supported by the Ministry of Education and Science of the Republic of Serbia and the Faculty of Mining and Geology, Belgrade

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	1–20	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172001T

Trans-border (north-east Serbia/north-west Bulgaria) correlations of the Jurassic lithostratigraphic units

Platon Tchoumatchenco[1], Dragoman Rabrenović[2], Vladan Radulović[3], Nenad Malešević[2] & Barbara Radulović[3]

Abstract. Herein, correlations of the Jurassic sediments from NE Serbia with those of NW Bulgaria are made. The following Jurassic palaeogeographic units: the Eastern Getic, the Infra-Getic and the Moesian Platform are included in the study. The East Getic was studied in the outcrops near Rgotina, where the sedimentation started in the Hettangian and continued during the Callovian–Late Jurassic and is represented by platform carbonates. The Infra-Getic is documented by the sections of Dobra (Pesača) and the allochtonous sediments near the Štubik. Very important for the Infra-Getic are the Late Jurassic volcano–sedimentary deposits of the Vratarnica Series, which crop out near Vratarnica Village. The Jurassic Moesian platform was studied in the sections near D. Milanovac and Novo Korito (Serbia) and in their prolongation in NW Bulgaria into the Gornobelotintsi palaeograben. Very important are the correlation in the region of Vrška Čuka (Serbia) and Vrashka Chuka (Bulgaria) – Rabisha Village (Magura Cave). A revision of the Jurassic sediments on the Vidin palaeohorst, which were studied in the Belogradchik palaeohorst, Gorno-Belotintsi palaeograben, Belimel palaeohorst and the Mihaylovgrad palaeograben, is made. The sedimentation on the Vidin palaeohorst started during different parts of the Middle Jurassic, and in the Mihaylovgrad palaeograben during the Hettangian (Lower Jurassic) where the sediments were deposited in relatively deeper water conditions. To south, the relatively shallow water sediments deposited on the Jurassic Vratsa palaeohorst on the southern board of the Mihaylovgrad palaeograben are described.

Key words: Jurassic, north-eastern Serbia, north-western Bulgaria, correlations, lithostratigraphic units.

Апстракт. Приказана је корелација јурских седимената североисточне Србије и северозападне Бугарске. У проучаваном подручју издвојене су следеће палеогеографске јединице: Источни Гетик, Инфра-гетик и Мезијска платформа. Источни Гетик је проучаван на изданцима у близини Рготине, где седиментација започиње од хетанжа, за време келовеј–горња јура таложе се платформни карбонати. Инфра-гетик је документован на профилима Добре (Песача) и алохтоним седиментима у близини Штубика. Главна карактеристика Инфра-гетика су горњојурско вулканско-седиментне творевине Вратарничке серије. Јурска Мезијска платформа је проучавана код Доњег Милановца и Новог Корита у Србији и Горнобелотинског рова у Бугарској. Урађена је корелација у области Вршке Чуке са обе стране границе и код села Рабиша (пећина Магура у Бугарској). Приказана је ревизија јурских седимената у Бугарској, код Видинског хорста, који су проучавани на Белоградчиском, Горње Белотинском, Белимелском и Михајловградском рову. Седиментација у Видинском хорсту започиње у различитим деловима средње јуре, а у Михајловградском рову за време хетанжа (доња јура) где се седиментација одвијала у релативно дубоководној средини. Јужно се одвијала плитководна седиментација на јурском Вратца гребену, на јужном крилу Михајловградског рова.

Кључне речи: Јура, североисточна Србија, северозападна Бугарска, корелација, литостратиграфске јединице.

[1] Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria. E-mail: platon@lark.tu-sofia.bg

[2] Department of Geology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, P. O. Box 162, 11000 Belgrade, Serbia. E-mails: rabrenovic@verat.net; malesevic.nesa@gmail.com

[3] Department of Palaeontology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, P. O. Box 162, 11000 Belgrade, Serbia. E-mail: vrad@eunet.rs; brad@net.co.rs

Introduction

It is well known that the rock strata – sedimentary, igneous or metamorphic are organized in lithostratigraphic units based on macroscopically discernable lithologic properties or combination of lithologic properties and their stratigraphic relations. Often these units cross the state boundaries. However, it is the general practice that on geological maps, the lithostratigraphic units from the two sides of a state border are different and have different names. This is also the case with the Jurassic lithostratigraphic units on the two sides of the Serbian/Bulgarian state boundary. Our aim is to make correlations of the Jurassic lithostratigraphic units from the two sides of this state border. For the beginning, in the literature existing trans-border units (TCHOUMATCHENCO *et al*. 2006a, 2008) are correlated. With the present paper, this stage of the correlation in the north-east Serbia/north-west Bulgaria is finished. The second step, must be, after an analysis of all data, to replace the later names of the lithostratigraphic units by the earlier ones, other considerations being equal, following, in general, the principle of reasonable priority. In this way, the exigencies of the International Stratigraphical Guide (SALVADOR 1994; "Relation of Names to Political Boundaries") will be satisfied.

The Jurassic sediments within the framework of the study area of eastern Serbia and western Bulgaria enter the following large palaeogeographic units (TCHOUMATCHENCO *et al*. 2006a, 2008) (from west to east): the Getic (Dragoman Jurassic Pale horst in Bulgaria and Karpatikum in Serbia), divided into two sub-units – Eastern and Western Getic (TCHOUMATCHENCO *et al*. 2008) based on the presence (in Eastern Getic) or absence (in Western Getic) of Liassic sediments; the Infra-Getic Unit (Izdremets Jurassic Palaeograben in Bulgaria and Stara Planina–Poreč Unit in Serbia); the Moesian Platform. The purpose of this paper is the correlation of the Jurassic sediments across the state border in north-east Serbia and north-west Bulgaria.

The Serbian lithostratigraphic units have been described by D. Rabrenović, V. Radulović, N. Malešević and B. Radulović with the participation of P. Tchoumatchenco and of the Bulgarian, by P. Tchoumatchenco.

Jurassic Lithostratigraphic units

Nota Bene. The number in the description of the lithostratigraphic units corresponds to the number of the lithostratigraphic units in Figures 1, 2, 3; N - indicates that the beds are not nominated.

Getic Palaeogeographic Unit

The Getic is developed on the back-ground of the Serbo-Macedonian – Thracian Massif. During the Early Jurassic the whole territory represents dry land. In eastern Serbia in this unit enters large parts of the Carpatho–Balkan region of ANDJELKOVIĆ *et al*. (1996). In study area enters only the East Getic Unit, where the sedimentation in the vicinities of Rgotina started in the Early Jurassic.

Rgotina section (Figs. 1: Sb-1, 2). Here were deposited: **(N 1)** – sandstones with conglomeratic pebbles (Hettangian–Sinemurian); **(1)** – Rtanj brachiopod beds (ANDJELKOVIĆ *et al*. 1996): bioclastic limestones, marls (Pliensbachian, analogous to the Ozirovo Formation); **(N 2)** – grey sandstones (Toarcian–Aalenian); **(N 3)** – grey sandstones in the base intercalated by a bed of grey limestone (Bajocian); **(2)** – Rgotina Beds (ANDJELKOVIĆ *et al*. 1996; analogous to the Gulenovci Beds); in the base **(2a)** – alternation between reddish limestones and grey sandstones (Upper Bajocian–Bathonian) and **(2b)** – red limestones with some corals (Upper Bathonian–Lower Callovian; analogous to the Polaten Formation in Bulgaria); **(3)** – Basara Limestones (Andjelković *et al*. 1996): grey limestones with chert nodules (Middle Callovian; similar to the Belediehan Formation), on their base is exposed a bed **(3a)** with many *Macrocephalites* sp. (Lower Callovian; analogous to the Sokolov Venets Zoogenous Marker in Bulgaria); **(4)** – Vidlič limestones (ANDJELKOVIĆ *et al*. 1996): grey to blue, well bedded, limestones (Middle Callovian–Kimmeridgian (*p. p.*); analogous to the Javorets and Gintsi formations); **(5)** – Crni Vrh Limestones (ANDJELKOVIĆ *et al*. 1996): white to reddish reef and sub-reef limestones, with corals, gastropods, *etc*. (Tithonian–?Berriasian; analogous to the Slivnitsa Formation in Bulgaria).

Infra-Getic Palaeogeographic Unit

During the Jurassic, the Supra-Getic and the Getic units developed on the framework of the Thracian Massif, which had been separated from the other large palaeogeographic unit, the Moesian Platform, by the Infra Getic Unit with a relatively deep water sedimentation since the Hettangian. In the study area, the sediments of the Infra-Getic crop out in the region of the Dobra Village (Pesača River, *etc*.), the Štubik Village and the Vratarnica Village.

Dobra–Pesača (Figs. 1: Sb-2, 2) (VESELINOVIĆ 1975; ANDJELKOVIĆ 1975). **(N-4)** – quartz sandstones at the base with quartz conglomerates, locally with coal **(N-5)** (Lower Liassic); **(N-6)** – quartz, calcareous sandstones to sandy limestones with brachiopods and bivalves (Middle Liassic); **(N-7)** – quartz sandstones without fossils (Toarcian?); **(N-8)** – sandy limestones and clays (Aalenian–Bajocian).

Štubik (Figs. 1: Sb-3, 2) (ANDJELKOVIĆ 1975; ANDJELKOVIĆ *et al*. 1996). **(6)** – Štubik clastites: quartz, thick bedded, reddish to whitish sandstones (Aaleni-

Fig. 1. Sketch map of the locations of the Jurassic outcrops. Legend: **Bg-0,** Vrashka Chuka; **Bg-1,** Magura (Rabisha Village); **Bg-2,** Granitovo Village (Gradishte Peak); **Bg-3,** Belogradchik–Railway Station Oreshets; **Bg-4,** Belogradchik –TV Tower; **Bg-5,** Yanovets Village; **Bg-6,** Dolni Lom Village; **Bg-7,** Prevala – Mitrovtsi Villages; **Bg-8,** Gaganitsa Village; **Bg-9,** Gaganitsa Lake; **Bg-10,** Nikolovo Village (Shugovitsa River); **Bg-11,** Vratsa (Ledenika Cave); **Bg-12,** Kamenna Riksa – Vinishte Villages; **Bg-13,** Gorno Belotintsi Village (Nechinska Bara River); **Sb-1,** Rgotina Village; **Sb-2,** Dobra Village (Pesača River); **Sb-3,** Štubik Village; **Sb-4,** D. Milanovac Town; **Sb-5,** Vrška Čuka; **Sb-6,** Miroč; **Sb-7,** Vratarnica Village.

an–Bajocian (*p. p.*)) – Krajina (analogous to the Gradets Formation); **(7)** – Štubik *"Posidonya"* beds with two horizons with *"Posidonia"*: **(7a)** – First horizon with *"Posidonia" alpina* - fine grained sandstones; **(7b)** Thick bedded sandstones; **(7c)** – Second horizon with *"Posidonia" alpina* - grey marls and marly sandstones (Bajocian–Lower Callovian; no analogy in Bulgaria); **(8)** – Štubik limestones: grey, thick bedded limestones (Middle Callovian–Kimmeridgian; probably analogous to the Javorets Formation).

Vratarnica (Figs. 1: Sb-7, 2) (ANDJELKOVIĆ 1975; ANDJELKOVIĆ *et al.* 1996; ANDJELKOVIĆ & MITROVIĆ-PETROVIĆ 1992). **(9)** – Vratarnica volcanogenous-sedimentary series: argillites, marls, sandstones and rare calcarenites and limestones with calcareous olistolites (Late Tithonian–?Berriasian; no analogy in Bulgaria) (Figs. 4A–C).

Moesian Platform Palaeogeographic Unit

The Moesian Platform is a crustal block, located beyond the south-western margin of the European craton. It was divided during the Jurassic (according PATRULIUS *et al.* 1972; SAPUNOV *et al.* 1988) into three parts: the West and East Carbonate Moesian Platforms separated by the Central Moesian Basin. Herein, only the West Moesian Platform, the sediments of which crop out from the two sides of the Bulgarian/Serbian state border, is studied. To west, it is limited by the Infra-Getic Unit.

The **West Moesian Platform** is structured by the Vidin Horst and the Vratsa Horst separated by the Mihaylovgrad Graben (with its Gornobelotintsi–Novo Korito Branch – Basin (Graben)).

The **Vidin Horst** (SAPUNOV *et al.* 1988) is the north-western part of the West Moesian Platform and

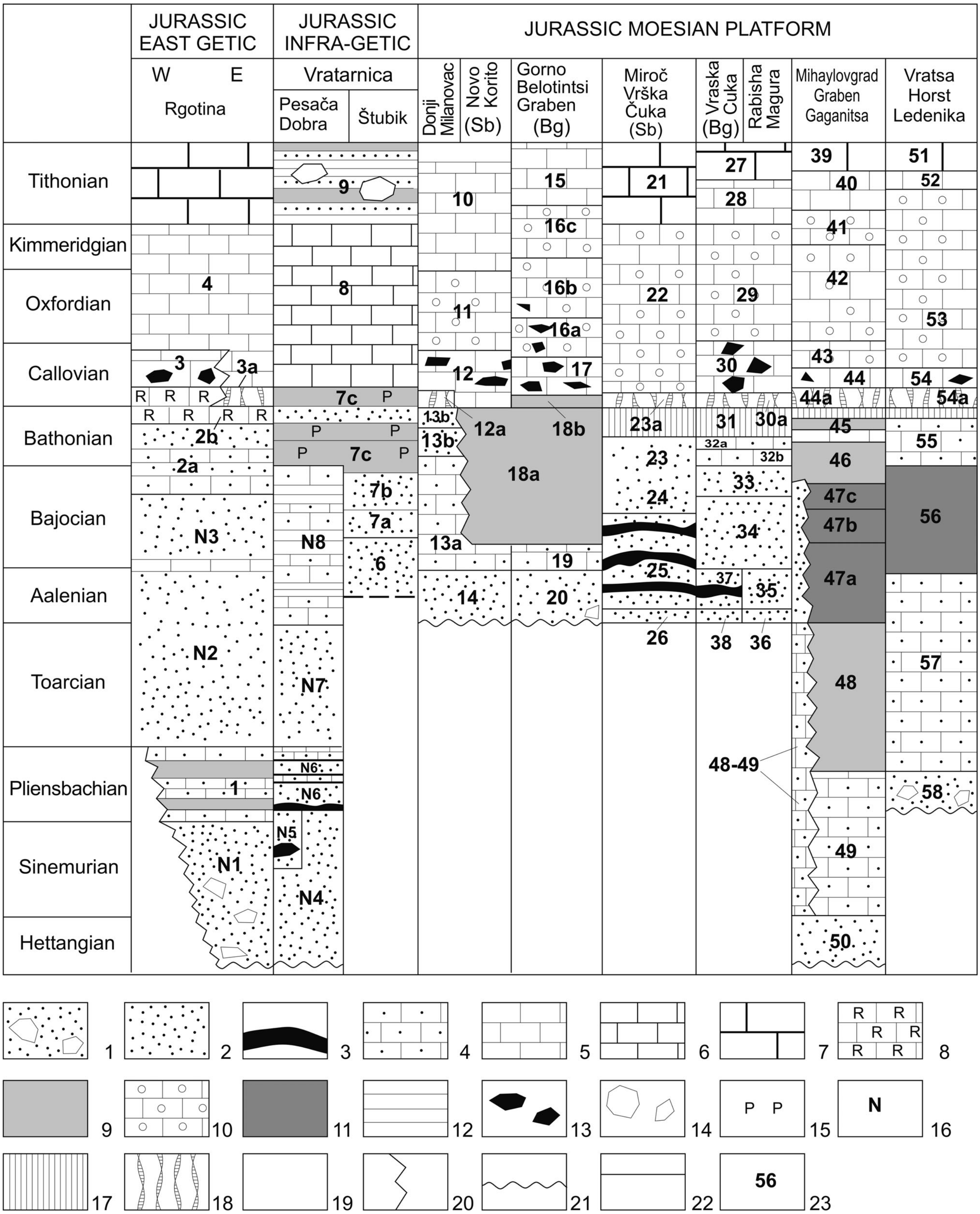


Fig. 2. Trans-border (north-east Serbia/north-west Bulgaria) correlation of the Jurassic lithostratigraphic units. Lithology: **1,** conglomerates and sandstones; **2,** sandstones; **3,** coal; **4,** sandy and bioclastic limestones; **5,** limestones; **6,** thin bedded limestones; **7,** thick bedded limestones; **8,** reddish limestones; **9,** clayey limestones; **10,** nodular and/or lithoclastic limestones; **11,** black shales; **12,** argillites; **13,** cherts nodules; **14,** olistolites; **15,** with "*Posidonia*"; **16,** non-nominated beds; **17,** submarine lack of sedimentation; **18,** zoogenous limestones; **19,** bioclastic and sandy limestones; **20,** horizontal transition; Lithostratigraphy: **21,** transgressive boundary; **22,** normal lithostratigraphic boundary; **23–56,** nominated lithostratigraphic units (explanation in the text).

is built up (from north to south) by the Gomotartsi Step, the Belogradchik Step, the Belotintsi Step, the Prevala Step and the Belimel Step.

The **Belogradchik Step** (SAPUNOV *et al.* 1988). During the Early Jurassic and the Aalenian, in the Belogradchik Step of the Vidin Horst entered the Miroč–Vrška Čuka Zone from NE Serbia and the Rabisha–Vrahska Chuka Zone from NW Bulgaria, which represented a dry land with a continental environment – a terrigenous, coal bearing formation. During the Bajocian, a large part was covered by sea water, in which existed a shallow, sublittoral environment with a sandy-pebbly bottom and agitated water with the sedimentation of oligomictic sandstones and conglomerates, covered by the aleuritic marls. To the north of Belogradchik Town, the sediments of the Bov Formation were subsequently eroded (under sub-marine condition) and the Callovian part of the Javorets Formation (micritic limestones) lied directly on the Lower Bathonian parts of the Polaten Formation.

Miroč Section (Figs. 1: Sb-6, 2) (ANDJELKOVIĆ & MITROVIĆ-PETROVIĆ 1992). **(21a–26a)** The sediments in the Miroč area are very similar to those of the Vrška Čuka area and will be described together with them.

Vrska Čuka Section (Figs. 1: Sb-5, 2). (21) Vratnac Limestones (ANDJELKOVIĆ *et al.* 1996): reef and sub-reef limestones (Tithonian); **(22)** – Greben ammonitic limestones (ANDJELKOVIĆ *et al.* 1996): clayey nodular limestones with cherts (Middle Callovian–Oxfordian–Kimmeridgian); in the base **(23a)** – sandy limestones with *Macrocephalites macrocephalus* (VESELINOVIĆ 1975; ANDJELKOVIĆ *et al.* 1996; analogous to the Bulgarian Sokolov Venets Marker (Lower Callovian)); **(23)** – Bujkovo sandstones (Bathonian); **(24)** – Staro Selo Beds (ANDJELKOVIĆ *et al.*, 1996): yellow marine sandstones (Upper Bajocian–Bathonian); **(25)** – Vrška Čuka coal beds (ANDJELKOVIĆ *et al.* 1996): yellow sandstones, coal schists and coal (Aalenian–Bajocian); **(26)** – Vrska Čuka clastites (Aalenian; ANDJELKOVIĆ *et al.* 1996): quartz conglomerates and sandstones, lying discordantly over Permian rocks.

Vrashka Chuka (Bg-0) – Rabisha (Magura) (Bg-1) Sections (Figs. 1, 2, 3) (SAPUNOV & TCHOUMATCHENCO 1995b). In the Bulgarian part of the Vidin Horst were sedimented: **(27)** – the Magura Formation: massive, light, organogenic (with bivalves, gastropods) and biodetritic limestones (Upper Tithonian–lower part of the Berriasian); **(28)** – the Glozhene Formation: grey-whitish limestones (Middle Kimmeridgian–Tithonian); **(29)** – the Gintsi Formation: grey, lithoclastic to nodular limestones with many ammonites (Oxfordian–Kimmeridgian; **(30)** – the Javorets Formation: grey micritic limestones (Lower Callovian–Oxfordian); at the base, there are many ammonites, as a breccia; **(30a)** – individualized as the Sokolov Venets Zoogenous Marker; **(31a)** – syn-sedimentary break in the sedimentation (Upper Bathonian); **(32)** – the Polaten Formation, divided into two members: **(32a)** – the Dessivitsa Member: built up of sandy, biodetritical limestones with ferrous ooids and quartz pebbles (Lower Bathonian); **(32b)** – Vratnitsa Member: grey to grey-beige calcareous sandstones with single quartz conglomerate pebbles and sandy limestones (Lower Bathonian); Kichera Formation: **(33)** – Oreshets Member: sandstones, yellowish, clayey, calcareous (Upper Bajocian); **(34–35)** – coarse grained sandstones, in the basal part, conglomeratic – non-divided lower part of the Kichera Formation (analogous to the Granitovo and Kreshtenitsa Members (Aalenian–Bajocian); **(36)** – yellow sandstones and grey to dark-grey sandy shales with coal substance - continental coal-bearing sediments, analogous to the continental sediments of Vrashka Chuka (Aalenian–?Toarcian); from the Vrashka Chuka Section **(Bg- 0)**; **(37)** – the Vrashka Chuka Member of the Kichera Formation: the base is structured by sandstones, interbedded with clays; above follow three coal beds, followed by clays and sandstone (Aalenian**)**; **(38)** – the Kiryaevo Member of the Kichera Formation: alternation of sandstones and clays (Aalenian–?Toarcian). Substratum: Late Carboniferous Stara Planina granodiorites.

Granitovo Section (Figs. 1: Bg-2, 3). The section is situated to the north-east of the Granitovo Village, on the slope of Gradishte Hill - western part of the Sokolovo Venets Peak. Here crop out: **(27a)** – the Magura Formation: grey, organodetritic, thick-bedded limestones (Upper Tithonian–lower part of the Berriasian); **(28a)** – the Glozhene Formation: grey-white, well bedded limestones (upper part of the Lower–Middle–Upper Tithonian); the Gintsi Formation, divided into **(29a)** – “Upper nodular limestones”: red nodular limestones (Upper Kimmeridgian–Lower Tithonian); in these sediments exist a west inclined fold (Fig. 4D), in many places, passes to a west-directed inverse fault (Fig. 4E), probably due to a sub-marine slump; **(29ab)** – “Grey quarry limestones”: grey micritic limestones, intercalated by grey lithoclastic limestones (Oxfordian–Lower Kimmeridgian); **(29ac)** – “Lower nodular limestones”: red to grey lithoclastic limestones, in some beds with many ammonites and belemnites (Middle Callovian–Lower Oxfordian); **(30a)** – the Sokolov Venets Zoogenous Marker of the Javorets Formation: calcareous zoogenic (ammonitic, belemnitic, *etc.*) breccia, upwards the ammonites became rarer (Lower Callovian?); **(31a)** – syn-sedimentary break in the sedimentation; the Bov Formation: **(31-1a)** – Verenitsa Member: grey aleuritic limestones with rare ammonites (lower part of the Upper Bathonian); **(31-2a)** – Gornobelotintsi Member: grey to brown aleuritic marbles with ammonites; the Polaten Formation: **(32a)** – the Desivitsa Member: grey bioclastic and sandy limestones (Lower Bathonian) and **(32b)** – the Vratnitsa Member: grey bioclastic and sandy limestones, in the base up to conglomerates (Upper Bajocian–Lower Bathonian); the Kichera Formation: **(33a)** – the Oreshets Member: yellow, medium grained sandstones with calcareous cement (?Bajocian); **(34a)** – the Granitovo Member: reddish to brownish gravelitic sandstones with rare quartz pebbles, well rounded (Bajocian); **(35a)** – the Kreshtenitsa Member: white gravelitic sandstones (?Aalenian); **(36a)** – the Venets Member: probably continental sandstones and conglomerates (analogous to the Kiryaevo Member of the Kichera Formation and to the Vrška Čuka clastites (Aalenian–?Toarcian). Substratum: the Toshkovo Formation - Middle Triassic limestones.

Belogradchik–Railway Station Oreshets section (Figs. 1: Bg-3, 3) (SAPUNOV & TCHOUMATCHENCO 1995e). The section is located along the road Belogradchik–Railway Station Oreshets. Here are located the holostratotypes of the members of the Kichera Formation and of the Sokolov Venets Zoogenous Marker. **(27b)** – the Magura Formation (for SAPUNOV & TCHOUMATCHENCO 1995e – the Slivnitsa Formation): grey to whitish thick bedded limestones (Berriasian). It is covered by the Simeonovo Formation (NIKOLOV & RUSKOVA 1989) – Urgonian type limestones with many special "nodules" in them (Upper Hauterivian–Aptian). This type urgonian sediments is developed only in the region of the Oreshets Village, deposited in a very active environment, which existed especially on the Belogradchik Step (horst); **(28b)** – the Glozhene Formation: grey to whitish clearly bedded micritic limestones with nodules or discontinued beds of chert (upper part of the Lower Tithonian–Upper Tithonian); the Gintsi Formation is with three packets: **(29ba)** – "Upper nodular limestones": red nodular limestones (Upper Kimmeridgian–Lower Tithonian); in these sediments exist a west directed inverse fault (Fig. 4F), probably due to a sub-marine slump; **(29bb)** –"Grey quarry limestones": grey micritic limestones, intercalated by grey lithoclastic limestones (Oxfordian–Lower Kimmeridgian); **(29bc)** – "Lower nodular limestones": red to grey lithoclastic limestones, in some beds with many ammonites and belemnites (Middle Callovian–Lower Oxfordian); **(30ab)** – the Javorets Formation, here, it is represented by the Sokolov Venets Zoogenous Marker. The type section is situated here, along the road Belogradchik–Railway Station Oreshets (Fig. 5A), described by STEPHANOV (1961), rediscribed by SAPUNOV & TCHOUMATCHENCO (1995e) and by BELIVANOVA & SAPUNOV (2003). After STEPHANOV (1961), here are exposed two beds – No. 6–7. Bed 7 (the upper) (Fig. 4E): thickness 0.30 m, brown-red limestones with ferrous hydroxide ooids: *Macrocephalites macrocephalus* (SCHLOTHEIM) (abundant), *Hecticoceras hecticum* (REINECKE) (rare), *Choffatia spirorbilis* (BONCHEV & POPOV). Bed 6 (the lower): thickness 0.12 m, yellowish-red clayey limestones (Fig. 5B) with scattered ooliths and with large flat-spherical lenticular ferrous hydroxide nodules, up to 25 cm in diameter around Bathonian calcareous pieces or Callovian ammonites - *Macrocephalites macrocephalus* (SCHLOTHEIM) (frequent) and others ammonites. In the two beds, there are many Perisphinctidae, Phylloceratidae, Litoceratidae, *etc*.; **(31b)** – sub-marine gap in the sedimentation, between the Lower Bathonian and the redeposited Lower Callovian sediments. The Polaten Formation is divided into two members: **(32a)** – the Desivitsa Member: built of sandy, biodetritical limestones with ferrous ooids and quartz pebbles with many ammonites (SAPUNOV & TCHOUMATCHENCO 1995e); **(32b)** – the Vratnitsa Member: structured by grey to grey-beige calcareous sandstones with single quartz conglomerate pebbles and sandy limestones with many ammonites (SAPUNOV & TCHOUMATCHENCO 1995e). The upper and lower surfaces are transitional**.** In both of them, STEPHANOV (1961) found ammonites, which indicated the Lower Bathonian *Zigzag* Zone; The Kichera Formation: **(33b)** – Oreshets Member: yellow, medium grained sandstones with calcareous cement (?Bajocian); **(34b)** – the Granitovo Member: reddish to brownish gravelitic sandstones with rare quartz pebbles, well rounded (Bajocian); **(35b)** – the Kreshtenitsa Member: white gravelitic sandstones (?Aalenian); **(36b)** – the Venets Member: probably continental sandstones and conglomerates, (analogous to the Vrashka Cuka Member and Kiryaevo Member of Kichera Formation) (Aalenian and ?Toarcian). Substratum – the Toshkovo Formation (Middle Triassic limestones).

Gornobelotintsi–Novokorito Graben (Basin) (Belotintsi Step) (SAPUNOV *et al.* 1988). During the Early Jurassic, this was also an area of continental sedimentation. At the beginning of the Bajocian started the formation of a new graben with sandy sedimentation under conditions of a shallow sublittoral environment with a sandy bottom and agitated water during the beginning of the Bajocian – the Gornobelotintsi–Novo Korito Graben. At the end of the Bajocian–Bathonian–Early Callovian, in it existed the conditions of a deep sublittoral environment with a muddy bottom and slightly agitated water with the sedimentation of marls, interbedded by clayey limestones. During the Middle Callovian–Late Jurassic started a stage of bathymetric differentiation and pelagic micritic and nodular limestones were sedimented. In east Serbia, will be described the sediments near Milanovac–Novo Korito and in Bulgaria, the Belogradchik TV Tower, Yanovets, Dolni Lom and Gornobelotintsi sections in the Gornobelotintsi Graben are described herein.

Belogradchik TV Tower Section (Figs. 1: Bg-4, 3). The section is along the road to the TV Tower, but the Magura **(27c)** (Upper Tithonian–Berriasian) and the Glozhene **(28c)** (upper part of Lower–Middle–Upper Tithonian) Formations are covered by a forest and do not crop out. The Gintsi Formation is built up of three packets: **(29ca)** – "Upper nodular limestones" (Middle Kimmeridgian–Lower Tithonian); in these sediments there is an inverse fault, inclined to SW, probably due to a sub-marine slump; **(29cb)** – "Middle

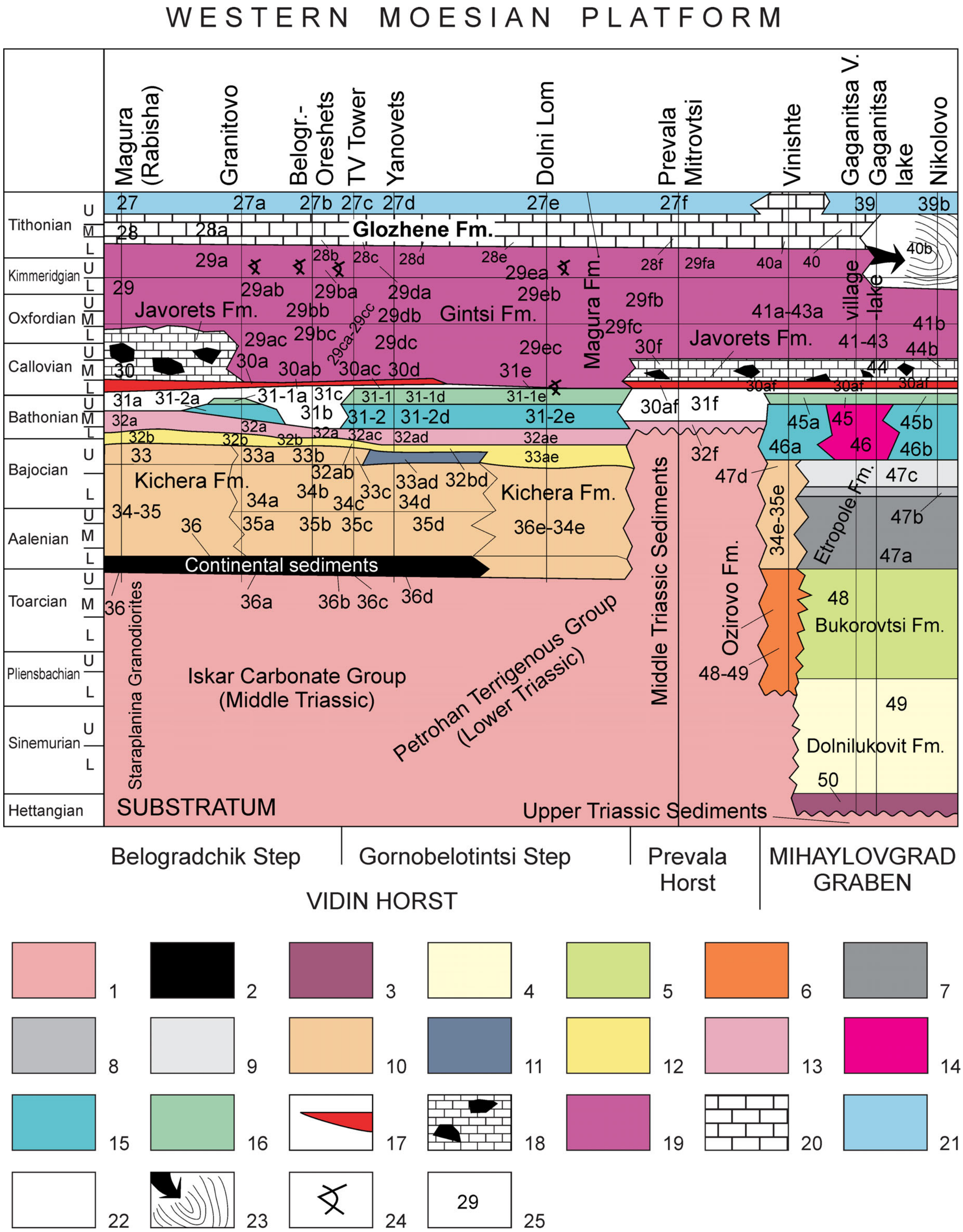


Fig. 3. Temporal-facial connections of the Jurassic lithostratigraphic units in NW Bulgaria (modified after Tchoumatchenco 1978; Sapunov & Tchoumatchenco 1995k, 1995l, 1995m; Tchoumatchenco *et al.* 2011). Legend: **1,** Substratum (Triassic sediments); **2,** continental Jurassic sediments; **3,** Kostina Formation; **4,** Dolnolukovit Formation; **5,** Bukorovtsi Formation; **6,** Ozirovo Formation; Etropole Formation: **7,** Nefela Member; **8,** Stefanets Member; **9,** Shipkovo Member; **10,** Kichera Formation; Polaten Formation: **11,** Yanovets Member; **12,** Vratnitsa Member; **13,** Desivitsa Member; **14,** Polaten-Bov Formation; Bov Formation: **15,** Gornobelotintsi Member; **16,** Verenitsa Member; **17,** Sokolov Venets Marker of the Javorets Formation; **18,** Javorets Formation; **19,** Gintsi Formation; **20,** Glozhene Formation; **21,** Brestnitsa Formation; **22,** sub-marine break in the sedimentation; **23,** Shugovitsa Slump; **24,** Granitovo angular discordance; **25,** number under which the lithostratigraphic units are described in the text.

quarry limestones" with many cherts (Oxfordian–Lower Kimmeridgian); **(29cc)** – "Lower nodular limestones" (Middle Callovian–Lower Oxfordian): beige to white nodular micritic limestones; **(30ac)** – the Sokolov Venets Marker of the Javorets Formation, 2–3 cm, blackish to grey marls (?Lower Callovian); **(31c)** – sub-marine gap in the sedimentation; the Bov Formation: **(31-1)** – the Verenitsa Member: alternation between micritic beige limestones and beige–grey aleuritic marls (Upper Bathonian–lowermost Lower Callovian); **(31-2)** – the Gornobelotintsi Member: grey-greenish marls with rare calcareous intercalations (Middle–Upper Bathonian); the Polaten Formation: **(32ad)** – the Desivitsa Member: grey sandy limestones with crinoids (Lower Bathonian); **(32bd)** – the Vratnitsa Member: grey sandy limestones to calcareous sandstones with many ammonites, well-preserved, non-flattened, probably resedimented (Lower Bathonian – *Zigzag* Zone); the Kichera Formation: **(33c)** – the Oreshets Member: calcareous sandstones (purely exposed (Bajocian); **(34c)** – the Granitovo Member: reddish sandstones and conglomerates (Bajocian); **(35c)** – the Kreshtenitsa Member: white sandstones (?Aalenian); **(36c)** – the Venets Member: probably continental sandstones and conglomerates (Aalenian and ?Toarcian?). Substratum: the Toshkovo Formation - Middle Triassic limestones.

Yanovets Section (Figs. 1: Bg-5, 3) (SAPUNOV & TCHOUMATCHENCO 1995f). Located at 2 km west of the Yanovets Village, Belogradchik community. The Magura **(27d)** (Upper Tithonian–Berriasian) and the Glozhene **(28d)** (Middle–Upper Tithonian) Formations are covered by a forest and do not crop out. The Gintsi Formation is built up of three packets: **(29da)** – "Upper nodular limestones" (Middle Kimmeridgian–Lower Tithonian); in these sediments, there is an inverse fault, inclined to the SW; **(29db)** – "Middle quarry limestones" with many cherts (Oxfordian–Lower Kimmeridgian); **(29dc)** – "Lower nodular limestones" (Middle Callovian–Lower Oxfordian): beige to white nodular micritic limestones; **(30d)** – the Sokolov Venets Marker of the Javorets Formation is covered by a talus gravity accumulation; the Bov Formation: **(31-1d)** – the Verenitsa Member: grey to greenish aleuritic marls, in alternation with rare beds of clayey limestones (Upper Bathonian–lowermost Lower Callovian); **(31-2d)** – the Gornobelotintsi Member: grey-greenish aleuritic marls (Middle–Upper Bathonian); the Polaten Formation: **(32ad)** – the Desivitsa Member: grey to dark grey aleuritic and biodetritic limestones, and in the base, irregular alternation between aleuritic, oolithic limestones and marls (Lower Bathonian); **(32bd)** – the Vratnitsa Member: grey coarse-grained biodetritic limestones with numerous quartz grains, passing into calcareous sandstones (uppermost Upper Bajocian–Lower Bathonian); **(33ad)** – the Yanovets Member: pink, crinoidal limestones with single fragments of bryozoans, echinids and oncolites; in the basal part, grey to grey-pinkish sandy limestones, with numerous pebbles of quartz or sandstones, built almost entirely by bryozoan fragments (Upper Bajocian); the Kichera Formation: **(34d)** – the Granitovo Member: red, coarse-grained sandstones with numerous quartz pebbles (Bajocian); **(35d)** – the Kreshtenitsa Member: light grey to whitish medium grained sandstones with planar cross-bedding in some beds (Aalenian); **(36d)** – the Venets Member: no outcrops. Substratum: reddish sandstones and conglomerates of the Lower Triassic Petrohan Terrigenous Group.

Dolni Lom Section (Figs. 1: Bg-6, 3) (SAPUNOV & TCHOUMATCHENCO 1995g). The section starts near the cemetery of Dolni Lom Village and continues across the quarry and the hill to west of the village. **(27e)** – the Magura Formation (Slivnitsa**,** SAPUNOV & TCHOUMATCHENCO 1995g): alternation between thick bedded and medium bedded micritic and biomicritic limestones (Upper Tithonian–Berriasian); **(28e)** – the Glozhene Formation: alternation between micritic thin and medium bedded limestones and, in the basal part, lithoclastic limestones (Lower–Upper Tithonian); the Gintsi Formation: **(29ea)** – "Upper Nodular limestones": grey to reddish nodular and lithoclastic limestones alternating with grey micritic limestones (Upper Kimmeridgian–Lower Tithonian); in this packet, there is an angular discordance; **(29eb)** – "Grey Micritic (Quarry) Limestones": micritic grey limestones in alternation with lithoclastic limestones containing grey chert (Oxfordian–Lower Kimmeridgian); **(29ec)** – "Lower Nodular Limestones": grey lithoclastic limestones alternating with micritic limestones (Middle Callovian–Oxfordian); these lithoclastic limestones are in angular contact with sediments of the Verenitsa Member; the Bov Formation: **(31-1e)** – the Verenitsa Member: alternation between grey-greenish aleuritic marls and grey micritic limestones, *Macrocephalites* sp. indet. (Upper Bathonian–Lower Callovian); **(31-2e)** – Gornobelotintsi Member: grey-greenish aleuritic marls, purely exposed (Upper Bathonian); the Polaten Formation: **(32ae)** – the Desivitsa Member: grey to dark-grey biodetritic limestones with chert nodules (Upper Bathonian); below, red to brown, oolithic, ferruginous limestones – "the Coarse Oolite Horizon" (STEPHANOV & TZANKOV 1970) (condensation of the Lower Bathonian *Zigzag* Zone and the Middle Bathonian *Subcontractus* Zone); **(33ae)** – the Vratnitsa Member: grey biodetritic, slightly sandy limestones (upper part of the Lower Bathonian – upper part of the Upper Bajocian); **(36e-34e)** – the Kichera Formation (not divided): grey–beige to whitish sandstones (?uppermost Upper Toarcian–lowermost part of the Upper Bajocian). Substratum: the Petrohan Terrigenous Group built of white to greenish sandstones with mica (Lower Triassic).

Novo Korito (Figs. 1: Sb-8, 2)–D. Milanovac (Figs. 1: Sb-4, 2) Sections (ANDJELKOVIĆ *et al*. 1996).

The sedimentation in the two areas was analogous during the Late Jurassic and the Callovian and differed only during the Middle Jurassic. Here was deposited the following sediments: **(10)** – Novokorito limestones: clayey biomicrites and dolomitic biomicrites with ammonites, *Saccocoma* and calpionelids - in the upper parts (Kimmeridgian–Tithonian) (analogous to the Glozhene Formation); **(11)** – Greben ammonitic limestones (ANDJELKOVIĆ *et al.* 1996): grey, clayey biomicrites to dolomitic limestones, nodular, with cherts (Middle Callovian–Oxfordian), analogous to the Bulgarian Gintsi Formation; **(12) –** Staro Selo beds: grey micritic limestones with cherts nodules (Callovian; analogous to the Bulgarian Javorets Formation); **(12a)** – Staro Selo beds: red and reddish ferrous limestones (0.20 m thick) with a rich association of ammonites - *Macrocephalites macrocephalus*, *etc*. (ANDJELKOVIĆ 1975; ANDJELKOVIĆ *et al*. 1996) (Lower Callovian, analogous to the Bulgarian Sokolov Venets Zoogenous Marker in this paper) and in Ribnica stream - grey-greenish clay and limestones with cherts with *Macrocephalites* (ANDJELKOVIĆ 1975). During the Middle Jurassic, a differentiation between the sections of D. Milanovac and Novo Korito commenced. In D. Milanovac **(Figs. 1: Sb-4, 2)** sedimented: **(13)** – the Staro Selo Beds (ANDJELKOVIĆ *et al.* 1996): in the upper part **(13b)** – yellow to reddish sandstones (Bathonian; no analogy in Bulgaria) and in the lower part **(13a)** – sandy oolithic limestones (Bajocian; analogous to the Vratnitsa Member of the Polaten Formation in Bulgaria); **(14)** – Staro Selo clastites (ANDJELKOVIĆ *et al.* 1996) – conglomerates and sandstones (Aalenian; analogous to the Kichera Formation). In the Novo Korito Section, during the Bajocian and the Bathonian, sedimented **(18a)** – grey-greenish aleuritic marls (locally with many *Zoophycos*) (horizontal analogue to the Bulgarian Gornobelotintsi Member of the Bov Formation).

Gornobelotintsi (Nechinska Bara River) Section (Fig. 1: Bg-13, 3) (SAPUNOV *et al.* 1988; SAPUNOV & TCHOUMATCHENCO 1995d). Here, the following Jurassic sediments were deposited: **(15)** – the Glozhene Formation: well-bedded micritic limestones (slightly lithoclastic in the base) (Middle–Upper Tithonian); the Glozhene Formation is covered by thick bedded limestones, which TCHOUMATCHENCO (2002) assigned to the Magura Formation with Berriasian age; in its uppermost parts. there are calcareous breccia-conglomerates; **(16)** – the Gintsi Formation: nodular and lithoclastic limestones in three packets: **(16c)** – the upper packet ("Upper nodular limestones"): reddish nodular and lithoclastic limestones (Middle–Upper Kimmeridgian – Lower Tithonian); **(16b)** – the middle packet: "Quarry limestones" - lithoclastic and micritic limestones (Middle and Upper Oxfordian–Lower Kimmeridgian); **(16a) –** the lower packet ("Lower nodular limestones"): grey nodular and lithoclastic limestones (Upper Callovian–Lower Oxfordian); **(17)** – the Javorets Formation: grey, medium bedded limestones interbedded by thin bedded clayey limestones (Middle Callovian); its lower boundary represents an angular disconformity, which is probably one of the manifestations of the Sokolov Venets Marker in the central part of the basin; **(18b)** – the Verenitsa Member of the Bov Formation: medium bedded micritic and clayey limestones in alternation with marls with *Macrocephalites* sp. (Lower Callovian); **(18a)** – the Gornobelotintsi Member of the Bov Formation: marls aleuritic (Bathonian – upper part of the Upper Bajocian); **(19)** – the Polaten Formation, Vratnitsa Member: sandy limestones and calcareous sandstones (Bajocian); **(20)** – the Kichera Formation (non-subdivided): whitish to yellowish quartz sandstones (Aalenian); it is possible that, in the lowermost part the sandstones, could be continental (analogous to the Venets Member).

Prevala Horst

Mitrovtsi–Prevala Sections (Figs. 1: Bg-7, 3) (SAPUNOV & TCHOUMATCHENCO 1995h). The section near the Mitrovtsi Village crops out as a cliff along the road Montana Town–Belogradchik, along the Ogosta River. The stratotype of the Desivitsa Member of the Polaten Formation crop out in the Desivitsa Valley between the villages Mitrovtsi and Prevala. **(27f)** – the Brestnitsa Formation; in the region of NW Bulgaria, it is connected in the horizontal direction with the Magura Formation; it is composed of whitish to beige massive biodetritic limestones (uppermost part of the Upper Tithonian–Berriasian); **(28f)** – the Glozhene Formation: represented by bright grey, grey-beige to dark grey micritic limestones (middle part of the Lower–Upper Tithonian); the Gintsi Formation; **(29fa)** – "Upper Nodular limestones": grey to reddish nodular and lithoclastic limestones alternating with grey micritic limestones (Upper Kimmeridgian–Lower Tithonian); in this packet there is an angular discordance; **(29fb)** – the "Grey Micritic (Quarry) Limestones": micritic grey limestones in alternation with lithoclastic limestones containing grey chert (Oxfordian–Lower Kimmeridgian); **(29fc)** – the "Lower nodular limestones": grey lithoclastic limestones alternating with micritic limestones (Middle Callovian–Oxfordian); **(30f)** – the Javorets Formation: grey, predominantly thin-bedded, micritic limestones with rare intercalation of lithoclastic limestones (Lower–Middle Callovian); **(30af)** – the Sokolov Venets Marker of the Javorets Formation (Fig. 5C): (a) – red to pink lithoclastic limestones; the lithoclasts are surrounded by red marly cement (thickness 80 cm); (b) – red to grey zoogenic (predominantly ammonitic) breccia - *Macrocephalites* sp. (20 cm); (c) – laminated red, ferruginous, calcareous marls - after Dr I. LAZAR (perssonal communication, 2011), they are stromatoid

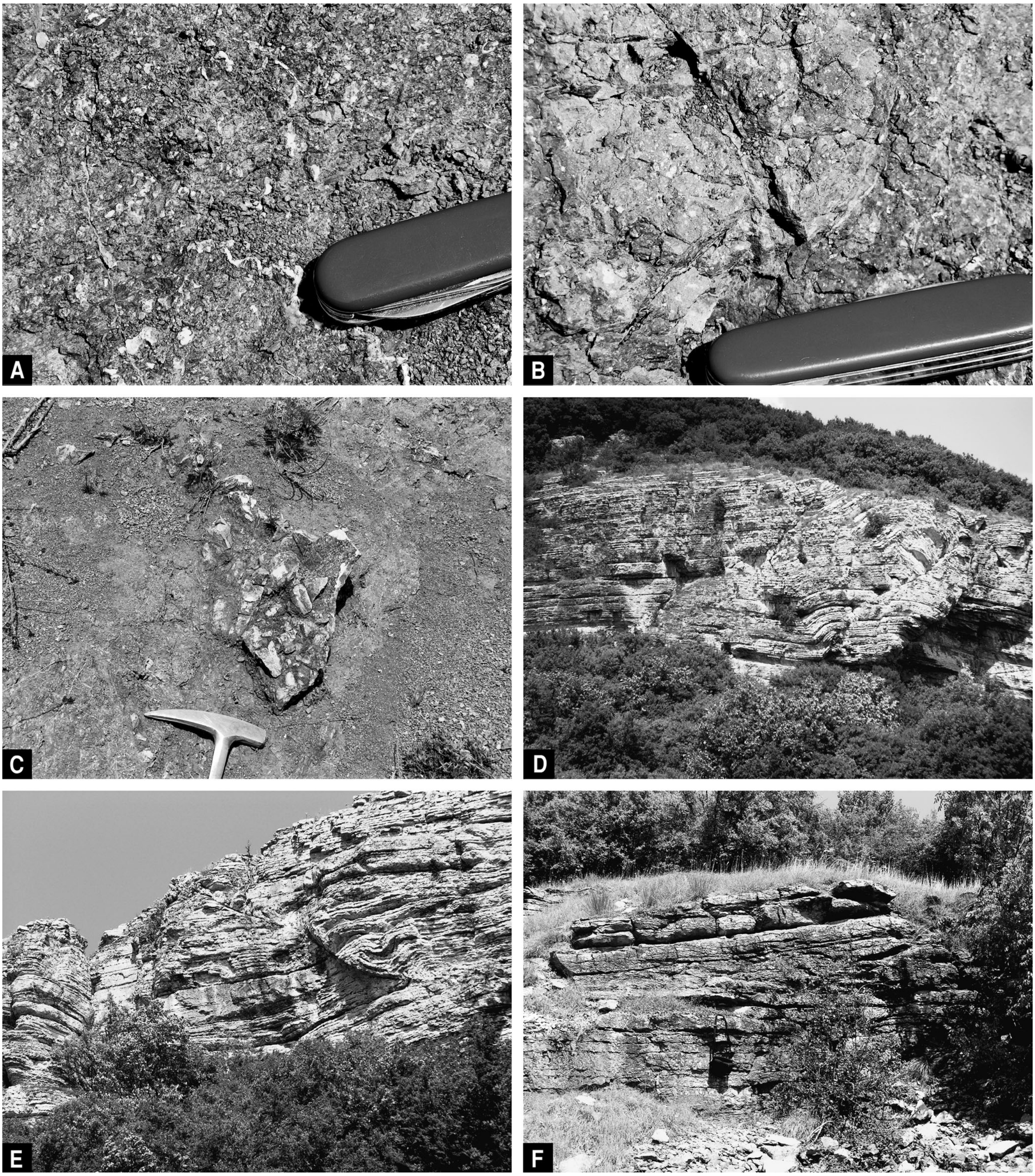


Fig. 4. **A,** Vratarnica Series, the "matrix" of the formation, near the road south of Vratarnica Village, Zaječar District; **B,** Vratarnica Series, olistolite of volcanogenous rock in the matrix, near the road south of Vratarnica Village, Zaječar District; **C,** Vratarnica Series, olistolite of coarse grained whitish limestone (analogous to the Crni Vrh Limestones of east Serbia or the Bulgarian Slivnitsa Formation) in the matrix, near the road south of Vratarnica Village, Zaječar District; **D,** Granitovo, Gradishteto Hill, syn-sedimentary fold in the upper part of the Gintsi Formation; **E,** Reverse fault in the upper part of the Gintsi Formation near Granitovo Village, Sokolov Venets Hill - in the upper part of the Gintsi Formation; **F,** reverse fault in the upper part of the Gintsi Formation, near the road Belogradchik–Railway Station Oreshets.

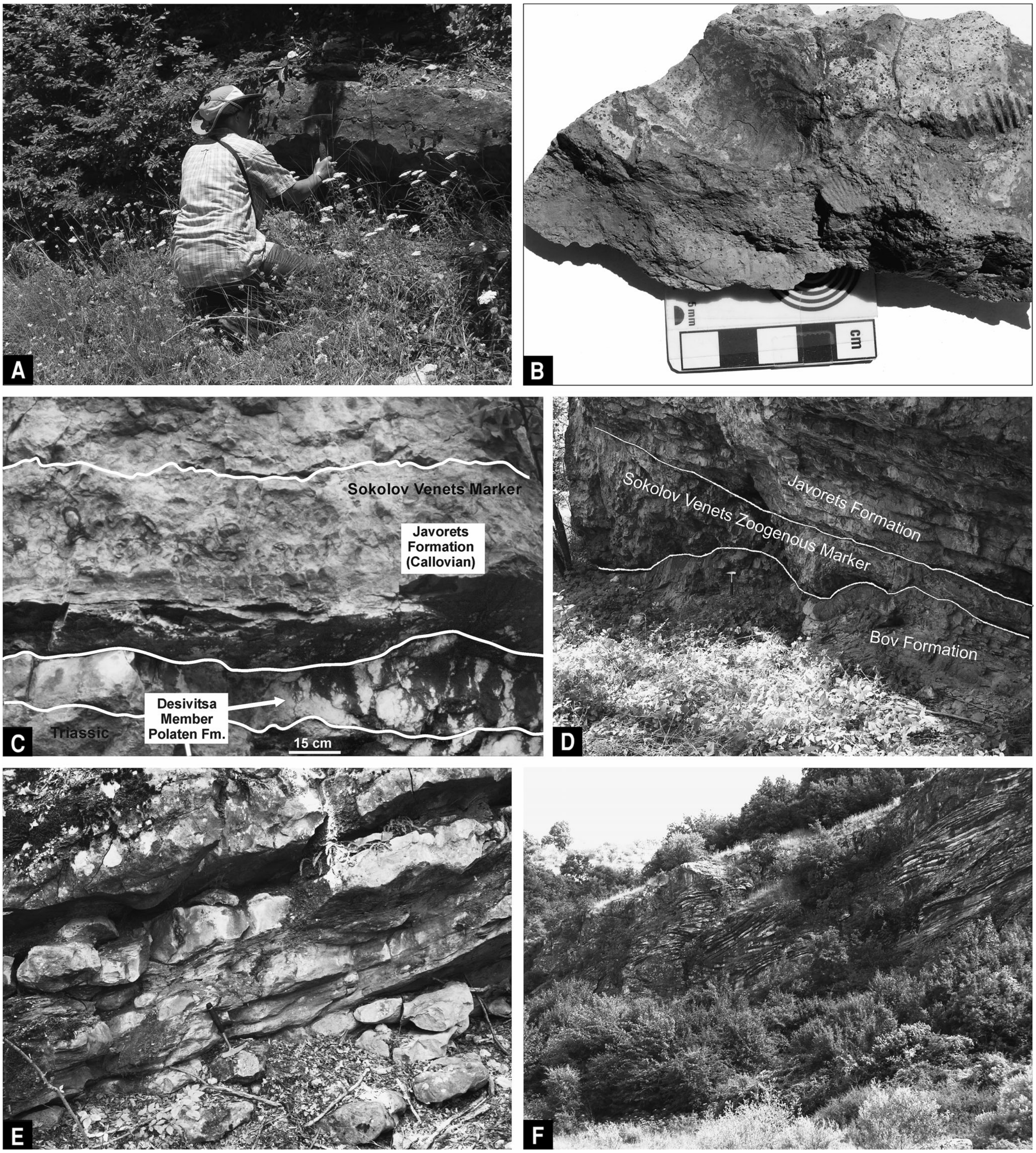


Fig. 5. **A,** Holotype section of the Sokolov Venets Zoogenous Marker, along the road Belogradchik–Railway Station Oreshets, general view and upper bed No 7; **B,** Holotype section of the Sokolov Venets Zoogenous Marker, along the road Belogradchik–Railway Station Oreshets, specimen from the lower bed No 6 – zoogenous breccia; **C,** Sokolov Venets Zoogenous Marker, view of the outcrop on the cliff by the road near Mitrovtsi Village, Montana District; **D,** Sokolov Venets Zoogenous Marker, view of the outcrop on the southern hill of the Gintski Venets (Cliff), near Gintsi Village, Sofia District, folded uppermost bed of the Bov (Polaten?) Formation; the sediments of the Sokolov Venets Zoogenous Marker fully fill the negative part of the ancient relief; in the right part of the photograph is seen the bed of the Polaten (Bov?) Formation overlaid by zoogenous breccia of the Sokolov Venets Zoogenous Marker; **E,** Desivitsa Member of the Polaten Formation in the Desivitsa Valley, near Prevala Village, Montana District; **F,** view of the Shugovitsa Slump; in the Shugovitsa River Valley, near Nikolovo Village, Montana District, the folds are in the Gintsi and the Glozhene Formations.

constructions; **(31f)** – sharp, irregular surface, probably the result of a sub-marine break in the sedimentation (Middle Bathonian–Lower Callovian); Polaten Formation: **(32af)** – the Desivitsa Member: red, ferruginous limestones (Lower Bathonian); in the Desivitsa Valley to the SE of Prevala Village is the stratotype of the Desivitsa Member (Fig. 5E), built by: (c) – violet-reddish micritic limestones with many ammonites (1.20 m); (b) – red to rose micritic limestones, in the basal part with irregular intercalation of red marls (3.30 m) and in the base with a dark zoogenous oolitic limestones (the "Prevala Beds", STEPHANOV 1966). This development of the Desivitsa Member – reddish marls and limestones are close to the Klaus Schichten from the Romanian and Serbian South Carpathian. Substratum: the Iskar Triassic Carbonate Group – the Cesmicka Formation (Lower Carnian).

Mihaylovgrad Graben (SAPUNOV *et al.* 1988) (Figs. 1, 2, 3)**.** This is a SW–NE negative palaeostructure, in which the Jurassic sediments show an integrated section from the Hettangian up to the end of the Early Cretaceous. To the east, it is connected transitionally with the Central Moesian Basin and to west, with the N–S oriented Infra-Getic Palaeogeographic Unit and in both of them existed analogous palaeogeographic conditions. The transgression started with the deposition of oligomictic sandstones, followed during the Pliensbachian by sandy bioclastic limestones deposited also in a shallow sublittoral environment, but with a calcareous bottom (Gresten facies – *grosso modo*). During the Aalenian and the Bajocian, in the Mihaylovgrad Graben existed a deep sublithoral environment when argilites of the facies "black shales with *Bositra–Possidonia alpina*" were deposited. During the Middle Callovian and the Late Jurassic, micritic limestones (Middle Callovian–Middle Oxfordian) were deposited, followed by nodular and lithoclastic limestones – "*ammonitico rosso* facies" (Late Oxfordian–Early Tithonian), lithoclastic and micritic limestones (Middle–Late Tithonian) and platform limestones (Late Tithonian–Berriassian).

The section Gaganitsa Village is the section where the complete development of the Jurassic sedimentation deposited in the central parts of the Mihaylovgrad palaeograben crop out. The Gaganitsa Lake section shows a lack of the upper part of the Gintsi Formation and the Glozhene Formation. The section Vinishte demonstrates the lateral changes connected with the board of the palaeograben and the section Nikolovo – the effect of a big slumping – the Shugavitsa Slump.

Gaganitsa Village Section (Figs. 1: Bg-8, 2, 3). In the vicinities of Gaganitsa Village (SAPUNOV & TCHOUMATCHENCO 1995i), in the central parts of the Mihaylovgrad Palaeograben, were deposited: **(39)** – the Brestnitsa Formation (NIKOLOV & KHRISCHEV 1965) – Slivnitsa Formation (after SAPUNOV & TCHOUMATCHENCO 1995i): light-grey to whitish, thick bedded limestones, often containing corals, bivalves, gastropods (*Nerinea*), *etc.* (Upper Tithonian–Berriasian); **(40)** – the Glozhene Formation: dark to light grey micritic limestones, locally lithoclastic in the base (Tithonian); **(41–43)** – the Gintsi Formation: nodular and lithoclastic limestones (Upper Callovian–Lower Tithonian); **(41)** – the "Upper nodular limestones: red nodular limestones (Upper Kimmeridgian–Lower Tithonian); **(42)** – the "Grey quarry limestones": grey micritic limestones, intercalated by grey lithoclastic limestones (Oxfordian–Lower Kimmeridgian); **(43)** – the "Lower nodular limestones": grey lithoclastic limestones (Middle Callovian–Oxfordian); **(44)** – the Javorets Formation: grey micritic, often clayey limestones with nodules of chert (Lower–Middle Callovian); **(30af)** – the Sokolov Venets Marker: grey aleuritic and oolitic limestones, containing numerous ammonitic fragments and glauconite (thickness 1.40 m) with *Hecticoceras (Brightia) nodosum* (BONARELLI), *H. (B.) tenuicostatum* ZEISS, *H. (B.) subnodosum* (DE TSYTOVITCH), *Choffatia villanoides* (TILL); the Bov Formation: **(45)** – the Verenitsa Member: alternation between greenish aleuritic marls and thin beds of micritic limestones (Upper Bathonian); **(46)** – the Bov/Polaten Formation: grey aleuritic marls in alternation with silicificated micritic limestones (analogous to the Gornobelotintsi Member) (Upper Bajocian–Bathonian); the Etropole Formation is divided into three members: **(47c)** – Shipkovo Member: dark grey to blackish shales (Lower Bajocian–Upper Bajocian); the **(47b) –** Nefela Member: dark clayey siltstones (Lower Bajocian); **(47a)** – the Stefanets Member: dark grey to black, slightly calcareous silty argillites (Aalenian – lower part of the Lower Bajocian); **(48)** – the Bukorovtsi Formation: slightly sandy clayey marls with rare interbeds of clayey limestones (Toarcian–Upper Pliensbachian); **(49)** – the Dolnilukovit Formation: dark-grey sandy to bioclastic limestones (lower part of the Lower Sinemurian – Upper Pliensbachian); **(50)** – the Kostina Formation: fine- to coarse-grained quartz sandstones (Hettangian).

Gaganitsa Lake Section (Figs. 1: Bg-9, 2, 3). This section is situated 3 km south-east from the Gaganitsa Village Section. Its sediments are the same as in the Gaganitsa Village Section, but differs from the latter by the fact that the thick bedded limestones with debris of corals, gastropods, *etc.* of the Brestnitsa Formation lie directly on the reddish clayey lithoclastic limestones of the middle packet of the Gintsi Formation; the uppermost part of the Gintsi Formation and the limestones of the Glozhene Formation are missing. The situation is the same in the east direction, on the Peak Ludeno and east wards. This is, after P.T., the effect of the Shugovitsa Slump; the missing parts of the section were slumped to north and now crop out as big folds in the Shugovitsa River Valley near the village of Nikolovo, Montana District, at a distance of 16 km**.**

Kamenna Riksa–Vinishte Section (Figs. 1: Bg-12, 3) (SAPUNOV & TCHOUMATCHENCO 1995k). The Jurassic sediments are poorly exposed in the section between Kamenna Riksa Village–Zabarge Hill–Viniste Village and the Kamiko Hill and the hills around it (to the north of Vinishte Village). Here, the Brestnitsa Formation is not developed and the Glozhene Formation is directly covered by the clayey limestones of the Salash Formation. **(40a)** – The Glozhene Formation: grey micritic limestones, partially with lithoclasts (Lower Tithonian–Berriasian); **(41a–43a)** – the Gintsi Formation: predominantly grey to pinkish lithoclastic limestones, intercalated by grey micritic limestones; **(44a)** – the Javorets Formation: grey, predominantly micritic limestones (?Middle Callovian – lower part of the Upper Oxfordian); **(30af)** – the Sokolov Venets Zoogenous Marker: limestones with ammonites and belemnites (Lower Callovian); The Bov Formation: **(45a)** – the Verenitsa Member (not far from here is situated the holostratotype): grey aleuritic more or less calcareous marls (uppermost Upper Bathonian (?) – Lower Callovian); **(46a)** – the Gornobelotintsi Member: grey aleuritic, clayey marls (Upper Bajocian–Upper Bathonian); **(47d)** – the Vratnitsa Member of the Polaten Formation: grey sandy limestones to calcareous sandstones with some brachiopods and belemnites (Upper Bathonian); **(34e–35e)** – the Kichera Formation (homogenous): white to pinkish, locally ferruginous oligomictic sandstones (Aalenian–Upper Bajocian); **(48–49)** – the Ozirovo Formation: grey to pinkish sandy limestones to calcareous sandstones, locally with rounded quartz pebbles, with bivalves, brachiopods and ammonites (Pliensbachian–Toarcian). The Ozirovo Formation is transgressive over the Upper Triassic sediments.

Nikolovo Section (Figs. 1: Bg-10, 3) (SAPUNOV & TCHOUMATCHENCO, 1995k). The Lower and partly the Middle Jurassic sediments were studied in the drill cores of many bore holes. On the surface crop out the sediments since the upper parts of the Etropole Formation. In this section, the Jurassic sediments are very similar to the Jurassic sediments developed in the Gaganitsa Village Section. The difference between them lies in the fact that the sediments of the Glozhene Formations here are folded in a few horizontal to reversed folds **(40b)** (Fig. 5F) to reverse faults (TCHOUMATCHENCO & SAPUNOV 1998), which slid on the surface, formed by the reddish lithoclastic limestones of the Gintsi Formation – the Shugovitsa Slump is probably the result of the slumping of these sediments from the region of the Gaganitsa Lake Section – the result of seismic shock.

Vratsa Horst (SAPUNOV *et al.* 1988). The dry land in a continental environment under conditions of erosion and denudation on the Vratsa Horst progressively diminished (destroyed during the Callovian) and was encountered by a shallow and moderately deep sublittoral environment with the sedimentation of sandy, bioclastic limestones (type of Gresten facies – *grosso modo*) during the Early and part of the Middle Jurassic (at the beginning of the Aalenian). During the end of the Aalenian and the Early, Middle and the early part of the Late Bajocian the conditions of a deep sublittoral environment dominated with the sedimentation of silty argillites (facies of black shale with *Bositra–Possidonya alpina*). At the end of the Late Bajocian and the Bathonian, sandy bioclastic limestone was deposited. During the Middle Callovian–Middle Oxfordian, micritic limestones were deposited, followed upwards by lithoclastic during the Middle Oxfordian–Tithonian. During the Latest Late Tithonian and the Berriasian, the conditions in the Vidin and Vratsa Horsts, and in the Mihaylovgrad (and in its branch, the Gornobelotintsi Graben) became more or less uniform and thick bedded, sometimes bioclastic limestones were deposited.

Ledenika Cave (Figs. 1: Bg-11, 2). On the Vratsa Horst the following sediments were deposited (SAPUNOV & TCHOUMATCHENCO 1995c, n): **(51)** – the Brestnitsa Formation (Slivnitsa Formation, after SAPUNOV & TCHOUMATCHENCO 1995c, n): massive, organogenous–biodetrital and biohermic, pelletal–oolithic limestones (Upper Tithonian–Lower Cretaceous); **(52)** – the Glozhene Formation: thick bedded limestones with biodetritus and lithoclasts (Middle Tithonian–Berriasian); **(53)** – the Ledenika Member of the Gintsi Formation (SAPUNOV *in* NIKOLOV & SAPUNOV 1977): thick bedded grey pelletal–oolithic limestones with numerous intercalations of lithoclastic limestones; they contain coral remains, echinoids spines, bivalves (Upper Oxfordian, *p. p.* –Lower Tithonian); **(54)** – the Javorets Formation: grey, micritic limestones with rare intercalation of lithoclastic limestones (Middle Callovian–lower part of the Upper Oxfordian *p. p.*); **(54a)** – the Sokolov Venets Organogenous Marker: grey, micritic limestones, rich in glauconite in the basal part – *Macrocephalites macrocephalus* (SCHLOTHEIM) and *Hecticoceras (Brightia) tuberculatum* (DE TSYTOVITCH) (Lower–Middle Callovian); **(55)** – the Polaten Formation: grey sandy limestones, in the base, a bed of conglomerates (0.15 m) with pebbles of black shales (the Etropole Formation?) and Triassic limestones (Upper Bajocian–Bathonian); **(56)** – the Etropole Formation (nonsubdivided): black shales (Aalenian–Bajocian); **(57)** – the Ozirovo Formation: pink to reddish, ferruginous sandy limestones (Upper Pliensbachian–Aalenian); **(58)** – the Kostina Formation: grey, medium-bedded, quartz sandstones to gravel-stones (Lower Pliensbachian–Upper Pliensbachian *p. p.*)

Notes on the Jurassic lithostratigraphy in NW Bulgaria

In this paper, one of us (P. Tchoumatchenco) express some opinions on the lithostratigraphy of the Jurassic which slightly differ from the "official" points of view of the Bulgarian lithostratigraghic interpretation, expressed, *e.g.*, in Sapunov & Metodiev (2009) – " Jurassic Geology", Chapter 5.3 of the "Mesozoic Geology of Bulgaria" and in many others publications, of which P. Tchoumatchenco is also a co-author. They will be studied in stratigraphical order.

Kostina Formation (Sapunov *in* Sapunov *et al.* 1967). It is used as in the original paper – quartz sandstones (Hettangian, some time up to the Lower Pliensbachian).

Ozirovo Formation (Sapunov *in* Sapunov *et al.* 1967). Herein it is used as in the original paper; later it was named "Homogenous Ozirovo Formation", without subdivision into members. Hence, it is the Ozirovo Formation in the holostratotype (Nachev *et al.* 1963). In this meaning, the Ozirovo Formation has a spotted distribution and is a very important palaeogeographic marker; it was deposited in shallow water conditions in a sublittoral area, often with the formation of iron-bearing sediments in the limestones (upper part of the Hettangian–Toarcian). It enters into the Malaplanina carbonate group.

Dolnilukovit Formation (Sapunov 1983). It was introduced as a member of the Ozirovo Formation. Here, it is used as an independent lithostratigraphic formation, built of bioclastic dark grey limestones. In some localities, it contains a few lithostratigraphic members: the Ravna, Romanovdol and Teteven members. Maximal range: Sinemurian–Toarcian. This Formation was sedimented in more quiet and deep localities in the Early Jurassic Basin. It enters into the Mala Planina carbonate group.

Bukorovtsi Formation (Sapunov *in* Sapunov *et al.* 1967). Here, is restituted its original meaning as an independent lithostratigraphic formation, as was created by Sapunov (1967). The Formation is built of clayey limestones and marls (Upper Pliensbachian–Toarcian or the lower part of the Aalenian). The Bukorovtsi Formation was sedimented in quiet and relatively deep environments. It enters into the Mala Planina carbonate group.

Etropole Formation (Sapunov *in* Sapunov *et al.* 1967). Black shales and argillites (similar to the "Black Shales with Possidonia" in the Southern Alps). In the study area, it is divided into three members: the Shipkovo, Nefela and Stefanets Members. They enter into the Chernivit terrigenous group.

Shipkovo Member (Sapunov & Tchoumatchenco 1989). Grey-blackish aleuritic argillites with sideritic concretions (uppermost part of the Lower Bajocian).

Nefela Member (Sapunov & Tchoumatchenco 1989). Grey-blackish clayey aleurolites with sideritic concretions (upper part of the Lower Bajocian–lower part of the Upper Bajocian).

Stefanets Member (Sapunov & Tchoumatchenco 1989). Grey-blackish aleuritic argillites with sideritic concretions (Aalenian–lower part of the Lower Bajocian).

Kichera Formation (Stephanov & Tzankov 1970). Bright sandstones and conglomerates (Aalenian–Upper Bajocian). In the study area, it is divided into the following members: the Oreshets Member, Granitovo Member, Venets Member, Kiryaevo Member and Vrashka Chuka Member.

Oreshets Member (Stephanov & Tzankov 1970). Brownish-beige non-calcareous to feebly calcareous sandstones (middle and upper parts of the Upper Bajocian).

Granitovo Member (Stephanov & Tzankov 1970). Brown-reddish sandstones and conglomerates (Lower Bajocian–lower part of the Upper Bajocian).

Venets Member (Tchoumatchenco 1978). Grey-pinkish conglomerates, gravelitic sandstones, pinkish clays (probably horizontal transition into the Kiryaevo Member) (?Aalenian).

Kiryaevo Member (Tchoumatchenco 1978). Continental sandstones and conglomerates (lower part of the Aalenian).

Vrashka Chuka Member (Tchoumatchenco 1978). Alternation between clays, coals and sandstones (Aalenian – ?uppermost part of the Toarcian).

Polaten Formation (Stephanov 1966). In northwestern Bulgaria, it is divided into three members: the Yanovets, Vratnitsa and Desivitsa members. They enter into the Mala Planina carbonate group.

Yanovets Member (Tchoumatchenco 1978). Based on pinkish limestones and calcareous sandstones (Upper Bajocian).

Vratnitsa Member (Stephanov 1966). It is built of calcareous sandstones to sandy limestones. The lectostratotype is described by Tchoumatchenco (1978) (upper part of the Lower Bajocian–lower part of the Bathonian).

Desivitsa Member (Stephanov 1966). Tchoumatchenco (1978) gave to these sediments the range of Formation which Sapunov & Tchoumatchenco (1986) accepted for them, the range of one marker – the Desivitsa Oolite Marker. Herein, the original meaning of the beds of the Polaten Formation, *i.e.*, above the Vratnitsa Member and below the Bov Formation, in which exists a local Oolite marker in the lower parts of the Desivitsa Member, is returned. It is not logic to have in the Polaten Formation in NW Bulgaria, in the base, a Vratnitsa Member, an Oolite Marker and the Polaten Formation. In the Desivitsa Valley, where these sediments are better developed, in the base exist a bed with oolites and above it, red micritic limestones and marls (Fig. 5E), which are the most important part of this Member. This is the reason for the return to the wider meaning, which was introduced by Tchoumatchenco (1978) (middle part of the Lower Bathonian–lower part of the Upper Bathonian). These sediments were deposited in a shallow part of the basin, with relatively strong water movement. The Desivitsa

Member of the Polaten Formation is the probable equivalent of the Klaus Schichten in the Southern Carpathians.

Bov Formation (Sapunov 1969). It is characterised by clayey limestones and marls (maximal range Upper Bajocian–Middle Callovian). Often it is divided in two members: the Gornobelotintsi and Verenitsa Members**.**

Gornobelotintsi Member (Sapunov & Tchoumatchenco 1989): grey-greenish aleuritic marls (Bathonian–upper part of the Upper Bajocian).

Verenitsa Member (Tchoumatchenco 1978): medium-bedded micritic and clayey limestones in alternation with marls with *Macrocephalites* sp. in the upper part (Lower Callovian – Bathonian).

Javorets Formation (Nikolov & Sapunov 1970). The Formation is based on micritic limestones with chert concretions (Middle Callovian–Oxfordian). Elsewhere in the basal part of this Formation, a horizon exists with zoogenous breccia-conglomerates, herein individualized as an independent lithostratigraphic unit, with the range of a lithostratigraphic marker, the Sokolov Venets Zoogenous Marker. It enters into the West-Balkan Carbonate Group.

Sokolov Venets Zoogenous Marker (Соколов Венец зоогени репер – new unit) (0.42 m thick in the holostratotype) (named after the peak Sokolov Venets, situated 3.5 km to the NNE of Belogradchik Town). The type section is situated along the road Belogradchik–Oreshets Railway Station (Fig. 4E), described by Stephanov (1961), rediscribed by Sapunov & Tchoumatchenco (1995e) and by Belivanova & Sapunov (2003). Here the description is also after Stephanov (1961). "Bed 7. Thickness 0.30 m; brown-red limestones with ferrous hydroxide ooids: *Macrocephalites macrocephalus* (Schlotheim) (abundant), *Hecticoceras hecticum* (Reinecke) (rare), *Choffatia spirorbilis* (Bonchev & Popov). Cover: lithoclastic, pinkish limestones (the Gintsi Formation). Bed 6. Thickness 0.12 m; yellowish-red clayey limestones with scattered ooliths and with large flat-spherical lenticular ferrous hydroxide nodules up to 25 cm in diameter around Bathonian calcareous pieces or Callovian ammonites: *Macrocephalites macrocephalus* (Schlotheim) (frequent) and others ammonites. In the two beds, there are many *Perisphinctidae*, *Phylloceratidae*, *Litoceratidae*, *etc*." The fossils were probably resedimented in the horizontal direction from the Verenitsa Member of the Bov Formation. In this sediment, the Callovian Stage was proven for the first time in Bulgaria by Bonchev & Popov (1935), substratum (Lower Bathonian *Zigzag* Zone): sub-marine hard ground, erosional surface over the Desivitsa Member: sandy, biodetritical limestones with ferrous ooids. Cover: sharp boundary with red nodular limestones containing *Hecticoceras* (Middle Callovian). Previous uses: "Macrocephalites beds" (Bonchev & Popov 1935) and "Red oolitic Callovian limestones" (Atanasov & Alexiev 1956; Atanasov 1957). Regional aspect: in the section near the Television Tower of Belogradchik, the substratum of the Sokolov Venets Zoogenous Marker is represented by alternation of marls and micritic limestones - the Verenitsa Member of the Bov Formation; cover: beige micritic lithoclastic limestones – the Gintsi Formation. The Sokolov Venets Marker is composed of a few centimetres of dark grey marly limestones. This marker is distributed in the Western, Central and East Stara Planina, the Pre-Balkan and in West Bulgaria. In some localities, it represent an erosional surface between the Polaten Formation and the cover of the Gintsi Formation (Staro selo, region of Pernik, western Bulgaria (Tchoumatchenco *et al*. 2010a, 2010b), between the Polaten Formation and the Belediehan Formation (Tchoumatchenco *et al*. 2010a), between the Polaten Formation and the turbidite Cerniosam Formation (in Konyava Planina Mt., demonstrated by I. Zagorchev), or between the Polaten and the Lobosh Formation (Tchoumatchenco *et al*. 2010a). More complicated is the situation in the area of Godech, to north-west of Sofia, near the Villages Gintsi and Komshtitsa. Belivanova & Sapunov (2003) wrote that "The section of the Gintsi Cliff, District of Sofia is an uninterrupted Bathonian–Callovian section". This is demonstrated in their figs. 1 and 2 and proven by the ammonitic data, the results of a microfacies study (samples 1, 2) and the analysis of the faunal spectra. This situation is true for the north Gintsi Venets (Cliff) and partly, for the south Gintsi Venets (Cliff), where the beds are concordantly. Interestingly, Belivanova & Sapunov (2003) do not comment on the paper of Tchoumatchenco & Sapunov (1998), in which the folded upper beds of the Polaten (or Bov?) Formation is demonstrated, and they comment only on this part of the section where it is represented by two horizontal beds, lower (called in the Komshtitsa Section, the Polaten Formation by Tchoumatchenco *et al*. (2001) and the Bov Formation by Belivanova & Sapunov (2003)) and the upper "Niveau condensé à ammonites" with indications of the "Z. à *Gracilis* (s/Z. à *Michalskii*)". Belivanova & Sapunov (2003) indicated that in the "Bov Formation" is collected *Clydoniceras* cf. *discus* (J. Sowerby 1813) (Upper Bathonian, upper part) the *C. discus* Zone and the upper bed, the Yavorets Formation – dark grey micritic limestones, in which, from the very base of the packet, is found *Macrocephalites cannizaroi* (Gemmellaro 1868) (Lower Callovian), *Grossouvria* sp. (Callovian) and *Macrocephalites* spp. (Lower Callovian). The determination of these ammonites is out of doubt. However, in the south Gintsi Venets (Cliff), these two beds in horizontal direction change over a short distance (in 2–3 meters) (Fig. 5B). The lower bed became folded (Tchoumatchenco & Sapunov 1998; refigured in Tchoumatchenco *et al*. 2010a, Fig. 4D), and the upper bed (with the Callovian ammonites) became thick, up to 1.80 m. This bed fully filled the negative parts of the folded lower bed (Fig. 5D). What is demonstrated in Figure 5d? At the end of the Bathonian, the beds were folded (the cause is unknown, probably slumping of the Bathonian sediments), then the negative folds were fully filled by current accumulations from the Lower Callovian sediments, which were the result of erosion and redeposition of sediments containing ammonites and other fossils (especially from the Lower Callovian part of the Bov Formation). In the vicinities of Komshtitsa Village (at the piedmont of the Elenine Vrah), the Sokolov Venets Zoogenous Marker was structured by a zoogenous breccia or locally, by an intraformational conglomerate (TCHOUMATCHENCO *et al*. 2010b, Fig. 4F). In the Nechinska Bara Valley, near Gorno Belotintsi Village, Montana District, the Sokolov Venets Marker is expressed only by an angular discordance (SAPUNOV & TCHOUMATCHENCO, 1998; SAPUNOV & TCHOUMATCHENCO, 1995d). In addition, a local discordance between the Verenitsa Member and the Gintsi Formation is expressed in the Dolni Lom Village section (SAPUNOV & TCHOUMATCHENCO 1995g). The substratum of the Sokolov Venets Zoogenous Marker is with different ages: Lower Bathonian in the type section, in western Bulgaria, *etc*.; Upper Bathonian in the Gintsi Village sections, in the Komshtitsa section, *etc*.; Lower Callovian in the Belogradchik TV Tower section, in the Nechinska Bara Valley section, in the Dolni Lom section, *etc*. and depends on the energy of the sub-marine erosion (after STEPHANOV 1961 – emersion and transgression). The Sokolov Venets Marker is analogous to the Middle Callovian Sultanci Formation in the bore holes in the area of Provadiya Town, eastern Bulgaria.

The Sokolov Venets Zoogenous Marker can be correlated with the Lower Callovian sediments with many ammonites in the area of Rosomač–Senokos (Stara Planina Mts.), near D. Milanovac (**23a** in the present paper) (ANDJELKOVIĆ 1975), *etc*.

What is the cause of the formation of the Sokolov Venets Zoogenous Marker? We agree with the notion of NACHEV (2010) that at the end of the Bathonian in the “Balkanids”, there were many hesitant movements with a tendency of general swallowing. One of us (P.T.) thinks that the post-Bathonian erosion was the most developed during the early Callovian and at this time, the Bathonian–Lower Callovian sediments of the Bov Formation (Verenitsa Member), which are well preserved in the section of the Belogradchik–T.V. Tower, were completely destroyed to the north-west (in the holostratotype of the Sokolov Venets Zoogenous Marker). Probably during the early Callovian, the north part of a syn-Early Callovian fault, crossing the seabed near the present day Belogradchik, was elevated and the sediments destroyed, and their ammonites resedimented in the sediment of the Sokolov Venets Zoogenous Marker. The aspect of this marker is different in different localities: in some localities, it is represented by an erosional surface, where there was only elevation of the area, and in other, where the erosion was weaker, after the erosion followed stage of deposition of sediments of Sokolov Venets Zoogenous Marker. It is interesting that the new sedimentation started in many localities during the Middle Callovian and in others later, during the Early or the Late Kimmeridgian.

Gintsi Formation (NIKOLOV & SAPUNOV 1970) – nodular and lithoclastic limestones; in NW Bulgaria, they are divided into three unformal packets; the upper packet (“Upper nodular limestones”) – reddish nodular and lithoclastic limestones (Middle–Upper Kimmeridgian–Lower Tithonian); the middle packet (“Quarry limestones”) – lithoclastic and micritic limestones (Middle and Upper Oxfordian–Lower Kimmeridgian); the lower packet (“Lower nodular limestones”) – grey nodular and lithoclastic limestones (Middle–Upper Callovian–Lower Oxfordian). It enters into the West-Balkan Carbonate Group.

Glozhene Formation (NIKOLOV & SAPUNOV 1970) – well bedded micritic limestones (slightly lithoclastic in the base) (Middle–Upper Tithonian–Berriasian). It enters into the West-Balkan Carbonate Group.

Brestnitsa Formation (NIKOLOV & KHRISCHEV 1965) – the Formation is structured by bright grey to grey-whitish limestones, thick bedded, often with corals, rudists, *etc*. (Upper Tithonian–Berriasian, (after some authors up to the Barremian). It enters into the West-Balkan Carbonate Group.

Magura Formation (NIKOLOV & TZANKOV 1996) – it is based on whitish to grey-beige thick bedded, shallow water limestones, in many localities containing corals, gastropods and bivalves. They also contain some calpionellids (Upper Tithonian–Berrisaian). It enters into the West-Balkan Carbonate Group.

Slivnitsa Formation (ZLATARSKI 1885) – it is based on bright thick-bedded limestones, in some locality with many corals and gastropods. It contain some calpionellids in its upper parts (Upper Tithonian–Berriasian; after some colleagues up to the Hauterivian). It enters into the West-Balkan Carbonate Group.

N. B.

These three lithostratigraphic units are with the same or very similar lithological characteristics and with almost the same stratigraphical position. The problems for the delimitation of their area of distribution are, to a high percent, subjective. Their outcrops are separated one from others by younger sediments and it is question of personal opinion whether one outcrop is connected with another or not. The discussion was opened by the paper of TCHOUMATCHENCO & SAPUNOV (1986). At this time, we did not know that in East Serbia, the Vratarnica Series of ANDJELKOVIĆ (1975) existed, and by analysis of the geological literature (known to this moment in Bulgaria), P.T. came to the decision that the Slivnitsa Formation is connected in the region of Vrashka Chuka with the Brestnitsa Formation. This idea was adopted by his colleague, Ivo Sapunov, and it was published by Tchoumatchenco & Sapunov (1986). In many of the sheets of the geological map of Bulgaria on the scale 1:100 000, concerning NW Bulgaria, this idea was adopted and on them is indicated the presence of the Slivnitsa Formation, but in the neighbouring map, for the same rocks, the Brestnitsa Formation was adopted. Later, Nikolov & Tzankov (1996) created for analogic rocks, a new lithostratigraphic formation – the Magura Formation. Finally, his (of P.T.) present day opinion is that the Slivnitsa Formation is developed only in western Bulgaria and is separated from the same rocks in NW Bulgaria and NE Serbia by the volcano–sedimentary rocks of the Vratarnica Formation ("Series") (Figs. 1, 2 and 3) of Andjelković (1975), Andjelković *et al*. (1996), Andjelković & Mitrović-Petrović (1992). His last opinion is that the Magura Formation is connected with the Brestnitsa Formation, but in text I, the idea of Ruskova & Nikolov (2009) is followed because it is a predominantly a Lower Cretaceous problem, *i.e.*, that they are separate lithostratigraphic bodies.

Syn-sedimentary discordances

In the Jurassic sediments of NW Bulgaria exist two regional syn-sedimentary discordances:

Sokolov Venets Discordance – in the subsided parts of the basin, it is expressed only by an angular discordance (without erosion of the substratum and new sedimentation – Nechinska Bara, Dolni Lom). In the moderately elevated region, the discordance is fossilized by few centimetre deposits – Belogradchik TV Tower, Teteven, *etc*. In the more elevated area was effectuated an erosion and subsequent accumulation of calcareous breccia-conglomerate, Belogradchik–Oreshets, Gintsi–Komshtitsa; the substratum is spotted; the erosion goes up to the Lower Bathonian beds, Belogradchik–Oreshets, Kremikovtsi, *etc*. In western Bulgaria, the result is a lack of sedimentation going up to the Early Kimmeridgian (Kremikovtsi – Sofia District), Staro Selo (Pernik District) or to the Late Kimmeridgian (Konyava Planina Mt.; a phenomenon demonstrated to me by I. Zagorchev).

Granitovo Discordance – as result of a seismic shock during the Late Kimmeridgian, in the sediments of the upper part of the Gintsi Formation, in the area of Belogradchik, a fold formed (Fig. 4D), which passed into an overthrust with NW vergency (Figs. 4E, F). In the Mihaylovgrad Paleograben, the result of this seismic shock was the formation of the Shugovitsa Slump (Fig. 5F). It commences in the region of the Gaganitsa Lake area and goes to the north of the Shugovitsa Valley, near Nikolovo Village. It is interesting that here the vergency of the folds and overthrusts are opposite to the fold-over thrust in the area of Belogradchik with north vergency and transport of material from south to north.

Acknowledgements

The new research was realized under the bilateral scientific project between the Bulgarian and the Serbian Academies of Sciences: "Trans-border stratigraphic correlations of the western Stara Planina Mts. in western Bulgaria and eastern Serbia". The research was also supported by the Ministry of Education and Science of the Republic of Serbia, Project No. 176015. We are thankful to reviewers, Acad. Todor Nikolov and Dr. Radoslav Nakov from the Bulgarian Academy of Sciences for their useful suggestions.

References

Andjelković, M. 1975. Stara Planina. *In*: K. Petković (ed.), *Geology of Serbia. II-2. Stratigraphy, Mesozoic*, 89–91. Univeristy of Belgrade, Faculty of Mining and Geology, Institute for Regional Geology and Paleontology (in Serbian).

Andjelković, M. & Mitrović-Petrović, J. 1992. *Paleogeography of Serbia. The Jurassic*. 125 pp. Belgrade University, Faculty of Mining and Geology, Institute for Regional Geology and Paleontology, Belgrade.

Andjelković, M., Mitrović-Petrović, J., Jankičević, J., Rabrenović, D., Andjelković, J. & Radulović, V. 1996. *Geology of Stara planina*. *Stratigraphy*. *In*: Andjelković, M. (ed.). 247 pp. Belgrade University, Faculty of Mining and Geology, Institute for Regional Geology and Palaeontology, Belgrade (in Serbian).

Atanasov, G. 1957. The microstructure of the rocks as stratigraphic marker. *Godišnik na Sofijskij univerzitet, Geologo-geografski fakultet, 2, Geology,* 50: 85–114 (in Bulgarian).

Atanasov, G. & Alexiev, B. 1956. Lithology of the Jurassic sediments in part of the West Stara Planina. *Bulletin of Geological Instiute of Bulgarian Academy of Science*, 4: 153–205 (in Bulgarian).

Belivanova, V. & Sapunov, I. 2003. The pre-Callovian stratigraphic gap in the Central Balkanids: a key for the interpretation of other Early–Middle Jurassic gaps in Bulgaria. *Geologica Balcanica,* 33 (1–2): 17–33.

Belivanova, V. & Sapunov, I. 2003. Features of some Early–Middle Jurassic diastems in Bulgaria. *Geologica Balcanica,* 33: 35–45.

Bonchev, E. & Popov, G. 1935. On the fauna of the *Macrocephalites* beds in the peak Belogradchishki Venets. *Geologica Balcanica,* 1 (3): 117–126.

Hedberg, H.D. (ed.). 1976. *International Stratigraphic Guide.* A guide to stratigraphic classification, terminology and procedure. 200 pp. John Wiley & Sons, New York.

MITROVIĆ-PETROVIĆ, J. & ANDJELKOVIĆ, M. 1992. *Paleoecology of Serbia. The Jurassic.* 77 pp. Belgrade University, Faculty of Mining and Geology, Institute for Regional Geology and Paleontology, Beograd.

NACHEV, I. 2010. Geological dreams and realities. 240 pp. *Asconi-izdat*, Sofia (in Bulgarian).

NACHEV, I., SAPUNOV, I. & STEPHANOV, J. 1963. Stratigraphy and lithology of the Jurassic between the villages of Gorno Ozirovo and Prevala (north-western Bulgaria). *Trudove vurhou Geologiata na B'lgaria, Seria stratigrafâ, tektonika*, 5: 99–146 (in Bulgarian).

NIKOLOV, T. & KHRISCHEV, KH. 1965. Base of the stratigraphy and the facial changes of parts of the Lower Createaceous sediments in the Pre-Balkan. *Trudove vurhou Geologiata na B'lgaria, Seria stratigrafâ, tektonika*, 6: 53–76 (in Bulgarian).

NIKOLOV, T. & ROUSKOVA, N. 1989. New formal lithostratigraphic units connected with the Lower Cretaceous in North-West Bulgaria. *Comptes rendus de l'Académie bulgare des Sciences,* 42: 93–94 (in Russian).

NIKOLOV, T. & SAPUNOV, I. 1970. On the regional stratigraphy of the Upper Jurassic and parts of the Lower Cretaceous in the Balkanids. *Comptes rendus de l'Académie bulgare des Sciences,* 23: 1397–1400 (in Russian).

NIKOLOV T. & SAPUNOV I. 1977. International symposium on the Jurassic/Cretaceous boundary in Bulgaria. Excursion guidebook. 120 pp. Bulgarian Commission on Stratigraphy, University of Sofia.

NIKOLOV, T. & SAPUNOV, I. 2002. Stratigraphic code of Bulgaria. Second revised and expanded edition. *National commission on stratigraphy of Bulgaria*. 137 pp. Prof. M. Drinov Academic Publishing House, Sofia.

NIKOLOV, T. & TZANKOV, TZ. 1996. Magura Formation – a new lithostratigraphic unit (Lower Cretaceous, Western Fore-Balkan). *Comptes rendus de l'Académie bulgare des Sciences,* 49: 71–74.

PATRULIUS D. (Coordinator). 1972. Atlas lithofacial. III. Jurassique. 1:200 000. 11 pp. Institul Geological Romaniei, Bucharest.

RUSKOVA, N. & NIKOLOV, T. 2009. Sedimentary associations and facies. Lower Cretaceous geology. *In:* ZAGORCHEV, I., DABOVSKI, CH. & NIKOLOV, T. (eds.), *Geology of Bulgaria*. Volume II, part 5. Mesozoic geology. 260–278. Prof. M. Drinov Academic Publishing House.

SALVADOR, A. (ed.). 1994. *International stratigraphic Guide.* A guide to stratigraphic classification, terminology and procedure. Second edition. 214 pp. International Union of Geological Sciences and Geological Society of America, Inc., Boulder, Colorado.

SAPUNOV, I. 1969. On some contemporary stratigraphic problems of the Jurassic system in Bulgaria. *Izvestiâ na geologičeskiâ institut, Seriâ Stratigrafiâ i litologiâ*, 18: 5–20.

SAPUNOV, I. 1976. Ammonite stratigraphy of the Upper Jurassic in Bulgaria. I. Rock and ammonite successions. *Geologica Balcanica*, 6 (3): 17–40.

SAPUNOV, I. 1983. Jurassic system. *In*: ATANASOV, A. & BOKOV, P. (eds.), *Geology and oil-gas perspectives of the Moesian Plateform in Central North Bulgaria,* 18–28. Tehnika, Sofia (in Bulgarian).

SAPUNOV, I. & BELIVANOVA, V. 2002. Origin of the Early – Middle Jurassic stratigraphic gaps in the Central Balkanids. *Geologica Balcanica,* 32 (2–4): 41–43.

SAPUNOV, I. & METODIEV, L. 2009. Jurassic geology. *In*: ZAGORCHEV, I., DABOVSKI, C. & NIKOLOV, T. (eds.), *Geology of Bulgaria*, Vol. II. Part 5, Mesozoic geology of Bulgaria, 133–222. Prof. M. Drinov Academic Publishing House.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1989. Some new ideas about the lithostratigraphy of the Middle Jurassic marine sediments in western and central Bulgaria. *Spisanie na B'lgarskoto geologičesko družestvo,* 50 (1): 15–25.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1993. Jurassic lithostratigraphic units. *In:* TENCHOV, Y. (ed.), *Glossary of the formal lithostratigraphic units in Bulgaria (1882–1992).* 397 pp. Bulgarian Academy of Sciences, Geolinvest, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995. Jurassic system. *In*: HAYDUTOV, I. (ed.). Explanatory note to the geological map of Bulgaria on scale 1:100 000, Belogradchik map sheet. 144 pp. Geologia & Geofizika, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995a. Jurassic system. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 9–10. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995b. The Jurassic section at the Rabishka Mogila Hill, *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 51–52. Bulgarian Academy of Sciences, Geological Institute Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995c. The Jurassic at the Ledenika Cave and in the Vratsata Gorge, near thye town of Vratsa. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 42–45. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995d. The Jurassic at the Gorno Belotintsi section, Montana District. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 46–48. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995e. The Jurassic at the Belogradchik–Oreshets Railway Station section. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 52–54. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995f. The Middle Jurassic in the section near the village of Yanovets, Belogradchik area. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 54–56. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995g. The Jurassic at the section village Dolni Lom, Montana District. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo,* 56–57. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995h. The Jurassic near the village of Mitrovtsi, Montana District. *In*:

TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo*, 57–58. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995i. The Jurassic at the village Gaganitsa section, Montana District. *In*: TZANKOV, TZ. (ed.), *Western Stara planina. Geological guidebook. Progeo*, 58–62. Bulgarian Academy of Sciences, Geological Institute, Sofia.

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995k. The Jurassic System. *In:* FILIPOV, L. (ed.), *Explanatory note to the geological map of Bulgaria on scale 1:100 000, Montana map sheet*. 25–45. Geology & Geophysics Corporation, Committee of Geology and Mineral Resources, Sofia (in Bulgarian with English summary).

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995l. The Jurassic System. *In:* HAYDUTOV, I. (ed.), *Explanatory note to the geological map of Bulgaria on scale 1:100 000, Belogradcik map sheet*. 68–89. Geology & Geophysics Corporation, Committee of Geology and Mineral Resources, Sofia (in Bulgarian with English summary).

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995m. The Jurassic System. *In:* HAYDUTOV, I. (ed.). *Explanatory note to the geological map of Bulgaria on scale 1:100 000, Berkovica map sheet*. 59–78. Geology & Geophysics Corporation, Committee of Geology and Mineral Resources, Sofia (in Bulgarian with English summary).

SAPUNOV, I. & TCHOUMATCHENCO, P. 1995n. The Jurassic System. *In:* TZANKOV, TZ. (ed.). *Explanatory note to the geological map of Bulgaria on scale 1:100 000, Vraca map sheet*. 36–46. Geology & Geophysics Corporation, Committee of Geology and Mineral Resources, Sofia (in Bulgarian with English summary).

SAPUNOV, I., TCHOUMATCHENCO, P., DODEKOVA, L. & CERNJAVSKA, S. 1985. Contribution to the formal lithostratigraphic scheme related to the Middle Jurassic deposits from North-eastern Bulgaria. *Spisanie na B'lgarskoto geologičesko družestvo,* 46 (2): 144–152.

SAPUNOV, I., TCHOUMATCHENCO, P. & MITOV, P. 1988. Jurassic development of Northwest Bulgaria. *Geologica Balcanica,* 18 (1): 3–82 (in Russian with English summary).

SAPUNOV, I., TCHOUMATCHENCO, P. & SHOPOV, V. 1967. On certain particularities in the paleogegraphy of the region of Teteven (western Balkanids). *Trudove vurhou Geologiata na B'lgaria, Seria Geotektonika, stratigrafâ, lithologâ*, 16: 125–143.

STEPHANOV, J. 1961. The Bathonian in the section of the Belogradchik-gara Oreshets road (North-West Bulgaria). *Bulletin of the Institute of Geology "Strasimir Dimitrov"*, 337–369 (in Bulgarian with English summary).

STEPHANOV, J. 1965. Belogradchishki venets. *Guide book to the excursion Sofia-Belogradchik-Sofia. VII Congres CBGA,* 78–81, Sofia (in Russian).

STEPHANOV, J. 1966. The Middle Jurassic ammonite genus *Oecotraustes* Waagen. *Trudove vurhou Geologiata na B'lgaria, Seria paleontologiâ,* 8: 29–69.

STEPHANOV, J. & TZANKOV, TZ. 1970. On the lithostratigraphy of the Lower and Middle Jurassic marine rocks in the Belogradchik area. *Trudove vurhou Geologiata na B'lgaria, Seria stratigrafâ, lithologâ*, 19: 41–59.

TCHOUMATCHENCO, P. 1975. Sur la stratigraphie de brachiopods du Jurassique moyen dans la region de Belogradtchik, *Spisanie na B'lgarskoto geologičesko družestvo*, 38 (3): 314–319, 23 (11): 1397–1400.

TCHOUMATCHENCO, P. 1978. Sur certains problemes de la lithostratigraphie du Jurassique moyen en Bulgarie du Nord-Ouest. *Godišnik na Sofijskij univerzitet, Geologo-geografski fakultet, 1, Geology,* 69 (for 1976/1977): 171–192 (in Bulgarian with French summary).

TCHOUMATCHENCO, P. 2002. Cyclostratigraphy of the Jurassic rocks in western Bulgaria. *Geologica Balcanica*, 32 (2–4): 123–126.

TCHOUMATCHENCO, P. 2009. Malaplanina carbonate group and Chernivit terrigenous group– new Jurassic lithostratigraphic units for the Hettangian – Bathonian (Lower – Middle Jurassic) sediments in Bulgaria. *Comptes rendus de l'Académie bulgare des Sciences,* 62 (7): 883–890.

TCHOUMATCHENCO, P. & SAPUNOV, I. 1986. The Brestnitsa Formation – a younger subjective synonyme of the Slivnitsa Formation. *Spisanie na B'lgarskoto geologičesko družestvo*, 47 (1): 74–77.

TCHOUMATCHENCO, P. & SAPUNOV, I. 1998. The Jurassic geological sites in Northwest Bulgaria. *Geologica Balcanica,* 28 (3–4): 137–142.

TCHOUMATCHENCO, P., SAPUNOV, I., THIERRY, J. & DURLET, C. 2001. The Jurassic between Komshtitsa and Gintsi Villages (western Balkan Range, western Bulgaria) – first Jurassic paleontological and stratigraphical site to be protected. *2nd International Symposium of Natural Monuments and Geological Heritage*, 143–150. Molyvos, Lesvos.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, B. & RADULOVIĆ, V. 2006a. Trans-border (east Serbia/west Bulgaria) correlation of the Jurassic sediments: main Jurassic paleogeographic units. *Geološki anali Balkanskoga poluostrva*, 67: 13–17.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, B. & RADULOVIĆ, V. 2006b. Trans-border (east Serbia/west Bulgaria) correlation of the Jurassic sediments: Infra-Getic unit. *Geološki anali Balkanskoga poluostrva*, 67: 19–33.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, V., MALEŠEVIĆ, N. & RADULOVIĆ, B. 2008. Trans-border (east Serbia/west Bulgaria) correlation of the Jurassic sediments: the Getic and Supra-Getic units. *Geološki anali Balkanskoga poluostrva*, 69: 1–12

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, V. & MALEŠEVIĆ, N. 2010a. Trans-border (east Serbia/west Bulgaria) Early–Middle Jurassic (Hettangian – Early Callovian) paleogeographical correlations. *Comptes rendus de l'Académie bulgare des Sciences,* 63 (10): 1505–1514.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, V. & MALEŠEVIĆ, N. 2010b. Trans-border (east Serbia/west Bulgaria) Middle–Late Jurassic (Middle Callovian –

Tithonian) paleogeographical correlations. *Comptes rendus de l'Académie bulgare des Sciences,* 63 (11): 1619–1630.

TCHOUMATCHENCO, P. , RABRENOVIĆ, D., RADULOVIĆ, V. & MALEŠEVIĆ, N. 2011. Thans-border (north-east Serbia/north-west Bulgaria) correlation of the Jurassic lithostratigraphic units. The 8th Romanian Symposium on Paleontology, 115–116, Bucharest.

TENCHOV, Y. (ed.) 1993. *Glossary of the formal lithostratigraphic units in Bulgaria (1882–1992)*. 393 pp. Bulgarian Academy of Science, Sofia.

TZANKOV, TZ. (ed.) 1995. *Western Stara planina. Geological guidebook. Progeo.* 72 pp. Bulgarian Academy of Sciences, Geological Institute, Sofia.

VESELINOVIĆ, D. 1975. Dobra on Danube; Vrška Čuka. *In*: PETKOVIĆ, K. (ed.), *Geology of Serbia. II-2. Stratigraphy. Mesozoic,* 73–75. University of Belgrade, Faculty of Mining ands Geology, Institute for Regional Geology and Paleontology (in Serbian with English summary).

ZLATARSKI, G. 1885. Materials for the geology and the mineralogy of Bulgaria. Periodično *Spisanie na B'lgarskoto Knižovno Družestvo,* 16: 1–27.

Резиме

Међугранична (североисточана Србија/северозападна Бугарска) корелација јурских литостратиграфских јединица

На геолошким и тектонским картама Србије и Бугарске приказане су различите структуре ограничене само на националне територије. У овом раду извршена је корелација јурских седимената североисточне Србије и северозападне Бугарске. Издвојене су следеће палеогеографске јединице: Источни Гетик, Инфра-гетик и Мезијска платформа. Источни Гетик је проучаван на изданцима у близини Рготине, где седиментација започиње од хетанжа, а за време келовеј– горња јура таложе се платформни карбонати. Инфра-гетик је документован на профилима Добре (Песача) и алохтоним седиментима у близини Штубика. Инфра-гетик карактеришу горњојурско вулканско–седиментне творевине Вратарничке серије. Јурска Мезијска платформа је проучавана код Доњег Милановца и Новог Корита у Србији и Горнобелотинског рова у Бугарској. Приказана је корелација јурских седимената у области Вршке Чуке, са обе стране границе и код села Рабиша (пећина Магура у Бугарској). Урађена је ревизија јурских седимената у Бугарској, код Видинског хорста, који су проучавани на Белоградичком, Горње Белотинском, Белимелском и Михајловградском рову. Седиментација у Видинском хорсту започиње у различитим деловима средње јуре, а у Михајловградском рову за време хетанжа (доња јура), где се седиментација одвијала у релативно дубоководној средини. Јужније, на јурском Вратском гребену, на јужном крилу Михајловградског рова, одвијала се плитководна седиментација.

У јурској литостратиграфији СЗ Бугарске описане су следеће формације, које се нешто разликују од оних приказе од стране САПУНОВА И МЕТОДИЈЕВА (2009):

Костинска формација (хетанж, понекад до доњег плензбаха); Озировска формација (горњи део хетанжа–тоар); Доњолуковичка формација (доња јура); Букуровска формација (горњи плензбах–тоар–део алена); Ентрополска-7 формација, која је подељена на три члана: Шипковски (највиши део доњег бајеса), Нефелски (највиши део доњег бајеса–доњи део горњег бајеса) и Стефански (ален–доњи део доњег бајеса); Кичерска формација је подељена је у чланове: Орешечки (средњи и горњи део горњег бајеса), Гранитовски (доњи бајес–доњи део горњег бајеса), Венечки (?ален), Кирјевски (доњи део алена) и Врашко Чукски (ален–највиши део тоара); Полетенска формација је подељена у три члана: Јановечки (горњи бајес), Вратнички (горњи део доњег бајеса–доњи део бата), Десевички (средњи део доњег бата–доњи део горњег бата; ?еквивалент Клауским слојевима); Бовска формација је подељена на два члана: Горнобелотински (бат–горњи део горњег бајеса) и Веренски (доњи келовеј–бат); Јаворечка формација (средњи келовеј–оксфорд), у бази ове формације уведена је литостратиграфска јединица – Соколовско–веначки зоогени репер; Гиначка формација (средњи–горњи келовеј–доњи оксфорд); Гложанска формација (средњи–горњи титон–беријас); Брестничка формација (горњи титон–беријас; према неким ауторима до барема); Магурска формација (горњи титон–беријас) и Сливничка формација (горњи титон–беријас).

У јурским седиментима СЗ Бугарске постоје две син-седиментне дискорданције: Соколовско–веничка и Гранитовска.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	21–27	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172021T

Trans-border (east Serbia/west Bulgaria) correlation of the morpho-tectonic structures

Platon Tchoumatchenco[1], Dragoman Rabrenović[2], Vladan Radulović[3], Barbara Radulović[3] & Nenad Malešević[2]

Abstract. In the Bulgarian and Serbian geological literatures, many maps, both geological and tectonic, exist showing the structures, but limiting them nationally. There are very few publications correlating the structures from both sides of the border and they preserve the local Bulgarian or Serbian names. Our aim is to create a base for the unification of the names defining the major morpho-tectonic structures: the Moesian Platform, the Miroč – Fore-Balkan Unit, the Poreč–Stara Planina Unit, the Krayna Unit, the Getic – Srednogorie Unit, the Supra Getic – Kraishtide Zone, the Serbo-Macedonian – Thracian Massif and the Vardar Zone, showing their synonyms from the Bulgarian and Serbian sides.

Key words: east Serbia, west Bulgaria, morpho-tectonic structures, correlation, synonyms.

Апстракт. У геолошкој литератури Србије и Бугарске постоје многе геолошке и тектонске карте које приказују различите структуре које су ограничене само на националне територије. Ретке су публикације које се баве корелацијом ових структура, а и у њима су структуре садржале, како српске, тако и бугарске називе. Циљ овог рада је да створи базу за унификацију назива, прикаже синониме са обе стране границе и дефинише главне морфо-тектонске структуре: Мезијска платформа, Мироч – Предбалкан, Поречко-Старопланинска јединица, Крајина јединица, Гетик – Средњогорје, Супрагетик – Крајиштиди, Српско-македонска маса – Тракијски масив, Вардарска зона.

Кључне речи: источна Србија, западна Бугарска, морфо-тектонске структуре, корелација, синоними.

Introduction

A collective of Serbian and Bulgarian geologists started a trans-border correlation of the Jurassic sediments in 2005 as an unofficial collaboration, which later extended into an official project. The first steps were made by correlating the Jurassic sediments from southeast Serbia and southwest Bulgaria (Tchoumatchenco *et al*., 2006a, b, 2008). The main Jurassic palaeogeographic units were correlated in Tchoumatchenco *et al*. (2006a). The lithostratigraphic units from both sides of the state border were compared in Tchoumatchenco *et al*. (2006b, 2008) with the aim of demonstrating their positions in the sections and the possibilities of their correlation. Later this correlation became the subject of a bilateral project between the Bulgarian Academy of Sciences (Project leader for Bulgaria Dr. Iskra Lakova) and the Serbian Academy of Sciences (Project leader for Serbia Dr. Dragoman Rabrenović). As results of this collaboration, the palaeogeographic correlations during the Hettangian–Early Callovian (Tchoumatchenco *et al*. 2010a) and the Middle Callovian–Tithonian (Tchoumatchenco *et al*. 2010b) were elaborated. The purpose of the present paper is to correlate the major morpho-tectonic units established in Serbia and in Bulgaria across the com-

[1] Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria. E-mail: platon@lark.tu-sofia.bg

[2] Department of Geology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, P. O. Box 162, 11000 Belgrade, Serbia. E-mails: rabrenovic@verat.net; malesevic.nesa@gmail.com

[3] Department of Palaeontology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, P. O. Box 162, 11000 Belgrade, Serbia. E-maisl: vrad@eunet.rs; brad@net.co.rs

mon state border and to show the synonyms used by the Bulgarian and the Serbian geologists as a first step for their unification. This idea came from recommendations of the International Stratigraphic Guide (SALVADOR 1994) that "Stratigraphic units are not limited by international boundaries and should not differ across them". If this suggestion is difficult to be followed for single lithostratigraphic units, which are quite numerous, in our opinion, it is much easier to be applied to tectonic units as they are much larger and can be followed easier.

From the two sides of the Bulgarian/Serbian state border, several morpho-tectonical units, having their local name in the two countries, are distinguished.

In the regional geology and the regional tectonics, two general ways to make trans-border correlations are accepted: (1) to prolong the geological/tectonical units established in a bordering neighbouring region to the local region subjected to investigation; (2) to study the geology in one local region and to try to extend the established units into the neighbouring regions. Some, mainly Serbian, geologists (ANDJELKOVIĆ 1996; SIKOŠEK 1955; ANDJELKOVIĆ & SIKOŠEK 1967; GRUBIĆ 1980; BOGDANOVIĆ 1974; DIMITRIJEVIĆ 1995; KRÄUTNER & KRSTIĆ 2003; *etc.*) proceeded in the first manner, which prolonged the classical units established in the Carpathians across the Danube into northeastern Serbia. The second way was applied by some Bulgarian geologists (S. BONČEV 1910, 1927; E. BONČEV 1936, 1978, 1986; etc.), who made efforts to draw out the units established in Bulgaria over the Bulgarian state border into Serbia. The two ways of study have their advantages and their weak points. However, the majority of authors limit their interpretations to the national territory (Bulgarian or Serbian) – YOVCHEV (1971, ed.), KARAMATA *et al.* (1997), HAYDUTOV *et al.* (1997), ANDJELKOVIĆ (1996), SIKOŠEK (1955), ANDJELKOVIĆ & SIKOŠEK (1967), GRUBIĆ (1980), BOGDANOVIĆ (1974), DIMITRIJEVIĆ (1995), DABOVSKI *et al.* (2002), DABOVSKI & ZAGORCHEV (2009), *etc.*

The problem of the trans-border correlation (according to BONČEV 1986) started in 1885 when E. Suess, launched the idea for the existence of a general bending (torsion?) of the directions in the Carpatho-Balkan arc. In 1904, CVIJIĆ (reference in: ANDJELKOVIĆ 1996) found in the valley of the Timok near the town of Zaječar a graben, a low structural zone, in which the axes of both South Carpathian and the Balkan structures are deepening. This was the starting point of the delimitation between the Carpathian and Balkanide structures. Later on, this view was also supported by S. BONČEV (1910, 1927). In the last paper, S. Bončev used for the first time the term Balkanides. In the opinion of E. BONČEV (1936), the Berkovitsa anticline is cut diagonally and its prolongation must occur to the west of Zaječar. Later, SIKOŠEK (1955) proved that along the Timok Valley passes a strike-slip fault, along which the Berkovitsa and the Belogradchik anticlines are displaced by up to 40–50 km. To the west, the Carpatho–Balkanides are represented by the Srednogorie (which according to S. BONČEV 1910, 1927, is a prolongation of the Getic). Many Serbian authors, such: ANDJELKOVIĆ & SIKOŠEK (1967), GRUBIĆ (1980), BOGDANOVIĆ (1974), DIMITRIJEVIĆ (1995), KARAMATA *et al.* (1997), KRÄUTNER & KRSTIĆ (2003), *etc.* published their views concerning the structure of East Serbia. In general, they all considered the area as consisting of a series of longitudinal structural zones, which differed from one another only by the explanation of their genesis (based on different positions: the geosynclinal theory, the plate-tectonic theory, the principles of the naps tectonic, the conception of the terranes, *etc.*), and in some details. Some Bulgarian geologists, such E. BONČEV (1936, 1986), *etc.*, also proposed their explanations about the correlation of the west Bulgarian/east Serbian structures, To explain our ideas for the trans-border correlation (Fig. 1), the Tectonical model for the Carpatho-Balkan arch of BONČEV (1986; fig. 38) was taken. In addition, the Tectonic Framework of the Carpatho-Balkanides of eastern Serbia of ANDJELKOVIĆ (1996; fig. 2) was employed. Despite the fact that his sketch map covers only eastern Serbia, we went beyond its regional value and furthermore it has already been used as a basis for palaeogeographic maps (TCHOUMATCHENCO *et al.* 2010a, 2010b).

Correlation of the morpho-tectonic units

We refer to eight morpho-tectonic units (Fig. 1) and we mention only some of their synonyms existing in the Bulgarian and Serbian literature. The reason for not making a full list of synonyms is that the literature treating the problems of the tectonic division of the region is too numerous, which makes it impossible to reference all the authors; nevertheless, their contributions are important.

(1) Moesian Platform (Fig. 1, 1) represents a platform with a Precambrian consolidated basement and a Palaeozoic–Mesozoic–Neozoic cover, part ("spur") of Eurasia. It is described as the Moesian Platform or the Moesian Plate by many authors: BONČEV (1978), IVANOV (1988), DABOVSKI *et al.* (2002), NACHEV & NACHEV (2008), TZANKOV (1995), IOVCHEV (1971), DABOVSKI & ZAGORCHEV (2009), ANDJELKOVIĆ (1996), DIMITRIJEVIĆ (1995), KARAMATA *et al.* (1997), KRÄUTNER & KRSTIĆ (2003), *etc.*

(2) Miroč – Fore-Balkan Unit (Fig. 1, 2) represents an area, consisting of autochthonous fold structures, which is separated from the Moesian Platform by the Fore-Balkan Fault or Balkanide Frontal Line, BONČEV (1978) (Fig. 1, A). Its western part is built-up by series of longitudinal folds, as the Miroč (ANDJELKOVIĆ 1996; DIMITRIJEVIĆ 1995), Belogradchik and Mihailovgrad anticlines (or anticlinoriums) (BONČEV

1971, 1978; TZANKOV 1995), *etc*., and the Milanovac–Novo Korito–Salash syncline (ANDJELKOVIĆ 1996; BONČEV 1910, 1927; BONCHEV 1971, *etc*). For this unit KRÄUTNER & KRSTIĆ (2003) used the name of Lower Danubian (Cosustea Unit, Lainici (Cerna-Miroč), Dragsan Unit) and BONCHEV *et al*. (1973) – Mesoalpine (Illyrian–Pyrenean) Unit: FB – Proper Fore-Balkan and TR – Transitional Zone (Northern Strip of the Fore-Balkan), ND – Danubicum.

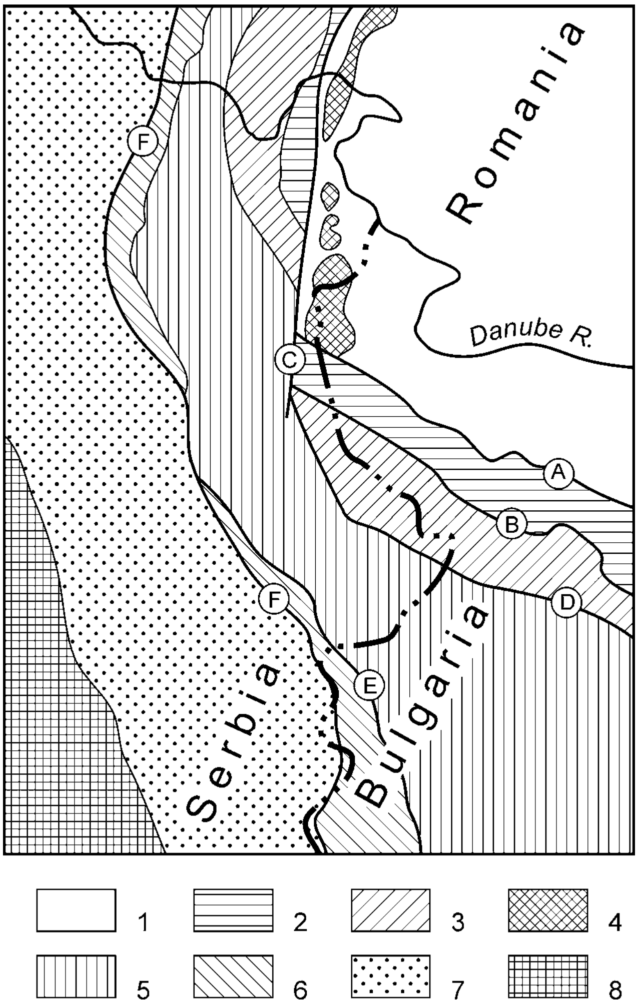


Fig. 1. Trans-border (east Serbia/west Bulgaria) correlations of the morpho-tectonic units. **1,** Moesian Platform; **2,** Miroč – Fore-Balkan Unit; **3,** Poreč-Stara Planina Unit; **4,** Krayna Unit; **5,** Getic – Srednogorie Unit; **6,** Supra Getic – Kraishtide Unit; **7,** Serbo-Macedonian–Rhodope Massif; **8,** Vardar Zone. **A,** Fore-Balkan Fault (Balkanide Frontal Line); **B,** Stara Planina Frontal Line; **C,** Timok Strike-Slip Fault; **D,** Vidlič Dislocation (Behind the Balkanide Fault); **E,** Tran–Ozren Fault; **F,** Morava Fault.

Synonyms: Fore-Balkan Tectonic Zone – YOVCHEV (1971); Fore-Balkan Zone (representing the northern part of the Balkanides) – E. BONČEV (1986); Proper Fore-balkan (with Miroč Anticlinorium, Belogradchik Anticlinorium, *etc*.) – BONČEV (1978); Koula–Obzor Unit of the Balkanide Alpine Folded System – Centralbalkan–Fore-Balkan – IVANOV (1988); Belogradchik Superunit – TZANKOV (1995); West Balkan Unit (*p.p.*) of the Balkan Zone of the Balkan Orogenic System – DABOVSKI *et al*. (2002); Stara Planina Tectonic Zone – Illirian structures – post-Lutetian – NACHEV & NACHEV (2008); Lower Danubian Units (Vraca Scale, Kutlovska Unit, Kula Unit) – KRÄUTNER & KRSTIĆ (2003); Mesoalpine (Illyrian–Pyrenean) Unit: FB – Proper Fore-Balkan and TR – Transitional Zone (Northern Strip of Fore-Balkan), ND – Danubicum – BONCHEV *et al*. (1973); Fore-Balkan Unit – DABOVSKI & ZAGORCHEV (2009); Danubikum, Miroč Unit – DIMITRIJEVIĆ (1995); Milanovac–Novokorito Unit and Miroč Unit of the Balkanikum – ANDJELKOVIĆ (1996); Vrška Čuka–Miroč Terrane, part of the Composite terrane of the Carpatho-Balkanides – KARAMATA *et al*. (1997); Lower Danubian (Cosustea Unit, Lainici (Cerna-Miroč), Dragsan Unit) – KRÄUTNER & KRSTIĆ (2003).

(3) Poreč–Stara Planina Unit (Fig. 1, 3) occupies the space covering the structures of Stara Planina – both in Bulgaria and East Serbia and the massifs of Deli Jovan, Miroč and Greben and continues to the massif Almash, north of the Danube, in Romania (BONČEV 1910). Its northern and eastern boundary with the Miroč – Fore-Balkan unit is the Stara Planina Frontal Line (an overthrust) (Fig. 1, B). The Poreč–Stara Planina Unit is severed and displaced by the Timok–Pirot Transcurrent (strike-slip) Fault (BONČEV 1986; known also as the Štubik–Timok Dislocation – ANDJELKOVIĆ 1996, *etc*.). The south-western slope of this unit builds-up a syncline, known in western Bulgaria as the Izdremets Syncline and in eastern Serbia, as the Dobri Dol–Grlište Zone (ANDJELKOVIĆ 1996). During the Jurassic, the relatively deeper marine sediments of the Infra-Getic Palaeogeographic Zone were deposited in this area. The western boundary of the Poreč–Stara Planina was placed by BONČEV (1986) between the Svoge and the Berkovitsa anticline (anticlinorium), while NACHEV & NACHEV (2008) in this unit included the Svoge Antiforme (anticline, anticlinorium) into the Stara Planina Tectonic Zone.

Synonyms: West-Balkan Tectonic Zone – YOVCHEV (1971); Balkan Structural Zone (with anticlinal structure of Deli Jovan, Berkovitsa Anticlinorium, Šipka Anticlinorium, *etc*.) – BONČEV (1986); Stara Planina Zone – BONČEV (1986; fig. 38); West Balkan Unit (*p.p.*) of the Balkan Zone of the Balkan Orogenic System – DABOVSKI *et al*. (2002); Western Balkan Zone – IVANOV (1988); Berkovitsa Superunit – TZANKOV (1995); Stara Planina Tectonic Zone – Illirian structures – post-Lutetian – NACHEV & NACHEV (2008); Upper Danubian Units (Melianska Scale) – KRÄUTNER & KRSTIĆ (2003); Mesoalpine (Illyrian–Pyrenean) Unit: SP – Stara Planina Zone – BONCHEV *et al*. (1973); Western Balkan Unit – DABOVSKI & ZAGORCHEV (2009); Stara Planina–Poreč Unit (B1) of the

Balkanikum or Balkan Autochthon – ANDJELKOVIĆ (1996); Poreć Unit – DIMITRIJEVIĆ (1995); Stara Planina–Poreč Terrane of the Composite Terrane of the Carpatho-Balkanides – KARAMATA *et al*. (1997); Upper Danubian Units (Arjana and Caleanu–Cuntu Units, Visoč Scale, Presacina–Comereva/Komska Unit, Poiana Mraconia–Gabrovnica Unit, Neamtu–Stakevci Unit) – KRÄUTNER & KRSTIĆ (2003).

(4) Krayna Unit (Fig. 1, 4), in its native land, was affected during the Tithonian by intensive geodynamic processes which caused significant fracturing and submarine volcanic activity that resulted in the formation of volcanogenic-sedimentary products (Vratarnica Series – ANDJELKOVIĆ 1996) and Upper Jurassic–Lower Cretaceous flysch sediments (NACHEV & NACHEV 2008). In the present day, they represent extensions of the Severin Nappes (DABOVSKI & ZAGORCHEV 2009; fig. 5, 1-1) from the South Carpathian and crop out along the state border between NE Serbia and NW Bulgaria.

Synonyms: Krayna Unit of the Moesian Microcraton – TZANKOV (1995); Kraina Unit of the South Carpathian Orogenic System – extension of the Severin Nappe in Serbia and Romania – DABOVSKI *et al*. (2003); Koula Tectonic Zone – YOVCHEV (1971); Severin Zone – BONČEV (1986); Kula Zone – IVANOV (1988); South Carpathians – early Autrichian structures – Aptian – NACHEV & NACHEV (2008); KR – Kraina Unit – BONCHEV *et al*. (1973); Severin Nappes, Krayna Unit of the South Carpathian Orogen System – DABOVSKI & ZAGORCHEV (2009); Kraina Thrust Nappe (Krainicum) – Severin Nappe – ANDJELKOVIĆ (1996); Getian Klippe – GRUBIĆ (1980); Krajina Nappes – DIMITRIJEVIĆ (1995).

(5) Getic – Srednogorie Unit (Fig. 1, 5) is a typical riftogenic system with magmatism of an island-arc type. It is manifested by the outcrops of Upper Cretaceous sedimentary and volcano-sedimentary rocks and a typical Ca-alkaline (to the east K-alkaline as well) magmatism in volcanic, subvolcanic and intrusive facies (BONČEV 1986). In its easternmost part occur big fold structures such as the Svoge–Vidlič anticlinorium, practically without Upper Cretaceous sediments. Its east boundary, with the Poreč–Stara Planina Unit, is the Vidlič dislocation or the Sub-Balkanide fault (Fig. 1, D) (in many localities with transition to an overthrust sheet).

Synonyms: Srednogorie – a zone of impermanent riftogenesis during the Late Alpine tectonic cycle and up to the present (developed on the Thracian Massif) – BONČEV (1978); Srednagora – Getic Strip – BONČEV (1986); Srednagora Zone – IVANOV (1988); Srednagora Tectonic Zone – YOVCHEV (1971); Svogue Superunit – TZANKOV (1995); Burela Unit of Troyan Superunit – TZANKOV (1995); West Srednogorie Unit of the Srednogorie Zone – DABOVSKI *et al*. (2002); Srednagora Tectonic Zone – Late Subhercynian structures – Ante-Maastrichtian – NACHEV & NACHEV (2008); SR – Srednogorie; TU – Tupižnica Zone; SUP – Suva Planina Zone; K – Kučaj Zone – BONCHEV *et al*. (1973); Srednogorie Zone with – Lyubash–Golo Bardo Unit, Western Srednogorie Unit, Svogue Unit – DABOVSKI & ZAGORCHEV (2009); Getikum – DIMITRIJEVIĆ (1995); Carpathicum or Carpathian Thrust Nappe – ANDJELKOVIĆ (1996); the composite terrane of the Carpatho-Balkanides – KARAMATA *et al*. (1997); Getic Units (Suva Planina–Samanjac Unit (included Dušnik Scale), Getic Unit (Kučaj, Ljubaš, Sredna Gora), Kučaj–Svoge Unit, Semenic–Osanica Unit, Luchita–Jidostita Unit, Iskâr Scale, Vidlič Scale, etc. – KRÄUTNER & KSTIĆ (2003). The Getic in Romanian South Carpathian, as the Srednogorie in Bulgaria must be regarded as the most outer fragment of the median Pannonian–Thracian Massif – BONČEV (1986; p. 212**).**

(6) Supra Getic – Kraishtide Zone (Fig. 1, 6) possesses relatively thick Precambrian high-grade metamorphic rocks covered by Palaeozoic, Mesozoic and Neozoic sequences. A very characteristic feature for it is the presence of a synsedimentary graben (Palaeozoic, Mesozoic and Neozoic) in which a specific sedimentation is expressed. Its eastern boundary with the Getic – Srednogorie unit is the Tran–Ozren Fault (Fig. 1, E).

Synonyms: Supra-Getic (Krepolin Strip), Kraistide Zone – BONČEV (1986; fig. 2); Kraishte Tectonic Zone – YOVCHEV (1971); Thracian Massif (Kraistides, Dardanian Massif, Rhodope Massif) – BONČEV (1978); Kraishte Zone – IVANOV (1988); West Kraishte (Elovitsa Exotic Terrane) (continues into the Ranovac–Vlassina–Osogovo Terrane) – HAYDUTOV *et al*. (1997); Strouma Unit of the Morava–Rhodope Zone – DABOVSKI *et al*. (2002); Srednagora Tectonic Zone – Late Cimmerian structures – Tithonian–Berriasian – NACHEV & NACHEV (2008); KE – Kraishtides, LU – Lužnica Zone – BONCHEV *et al.* (1973); Struma Unit of the Morava–Rhodope Zone – DABOVSKI & ZAGORCHEV (2009); Supra-Getikum (Golubac–Lužnica Zone) – DIMITRIJEVIĆ (1995); Lužnica Tectonic Unit – DIMITRIJEVIĆ (1995); Carpathicum or Carpathian Thrust Nappe – ANDJELKOVIĆ (1996); Kraishte Units – Zemen Unit, Lužnica Unit (Vlahina, Osogovo–Cmook, Ograzden–Verila), Koritnik Scale – KRÄUTNER & KRSTIĆ (2003).

(7) Serbo-Macedonian – Thracian Massif (Fig. 1, 7) is the area between the Vardar Zone and the Carpatho-Balkanides. Its principal feature is the presence of metamorphic rocks, which served as the source area for the Palaeozoic–Mesozoic seas. Its eastern boundary is the large Morava Fault (Fig. 1, F).

Synonyms: Thracian Massif (Kraistides, Dardanian Massif, Rhodope Massif) – BONČEV (1978); Dardanian (Serbo-Macedonian) – Thracian massif – BONČEV (1986); Rhodope Composite Terrane (composed of a few metamorphic blocs: Serbo-Macedonian Massif, Rhodope Massif, Sredna Gora Block and Sakar–Istranca Zone – HAYDUTOV *et al.*) (1997); Rhodope

Massif – IVANOV (1988); Morava Unit of the Morava–Rhodope Zone (Morava, Ograzhden, Strouma, Pirin–Pangaion, Rila–Rhodope, East-Rhodope, Mandritsa–Makri Units) – DABOVSKI *et al*. (2002); R – Rhodope Massif, GP – Golubac–Penkovo Nappe, SM – Serbo-Macedonian Massif – BONCHEV *et al*. (1973); Morava Unit and Struma Unit of the Morava–Rhodope Zone – DABOVSKI & ZAGORCHEV (2009); Morava Nappes – DIMITRIJEVIĆ (1995); Serbian-Macedonian Mass, Morava Tectonic Unit – DIMITRIJEVIĆ (1995); Serbian-Macedonian composite Terrane – KARAMATA *et al*. (1997); Moravides, Morava Zone – ANDJELKOVIĆ (1996); Morava Structural Unit – DIMITRIJEVIĆ (1995); Serbo-Macedonian Units, not differentiated; Supragetic Units (included the Morava, Ranovac–Vlasina and Elešnica Units) – KRÄUTNER & KRSTIĆ (2003).

(8) Vardar Zone (Fig. 1, 8) is situated between the Serbo-Macedonian Massif (to the east) and the Dinarides (to the west).

Synonyms: Vardar Zone Composite Terrane – KARAMATA *et al*. (1997); Vardar Units – KRÄUTNER & KRSTIĆ (2003); Vardar Zone – BONCHEV *et al*. (1973). This Zone is mentioned with the aim of completing the western boundary of the Serbian-Macedonian–Rhodope Massif. It does not cross the Serbian/Bulgarian border area.

Acknowledgements

The present study was realised under a bilateral project between the Bulgarian Academy of Sciences and the Serbian Academy of Sciences and Art and was supported by the Ministry of Education and Science of the Republic of Serbia, Project No. 176015. We are thankful to reviewers, Acad. TODOR NIKOLOV and RADOSLAV NAKOV from the Bulgarian Academy of Sciences for their useful suggestions.

References

ANDJELKOVIĆ, M. 1996. *Geology of Stara Planina. Tectonics.* 230 pp. Belgrade University, Faculty of Mining and geology, Institute for Regional geology and paleontology, Beograd (in Serbian).

ANDJELKOVIĆ, M. & SIKOŠEK, B. 1967. Opšte tektonske crte (General tectonics outline). *In:* STEVANOVIĆ, P., ANDJELKOVIĆ, M., PANTIĆ, N., PROTIĆ, M., KARAMATA, S., GRUBIĆ, A., SIKOŠEK B., VESELINOVIĆ D. & NIKOLIĆ, P. (eds.), *Geološki pregled Karpato-balkanida istočne Srbije (stratigrafija, tektonika i magmatizam) (Geological view of Carpathian-Balkan of eastern Serbia)*, 8th Congress of the Carpathian-Balkan Geological Association, 120–126, Belgrade.

BOGDANOVIĆ, P. 1974. Das geotektonische reonieren von Ostserbien. *Vesnik zavoda za geološka i geofizička istraživanja,* A, 31/32: 287–302 (in Serbian, German summary).

BONČEV, E. 1936. Attempted synthesis of the tectonic western Bulgaria. *Geologica Balcanica,* 2 (1): 5–48 (in Bulgarian).

BONČEV, E. (ed.). 1971. *Tectonics of the Fore-Balkan*. 584 pp. Publishing house of the Bulgarian Academy of Sciences, Sofia (in Bulgarian, English summary).

BONČEV E. 1978. Geotectonic position of the Balkanides. *Geologica Balcanica*, 8 (1): 23–40.

BONČEV, E. 1986. *The Balkanides. Geotectonic position and development.* 273 pp. Geologica Balcanica, Series Operum Singulorum, Publishing house of the Bulgarian Academy of Sciences, Sofia (in Bulgarian, English summary).

BONCHEV, E., DABOVSKY, H., GOCHEV, P., HAJDUTOV, I., IVANOV, I.B., KARAGYULEVA, J., KOSTADINOV, V., TZANKOV, T. & ZAGORCHEV, I. 1973. *In*: MAHEL, M. (ed.), *Tectonic map of the Carpathian–Balkan Mountain system and adjacent areas*. Scale 1:10 000 000. Sheets Sofia, Publ. D. Strura/UNESCO, Bratislava.

BONČEV, S. 1910. General lines of the geological structure of the west Stara Planina Mts. *Trudove na Bulgarskoto Prirodoizpitatelno Dužestvo,* 4: 1–59 (in Bulgarian).

BONČEV, S. 1927. Why the northern slopes to west Stara Planina Mts. are steep and to Central – the southern? *Ann. Sofia University, Faculty of Physics and mathematics,* 23 (3): 157–180 (in Bulgarian).

DABOVSKI, C., BOYANOV, I., KHRISCHEV, C., NIKOLOV, T., SAPUNOV, I., YANEV, Y. & ZAGORCHEV, I. 2002. Structure and Alpine evolution of Bulgaria. *Geologica Balcanica*, 32 (2–4): 9–15.

DABOVSKI, H. & ZAGORCHEV, I. 2009. Alpine subdivision of Bulgaria. *In*: ZAGORCHEV *et al*. (eds.), *Geology of Bulgaria*. Volume 2, part 5: Mesozoic geology, p. 30–37. Marin Drinov Academic Publishing House, Sofia (in Bulgarian).

DIMITRIJEVIĆ, M.D. 1995. *Geology of Yugoslavia*. 187 pp. Geological Institute Gemini, Special Publication, Barex, Belgrade (in Serbian).

GRUBIĆ, A. 1980. Yugoslavia. An Outline of Geology of Yugoslavia. *26th International Geological Congress, Guide Book*, 5–49, Paris.

HAYDUTOV, I., GOCHEV, P., KOZHOUHAROV, D. & YANEV, S. 1997. Terranes in the Balkan area. *In*: PAPANIKOLAUA, D. (coordinator), *IGCP Project No. 276, Terrane Maps and Terrane descriptions Annales Géologiques des Pays Helléniques*, 37: 479–494.

IOVCHEV, I. (ed.). 1971. *Tectonic structure of Bulgaria*. 558 pp. Technika, Sofia (in Bulgarian).

IVANOV, Z. 1988. Tectonics of Bulgaria. *Problem commission IX of multilateral collaboration between the Academies of Sciences of the Socialistic countries "Earth crust – structure, evolution, metalogeny" – project 4*: 49–57 (in Russian).

KARAMATA, S., KRSTIĆ, B., DIMITRIJEVIĆ, D., DIMITRIJEVIĆ, M., KNEŽEVIĆ, V., STOJANOV, R. & FILIPOVIĆ, J. 1997. Terranes between the Moesian Plate and the Adriatic Sea. *In*: PAPANIKOLAUA, D. (coordinator), *IGCP Project No. 276, Terrane Maps and Terrane descriptions*. *Annales Géologiques des Pays Helléniques*, 37: 429–477.

KRÄUTNER, H.G. & KRSTIĆ, B.P. 2003. *Geological map of the Carpatho-Balkanides between Mehadia, Oravita, Niš and Sofia*. Geoinstitute, Belgrade.

NACHEV, I. & NACHEV, C. 2008. *Turbidites and plate tectonics of Bulgaria*. 177 pp. Multiprint Ltd., Sofia (in Bulgarian, English summary).

SALVADOR, A. (ed.). 1994. *International Stratigraphic Guide – A guide to stratigraphic classification, terminology and procedure.* Second edition. 214 pp. International Union of Geological Sciences and Geological Society of America, Inc., Boulder, Colorado.

SIKOŠEK, B. 1955. Einige geotektonische beobachtungen im ostteil Ostserbiens. *Zbornik radova geološkog instituta "Jovan Žujović"*, 8: 11–19 (in Serbian, German summary).

TCHOUMATCHENCO, P., RABRENOVIĆ D., RADULOVIĆ, B. & RADULOVIĆ, V. 2006a. Trans-border (east Serbia/west Bulgaria) correlation of the Jurassic sediments: main Jurassic paleogeographic units. *Geološki anali Balkanskoga poluostrva*, 67: 13–17.

TCHOUMATCHENCO, P., RABRENOVIĆ D., RADULOVIĆ, B. & RADULOVIĆ, V. 2006b. Trans-border (east Serbia/west Bulgaria) correlation of the Jurassic sediments: Infra-Geticum. *Geološki anali Balkanskoga poluostrva*, 67: 19–33.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, V., N. MALEŠEVIĆ, N. & RADULOVIĆ, B. 2008. Trans-border (south-east Serbia/south-west Bulgaria) correlations of the Jurassic sediments: the Getic and Supra-Getic units. *Geološki anali Balkanskoga poluostrva*, 69; 1–12.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, V. & MALEŠEVIĆ, N. 2010a. Trans-border (east Serbia/west Bulgaria) Early–Middle Jurassic (Hettangian-Early Callovian) palaeogeographical correlation. *Comptes rendus de l'Académie bulgare des Sciences*, 63 (10): 1505–1514.

TCHOUMATCHENCO, P., RABRENOVIĆ, D., RADULOVIĆ, V. & MALEŠEVIĆ, N. 2010b. Trans-border (east Serbia/west Bulgaria) Middle–Late Jurassic (Middle Callovian–Tithonian) paleogeographical correlations: an essay. *Comptes rendus de l'Académie bulgare des Sciences*, 63 (11): 1619–1630.

TZANKOV, T. (ed.). 1995. Western Stara Planina. Geological guidebook, 71 pp., Geological Institute, Bulgarian Academy of Sciences, Sofia.

Резиме

Међугранична (источна Србија/западна Бугарска) корелација морфо–тектонских структура

Циљ овог рада је да се прикаже корелација главних морфо-тектонских структура Србије и Бугарске дуж државних граница и дају њихови синоними коришћених од стране бугарских и српских геолога. Дефинисане су следеће морфо-тектонске структуре: Мезијска платформа, Мироч – Предбалкан, Поречко-Старопланинска јединица, Крајина јединица, Гетик – Средњогорје, Супрагетик – Крајиштиди, Српско-македонска маса – Тракијски масив, Вардарска зона.

(1) Мезијска платформа (сл. 1.1) представља платформу са прекамбријском подином и палеозојско–мезозојско–неозојским покривачем повлатом кји је део Евразијског копна. Она је описана као Мезијска платформа или Мезијска плоча од стране многих аутора: BONČEV (1978), ИВАНОВ (1988), DABOVSKI *et al*. (2002), НАЧЕВ и НАЧЕВ (2008), ЦАНКОВ (1996), ЈОВЧЕВ (1971), ДАБОВСКИ и ЗАГОРЧЕВ (2009), АНЂЕЛКОВИЋ (1996), DIMITRIJEVIĆ (1995), KARAMATA *и др*. (1997), KRÄUTNER & KRSTIĆ (2003) и др.

(2) Мироч – Предбалкан (сл. 1.2) представља област која се састоји од аутохтоних наборних структура, а која је раздвојена од Мезијске платформе предбалканским раседом или балканском фронталном линијом (БОНЧЕВ 1978) (сл. 1.А): Његов западни део је изграђен од серије лонгитудиналних набора, као што је Мироч (АНЂЕЛКОВИЋ 1996; DIMITRIJEVIĆ 1995), Белоградчикским и михајловградским антиклиналама (или антиклиноријумима) (БОНЧЕВ 1971, 1978; CANKOV 1995) итд., и Милановачко-новокоритска (Салашка) синклинала (АНЂЕЛКОВИЋ 1996; СТ. БОНЧЕВ 1910, 1927; БОНЧЕВ 1971). За ову јединицу KRÄUTNER & KRSTIĆ (2003) употребљавају називе: Доњи данубиан (Косустеа јединица, Лаинци (Церна–Мироч), Драгсан јединица), а BONCHEV *и др*. (1973 Мезоалписка (Илирско–пиринејска) јединица: FB – Предбалкан, TR – прелазна zона (северни део Предбалкана), и ND – Данубикум.

(3) Пореч – Стара планина (сл. 1.3). Заузима простор који покривају структуре Старе планине, како у Бугарској тако и у источној Србији, масиви Дели Јован, Мироч и Гребен и наставља ка масиву Алмаш, северно од Дунава, у Румунији. Његову северну и источну граница са јединицом Мироч – Предбалкан јединицом је Поречко–старопланинска фронтална линија. Ова јединица је пресечена и померена Тимочко–пиротским транскурентним раседом (БОНЧЕВ 1986), који је, такође, познат као Штубичко–тимочка дислокација – АНЂЕЛКОВИЋ (1996).

Југозападне падине ове зоне изграђују синклиналу, познату у Бугарској као Издреметска синклинала, а у источној Србији као Добродолско–грлишка зона (АНЂЕЛКОВИЋ 1996).

За време јуре у овој области се депонују релативно дубоководни морски седименти инфрагетске палеогеографске зоне. Западна граница ове јединице, према БОНЧЕВУ (1986), је између Свођске и Берковичке антиклинале, док НАЧЕВ и НАЧЕВ (2008) укључују и Свођску антиформу (антиклиналу, антиклинориjум) у Старопланинску тектонску зону.

(4) Крајина (сл. 1.4) је аутохтоно копно које је захваћено за време титона интезивним геодинамичким процесима који су изазвали значајне фрактуре и подморску вулканску активност, што је довело до формирања вулканогено–седиментних творевина (Вратарничка серија – Анђелковић 1996) и горњојурско–доњокредно флишних седимената (Начев и Начев 2008). Данас су то продужетци Северинске навлаке (Дабовски и Загорчев 2009, сл. 5, 1–1) од Јужних Карпата који прелазе границу СИ Србије и СЗ Бугарске.

(5) Гетик – Средњогорје (сл. 1.5) је типичан рифтогени систем са магматизмом острвско-лучног типа. Карактерише се изданцима горњокредне старости, вулканогено-седиментним стенама и Ca–алкалним (према истоку и K–алкалним) магматизмом у вулканским, субвулканским и интрузивним фацијама (Bončev 1986). У најисточнијим деловима појављују се велике наборне структуре, као што је Свође–Видлички антиклиноријум, углавном без горњокредних седимената. Источна граница ове јединице, са Поречко–старопланинском јединицом, је Видличка дислокација или суббалкански расед (сл. 1.D) (код многих локалитета са прелазом ка навлакама).

(6) Супра-гетик – Крајиште (сл. 1.6) поседује карактерише се релативно дебелим прекамбријским високо метаморфисаним стенама прекривених палеозојским, мезозојским и неозојским секвенцама. Његова веома карактеристична особина је присуство синседиментационих рова (палеозојског, мезозојског и неозојског) у којем се одвијала специфична седиментација. Његова источна граница са Гетик – Средњегорском јединицом је Тран–озренски расед (сл. 1.E).

(7) Српско македонски масив (сл. 1.7) је област која се налази између Вардареске зоне и Карпато-балканида. Његова главна особина је присуство метаморфних стена, које представљају изворну област палеозојских–мезозојских мора. Његова источна граница је велики Моравски расед (сл. 1.F).

(8) Вардарска зона (сл. 1. 8) налази се између Српско-македонског масива на истоку и Динарида на западу.

У енглеском тексту приказани су неки од синонима који се помињу у српској и бугарској литератури. Разлог што није приказана целокупна листа синонима је тај што у литератури о тектонским поделама поменуте области постоји велики број синонима који не допуштају да поменемо све ауторе.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	29–46	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172029R

Late Cretaceous marine biodiversity dynamics in the Eastern Caucasus, northern Neo-Tethys Ocean: regional imprints of global events

Dmitry A. Ruban[1], Astrid Forster[2] & Delphine Desmares[3]

Abstract. During the Late Cretaceous, marine organisms experienced significant changes in their biodiversity. These diversity changes were influenced, particularly, by the Oceanic Anoxic Event 2 near the Cenomanian/Turonian boundary (93.6 Ma). Here, stratigraphic ranges of 80 marine macroinvertebrate genera (cephalopods, brachiopods, gastropods, corals, and echinoids) were employed to assess the Late Cretaceous biodiversity dynamics in the Eastern Caucasus, which covered a large region located in the northern Neo-Tethys Ocean. Our results outline three prominent diversity minima, which occurred in the late Cenomanian–late Turonian, the early Santonian-late Campanian, and the late Maastrichtian. Probably, the latter two were just local. Despite of some differences in trends between the regional and global marine biodiversity dynamics, the late Cenomanian-late Turonian biotic crisis appeared both on the regional and global scales and was probably a long-term consequence of the Oceanic Anoxic Event 2. Oxygen depletion and eustatically-driven shoreline shifts are considered as plausible causes of the observed biodiversity dynamics.

Key words: marine macroinvertebrates, diversity, biotic crisis, OAE2, Eastern Caucasus, Cenomanian/Turonian, Late Cretaceous.

Апстракт. За време горње креде, морски организми доживљавају значајне промене у њиховом биодиверзитету. Ове промене биле су углавном последица океанског аноксицног догађаја 2 на граници ценоман/турон (93,6 Ma). За процену динамике горњокредног биодиверзитета Источног Кавказа, који је покривао пространу област Северног Нео-Тетиског океана, коришћено је стратиграфско распрострањење 80 морских макробескичмењачких родова (цефалопода, брахиопода, гастропода, корала и јежева). Добијени резултати указују на три значајна диверзитетска минимума, који су се десили за време горњи ценоман–горњи турон, доњи сантон–горњи кампан и горњи мастрихт. Највероватније су два последња минимума локалног значаја. Насупрот неких разлика у трендовима између регионалне и глобалне динамике морског биодиверзитета, горње ценоманска–горње туронска биотска криза имала је регионални и глобални значај, вероватно као последица дугог океанског аноксичног догађаја 2. Смањење кисеоника и еустатички контролисане промене обалске линије се могу сматрати као узрочници посматране биодиверзитетске динамике.

Кључне речи: морски макробескичмењаци, биодиверзитет, биотске кризе, OAE2, Источни Кавказ, ценоман/турон, горња креда.

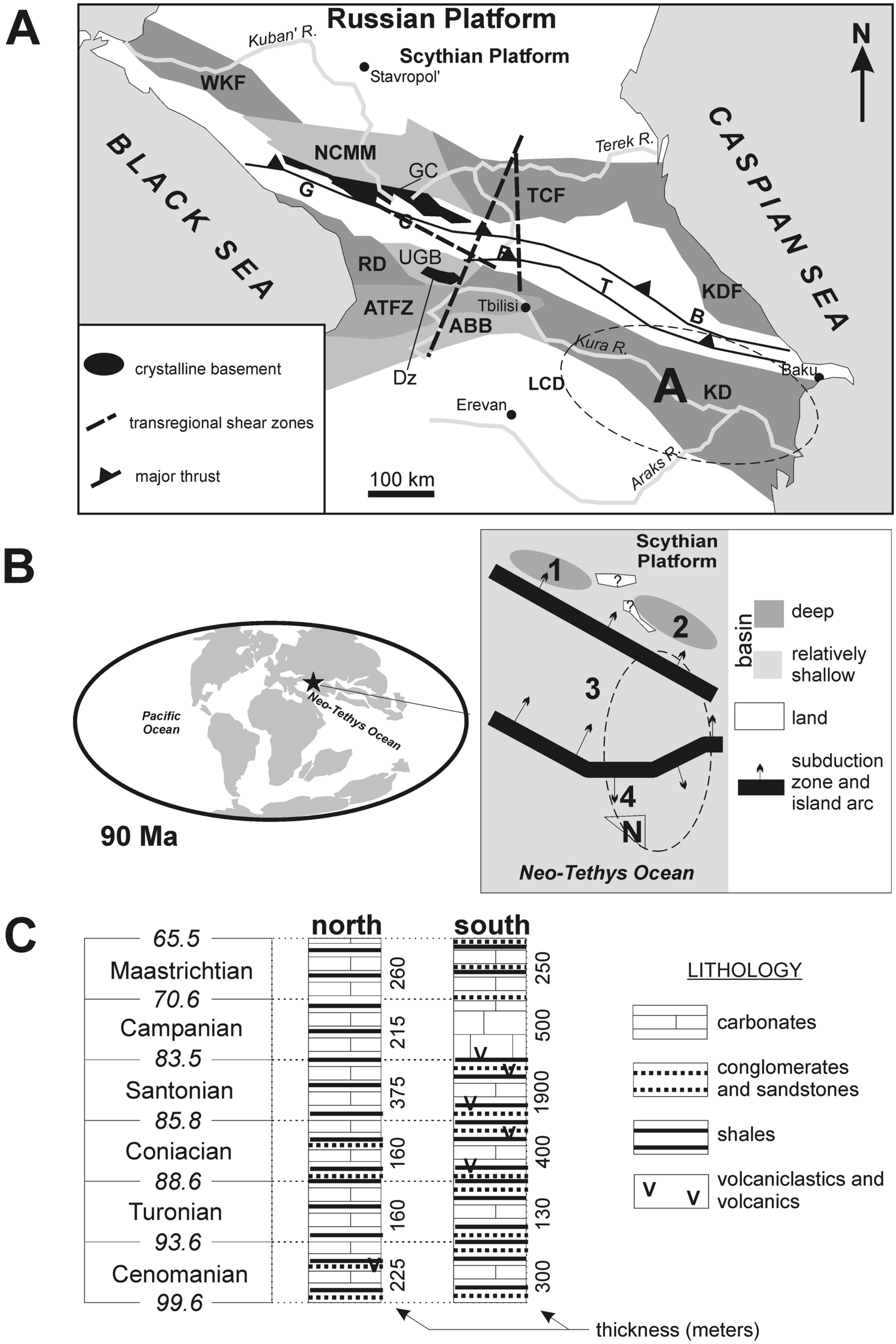
Introduction

The global marine biodiversity changed rapidly during the Late Cretaceous (Purdy 2008). Peculiar events were superposed on the general evolutionary trends. The Cenomanian/Turonian (C/T) boundary (93.6 Ma according to Ogg *et al.* 2008), which was suggested tentatively as the upper boundary of the Middle Cretaceous series (Gradstein *et al.* 2008), was a time slice characterized by strong environmental perturbations on a planetary scale. Intense turnovers and some extinctions among the entire range of marine biota (e.g., Sepkoski 1986; Hallam & Wignall 1997, 1999; Harries & Little 1999; Wignall 2001; Leckie *et al.* 2002; Keller 2008), an oceanic anoxic event (OAE2; e.g., Jenkyns, 1980,

[1]Division of Mineralogy and Petrography, Geology and Geography Faculty, Southern Federal University, Zorge Street 40, Rostov-na-Donu, 344090, Russia; address for postal communication: P.O. Box 7333, Rostov-na-Donu, 344056, Russia. E-mails: ruban-d@mail.ru, ruban-d@rambler.ru

[2] Lausner Weg 16A, Leipzig 04207, Germany. E-mail: astrid.forster@gmx.net

[3] UPMC Université Paris 06, UMR7207, CR2P, Paris 75005, France. E-mail: delphine.desmares@upmc.fr


A
Russian Platform
Scythian Platform
Kuban' R.
Stavropol'
WKF
NCMM
GC
G
TCF
Terek R.
BLACK SEA
CASPIAN SEA
N
RD
UGB
ATFZ
ABB
Tbilisi
T
KDF
B
Kura R.
Baku
Dz
LCD
Erevan
A
KD
Araks R.
100 km
crystalline basement
transregional shear zones
major thrust
B
Pacific Ocean
Neo-Tethys Ocean
90 Ma
Scythian Platform
1
2
3
4
N
Neo-Tethys Ocean
basin
deep
relatively shallow
land
subduction zone and island arc
C
north
south
65.5
Maastrichtian
70.6
Campanian
83.5
Santonian
85.8
Coniacian
88.6
Turonian
93.6
Cenomanian
99.6
260
215
375
160
160
225
250
500
1900
400
130
300
LITHOLOGY
carbonates
conglomerates and sandstones
shales
volcaniclastics and volcanics
thickness (meters)

2010; ARTHUR *et al.* 1987; SCHLANGER *et al.* 1987; BRALOWER 1988; KAIHO & HASEGAWA 1999; PREMOLI SILVA *et al.* 1999; WANG *et al.* 2001; DESMARES *et al.* 2004; ERBA 2004; KURODA *et al.* 2005; GROSHENY *et al.* 2006; JARVIS *et al.* 2006; KURODA & OHKOUCHI, 2006; TAKASHIMA *et al.* 2006, 2009; MORT *et al.* 2007; FORSTER *et al.* 2008; ELRICK *et al.* 2009; PEARCE *et al.* 2009), and increased mantle plume activity (e.g., LARSON *et al.* 1991a,b; WIGNALL 2001; ABBOTT & ISLEY 2002; SNOW *et al.* 2005; BRALOWER 2008) left remarkable imprints on the global fossil, sedimentary and geochemical records. However, extent and strength of the biotic crisis near the C/T boundary remain debated. E.g., GALE *et al.* (2000) and SMITH *et al.* (2001) argued that the mass extinction related to OAE2 may be an artifact. While more data is available from Mediterranean Europe (e.g., LAMOLDA & PERYT 1995; PERYT & LAMOLDA 1996; COCCIONI & LUCIANI 2005), England (e.g., JARVIS *et al.* 1988a,b; PAUL *et al.* 1999; GALE *et al.* 2005), and Japan (TOSHIMITSU & HIRANO 2000; TAKAHASHI 2005), palaeontological records of many other potentially important regions are still inadequately explored.

This paper addresses the Eastern Caucasus, which seems to be an important region because of its key palaeoposition on the northern margin of the Neo-Tethys Ocean between the Alpine structures of Europe and the terranes of the Middle East (Fig. 1). This region exhibits a representative Upper Cretaceous succession with the documented distribution of diverse marine macroinvertebrates. A discussion on the regional biotic signature of the C/T event in the northernmost part of the Eastern Caucasus has been attempted by TUR *et al.* (2001) and RUBAN (2003a), who considered data on foraminifers. Earlier, KOTETISHVILI (1999) investigated the diversity of the entire Caucasian ammonites, which also contributed to the noted task. On a broader scope, it is the aim of this paper to examine the regional marine biodiversity dynamics during the Late Cretaceous and, particularly, to evaluate the relative impact of the C/T event in the Eastern Caucasus.

This study is a result of cooperation of specialists in general palaeobiology (DA.R.), geochemistry and palaeoenvironments (A.F.), and micropalaeontology (D.D.). The authors participated equally in writing the manuscript.

Geologic setting

The Eastern Caucasus region encompasses entire Azerbaijan and some adjacent areas (Fig. 1A). Its tectonic structure includes various structural domains of the Greater Caucasus and the Lesser Caucasus (GAMKRELIDZE 1986, 1997; RUBAN *et al.* 2007). The regional geodynamic setting of this region in the Late Cretaceous is revealed on the basis of present models of this region's geologic evolution (LORDKIPANIDZE *et al.* 1984; ERSHOV *et al.* 2003; KAZMIN & TIKHONOVA 2006; SAINTOT *et al.* 2006; TAWADROS *et al.* 2006) and modern plate tectonic reconstructions (STAMPFLI & BOREL 2002; GOLONKA 2004; SCOTESE 2004). During the Late Cretaceous, the Eastern Caucasus lay at the northern active margin of the Neo-Tethys Ocean (Fig. 1B). It included the entire Eastern Greater Caucasus back-arc basin, the eastern part of the Black Sea-Caspian extended – probably rifted – basin, and some parts of the Lesser Caucasus Basin and the Nakhychvan Block (Fig. 1A).

Sedimentation regimes differed within the Eastern Caucasus. Whereas carbonate deposition prevailed in the entire region, the quantity of siliciclastic and volcaniclastic sedimentation increased southwards (Fig. 1C). During the Late Cretaceous, the Eastern Caucasus was embraced by a large marginal sea (Fig. 1B) with normal salinity and relatively high bottom temperatures (JASAMANOV 1978). In contrast to the surrounding platform area to the north, the Western and Eastern Greater Caucasus marine basins were relatively deep (Fig. 1B), which is indicated by flysch deposits. Palaeobiogeographically, the study region belonged to the Mediterran-Caucasian Subrealm of the Tethyan Realm (WESTERMANN 2000). Generally,

Fig. 1. Geologic setting of the Eastern Caucasus. **A,** principal structural units of the Caucasus (modified after GAMKRELIDZE 1986, 1997; RUBAN *et al.* 2007). A, Azerbaijan. Areas shown in different shadings of dark grey indicate the here distinguished structural units: ABB, Arthvin-Bolnisi Block; ATFZ, Adjara-Thrialethian Fold Zone; Dz, Dzirula Massif; GC, Greater Caucasian Massif; GCFTB, Greater Caucasian Fold and Thrust Belt; KD, Kura Depression; KDF, Kusar-Divichian Foredeep; LCD, Lesser Caucasus Domain; NCMM, North Caucasian Marginal Massif; RD, Rioni Depression; TCF, Terek-Caspian Foredeep; UGB, Uplifted Georgian Block; WKF, West Kubanian Foredeep. Dashed ellipse indicates the approximate position of the region considered in this study. **B,** location of the Caucasus in the Late Cretaceous. Left: global plate tectonic reconstruction after SCOTESE (2004). According to LORDKIPANIDZE *et al.* (1984), the Eastern Caucasus lay between 25°N and 35°N. Right: regional palaeotectonic sketch map; modified from LORDKIPANIDZE *et al.* (1984). Basins: 1, Western Greater Caucasus Basin; 2, Eastern Greater Caucasus Basin; 3 Black Sea-Caspian Basin; 4, Lesser Caucasus Basin; N, Nakhychvan Block. Palaeobathymetry of basins is indicated by areas shown in different shadings of grey, white areas represent land. Dashed ellipse indicates the approximate position of the region considered in this study. **C,** composite lithologic sections of Upper Cretaceous deposits of Azerbaijan (on the basis of ALI-ZADEH 1988). Absolute ages after OGG *et al.* (2008).

the abundance and diversity of the Late Cretaceous marine biota in this region were high. Macroinvertebrates included cephalopods, bivalves, brachiopods, gastropods, corals, and echinoids (ALI-ZADEH 1988). Coral reef communities with especially high diversity flourished during the Coniacian (ALI-ZADEH 1988).

Material and method

Stratigraphic ranges of 80 marine macroinvertebrate genera from the Late Cretaceous deposits of Azerbaijan are compiled here from the most comprehensive source (ALI-ZADEH 1988). These data were collected from dozens of localities within the territory of the Republic of Azerbaijan, but they were never used before in order to discuss changes in marine biodiversity. The analyzed fossil groups include (number of genera): cephalopods (11), brachiopods (9), gastropods (21), corals (12), and echinoids (27) (Appendix 1). Bivalves are excluded from the present analysis because of their outdated taxonomy. Sampling biases are unavoidable for studies of individual sections, however, as we here deal with summarized data for the entire study region, probable sampling biases should be minimized. When possible and necessary (as in the case of brachiopods and cephalopods), the original palaeontological data given by ALI-ZADEH (1988) were verified with some taxonomic corrections. For few taxa, the stratigraphic ranges are only known with some uncertainty. When the presence of a taxon in the whole stage is indicated without a reference to any particular substage in the original literature, we may hypothesize an equal probability of its occurrence in these substages. To account for this, the presence of such a taxon is recognized for each substage, but as a proportion, e.g., the presence is indicated as 0.5 for each substage if the stage consists of two substages.

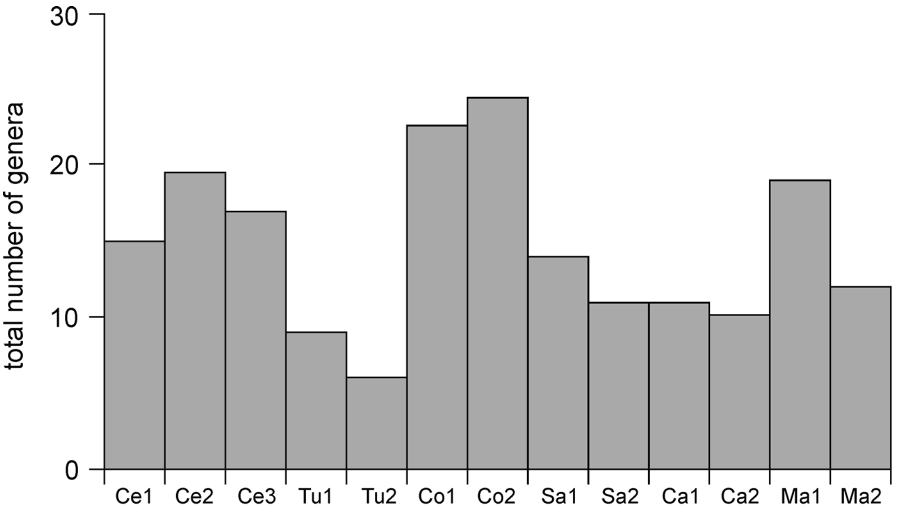


Fig. 2. Dynamics of the Late Cretaceous diversity of marine macroinvertebrates in the Eastern Caucasus (Azerbaijan). Stage abbreviations: Ce, Cenomanian; Tu, Turonian; Co, Coniacian; Sa, Santonian; Ca, Campanian; Ma, Maastrichtian. Stages are additionally subdivided into regional units indicated by numbers (e.g., Ce1; see text for explanation).

The regional stratigraphic framework used here is taken from the original source (ALI-ZADEH 1988). The latter study relates the palaeontological data to the Late Cretaceous stages and substages. According to the original data source, all stages are divided into 2 substages, namely early and late, and the Cenomanian into 3 substages (Ce1 to Ce3, as for example shown in Fig. 2). Some minor differences between the regional stratigraphic framework (ALI-ZADEH 1988) and the modern chronostratigraphy of the Late Cretaceous (RAWSON *et al.* 1996; OGG *et al.* 2008) may exist, but they seem to be insignificant for the purposes of the present study that is emphasized on long-term patterns. Substages considered in this manuscript (in contrast to stages) are informal time units, which may differ from the conventional substages treated, for example, by RAWSON *et al.* (1996). To make a distinction from formal substages, the names of regional substages are not capitalized. A peculiarity of regional substages may explain the documented taxa ranges (Appendix 1); e.g., *Acanthoceras*, which is a Middle Cenomanian taxon, is reported from lower, middle, and upper Cenomanian of the Eastern Caucasus. The informal regionally-restricted substages are useful, nonetheless, for a more precise documentation of the biodiversity patterns. The stratigraphic age of the Late Cretaceous deposits in the Eastern Caucasus was established with an integrated analysis of the entire assemblage of marine invertebrates (ALI-ZADEH 1988). Although the regional foraminifer-based biozonation framework is available, foraminifers were not the only group used for relative age determination. Generally, ALI-ZADEH (1988) attempted to assign faunistic assemblages to the Upper Cretaceous stages, even if biozonation still needs to be improved. Another study attempted by RUBAN (2003b) for the Northern Caucasus confirmed that changes in both standard biozonation and foraminifer taxonomy did not affect significantly the regional chronostratigraphic record and, thus, the earlier-established stages remain generally valid.

The main biodiversity pattern considered in this study is the total number of genera. In order to compare regional and global records, the global marine biodiversity curve proposed by Purdy (2008) is employed herein. The latter curve is based on the well-known compendium by Sepkoski (2002) with an exclusion of some stratigraphically-uncertain data. The global marine diversity is measured by Purdy (2008) per stages only. For direct comparison of our regional biodiversity curve with that published by Purdy (2008), the palaeontological data from the Eastern Caucasus were arranged and re-calculated so to show stage-by-stage dynamics. We do not involve the rates of originations and extinctions in this study, because only appearances and disappearances are possible to be established in every regional fossil record. Probabilistic approach, which permits to solve this problem (e.g., Ruban & van Loon 2008), is available, but it does not permit to reveal the true extinction rate, which can be compared with the global rate measured by Purdy (2008).

Although an analysis of marine biodiversity dynamics at the level of species is always informative, the present study focuses on genera because of two main reasons. Firstly, regional dynamics is brought in comparison with global trends, and assessment of the latter is restricted to genera (Alroy *et al*. 2008; Purdy 2008). Secondly, palaeontological data generated in the former USSR are often better justified at the level of genera, which favours an analysis of generic, not species diversity (Ruban, 2011).

Results

Marine biodiversity dynamics

In the Eastern Caucasus, the generic diversity as monitored by this study (expressed by the total number of genera: cephalopods, brachiopods, gastropods, corals and echinoids; see Appendix 1) fluctuated strongly during the Late Cretaceous (Fig. 2). It rose weakly during the early-middle Cenomanian, then dropped by ~2/3 through the late Cenomanian-late Turonian, but rose again in the early Coniacian. A new abrupt biodiversity decline (by about half) occurred in the early Santonian and then continued gradually, but weakly until the end of the Campanian. A biotic radiation took place in the early Maastrichtian to be followed by a decline in the late Maastrichtian. These results indicate significant diversity disruptions that the regional macroinvertebrate assemblages experienced during the late Cenomanian-late Turonian, the early Santonian-late Campanian and the late Maastrichtian.

Available data (Appendix 1) permit to evaluate the influence of the three above-mentioned diversity minima on the particular fossil groups (Fig. 3). The late Cenomanian–late Turonian event affected corals, cephalopods, and gastropods, whereas echinoids were weakly influenced. The early Santonian–late Campanian event stressed brachiopods, corals, cephalopods, and gastropods. Representing a unique exception, the echinoids even radiated gradually during the entire late Turonian–early Campanian time interval. The late Maastrichtian event affected brachiopods and echinoids. Cephalopods apparently survived this crisis without suffering any stress, i.e., their total diversity didn't change. Conclusively, all three events have in common that they affected several groups of macroinvertebrates, but not necessarily the same groups every time. Each event was characterized by a certain degree of selectivity. Moreover, some groups of fossils declined at different rates through time; e.g., the total diversity of cephalopods dropped gradually already since the middle Cenomanian, whereas demise of corals at the late Cenomanian–early Turonian transition was abrupt. From three noted diversity minima, that early Santonian–late Campanian disruption had especially dramatic consequences on regional marine macroinvertebrates. Two groups, namely corals and gastropods, disappeared completely from the regional Cretaceous record, whereas brachiopods declined strongly to never recover completely.

Regional versus global patterns

The regional changes in the marine biodiversity can be compared to global data shown in Fig. 4. The global marine biodiversity reached a relatively high level in the Cenomanian, but dropped by about 10% in the Turonian and remained diminished until the Santonian, when its gradual, but pronounced acceleration began to reach a diversity peak in the Maastrichtian (Purdy 2008). This biodiversity dynamics differed strongly from that established in the Eastern Caucasus (Fig. 4) with two exceptions. Both regionally and globally, the Turonian appears to be characterized by a diminished marine biodiversity. If so, we need to consider not only short-term (e.g., Leckie *et al*. 2002), but also possible long-term consequences from the C/T event on both regional and global scales. The other possible exception concerns the Maastrichtian, when marine biodiversity was high both regionally and globally.

Discussion

Interpretations of biodiversity dynamics

Our results (Fig. 3) demonstrate that the changes in total diversity of the studied fossil groups exhibit

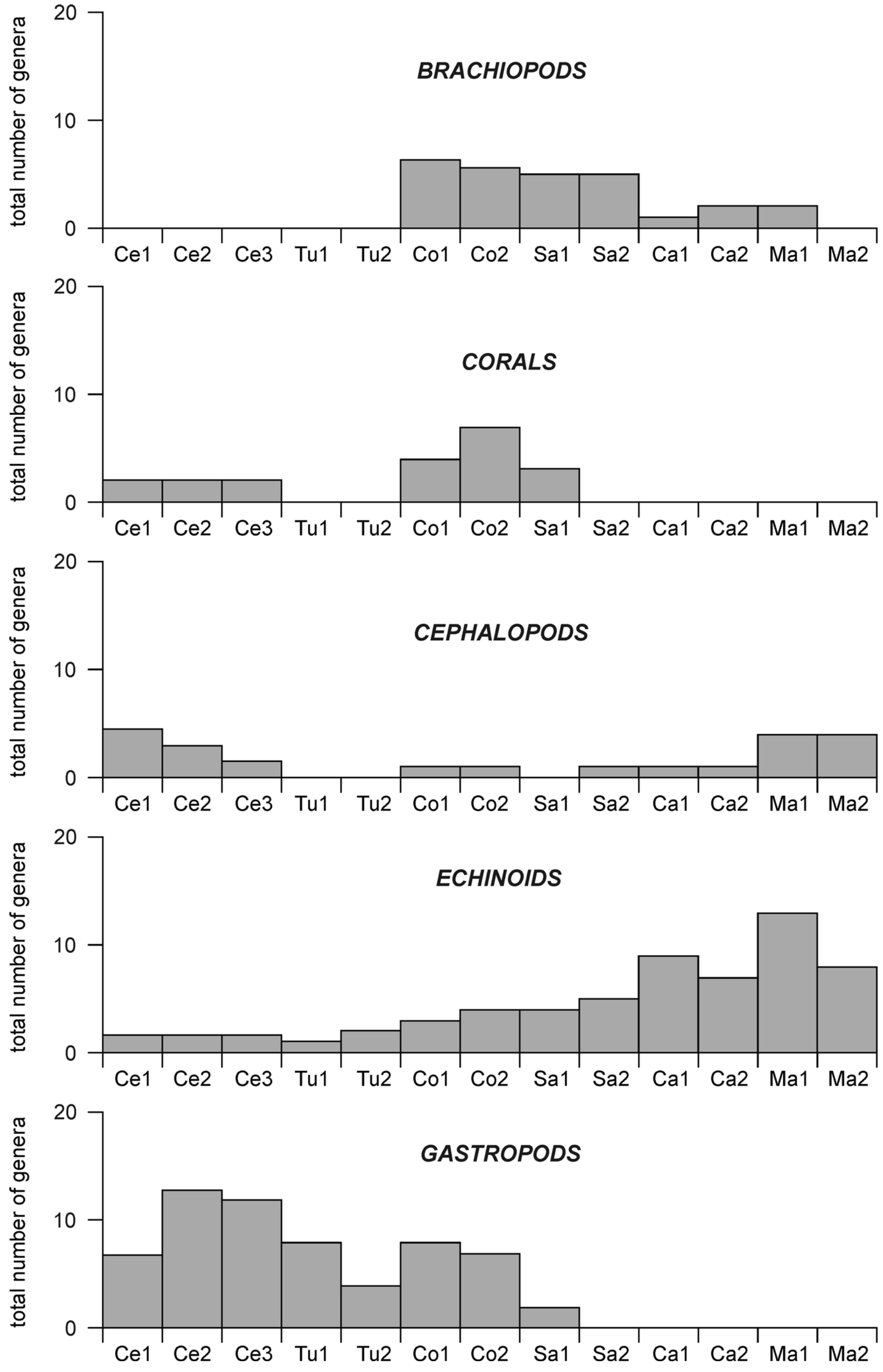


Fig. 3. Changes in the total number of genera of particular fossil groups in the Eastern Caucasus (Azerbaijan) during the Late Cretaceous. See Fig. 2 for stage abbreviations.

some more or less common pattern, which does not permit to judge the cumulative diversity of macroinvertebrates as haphazard (Fig. 2). In contrast, this cumulative diversity reflects the more or less true dynamics of the entire marine ecosystems in the Eastern Caucasus.

The main recognized events are three diversity maxima (middle Cenomanian, late Coniacian and early Maastrichtian) and three minima (late Cenomanian-late Turonian, the early Santonian-late Campanian and the late Maastrichtian). Interestingly, it remains unclear which of these events were unusual, i.e., what of them reflected the "normal" biodiversity and what reflected deviations from this norm. E.g., it is possible that the Coniacian and the early Maastrichtian diversity peaks were unusual events, which were superimposed on the constant and relatively low diversity that persisted during the Turonian–Maastrichtian. If so, the early Santonian–late Campanian and late Maastrichtian minima represent neither diversity disruptions nor biotic crises. In other words, the Late Cretaceous evolution of marine invertebrates in the Eastern Caucasus could have been marked by few spontaneous radiations, not diversity drops.

The biotic signature of the C/T event seems to appear both, globally and regionally as a diversity minimum in the Turonian. The two other events registered in the Eastern Caucasus, namely the early Santonian-late Campanian and the late Maastrichtian diversity minimums (Fig. 2), are not reflected by the global curve (Fig. 4). In the case of the late Maastrichtian, however, this discrepancy can be explained by the low-resolution of the curve given by Purdy (2008). If the Coniacian and early Maastrichtian diversity peaks were regionally-specific unusual events, which can be omitted from comparison, the noted discrepancy between the regional and global records is not something unexpected.

However, analogs of the early Santonian-late Campanian and late Maastrichtian regional biotic crises can be traced with some other geological data, if they cannot be established with the global biodiversity curve of Purdy (2008). The regionally-documented early Santonian-late Campanian biotic crisis might have been linked to the OAE3 event recognized in some other regions (ARTHUR & SCHLANGER 1979; JENKYNS 1980; ARTHUR *et al.* 1990; JENKYNS *et al.* 1994; REY *et al.* 2004; WAGNER *et al.* 2004; TAKASHIMA *et al.* 2006; JONES *et al.* 2007) and left some imprint on marine organisms (e.g., PREMOLI SILVA & SLITER 1999, TOSHIMITSU & HIRANO 2000; TAKAHASHI 2005). But both, duration and global extent of the OAE3 itself remain questionable, which precludes us from drawing any definite conclusion about its signature in the Eastern Caucasus. Similarly, we are not aware of any supporting evidence (either geochemical or lithological) of significant oxygen depletion at the Coniacian-Santonian transition in the study area. On the other hand, if the OAE3 was a global event affecting the marine biota, the biodiversity loss in the Eastern Caucasus was quite likely related to this event. Furthermore, the presence of the Coniacian/Santonian disruption in the marine ecosystems in the Eastern Caucasus region could be interpreted towards a broader extent of the OAE3 event. However, all above-said is valid only, if the early Santonian-late Campanian biotic crisis was a true event. If it was just apparent (see above), none regional evidence of the OAE3 should be hypothesized.

Considering the regionally-reported late Maastrichtian biodiversity minimum, it should be noted that KELLER (2008) suggested the diversity of marine species reached its maximum during the mid-Maastrichtian to be followed by stress started ~ 400 kyr before the end of the Cretaceous. If so, the reduction in macroinvertebrate diversity during the late Maastrichtian (Fig. 2) in fact can be an only regional phenomenon traced in the Eastern Caucasus.

One may hypothesize that the observed biodiversity dynamics, both regional and global, is influenced by the chosen stratigraphic scale. In other words, the stages with longer time duration may exhibit an apparent higher diversity. A comparison of the absolute length of stages with changes in diversity (Fig. 4) does not indicate any dependence. The regional diversity peak occurred in the stage with the shortest duration (Coniacian), whereas the global diversity also peaked in the relatively short stages (e.g., Maastrichtian). Thus, the chosen stratigraphic scale seems not to have a biasing affect on the biodiversity results here.

The documented diversity minima may be interpreted as the true expressions of regional biotic crises. However, it needs to be considered that every set of regional palaeontological data is incomplete because of interruptions of the fossil record (so-called 'Lazarus effect' - see RUBAN & VAN LOON 2008). Temporal disappearance of genera because of migrations, changes in the preservation state, etc. might have caused those total diversity minima mentioned above. Our data (Appendix 1) indicate that ranges of only two genera were temporally interrupted at the time of the late Cenomanian-late Turonian diversity minimum, whereas 6 interruptions were found at a time of the early Santonian-late Campanian diversity minimum. In both cases, however, this incompleteness is not so significant to postulate the minima were just apparent because of pseudoextinctions. We can just point out that the early Santonian-late Campanian biotic crisis was more affected by the state of the regional fossil record than that during the late Cenomanian-late Turonian.

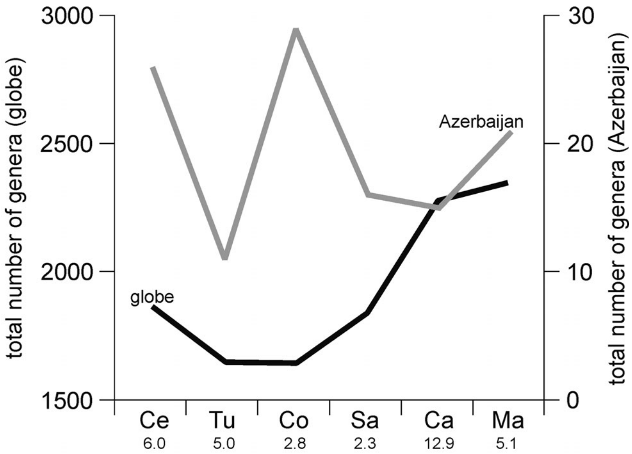


Fig. 4. Dynamics of the Late Cretaceous global (after PURDY 2008) and regional (Azerbaijan, this study) marine biodiversity calculated per stage. See Fig. 2 for stage abbreviations. Numbers given below the stage abbreviations on the horizontal axis indicate the absolute duration (in Ma) of the stages (calculated on the basis of OGG *et al.* 2008).

Possible factors of biodiversity dynamics

Our results raise the question about the factors, which drove the diversity of marine macroinvertebrates in the Eastern Caucasus throughout the Late Cretaceous and triggered the documented biotic events. We consider oceanic anoxia, seawater palaeotemperature changes and shoreline shifts as possible environmental controls on biodiversity dynamics. Regional patterns, which coincide with global ones, may be explained by the possible influence of global mechanisms like oceanic anoxia. This does not mean, however, that only global influences were a driving force. In contrast, they interacted with regional factors such as seawater palaeotemperature changes and shoreline shifts.

Although detailed geochemical studies of the Cenomanian-Turonian transition in Azerbaijan still need to be done, black shales, which bear an evidence of synsedimentary oxygen depletion, are locally reported from this transition (e.g., ALI-ZADEH 1988). Additionally, black organic-rich laminated marlstones that reveal total organic carbon concentrations (TOC) of up to 12% and a stable carbon isotopic excursion with a magnitude of about 5.6 ‰ ($\delta^{13}C_{org}$) are reported from the Cenomanian-Turonian transition of Mountainous Dagestan, i.e., northward of Azerbaijan (Tur *et al.* 2001; Gavrilov *et al.* 2009). At least, the local presence of C/T-black shales in Azerbaijan and Mountainous Dagestan suggests that marine oxygen depletion related to the global OAE2 might have stressed macroinvertebrate communities and triggered their collapse, which resulted in the minimal diversity during the Turonian. A pioneering bottom seawater palaeotemperature study by Jasamanov (1978) employed stable oxygen isotopes ($\delta^{18}O$) and Ca/Mg methods that permit to reconstruct the regional changes in seawater temperature on the basis of benthic organisms during the Late Cretaceous (Fig. 5). It should be noted, however, that any absolute palaeotemperatures reconstructed based on oxygen isotope palaeothermometry face a wide range of uncertainties potentially associated with such techniques (e.g., Longinelli 1996, pers. comm.; Leckie *et al.* 2002; Voigt *et al.* 2004; Wilson *et al.* 2002; Forster *et al.* 2007b). Generally, no definite relationship between the changes in seawater temperatures and macroinvertebrate diversity is observed here for the Eastern Caucasus region. The high total number of genera in the Cenomanian and the Coniacian as well as the low number of genera in the Santonian-Campanian (Fig. 2) corresponded to the relatively cool state of water masses (Fig. 5). The low total number of genera in the Turonian (Fig. 2) occurred at a warmer episode (Fig. 5). This is in some agreement with a suggestion by Keller (2008), who implied that Late Cretaceous biodiversity increased in a cool climate. Although it is self-evident that bottom seawater temperatures might have been more important for benthic organisms, our results on particular fossil groups do not confirm this assumption (Figs. 3 and 5). Diversity of benthic organisms changed with no relations to changes in the bottom seawater temperatures.

Interestingly, both, the global and regional biotic crisis, which followed the C/T boundary, coincided with a warming episode. Acceleration in temperatures at the time of the OAE2 is known not only in the Eastern Caucasus (Jasamanov 1978), but also in the subtropical proto-North Atlantic ocean (e.g., Huber *et al.* 1999; Kuhnt *et al.* 2005; Forster *et al.* 2007a, b), the north European midlatidude shelf seas (e.g., Jenkyns *et al.* 1994; Voigt *et al.* 2004, 2006) and the midlatidudes of the Southern Ocean (e.g., Huber *et al.* 1995; Clarke & Jenkyns 1999). According to various existing long-time Late Cretaceous palaeotemperature records, the relative palaeotemperature maximum corresponds to the Turonian stage (Cretaceous thermal maximum sensu Wilson *et al.* 2002). Nevertheless, evidence for intermittent cooler intervals exists even during this interval of extended global warmth (i.e., during the mid-Turonian: e.g., Clarke & Jenkyns 1999; Forster *et al.* 2007b; Bornemann *et al.* 2008; Sinninghe Damsté *et al.* 2010). Therefore, it appears likely that even the most elevated Cretaceous sea temperatures as recorded during the Turonian stage may not have been prevailing and, thus, these high temperatures were probably not the only underlying cause for the general marine biodiversity decline. More high-resolution palaeotemperature studies in Azerbaijan are necessary to evaluate this consideration on a regional scale.

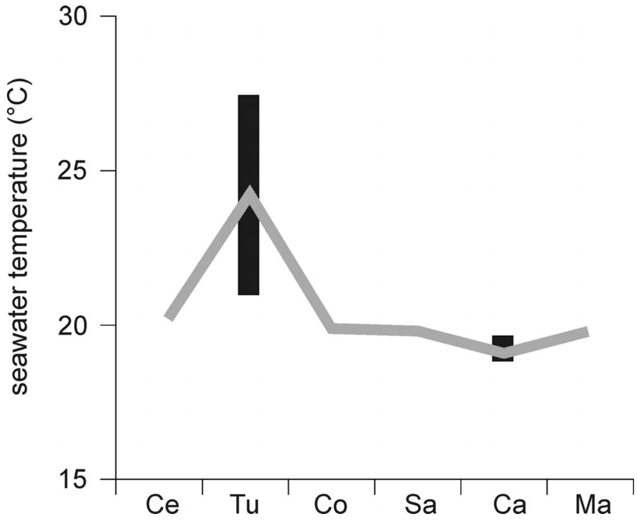


Fig. 5. Changes in the bottom seawater palaeotemperatures in the Eastern Caucasus during the Late Cretaceous. Deduced from Jasamanov (1978). Black bars indicate palaeotemperature ranges observed within the Eastern Caucasus for the Turonian and Campanian stages. See Fig. 2 for stage abbreviations.

When discussing the regional record, shoreline shifts, which are corresponding to transgressions and regressions (sensu Catuneanu 2006), should be separated clearly from changes in basin depth (Ruban 2007). In case of the Eastern Caucasus, the available palaeogeographical reconstructions (e.g., Jasamanov 1978) suggest that both shallow- and deep-marine environments persisted on its territory throughout the Late Cretaceous. Therefore, a similar range of niches remained during the epoch. If so, changes in the basin's depth cannot be considered among main factors of the biodiversity dynamics (although indirectly they may have influenced on some palaeotemperature estimations).

The record of regional transgressions/regression remains scarce. Some information is available for the Turonian and Campanian stages, which are discussed below. The early Turonian regressive episode, which followed the latest Cenomanian transgression, is well-documented in some Peri-Tethyan regions, including the Caucasus (Jasamanov 1978; Baraboshkin *et al.*

2003). In the Lesser Caucasian counterpart of Azerbaijan, the distribution of Turonian deposits is restricted, whereas in the Greater Caucasian counterpart, a transgressive contact between Turonian and underlying upper Albian-Cenomanian deposits is traced (ALI-ZADEH 1988). Globally, the early Late Cretaceous sea level experienced changes, which are now considered as glacioeustatic by some authors (e.g., GALE *et al*. 2002; MILLER *et al*. 2005; KOCH & BRENNER 2009; GALEOTTI *et al*. 2009). The C/T event occurred during a sea-level rise, which is documented across the globe (HAQ *et al*. 1987; HALLAM & WIGNALL 1999; HAQ & AL-QAHTANI 2005; VOIGT *et al*. 2006; GROSHENY *et al*. 2008; PEARCE *et al*. 2009). HAQ & AL-QAHTANI (2005), who updated the earlier eustatic curve proposed by HAQ *et al*. (1987), imply a slight fall of the global sea-level during the Turonian, which followed its C/T highstand. The same is suggested by alternative constraints of MILLER *et al*. (2005), who indicated even a sharper eustatic fall in the Turonian relatively to the Cenomanian. ZORINA *et al*. (2008) report a global concentration of hiatuses within the Turonian sedimentary successions. Thus, there is clear evidence of eustatic lowstand during the Turonian after the latest Cenomanian highstand. This is in line with the sea level history observed in the Eastern Caucasus (see above), and also consistent with the regional and global marine biodiversity dynamics (Fig. 4). The Campanian transgression is another regionally-documented feature (JASAMANOV 1978). The global curves presented by HAQ & AL-QAHTANI (2005) and MILLER *et al*. (2005) propose a different history of the sea level during this stage. The former authors depict a rise followed by a highstand. If so, the eustatic mechanism of the regional transgression in the Eastern Caucasus should be considered. MILLER *et al*. (2005) depict a highstand followed by a stepwise fall. In this case, the regional shoreline shifts would not reflect global influences. Interestingly, the Campanian diversity of marine invertebrates declined in the Eastern Caucasus, but rose globally (Fig. 4). This dissimilarity is in good agreement with the difference between regional shoreline shift and the eustatic change documented by MILLER *et al*. (2005), although this does not clarify the links between diversity and shoreline shifts. Anyway, despite of the above-made observations, it is too early to tell about any direct relationships between marine biodiversity and eustatically-driven shoreline shifts.

Differences between the conventional (PURDY 2008) and modelled (sample-standardized) (ALROY *et al*. 2008) global biodiversity curves indicate a wide range of possible errors in quantitative assessments of the fossil record. GALE *et al*. (2000) and SMITH *et al*. (2001) question the completeness of palaeontological data relevant to the Cenomanian-Turonian transition. It is possible that huge facies shifts as well as hiatuses were able to produce significant biases in the fossil record, both regionally and globally. If this is true, not shoreline motions themselves, but the relevant changes in the habitats and preservation of the fossil organisms should be considered as important controls on the regional biodiversity dynamics.

Comparison with the available foraminiferal record

Foraminiferal assemblages were very sensitive to the C/T event (e.g., JARVIS *et al*. 1988 a,b; KAIHO & HASEGAWA 1994; LAMOLDA & PERYT 1995; PERYT & LAMOLDA 1996; ULIČNY *et al*. 1997; HASEGAWA 1999; PAUL *et al*. 1999; PREMOLI SILVA *et al*. 1999; AGUILERA-FRANCO *et al*. 2001; KELLER *et al*. 2001; DESMARES *et al*. 2004; COCCIONI & LUCIANI 2005; GROSHENY *et al*. 2006; FRIEDRICH *et al*. 2006; KELLER *et al*. 2008). Two regional datasets on foraminiferal distributions in the Upper Cretaceous deposits of the Eastern Caucasus are available. The first one compiled by ALI-ZADEH (1988) permits to outline stratigraphic ranges of 36 genera from Azerbaijan, whereas the other one compiled by SAMYSHKINA (1983) allows to delineate stratigraphic ranges of 73 genera from Mountainous Dagestan. These regional micropalaeontological data are important for this study because of two main reasons. First, the current paper discusses the utility of the available (i.e., published) data for palaeobiodiversity studies. If so, each available dataset should be examined in order to understand its possible importance. Second, even invalid datasets may reveal some interesting patterns, especially with regard to the regional signature of bioevents.

In our view, the foraminiferal data from the Eastern Caucasus require a certain (if not significant) correction. For example, *Rotalipora* and other rotaliporids should not be reported from the Turonian because these taxa were disappearing during the C/T event before the uppermost Cenomanian (CARON 1985; ROBASZYNSKI & CARON 1995). However, it is not excluded that minor inaccuracies exist in the regional biostratigraphic framework (cf. RUBAN, 2003b). This should not affect significantly the stage-by-stage examination of the whole marine biodiversity, but may lead to deviation of particular taxa ranges. Similarly, as documented by SAMYSHKINA (1983), the assemblages of the different species of *Globotruncana* are, at the earlier, characteristics of Santonian (CARON, 1985; ROBASZYNSKI & CARON, 1995), but they should not be identified in Turonian as reported in her study of this region (SAMYSHKINA, 1983). Moreover, *Rugoglobigerina* should not be commonly found prior the Campanian (even if the appearance of some *Rugoglobigerina* yet in the Santonian as suggested by some new unpublished data cannot be fully excluded). This contradiction could be explained here by a taxonomic uncertainty. Indeed, the species of

Rugoglobigerina are described here as intermediate forms between *Archaeoglobigerina* and *Rugoglobigerina*, and the former can be identified in the Turonian. Thus, these, as those which are regrouped in *Globotruncana*, need taxonomic reassignment. As an other example, in the works of SAMYSHKINA (1983) and ALI-ZADEH (1988), Turonian species of *Globotruncana* are now classified in *Marginotruncana*. These discrepancies restrict the utility of foraminiferal data from the Eastern Caucasus. Its deep revision, if it is possible, may lead to changes in taxa ranges and, thus, somewhat different diversity patterns. However, as warned above, minor stratigraphic inaccuracies should also be considered.

Thus, the micropalaeontological records available from both Azerbaijan and Dagestan are semi-valid, but not invalid. The lack of validity, however, may explain differences in Late Cretaceous diversity dynamics of marine macroinvertebrates and foraminifers (Figs. 4 and 6) as well as differences between regional and global foraminiferal diversity changes (Fig. 6). It is worth to note that global changes in the number of genera of marine invertebrates recorded by PURDY (2008) and foraminifers recorded by TAPPAN & LOEBLICH (1988) coincided pretty well (Figs. 4 and 6). Such coherence proves indirectly an idea that deficiencies of micropalaeontological data from the Eastern Caucasus explain the above-mentioned differen-

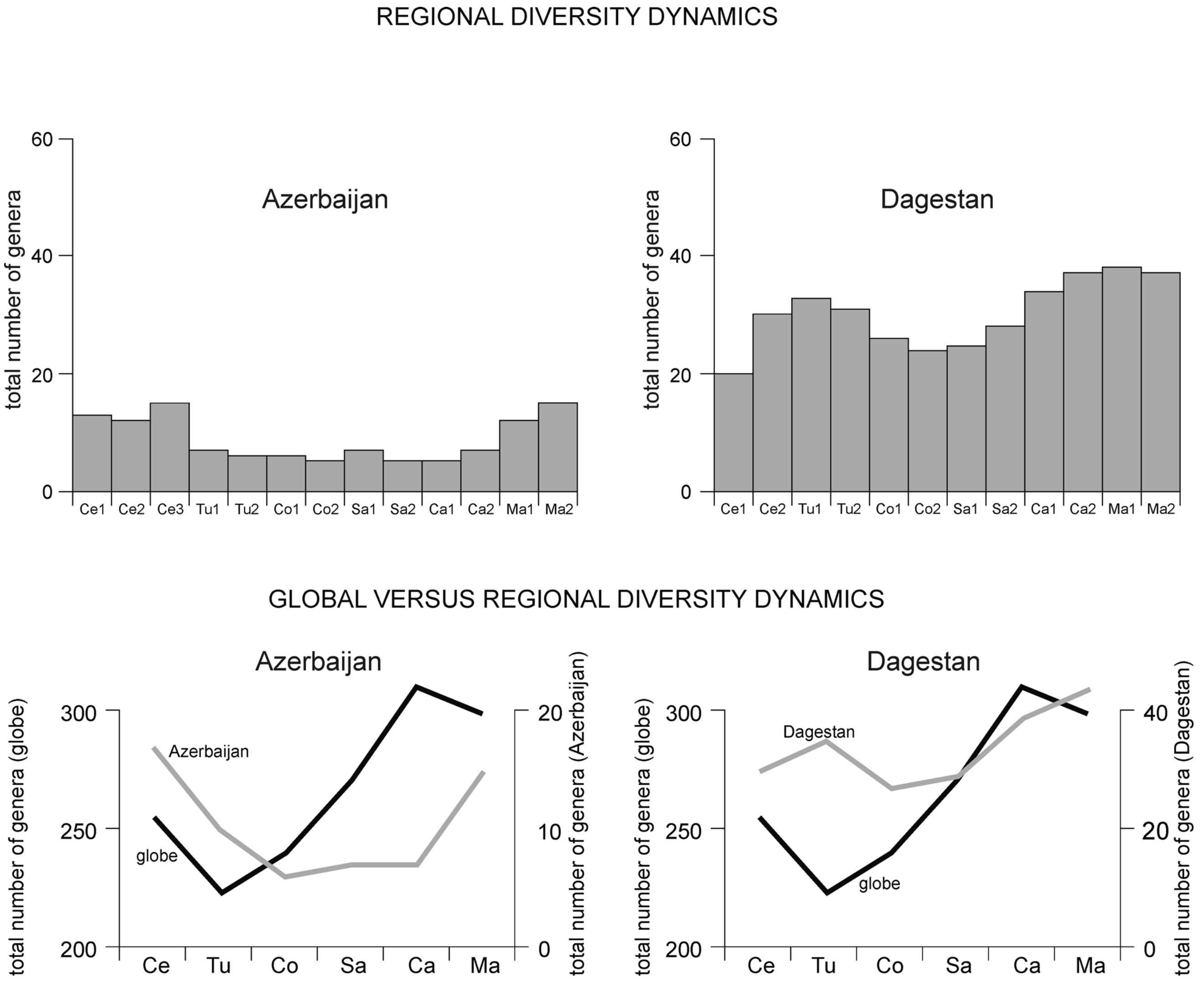


Fig. 6. Regional versus global foraminiferal diversity. Upper graphs: regionally differentiated dynamics of the Late Cretaceous foraminiferal diversity in the Eastern Caucasus. Lower graphs: regional diversity dynamics normalized per stage in comparison with global diversity dynamics (after TAPPAN & LOEBLICH 1988). See Fig. 2 for stage abbreviations. Note that only a two-folded subdivision of the Cenomanian stage is implemented in Mountainous Dagestan (upper right: Ce1 and Ce2).

ces. However, the total generic diversity of foraminifers declined both globally and in Azerbaijan.

Conclusions

In the Eastern Caucasus, marine macroinvertebrates experienced losses in the total generic diversity during the late Cenomanian-late Turonian, the early Santonian-late Campanian, and the late Maastrichtian, some of which may be judged regional imprints of global events. There is strong evidence of a regional biotic signature of the C/T event, which stressed corals, cephalopods, and gastropods. With respect to this regionally-documented event, regional and global patterns of long-term marine biodiversity changes match well. The causes of this event may be linked with oxygen depletion (OAE2) and eustatic fluctuations. Available information on foraminifers only provides a very unclear evidence of the C/T event within the study region. The Santonian-Campanian diversity minimum as documented by our study poses another intriguing question about the spatial extent of the palaeoenvironmental perturbations linked to the OAE3 event. It cannot be excluded that impact of the latter event on marine ecosystems still remains underestimated. However, the noted regional minimum can be just apparent and explained by location on the graph (Fig. 2) between short-term radiations in the Coniacian and the early Maastrichtian. Both, the global and regional palaeoenviromenal changes might have been important controls on biodiversity changes. In particular, an importance of the OAE2 for the Turonian diversity decline is recognized both in the Eastern Caucasus and on the global scale.

The results presented in this paper emphasize that regional tracing of signatures of potentially-global events is a powerful tool to test their consistency. This is important, particularly, with regard to the biotic effect of OAE2, whose global extent was recently questioned (Westermann *et al*. 2010). On a regional scale, further geochemical exploration at the C/T boundary interval as well as palaeotemperature and sea-level studies are urgently needed in order to unravel the controls on the regional marine biodiversity dynamics. Another task for future studies is an explanation of the Coniacian and early Maastrichtian diversity peaks. This will permit to realize whether these two were unusual events, and, thus, whether the early Santonian–late Campanian and late Maastrichtian diversity minima do not indicate true crises.

Acknowledgements

The authors gratefully thank V. Radulović (Serbia) for his editorial help, M. Machalski (Poland) and P. Tchoumatchenco (Bulgaria) for their helpful reviews, K. Moriya (Japan) and A. Vörös (Hungary) for their valuable suggestions to preliminary versions of this paper, M.A. Bitner (Poland) for her verification of brachiopod taxonomy, W. Riegraf (Germany) for his verification of cephalopod taxonomy, E. Yazykova-Jagt (Poland) for her corrections of some taxa names, A. Kahn (USA) and P. Neumann (Germany) for their suggestions to parts of the very early versions of this paper, A. Longinelli (Italy) for his opinion on seawater palaeotemperature analysis, and also M.A. Efendiyeva (Azerbaijan), N.M.M. Janssen (Netherlands), E.G. Purdy (UK), W. Riegraf (Germany), R. Takashima (Japan), D.S. Woodruff (USA), and many other colleagues for their help with literature. D.A.R. thanks both the Southern Federal University (Russia) and the Institute of Geology (Azerbaijan) for co-sponsoring his conference trip to Azerbaijan in 2007.

References

Abbott, D.H. & Isley, A.E. 2002. The intensity, occurrence, and duration of superplume events and eras over geological time. *Journal of Geodynamics*, 34: 265–307.

Aguilera-Franco, N., Hernandez-Romano, U. & Allison, P.A. 2001. Biostratigraphy and environmental changes across the Cenomanian-Turonian boundary, southern Mexico. *Journal of South American Earth Sciences*, 14: 237–255.

Ali-zadeh, Ak.A. (ed), 1988. *Cretaceous fauna of Azerbaijan.* 455 pp. Elm, Baku (in Russian).

Alroy, J., Aberhan, M., Bottjer, D.J., Foote, M., Fürsich, F.T., Harries, P.J., Hendy, A.J.W., Holland, S.M., Ivany, L.C., Kiessling, W., Kosnik, M.A., Marshall, C.R., McGowan, A.J., Miller, A.I., Olszewski, T.D., Patzkowsky, M.E., Peters, S.E., Viller, L., Wagner, P.J., Bonuso, N., Borkow, P.S., Brenneis, B., Clapham, M.E., Fall, L.M., Ferguson, C.A., Hanson, V.L., Krug, A.Z., Layou, K.M., Leckey, E.H., Nürnberg, S., Powers, C.M., Sessa, J.A., Simpson, C., Tomašových, A. & Visaggi, C.C. 2008. Phanerozoic Trends in the Global Diversity of Marine Invertebrates. *Science*, 321: 97–100.

Arthur, M.A. & Schlanger, S.O. 1979. Cretaceous “oceanic anoxic events” as causal factors in development of reef-reservoired giant oil fields. *American Association of Petroleum Geologists Bulletin*, 63: 870–885.

Arthur, M.A., Schlanger, S.O. & Jenkyns, H.C. 1987. The Cenomanian-Turonian oceanic anoxic event II. Palaeoceanographic controls on organic-matter production and preservation. *In*: Brooks, J. & Fleet, A.J. (eds.), *Marine Petroleum Source Rocks*. Geological Society Special Publication, 26: 401–420.

Arthur, M.A., Jenkyns, H.C., Brumsack, H.-J. & Schlanger, S.O. 1990. Stratigraphy, geochemistry, and paleoceanography of organic carbon-rich Cretaceous sequences: Background and Plans for Research. *In*: Ginsburg, R.N. & Beaudoin, B. (eds.), *Cretaceous Resources, Events, and Rhythms*. NATO ASI Series, Series

C: Mathematical and Physical Sciences, 304: 75–119. Kluwer Academic Publishers, Dordrecht.

Baraboshkin, E.Y., Alekseev, A.S. & Kopaevich, L.F. 2003. Cretaceous palaeogeography of the North-Eastern Peri-Tethys. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 196: 177–208.

Bralower, T.J. 1988. Calcareous nannofossil biostratigraphy and assemblages of the Cenomanian-Turonian boundary interval: Implications for the origin and timing of oceanic anoxia. *Paleoceanography*, 3: 275–316.

Bralower, T.J. 2008. Volcanic cause of catastrophe. *Nature*, 454: 285–287.

Bornemann, A., Norris, R.D., Friedrich, O., Beckmann, B., Schouten, S., Sinninghe Damsté, J.S., Vogel, J., Hofmann, P. & Wagner, T. (2008). Isotopic Evidence for Glaciation During the Cretaceous Supergreenhouse. *Science*, 319: 189–192.

Caron, M. 1985. Cretaceous planktic foraminifera. *In*: Bolli, H.M., Saunders, J.B. & Perch-Nielsen, K. (eds.), *Plankton stratigraphy*, 17–86. Cambridge University Press, Cambridge.

Catuneanu, O., 2006: *Principles of Sequence Stratigraphy*. 375 pp. Elsevier, Amsterdam.

Clarke, L.J. & Jenkyns, H.C. 1999. New oxygen isotope evidence for long-term Cretaceous climatic change in the Southern Hemisphere. *Geology*, 27: 699–702.

Coccioni, R. & Luciani, V. 2005. Planktonic foraminifers across the Bonarelli Event (OAE2, latest Cenomanian): The Italian record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 224: 167–185.

Desmares, D., Grosheny, D., Beaudoin, B., Gardin, S. & Gauthier-Lafaye, F. 2004. Enregistrement à haute résolution des modifications environnementales inscrites dans un cadre téphrochronologique: le bassin du Western Interior au passage Cénomanian-Turonien (USA). *Bulletin de la Société géologique de France*, 175: 561–572.

Elrick, M., Molina-Garza, R., Duncan, R. & Snow, L. 2009. C-isotope stratigraphy and paleoenvironmental changes across OAE2 (mid-Cretaceous) from shallow-water platform carbonates of southern Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 277: 295–306.

Erba, E. 2004. Calcareous nannofossils and Mesozoic oceanic anoxic events. *Marine Micropalaeontology*, 52: 85–106.

Ershov, A.V., Brunet, M.-F., Nikishin, A.M., Bolotov, S.N., Nazarevich, B.P. & Korotaev, M.V. 2003. Northern Caucasus basin: thermal history and synthesis of subsidence models. *Sedimentary Geology*, 156: 95–118.

Forster, A., Schouten, S., Baas, M. & Sinninghe Damsté, J.S. 2007a. Mid-Cretaceous (Albian-Santonian) sea surface temperature record of the tropical Atlantic Ocean. *Geology*, 35: 919–922.

Forster, A., Schouten, S., Moriya, K., Wilson, P.A. & Sinninghe Damsté, J.S. 2007b. Tropical warming and intermittent cooling during the Cenomanian/Turonian oceanic anoxic event 2: Sea surface temperature records from the equatorial Atlantic. *Paleoceanography*, 22: PA1219, doi:10.1029/2006PA001349.

Forster, A., Kuypers, M.M.M., Turgeon, S.C., Brumsack, H.-J., Petrizzo, M.R. & Sinninghe Damsté, J.S. 2008. The Cenomanian/Turonian oceanic anoxic event in the South Atlantic: New insights from a geochemical study of DSDP Site 530A. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 267: 256–283.

Friedrich, O., Erbacher, J. & Mutterlose, J. 2006. Paleoenvironmental changes across the Cenomanian/Turonian Boundary Event (Oceanic Anoxic Event 2) indicated by benthic foraminifera from the Demerara Rise (ODP Leg 207). *Revue de Micropaléontologie*, 49: 121–139.

Gale, A.S., Smith, A.B., Monks, N.E.A., Young, J.A., Howard, A., Wray, D.S. & Huggett, J.M. 2000. Marine biodiversity through the Late Cenomanian-Early Turonian: palaeocenographic controls and sequence stratigraphic biases. *Journal of the Geological Society, London*, 157: 745–757.

Gale, A.S., Hardenbol, J., Hathway, B., Kennedy, W.J., Young, J.R. & Phansalkar, V. 2002. Global correlation of Cenomanian (Upper Cretaceous) sequences: Evidence for Milankovitch control on sea level. *Geology*, 30: 291–294.

Gale, A.S., Kennedy, W.J., Voigt, S. & Walaszczyk, I. 2005. Stratigraphy of the Upper Cenomanian-Lower Turonian Chalk Succession at Eastbourne, Sussex, UK: ammonites, inoceramid bivalves and stable carbon isotopes. *Cretaceous Research*, 26: 460–487.

Galeotti, S., Rusciadelli, G., Sprovieri, M., Lanci, L., Gaudio, A. & Pekar, S. 2009. Sea-level control on facies architecture in the Cenomanian-Coniacian Apulian margin (Western Tethys): A record of glacio-eustatic fluctuations during the Cretaceous greenhouse? *Palaeogeography, Palaeoclimatology, Palaeoecology*, 276: 196-205.

Gamkrelidze, I.P. 1986. Geodynamic evolution of the Caucasus and adjacent areas in Alpine time. *Tectonophysics*, 127: 261–277.

Gamkrelidze, I.P. 1997. Terranes of the Caucasus and Adjacent Areas. *Bulletin of the Georgian Academy of Science*, 155: 75–81.

Gavrilov, Yu.O., Shcherbinina, E.A., Golovanova, O.V. & Pokrovsky, B.G. 2009. Late Cenomanian anoxic event (OAE2) in the Aimaki section of Mountainous Dagestan. *Bulletin of Moscow Society of Naturalists, Geological series*, 84: 94–108. (in Russian)

Golonka, J. 2004. Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic. *Tectonophysics*, 381: 235–273.

Gradstein, F.M., Ogg, J. & Ogg, G., 2008. The geological time scale. *In*: Rey, J. & Galeotti, S. (eds), *Stratigraphy. Terminology and practice*, 125–136. Editions TECHNIP, Paris.

Grosheny, D., Beaudoin, B., Morel, L. & Desmares, D. 2006. High-resolution biostratigraphy and chemostratigraphy of the Cenomanian/Turonian boundary event in the Vocontian Basin, southeast France. *Cretaceous Research*, 27: 629–640.

GROSHENY, D., CHIKHI-AOUIMEUR, F., FERRY, S., BENKHEROUF-KECHID, F., JATI, M., ATROPS, F. & REDJIMI-BOUROUIBA, W. 2008. The Upper Cenomanian-Turonian (Upper Cretaceous) of the Saharan Atlas (Algeria). *Journal of the Geological Society, London*, 179: 593–603.

HALLAM, A. & WIGNALL, P.B. 1997. *Mass Extinctions and their Aftermath*. Oxford University Press, Oxford, 320 pp.

HALLAM, A. & WIGNALL, P.B. 1999. Mass extinctions and sea-level changes. *Earth-Science Reviews*, 48: 217–250.

HAQ, B.U. & AL-QAHTANI, A.M. 2005. Phanerozoic cycles of sea-level change on the Arabian Platform. *GeoArabia*, 10: 127–160.

HAQ, B.U., HARDENBOL, J. & VAIL P.R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, 235: 1156–1167.

HARRIES, P. & LITTLE, C.T.S. 1999. The early Toarcian (Early Jurassic) and the Cenomanian-Turonian (Late Cretaceous) mass extinctions: similarities and contrasts. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 154: 39–66.

HASEGAWA, T. 1999. Planktonic foraminifera and biochronology of the Cenomanian-Turonian (Cretaceous) sequence in the Oyubari area, Hokkaido, Japan. *Paleontological Research*, 3: 173–192.

HUBER, B.T., HODELL, D.A. & HAMILTON, C.P. 1995. Middle-Late Cretaceous climate of the southern high latitudes; stable isotopic evidence for minimal equator-to-pole thermal gradients. *Geological Society of America Bulletin*, 107: 1164–1191.

HUBER, B.T., LECKIE, R.M., NORRIS, R.D., BRALOWER, T.J. & COBABE, E. 1999. Foraminiferal assemblages and stable isotopic change across the Cenomanian-Turonian boundary in the subtropical North Atlantic. *Journal of Foraminiferal Research*, 29: 392–417.

JARVIS, I., CARSON, G., HART, M., LEARY, P. & TOCHER, B. 1988a. The Cenomanian-Turonian (late Cretaceous) anoxic event in SW England: evidence from Hooken Cliffs near Beer, SE Devon. *Newsletters on Stratigraphy*, 18: 147–164.

JARVIS, I., CARSON, G.A., COOPER, M.K.E., HART, M.B., LEARY, P.N., TOCHER, B.A., HORNE, D. & ROSENFELD, A. 1988b. Microfossil assemblages and the Cenomanian-Turonian (late Cretaceous) Oceanic Anoxic Event. *Cretaceous Research*, 9: 3–103.

JARVIS, I., GALE, A.S., JENKYNS, H.C. & PEARCE, M.A. 2006. Secular variation in Late Cretaceous carbon isotopes: a new $\delta^{13}C$ carbonate reference curve for the Cenomanian-Campanian (99.6-70.6 Ma). *Geological Magazine*, 143: 561–608.

JASAMANOV, N.A. 1978. *Landscape and climatic conditions in the Jurassic, Cretaceous and Paleogene in the south of the USSR*. Nedra, Moskva, 224 pp. (in Russian)

JENKYNS, H.C. 1980. Cretaceous anoxic events: from continents to oceans. *Journal of the Geological Society, London*, 137: 171–188.

JENKYNS, H.C. 2010. Geochemistry of oceanic anoxic events. *Geochemistry, Geophysics, Geosystems*, 11: Q03004, doi:10.1029/2009GC002788.

JENKYNS, H.C., GALE, A.S. & CORFIELD, R.M. 1994. Carbon- and oxygen-isotope stratigraphy of the English Chalk and Italian Scaglia and its palaeoclimatic significance. *Geological Magazine*, 131: 1–34.

JONES, E.J.W., BIGG, R.G., HANHOD, I.C. & SPATHOPOULOS, F. 2007. Distribution of deep-sea black shales of Cretaceous age in the eastern Equatorial Atlantic from seismic profiling. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 248: 233–246.

KAIHO, K. & HASEGAWA, T. 1994. End-Cenomanian benthic foraminiferal extinctions and oceanic dysoxic events in the northwestern Pacific. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 111: 29–43.

KAZMIN, V.G. & TIKHONOVA, N.F. 2006. Evolution of Early Mesozoic back-arc basins in the Black Sea-Caucasus segment of a Tethyan active margin. *In*: ROBERTSON, A.H.F. & MOUNTRAKIS, D. (eds), *Tectonic Development of the Eastern Mediterranean Region*. Geological Society of London Special Publication, 260, 179–200.

KELLER, G. 2008. Cretaceous climate, volcanism, impacts, and biotic effects. *Cretaceous Research*, 29: 754–771.

KELLER, G., HAN, Q., ADATTE, TH. & BURNS, S.J. 2001. Palaeoenvironment of the Cenomanian-Turonian transition at Eastbourne, England. *Cretaceous Research*, 22: 391–422.

KELLER, G., ADATTE, T., BERNER, Z., CHELLAI, E.H. & STUEBEN, D. 2008. Oceanic events and biotic effects of the Cenomanian-Turonian anoxic event, Tarfaya Basin, Morocco. *Cretaceous Research*, 29: 976–994.

KOCH, J.T. & BRENNER, R.L. 2009. Evidence for glacioeustatic control of large, rapid sea-level fluctuations during the Albian-Cenomanian: Dakota formation, eastern margin of western interior seaway, USA. *Cretaceous Research*, 30: 411–423.

KOTETISHVILI, E. 1999. Upper Cretaceous Ammonites and their extinction: interpretation of data from the Caucasus and comparison with Mangyshlak, the Crimea and the Maastricht area. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique. Sciences de la Terre*, 69 (supplement A): 167–172.

KUHNT, W., LUDERER, F., NEDERBRAGT, S., THUROW, J. & WAGNER, T. 2005. Orbital-scale record of the late Cenomanian-Turonian oceanic anoxic event (OAE-2) in the Tarfaya Basin (Morocco). *International Journal of Earth Sciences*, 94: 147–159.

KURODA, J. & OHKOUCHI, N. 2006. Implication of spatiotemporal distribution of black shales deposited during the Cretaceous Oceanic Anoxic Event-2. *Paleontological Research*, 10: 345–358.

KURODA, J., OHKOUCHI, N., ISHII, T., TOKUYAMA, H. & TAIRA, A. 2005. Lamina-scale analysis of sedimentary components in Cretaceous black shales by chemical compositional mapping: Implications for paleoenvironmental changes during the Oceanic Anoxic Events. *Geochimica et Cosmochimica Acta*, 69: 1479–1494.

LAMOLDA, M. & PERYT, D. 1995. Benthonic foraminiferal response to the Cenomanian-Turonian Boundary Event in the Ganuza section, northern Spain. *Revista Española de Paleontología*. No Homenaje al Dr. G. Colom: 101–118.

LARSON, R.L. 1991a. Geological consequences of superplumes. *Geology*, 19: 963–966.

LARSON, R.L. 1991b. Latest pulse of Earth: Evidence for a mid-Cretaceous superplume. *Geology*, 19: 547–550.

LECKIE, R.M., BRALOWER, T.J. & CASHMAN, R. 2002. Oceanic anoxic events and plankton evolution: Biotic response to tectonic forcing during the Mid-Cretaceous. *Paleoceanography*, 17: 1–29.

LONGINELLI, A. 1996. Pre-Quaternary isotope palaeoclimatological and palaeoenvironmental studies: science or artifact? *Chemical Geology*, 129: 163–166.

LORDKIPANIDZE, M.B., ADAMIA, SH.A. & ASANIDZE, B.Z. 1984. Active margin evolution of the Tethys Ocean. *In*: LISITZIN, A.P. (ed), *Paleookeanologija*. Doklady 27 Mezhdunarodnogo geologitcheskogo kongressa, 72-83. Nauka, Moskva. (in Russian)

MILLER, K.G., KOMINZ, M.A., BROWNING, J.V., WRIGHT, J.D., MOUNTAIN, G.S., KATZ, M.E., SUGARMAN, P.J., CRAMER, B.S., CHRISTIE-BLICK, N. & PEKAR, S.F. 2005. The Phanerozoic Record of Global Sea-Level Change. *Science*, 310: 1293–1298.

MORT, H., JACQUAT, O., ADATTE, T., STEINMANN, P., FÖLLMI, K., MATERA, V., BERNER, Z. & STÜBEN, D. 2007. The Cenomanian/Turonian anoxic event at the Bonarelli Level in Italy and Spain: enhanced productivity and/or better preservation?. *Cretaceous Research*, 28: 597–612.

OGG, J.G., OGG, G. & GRADSTEIN, F.M. 2008. *The Concise Geologic Time Scale*. 177 pp. Cambridge University Press, Cambridge.

PAUL, C.R.C., LAMOLDA, M.A., MITCHELL, S.F., VAZIRI, M.R., GOROSTIDI, A. & MARSHALL, J.D. 1999. The Cenomanian-Turonian boundary at Eastbourne (Sussex, UK): a proposed European reference section. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 150: 83–121.

PEARCE, M.A., JARVIS, I. & TOCHER, B.A. 2009. The Cenomanian-Turonian boundary event, OAE2 and palaeoenvironmental change in epicontinental seas: New insights from the dinocyst and geochemical records. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 280: 207–234.

PERYT, D. & LAMOLDA, M. 1996. Benthonic foraminiferal mass extinction and survival assemblages from the Cenomanian-Turonian Boundary Event in the Menoyo section, northern Spain. *In*: HART, M.B. (ed.), *Biotic Recovery from Mass Extinction Events*. Geological Society Special Publication, 102: 245–258.

PREMOLI SILVA, I. & SLITER, W.V. 1999. Cretaceous paleoceanography: Evidence from planktonic foraminiferal evolution. *In*: BARRERA, E. & JOHNSON, C.C. (eds.), *Evolution of the Cretaceous Ocean-Climate System*. Geological Society of America, 332: 301–328.

PREMOLI SILVA, I., ERBA, E., SALVINI, G., LOCATELLI, C. & VERGA, D. 1999. Biotic changes in Cretaceous anoxic events of the Tethys. *Journal of Foraminiferal Research*, 29: 352–370.

PURDY, E.G. 2008. Comparison of taxonomic diversity, strontium isotope and sea-level patterns. *International Journal of Earth Sciences*, 97: 651–664.

RAWSON, P.F., DHONDT, A.V., HANCOCK, J.M. & KENNEDY, W.J. (eds.) 1996. Proceedings "Second International Symposium of Cretaceous Stage Boundaries", Brussels 8-16 September 1995. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique*, 66 (supplement): 1–117.

REY, O., SIMO, J.A. & LORENTE, M.A. 2004. A record of long- and short-term environmental and climatic change during OAE3: La Luna Formation, Late Cretaceous (Santonian-early Campanian), Venezuela. *Sedimentary Geology*, 170: 85–105.

ROBASZYNSKI, F. & CARON, M. 1995. Foraminifères planctoniques du Crétacé: commentaire de la zonation europe-méditerranée. *Bulletin de la Société Géologique de France*, 166: 681–692.

RUBAN, D.A. 2003a. Dynamics of the taxonomic diversity of the Cenomanian-Coniacian foraminifers within the Norrthern Caucasus and the global events. *Izvestija VUZov. Severo-Kavkazskij region. Estestvennyje nauki*, 2: 112–113. (in Russian)

RUBAN, D.A. 2003b. Towards the stage subdivision of the Upper Cretaceous of the Northern Caucasus by foraminifers. *Izvestija VUZov. Severo-Kavkazskij region. Estestvennyje nauki*, 3: 115. (in Russian)

RUBAN, D.A. 2005. Mesozoic marine fossil diversity and mass extinctions: an experience with the middle XIX century paleontological data. *Revue de Paléobiologie*, 24: 287–290.

RUBAN, D.A. 2007. Jurassic transgressions and regressions in the Caucasus (northern Neotethys Ocean) and their influences on the marine biodiversity. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 251: 422–436.

RUBAN, D.A. 2011. Do outdated palaeontological data produce just a noise? An assessment of the Middle Devonian-Mississippian biodiversity dynamics in central Asia on the basis of Soviet-time compilations. *Geologos*, 17: 29–47.

RUBAN, D.A. & VAN LOON, A.J. 2008. Possible pitfalls in the procedure for paleobiodiversity-dynamics analysis. *Geologos*, 14: 37–50.

RUBAN, D.A., ZERFASS, H. & YANG, W. 2007. A new hypothesis on the position of the Greater Caucasus Terrane in the Late Palaeozoic-Early Mesozoic based on palaeontologic and lithologic data. *Trabajos de Geología*, 27: 19–27.

SAINTOT, A., BRUNET, M.-F., YAKOVLEV, F., SEBRIER, M., STEPHENSON, R., ERSHOV, A., CHALOT-PRAT, F. & MCCANN, T. 2006. The Mesozoic-Cenozoic tectonic evolution of the Greater Caucasus. *In*: GEE, D.G. & STEPHENSON, R.A. (eds), *European Lithosphere Dynamics*. Geological Society of London Memoirs, 32: 277–289.

SAMYSHKINA, K.G. 1983. *Foraminifers and stratigraphy of the Cretaceous deposits of the Eastern Caucasus*. 169 pp. Nauka, Moskva (in Russian).

SCHLANGER, S.O., ARTHUR, M.A., JENKYNS, H.C. & SCHOLLE, P.A. 1987. The Cenomanian-Turonian oceanic anoxic event, I. Stratigraphy and distribution of organic carbon-rich beds and the marine d13C excursion. *In*: BROOKS, J. & FLEET, A.J. (eds), *Marine Petroleum Source Rocks*. Geological Society Special Publication, 26: 371–399.

SCOTESE, C.R. 2004. A Continental Drift Flipbook. *Journal of Geology*, 112: 729–741.

SEPKOSKI, J.J., JR. 2002. A compendium of fossil marine animal genera. *Bulletins of American Paleontology*, 63: 1–560.

SEPKOSKI, J.J., JR. 1986. Phanerozoic overview of mass extinction. *In*: RAUP, D.M. & JABLONSKI, D. (eds). *Patterns and processes in the history of life*, 277–295. Springer, Berlin.

SINNINGHE DAMSTÉ, J.S., VAN BENTUM, E.C., REICHART, G.-J., PROSS, J. & SCHOUTEN, S. 2010. A CO_2 decrease-driven cooling and increased latitudinal temperature gradient during the mid-Cretaceous Oceanic Anoxic Event 2. *Earth and Planetary Science Letters*, 293: 97–103.

SMITH, A.B., GALE, A.S. & MONKS, N.E.A. 2001. Sea-level change and rock-record bias in the Cretaceous: a problem for extinction and biodiversity studies. *Paleobiology*, 27: 241–253.

SNOW, L., DUNCAN, R.A. & BRALOWER, T.J. 2005. Trace element abundances in the Rock Canyon Anticline, Pueblo, Colorado, marine sedimentary section and their relationship to Caribbean plateau construction and oxygen anoxic event 2, *Paleoceanography*, 20: 1–14.

STAMPFLI, G.M. & BOREL, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetis oceanic isochrons. *Earth and Planetary Science Letters*, 196: 17–33.

TAKAHASHI, A. 2005. Diversity changes in Cretaceous inoceramid bivalves of Japan. *Paleontological Research*, 9: 217–232.

TAKASHIMA, R., NISHI, H., HUBER, B.T. & LECKIE, M.R. 2006. Greenhouse World and the Mesozoic Ocean. *Oceanography*, 19: 64–74.

TAKASHIMA, R., NISHI, H., HAYASHI, K., OKADA, H., KAWAHATA, K., YAMANAKE, T., FERNANDO, A.G. & MAMPUKU, M. 2009. Litho-, bio- and chemostratigraphy across the Cenomanian/Turonian boundary (OAE 2) in the Vocontian Basin of southeastern France. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 273: 61–74.

TAPPAN, H. & LOEBLICH, A.R., Jr. 1988. Foraminiferal evolution, diversification, and extinction. *Journal of Paleontology*, 62: 695–714.

TAWADROS, E., RUBAN, D. & EFENDIYEVA, M. 2006. Evolution of NE Africa and the Greater Caucasus: Common Patterns and Petroleum Potential. *The Canadian Society of Petroleum Geologists, the Canadian Society of Exploration Geophysicists, the Canadian Well Logging Society Joint Convention*, 531–538. Calgary.

TOSHIMITSU, S. & HIRANO, H. 2000. Database of the Cretaceous ammonoids in Japan. Stratigraphic distribution and bibliography. *Bulletin of the Geological Survey of Japan*, 51: 559–613.

TUR, N.A., SMIRNOV, JU.P. & HUBER, B.T. 2001. Late Albian-Coniacian planktic foraminifera and biostratigraphy of the northeastern Caucasus. *Cretaceous Research*, 22: 719–734.

ULIČNY, D., HLADIKOVA, J., ATTREP, M.J., JR., CECH, S., HRADECKA, L. & SVOBODOVA, M. 1997. Sea-level changes and geochemical anomalies across the Cenomanian-Turonian boundary: Pecinov quarry, Bohemia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 132: 265–285.

VOIGT, S., GALE, A.S. & FLÖGEL, S. 2004. Midlatitude shelf seas in the Cenomanian-Turonian greenhouse world: Temperature evolution and North Atlantic circulation. *Paleoceanography*, 19: PA4020, doi:10.29/2004PA001015.

VOIGT, S., GALE, A.S. & VOIGT, T. 2006. Sea-level change, carbon cycling and palaeoclimate during the Late Cenomanian of northwest Europe; an integrated paleoenvironmental analysis. *Cretaceous Research*, 27: 836–858.

WAGNER, T., SINNINGHE DAMSTÉ, J.S., HOFMANN, P. & BECKMANN, B. 2004. Euxinia and primary production in Late Cretaceous eastern equatorial Atlantic surface waters fostered orbitally driven formation of marine black shales. *Palaeoceanography*, 19: PA3009, doi:10.1029/2003PA000898.

WANG, C.S., HU, X.M., JANSA, L., WAN, X.Q. & TAO, R. 2001. The Cenomanian-Turonian anoxic event in southern Tibet. *Cretaceous Research*, 22: 481–490.

WESTERMANN, G.E.G. 2000. Marine faunal realms of the Mesozoic: review and revision under the new guidelines for biogeographic classification and nomenclature. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 163: 49–68.

WESTERMANN, S., CARON, M., FIET, N., FLEITMANN, D., MATERA, V., ADATTE, T. & FÖLLMI, K.B. 2010. Evidence for oxic conditions during oceanic anoxic event 2 in the northern Tethyan pelagic realm. *Cretaceous Research*, 31: 500–514.

WILSON, P.A., NORRIS, R.D. & COOPER, M.J. 2002. Testing the Cretaceous greenhouse hypothesis using glassy foraminiferal calcite from the core of the Turonian tropics on the Demerara Rise. *Geology*, 30: 607–610.

WIGNALL, P.B. 2001. Large igneous provinces and mass extinctions. *Earth-Science Reviews*, 53: 1–33.

ZORINA, S.O., DZYUBA, O.S., SHURYGIN, B.N. & RUBAN, D.A. 2008. How global are the Jurassic-Cretaceous unconformities? *Terra Nova*, 20: 341–346.

Appendix 1. Late Cretaceous genera of macroinvertebrates from Azerbaijan (compiled from ALI-ZADEH 1988). See Fig. 2 for stage abbreviations

GENERA	Ce1	Ce2	Ce3	Tu1	Tu2	Co1	Co2	Sa1	Sa2	Ca1	Ca2	Ma1	Ma2
Brachiopods													
Basiliola											×	×	
Bolgarithyris						×	×	×	×				
Concinnithyris						×	×	×	×				
Cretirhynchia						×	×	×	×				
Cyclothyris						×	×	×	×				
Kingena						?	?						
Najdinothyris						×	×			×	×	×	
Orbirhynchia						×							
Ornathothyris								×	×				
Corals													
Actinastraea						×	×						
Agathella								×					
Astrogyra								×					
Aulosmilia						×	×						
Conicosmilotrochus	×	×	×										
Cunnolites							×						
Dimorphastraea							×						
Felixyra	×	×	×										
Fungiastraea							×						
Meandrosmilia								×					
Placocoenia						×	×						
Vallimeandra						×	×						
Cephalopods													
Acanthoceras	?	×	?										
Baculites						×	×						
Belemnella												×	×
Belemnitella									×	×	×		
Diplomoceras												×	×
Neohibolites	×	×											
Pachydiscus													
Parahibolites	×											×	×
Pseudokossmaticeras												×	×
Puzosia	×	×	×										
Schloenbachia	×												
Echinoids													
Cardiaster							×					×	
Catopygus	?	?	?									×	
Conulus	?	?	?	×	×	×	×		×	×		×	×
Coraster										×	×		
Echinocorys						×		×	×	×	×	×	×
Galeaster												×	
Galeola										×			
Galerites												×	×

GENERA	Ce1	Ce2	Ce3	Tu1	Tu2	Co1	Co2	Sa1	Sa2	Ca1	Ca2	Ma1	Ma2
Echinoids													
Guettaria											×	×	
Hemipneustes													×
Holaster	?	?	?										
Holectypus	?	?	?										
Homoeaster												×	×
Isomicraster								×	×	×		×	
Isopneustes													×
Micraster					×	×	×			×	×		
Ornithaster											×		
Peronaster										×			
Phymosoma								×	×				
Plesiocorys							×						
Pseudopyrina								×	×				
Pseudoffaster										×	×	×	
Pygurus	?	?	?										
Rachiosoma												×	
Seunaster										×		×	×
Stegaster												×	×
Turanglaster											×		
Gastropods													
Actaeon	×	×	×										
Actaeonella	×	×	×	×	×	×	×						
Ampullospira		×	×			×	×						
Dalmatea		×	×	×									
Eotrochactaeon	×	×	×										
Glauconiella						×	×						
Gymnentoma		×	×	×	×	×	×						
Haploptyxis						×	×						
Helicaulax					×	×							
Itruvia		×	×	×									
Jaccardiella	×	×											
Neoptyxis	×	×	×										
Nerinella		×	×										
Oligoptyxis		×	×	×									
Omphaloactaonella		×	×	×									
Parasimploptyxis							×	×					
Plesioplocus	×												
Pseudomesalla	×	×	×	×									
Simploptyx													
Trajanella						×							
Trochactaeon				×	×	×	×						

×- presence, ? - possible presence

Резиме

Горњокредна динамика морског биодиверзитета Источног Кавказа, северни Нео-Тетиски океан: регионалне промене узроковане глобалним догађајима

За време горње креде долази до значајне промене у биодиверзитету морских организама. Општи еволуциони трендови били су проузроковани специфичним догадјајима.

Граница ценоман/турон (93,6 Ма), која вероватно указују на горњу границу средњокредне серије, је период који се карактерисао израженим променама средине на читавој планети. Интезивне промене и изумирање појединих морских организама, океански аноксични догађај и повећање вулканске активности значајно се одразило на фосилне, седиментационе и геохемијска податке. Обим и јачина биотских криза близу границе ценоман/турон још увек су дискутабилни. И ако већи део података којима се располаже потиче из подручја Медитерана, Енглеске и Јапана, палеонтолошки подаци, многих потенцијално значајних региона, још увек нису довољно проучени. Источни Кавказ, би могао да буде регион од палеоеколошког значаја због његове специфичне палеопозиције на северној маргини Нео-Тетиског океана, између Алпских структура Европе и терана Средњег Истока, и с обзиром на то да показује репрезентативну горњокредну сукцесију са документованим распрострањењем разноврсне фауне морских макробескичмењака. Овом приликом приказано је стратиграфско распрострањење 80 родова морских макробескичмењака горњокредних седимената Азербејџана. Анализиране фосилне групе укључују (број родова): цефалоподе (11), брахиоподе (9), гастроподе (21), корале (12) и ехиниде (27). За време горње креде у Источном Кавказу разноврсност родова је била јако изражена. Током доњег и средњег ценомана долазо до благог пораста разноврсности која затим опада за 2/3 за време горњег ценомана–горњег турона, да би опет дошло до пораста у горњем конијаку. У доњем сантону долази до следећег наглог опадања у биодиверзиту (за око половину) и овај тренд се постепено наставља све до краја кампана. У доњем мастрихту долази поново до биотске радијације, да би у горњем мастрихту уследило њено опадање. Горњоценомански-доњотуронски догађај утицали су на корале, цефалоподе и гастроподе, док су ехиниди били мање угрожени. Доњосантонски-горњокапмански догађаји били су неповољни за брахиоподе, корале, цефалоподе и гастроподе. Једини изузетак представљају ехиниди чија се разноврсност постепено повећава за време целог горњег турона и доњег кампана. Горњомастрихтски догађај утиче на брахиоподе и ехиниде. Цефалоподи очигледно преживљавају ову кризу без икаквих последица, тј. њихов укупан диверзитет није се променио. Заједничко за поменуте догађаје јесте да су били неповољни за неколико група макробескичмењака, мада то нису биле сваки пут исте групе. Глобална динамика биодиверзитета се разликовала од динамике која се дешавала у Источном Кавказу.

Добијени резултати показују да су промене у укупном диверзитету проучаваних фосилних група одвијале по мање или више заједничким обрасцима, што указује на то да промене које су довеле до велике разноврсности макробескичмењака нису никако биле случајност. Најзначајнији догађаји су довели до три максимума (средњи ценоман, горњи конијак и доњи мастрихт) и три минимума (горњи ценоман–горњи турон, доњи сантон––горњи кампан и горњи мастрихт) у њиховом диверзитету. Значајни догађаји који су се десили током ценомана и турона довели су до појаве минимума у диверзитету током турона, и то како глобално тако и регионално. Диверзитетски минимум који се догађао током сантона и кампана, а који је документован нашом студијом, указује на суштинско питање које се односи на промене у распореду палеосредина и њихове повезаности са ОАЕ3 догађајем. Међутим, запажени регионални мимимум може бити објашњен краткотрајном радијацијом у конијаку и доњем мастрихту. Смањење диверзитета у оквиру макробескичмењака за време горњег мастрихта може у ствари бити само регионални феномен забележен у Источном Кавказу. Глобалне и регионалне промене палеосредина имале су јак утицај на промене биодиверзитета. Значај океанског аноксичног догађаја 2 за опадање туронског диверзитета је утврђен како у Источном Кавказу као тако и на глобалном нивоу. Резултати рада указују да праћење регионалних промена које су проузроковане потенцијално глобалним догађајима могу бити од изузетног значаја при провери њихове конзистенције.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	47–61	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP11720047R

Involutina farinacciae Bronnimann & Koehn-Zaninetti 1969, a marker for the Middle Liassic in basinal and some platform facies of Mediterranean and near east areas: the discussion concerning the paleogeography of Montenegro-Albania border region (the Scutari–Peć Lineament)

Rajka Radoičić & Divna Jovanović

Abstract. Foraminiferal species *Involutina farinacciae* Bronnimann & Koehn-Zaninetti, is a marker of Middle Liassic basinal and transitional platform bassin facies widely distributed in Mediterranean area (Umbria–Marche, Pindos, Budva, Sicilia and the Inner Dinarides basin), also in Iraqi Kurdistan ("Avroman" Basin). In the Dinaric Carbonate Platform (DCP) it indicates intramarginal and intraplatform depressions.

Paleogeography of the Montenegro–Albania border area formed by the inherited prealpine paleogeographic scenario that resulted in a different arrangement of the paleogeographic units westward and eastward of the paleostructure (Scutari–Peć Lineament) which controlled the geological history of the region. This transverse paleostructure was a) coincident with the paleogeographic front of the DCP, and b) the westward limit of the overtrusted Mirdita Zone. The difference in the paleogeographic features in the prolongation from the DCP througout Albania, controlled by paleostructure, are the source of seizmicity, rotation and deviation (SE to NW, into NE) of the Complex Mirdita Zone.

Key words: *Involutina farinacciae*, marker, Middle Liassic, distribution, Budva Basin, Scutari–Peć lineament.

Апстракт. Приказани су наласци врсте *Involutina farinacciae* Bronnimann-Koehn Zaninetti у басенским сукцесијама Ирачког Курдистана (област Авромана), у јединицама унутрашњих Динарида, Умбрија–Марке, Будва–Краста, Пиндос и Сицилија. На простору Динарске карбонатне платформе ова врста се јавља у интрамаргиалним или трансверсалним депресијама, ареалма отворене маргине и прелазног појаса платформа–басен. Поред неколико општих података о Будва басену, зложени су податци о палеогеографији граничне области Црна Гора–Албанија (Скадар–Пеђ линија).

Кључне речи: *Involutina farinacciae*, маркер, средњи лијас, распрострањење, Будва басен, Скадар–Пеђ линија.

Introduction

Bronnimann & Zaninetti (1969) described *Involutina farinacciae*, a new foraminifera species, based on specimens from the Middle Liassic of Lacium, southern Italy, ascribed by Farinacci (1967), to *Semiinvoluta clari* Kristan.

The species *Aulotortus regularis* Zuccari, 1969, described from the Middle Liassic of Umbria, is a younger synonym of *I. farinacciae*, because the note with the description of the species was being in print when *I. farinacciae* was published (Zuccari 1969, postscriptum on p. 426).

Involutina scandonei (Radoičić 1969) is also a younger synonym of *I. farinacciae* being published at the end of year 1969. *I. scandonei* was described from the Lower Dogger of the Budva Basin (Lastva section), also known from similar basinal sediments of Pindos (Koziakas), Sicily (Valone Crisanti) and from the Inner Dinarides of SW Serbia. According to the manuscript geological map SW Serbia, sheet Užice, limestone with *I. scandonei* forms the lower part of Diabase Chert Formation ("Lower Dogger"). Therefore, without additional information the same age is given to the sediments bearing this species, which has been revised. *I. farinacciae* occurs, as in the

[1] Kralja Petra I, 38, 11000 Belgrade, Serbia. E-mail: rradoicic@sezampro.rs

[2] Geological Institute of Serbia, Rovinjska 12, 11000 Belgrade, Serbia. E-mail: djdivna@gmail.com

type area, through the middle part of the Liassic stratigraphic column (RADOIČIĆ 1987). No finer stratigraphic distribution can be given at present.

In addition to information about the Liassic sequences in which *I. farinacciae* occurs, few references are made to the Budva Basin and to the paleogeography of the Montenegro–Albania border area (the Scutari–Peć lineament).

Geographic distribution and biostratigraphy

I. farinacciae is the species of very large geographic distribution. In addition to the mentioned areas, it is reported from Iraqi Kurdistan, from the Inner Dinarides, Dinaric Carbonate Platform, and from the Budva Basin.

Iraqi Kurdistan

In the Avroman Range area, NE Iraq, the Jurassic–Cretaceous carbonate clastics- cherty series are very similar to those of the Budva and Pindos Basins. The Liassic intervals consist of siliceous calcilutites, calcutites with radiolaria and resedimented carbonates and microbreccias. Resedimented limestones bearing *I. farinacciae* have been found in five locations: NW and SW of the village Seh Riyawra, NW of Tut Agaj, the right bank of the Wadi Chagan (toward Gala Zadri) and near to the village Zangi Sura (RADOIČIĆ 1987, foot-note in the Serbian text).

Inner Dinarides

Mountain Zlatibor

Liassic ooidal-peloidal limestones with *I. farinacciae* from Drežnik (Pl. 1, Fig. 1), the NW area of the Zlatibor ophiolite massif, previously ascribed to the "Diabase Chert Formation"(DCF), are most likely only the middle Liassic sequence in the succession underlying DCF (MOJSILOVIĆ *et al.* 1971). Identical limestone with *I. farinacciae, Agerina martana* and some other foraminifera, are found near the Bela Reka on SE Zlatibor Range (Pl. 1, Figs. 10, 11).

The stratigraphic gap between the DCF and the underlying carbonate sediments, in Zlatibor region, occurs at different ages: from the Rhaetian–Liassic, upper Liassic or ?lower Dogger.

Sjenica–Prijepolje

The "Dogger and Malm limestones with chert" of the Diabas Chert Formation are outcropped near Sjenica and WSW of Sjenica toward Prijepolje (Geological Map sheets Sjenica and Prijepolje; MOJSILOVIĆ *et al.* 1973; ĆIRIĆ *et al*. 1977). In a paper on DCF in this area, JOVANOVIĆ *et al.* (1979) describe the limestone-chert unit near Vrelo as the Diabase Chert Formation "III litotype". Ooidal limestone is mentioned from the older part of the stratigraphic succession, in which certain layers bear "atypical microfossil association". Tithonian marly micrite containing *Calpionella alpina* and *Calpionella elliptica* is the youngest of the described geological column. Evidence of an older, Liassic part of the limestone-chert unit that was taken to be a member of the DCF, are the association *I. farinacciae*, *Bosniella* cf. *oenensis, A. martana* from the sediments near Vrelo (Pl. 1, Fig. 7). Consequently, the ?continous stratigraphic succession at Vrelo includes sediments both older and younger than the Diabase Chert Formation, respectively underlying and overlying formations (age correlative to Krš Gradac, RADOIČIĆ *et al.* 2009). The same Liassic resedimented ooidal-peloidal limestones are sampled in the belt Sjenica–Gomila and at Duboki potok in Aljinovići–Prijepolje area (Pl. 1, Figs. 2–6).

Dinaric Carbonate Platform

Slovenia, northern sector of the Dinaric Carbonate platform.

I. farinacciae occurs in:

– Potpeč shallow intamarginal depression; the succession consists of largely of resedimented biota (*Lithiotids,Orbitopsella, Paleodasycladus*), from a shallow platform, less of ooidal shoals distributed on an open margin (RADOIČIĆ 1987). *I. farinacciae* was found in a few beds bearing resedimented material from ooidal shoals or even mixed material from both areas.

– a transitional platform-basin succession observed at a gallery near the Avče Railway Station, where *I. farinacciae* is associated with *A. martana* and *Mesoendothyra croatica* (species described from Dogger: GUŠIĆ 1969), genus? "A1", tekstulariform and other foraminifera (Pl. 2, Figs. 1–11); and

– a section near the village of Kovk, northern margin of the Dinaric Carbinate Platform. This Pliensbachian into Toarsian succession consists of (a) lithiotid limestone, (b) peloidal limestone, and (c) brownish-redish limestones with hard ground. Peloidal limestone with *Orbitopsella primaeva* bears also *I. farinacciae, Ammobabulites* sp., ? *Haplophragmoides*, ?*Spiraloconulus* (ČRNE & GORIČAN 2009).

Montenegro, southern sector of the Dinaric Carbonate Platform

I. farinacciae occurs in the Liassic Viluse succession (Grahovo–Viluse area) as deposits in a very shallow depression (laterally, westward and eastward, gradually passing into lithiotid facies), situated along the Boka Kotorska–Gacko transversal lineament.

The section, discontinually exposesd consists in part of thin bedded limestones mainly with few fossils: sponge spicules, crinoid fragments and lagenids; ooidal peloidal limestones with sparse benthic foraminifera, few beds with brachiopod coquina. Dolomitized limestone is also present. The oldest sampled bed, twenty meters below the first occurence of *I. farinacciae*, is Lower Liassic limestone with *Involutina turgida* KRISTAN (Pl. 3, Fig. 9). *I. farinacciae,* associated with *A. martana* and some other foraminifera, was found in several samples from the column interwal of about 35 meters (Pl. 3, Figs. 1–7).

Budva Basin (Budva–Krasta–Pindos)

Different stratigraphic successions formed in the intracontinental Budva Basin (Upper Permian to Upper Miocene) are exposed largely along the Montenegrin coast. Data concerning the sedimentary evolution of the Basin and the spatial distribution of the stratigraphic successions are based on the facies analysis. Internal proximal (more or less proximal, distally proximal), axial subaxial, and external proximal-subaxial successions are recognized on the territory covered by the geological map sheets Kotor and Budva. Some successions reveal gradual facies change to the NW (present-day direction) through the length of the Basin. The transitional DCP–BB proximal series are especially different (and inadequately known), which suggests a complex and highly variable (through successive cycles) scenario of the periplatform paleogeography.

Intrabasinal and basin-platform sinsedimentary tectonic activity of varied magnitude and effects (fractures, breccias, stratigraphic gaps, great proportion of resedimented carbonates, different slump structures and trust faults) are clearly manifested in the history of the Basin. Some time-stratigraphic intervals were more intensive in tectonic activity (Middle Triassic, Rhaetian–Liassic, Kimmeridgian–Berriasian, Middle Cretaceous, Campanian and others). Miocene tectonic events greatly affected the successions: some were thrust folded, overturned, others were more fractured, or greatly or almost completely reduced. West of the Kotor Gulf, the Budva Basin successions are traceable to the transverse Zupci Fault where this notable unit disappears abruptly under the Dinaric Carbonate Platform. Assumed based on the facial changes in some belts down the basin length to NW, the basin must have narrowed gradually (changed dimensions and depth) to become (NW of Split?), a lower-rank unit.

Biostratigraphical data for the unit, acquired during geological mapping for the sheets Kotor and Budva and by subequent studies, are published in part (ANTONIJEVIĆ *et al.* 1973; RADOIČIĆ & D'ARGENIO 1999).

The biostrarigraphy of the pelagic Upper Triassic (?uppermost Ladinan–Upper Triassic) is interpreted based on *Daonella* and *Halobia* (DE CAPOA BONARDI 1985; CAFFIERO & DE CAPOA BONARDI 1980a) and conodonts (CAFFIERIO & DE CAPOA BONARDI 1980b).

The most informative, detailed and conpehensive study by ŠPELA GORIČAN (1994) of the Jurassic and Cretaceous biostratigraphy and sedimentary evolution on the Budva Basin is based prmarily on radiolarian stratigraphy and subordinately on other fossil groups. The study considered the extent of the Budva Basin successions on the map sheets Kotor, Budva and Bar.

Previously taken for Upper Eocene or Upper Eocene–Lower Oligocene, the main deformation of the Outer Dinarides is now dated not older than early Tortonian, bases on calcareous nanoplankton from the Tertiary sediments of the Budva Basin and of both, the Dinaric and Adriatic Carbonate Platforms (CN7b biozone: DE CAPOA & RADOIČIĆ 1995).

Liassic sequences (calcilutites with chert, cherts, thin marly layers, subordinate breccias and more or less fine resedimented carbonates) 20–35 meter thick, in which *I. farinacciae* is present, known from the sections Vrmac–Verige, Donja Lastva, Devesilje, Košljun and from the external distally-proximal, subaxial Meljine, Banići and Buljarica–Čanj.

Vrmac–Verige succession

Liassic sediments of the Vrmac–Verige belt is cropps out westward (Verige section, N of Kamnari) and eastward from the Verige Strait (in a small quarry of Lepetane, now urbanized). Lowermost in the upper Triassic–?lowermost Liassic exposure is breccia (1.5 m) containing large Triassic intraclasts, overlain by about 40 meters of siliceous calcilutites, calcilutites with thin chert intercalation and nodules (radiolarians, pelagic lammelibranches, sponge spicules) and calcarenites. Limestone with *Galleanella tolmmanni* and few other foraminifera were found in the lower part of this sequence. Sedimentation was interrupted (Lower Liassic events) by an episode of graded bed (*G. tolmmanni* in one clast) and very coarse breccia with large Triassic limestones clasts. The Liassic sequence about 2 metres thick, consists of calcilutites with nodules and chert intercalations, few thin marly lamina, resedimented calcarenites and microbreccias. The resedimeted limestones contain *A. martana, I.farinacciae, M.* cf. *croatica, M. izjumiana, Glomospira* (Pl. 4, Figs. 1–11) small trocholinas, textularform foraminifera and different metazoan and algal debris; some beds also contain small micritic intraclasts with sparse radiolaria or unclear organogenous detritus. The microbreccias contain different intraclasts with radiolaria, sponge spicules and peloidal limestones in partly recrystallized matrix (Fig. 1). The sedimentation was newly interrupted (Dogger events) by very coarse breccia, large clasts (up to tens of cm) that include those of Liassic limestones, one with *Involutina liassica*.

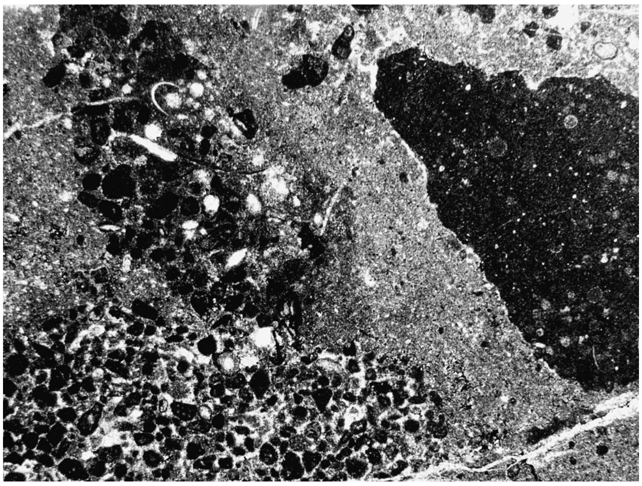


Fig. 1. Microbreccia from the Liassic sequence of the Verige Section.

The tests of *I. farinacciae* (forms A and B, D = 0.297–0.396 mm, thickness of test 0.138–0.247 mm, 4–6 whorls) are commonly poorly preserved, they are more or less recrystallized and not infrequently barely recognizable.

A Liassic sequences similar in lithology and thickness to that of Verige, are Liassic sequences of the Crisanti succession (Sicily) and the Koziakas of Pindos, Greece (a clast bearing *G. tolmmanni* is also from Lower Liassic breccia – Fig. 2).

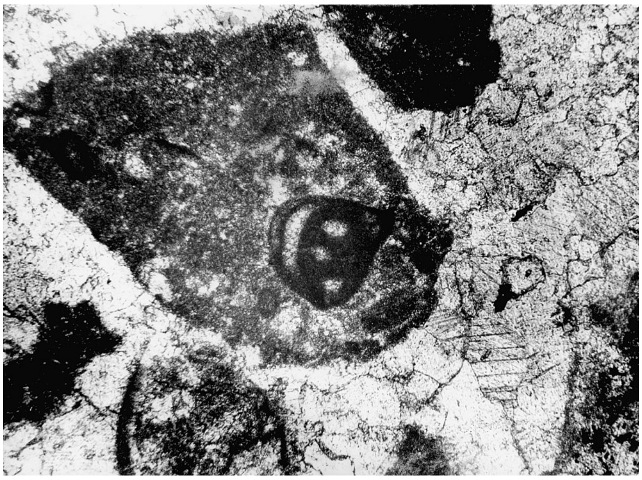


Fig. 2. The clast of the Triassic limestone with *Galleanella tolmma*nni in the Liassic breccia of the Koziakas succession, Pindos, Greece.

The Liassic sequence of Vrmac–Verige Belt, the inner distally-proximal succession, is the time or nearly the time equivalent of the "Passée Jaspeuse" Unit *sensu* GORIČAN (1994), from which partly differs in lithology because described "Passée Jaspeuse" is based on the succession in one of subaxial basin belts.

Donja Lastva succession

Part of the axial Donja Lastva succession, older than the sediments with *I. farinacciae*, is not well exposed. In the limestone, estimated at a few tens meters lowerward, the early Liassic species *Involutina turgida* occurs (KRISTAN–TOLLMANN & COLWELL 1992). *I. farinacciae* is associated with *A. martana, ?Mesoendothyra* and some other small foraminifera. Upward (not measured) in the laterally outcropped resedimented ooidal limestone, Aalenian–?Bajosian *Gutnicella cayeuxi* occurs.

The discussion concerning the paleogeography of Montenegro–Albania border region (the Scutari–Peć Lineament)

SUESS (1901) defined the Dinarides as a mountain chain extending from the south of the Eastern Alps, along the Adriatic and Ionian Seas and across the Aegean Sea, to the Taurides in Turkey. CVIJIĆ (1901) described a mild deviation of the Dinaric fold structures from NW to SE to E and NE, beginning from Njeguši to Scutari and further northward (the Dinaric Carbonate Platform! area). The name of the phenomenon "'Scharung" was borrowed from E. Suess, who used it to designate an identical structural feature (CVIJIĆ 1901, p. 106). The name Dinarides (CVIJIĆ 1924, p. 107) was used only for the Dinaric Mountain System extending to "the known deviation at Scutari", where the Dinaric and the Pindos System are in "collision". KOBER (1929) also suggested that the transversal line Scutai–Peć separates the Dinarides from the Helenides. According to CVIJIĆ (1924, fig. 88: cusp; Fig. 3), two outhers Dinaridic units are not involved by "collision": the Adriatic Carbonate Platform (ACP) that continues from Montenegro throughout Albania (Kruja) and Greece (Gavrovo) and the basinal Budva–Krasta Unit. Numerous publications, however, ignore this information and designate the Adriatic Carbonate Platform and the Budva Basin, as Dinarides and their prolongation in Albania, as Helenides.

The paleogeography of this area of the Dinarides formed on the inherited tectonic potentially active prealpine pleogeographic scenario which resulted in a different arrangement of the paleogeographic units westward and eastward of a paleostructure, that controlled the geological history of the region (for neotectoonic activity see KISSEL *et al.* 1995; MAROVIĆ & DJOKOVIĆ 1995)

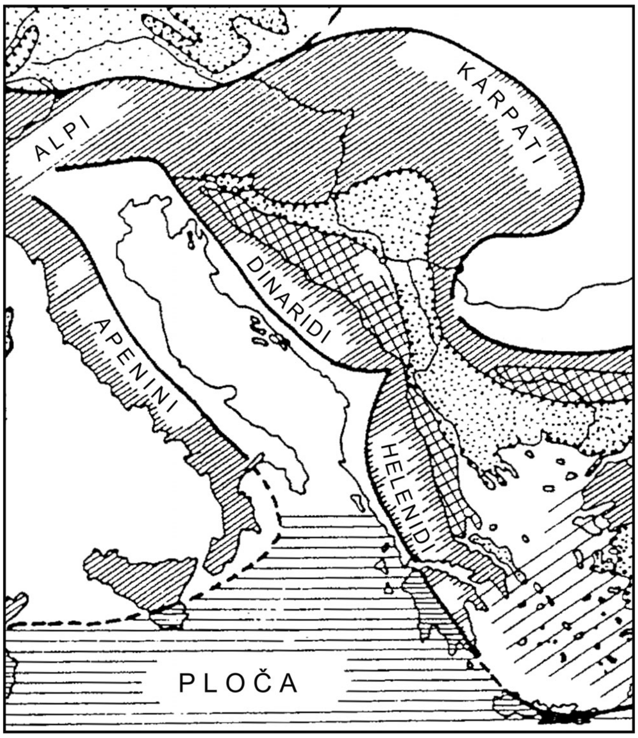


Fig. 3. The cusp between Dinarides and Helenides, from CVIJIĆ (1924, part of fig. 88).

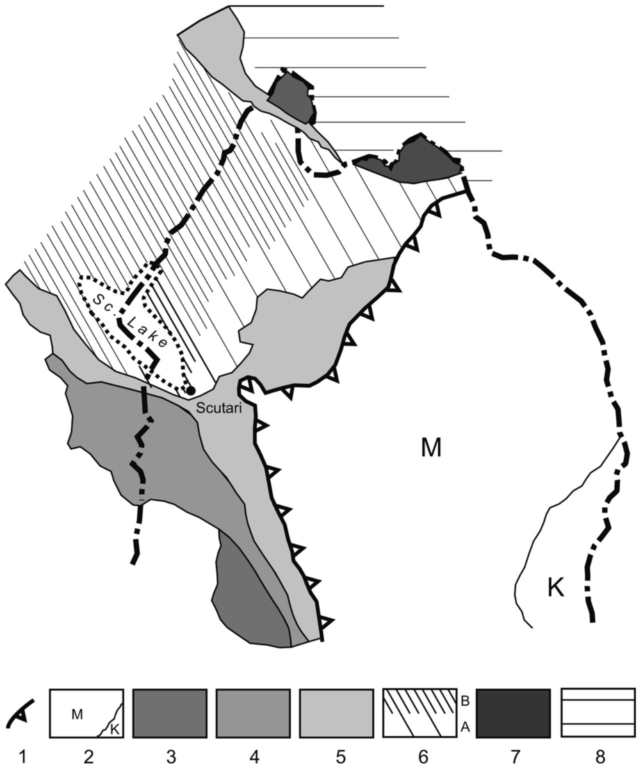


Fig. 4. Paleogeographic units in the Montenegro–Albania border region. Simplified according Geological Map of Albania, 1: 500 000; Geological Map of Albania in DURMISHI *et al.* (2010); Geological Map of SFRJ 1:500 000. Legend: **1,** Overthrust of the Complex Mirdita Zone; **2,** Complex Mirdita Zone (M) and Korab Zone (K); **3,** Ionian Zone; **4,** Adriatic Carbonate Platform – Kruja Carbonate Platform; **5,** Basins: Budva–Krasta, with NE branch Cukali (facing DCP) and South Durmitor Basin. The particularity in the sedimentary evolution of those basins depends of their position in the passive margine; **6,** Dinairc Carbonate Platform, terminal features in Albania: Malesia Madhe Subzone (platform facies) and Valbona Subzone (slope deposits, the transitional platform-basin and partly proximal Cukali successions; **7,** Gashi Zone; **8,** North Durmitor–Albanian Alps (Prokletije) Carbonate Platform.

The Dinaric Carbonate Platform ("High Karst") extends over 650 km from the Friuli–Slovenia to the Montenegro–Albania border (RADOIČIĆ 1984; RADOIČIĆ & D'ARGENIO 1999). The eastern end of the Platform in NW Albania is named the Albanian Alps Zone, composed of the Malesia Madhe Subzones (platform facies) and the Valbona Subzone which "extends in the environs of Malesia Madhe Subzone and, during the Jurassic and the Cretaceous, is represented by slope deposits connecting the Malesia Madhe carbonate platform with the Cukali and Kelmendi troughs" (PEZA 1994). The Valbona Subzone also includes the proximal successions of the Cukali Basin (THEODHORI *et al.* 1993; XHOMO *et al*. 1969: fide PEZA 1994). Albanian Alps Zone is a paleogeographic terminal feature of this large carbonate unit. The deviation of the fold structures ("Scharung") in the SE segment of the Dinaric Carbonate Platform fitted the morphology of the broad platform front cast by a major feature of the inherited Paleozoic basement. According to Albanian geologists, in the Albanian Alps Zone a deep minimum of the Bougeur amomaly is identfied "which continues uninterruptedly in the High Karst Zone in Dinarides" i.e. that are direct continuation "even in deep part" (LUBONJA *et al.* 1994).

The Basin around the DCP, known as the Krasta Basin throughout Albania, extens into Montenegro under the name Budva Basin, and near Scutari to the NE in a branche named the Cukali Basin (facing DCP) deviates even more into the South Durmitor Basin (RADOIČIĆ 1984; RADOIČIĆ & D'ARGENIO 1999) or Kelmendi which is continuous with the South Durmitor Basin (PEZA 1987; 1994, fig. 1 = Bonsniac Zone).

Durmitor Zona or South Durmitor Basin (?Triassic, Jurassic–Paleogene–?Miocene): Durmitor Flysch is the name given by BEŠIĆ (1940, 1948); The Durmitor Flysch zone renamed by Blanchet into the Bosnian Zone, an overthrusted carbonate platform is named Durmitor Zone (BLANCHET 1966; BLANCHET *et al.* 1969). To avoid confusion, and with respect to the first given name and to the geographic position, a compromise is suggested: to give the name South Durmitor Basin to the basinal unit, and the name North Durmitor–Albanian Alps Carbonate Platform to the large carbonate unit (RADOIČIĆ 1984; RADOIČIĆ &

D'ARDENIO 1999). A new name "Sarajevo Sygmoid" was introduced by DIMITRIJEVIĆ (1974, 1997). In the interpretation of Dimitrijević, this basinal unit involves a large part of the SE segment of Dinaric Carbonate Platform (sic!).

The North Durmitor–Albanian Alps Carbonate Platfotrm (ND–AACP, Permian–uppermost Tithonian) was reduced by the Liassic event; the late Cimmeria – late Tithonian events caused subsidence that led to subsequent "flysch"-carbonate clastic sedimentation in the late Tithonian–Berriasian (exposed in the Ljubišnja–Durmitor–Sinjajevina segment: RADOIČIĆ 1961, 1966; RAMPNOUX & FOURCADE 1969). The platform tectonic ends at the N and W rim of the Metohija Depression, and at the Scutari–Peć Lineament south of Peć (ANTONIJEVIĆ *et al.* 1968, 1978; SILO *et al.* 2010). Durmitor, both the basin and the platform, had sedimentary evolution to the late Jurassic characteristic for a passive margin, hence taken as Externides–Internides transitional units.

The Gashi Zone (Paleozoic basement of the ND–AA Carbonate Platform) exposed between Durmitor–Kelmendi Zone and overthrust ND–AA Carbonate Platform, consists of four Paleozoic formations (Lower Silurian to Upper Permian) and presumably Lower Triassic conglomeratre-sandstone quartzite formations (HOXHAJ 1996).

The Scutari–Peć Lineament is "a most prominent deep transversal fracture, which separates the northern Albanides (the Dinarideds of Yugoslavia) from the sourhern Albanide (the Helenide in Greece)" (LUBONJA *et al.* 1994; *DURMISHI et al.* 2010). Long after Cvijić, this feature was considered as a nucleus in the Scutari area, in addition it was interpreted as line accross the DCP from Scutari or even SW from Scutari in some recent publication (PAMIĆ & HRVATOVIĆ 2003; ZELILIDIS *et al.* 2003). The inference based on different geological maps and sketches is that this transverse paleostructure was (a) coincident with the paleogeographic front of the DCP and (b) the westward overthrust limit and deviation of the Mirdita Zone that covers a large part of the Cukali–Kelmendi Basin (SILO *et al.* 2010, fig. 2; DURMISHI *et al.* 2010, fig. 1). The differences in the alpine paleogeographic features in the prolongation from the DCP throughout Albania, controlled by paleostructure, are the source of seizmicity, rotation and deviation (SE to NW, into NE) of the Complex Mirdita Zone.

Acknowledgements

We wish to thank the reviewers NIKOLAOS CARRAS (Athens, Greece) and PAOLA DE CAPOA (Naples, Italy) for useful comments taht significantly improved the paper. The study was supported by the Ministry of Education and Science of the Republic of Serbia, Project No. 176015.

References

ANTONIJEVIĆ, R., PAVIĆ, A. & KAROVIĆ, J. 1969. Geological Map of the sheet Kotor K34-50, Budva K34-62, 1:100 000, Explanatory text: 1973. *Savezni geološki zavod.*

ANTONIJEVIĆ, R., PAVIĆ, A., KAROVIĆ, J. & MENKOVIĆ, LJ. 1977. Geological Map of the sheet Peć K34-53 and Kukes K34-65. Explanatory text: 1978. *Savezni geološki zavod.*

BLANCHET, R. 1966. Sur l'âge tithonique-éocrétacé d'un flysch des Dinarides internes en Bosnie. Le flysch de Vranduk (Yougoslavie). *Compte Rendu sommarie Société des séances de la Géologique de France*, 401–402.

BLANCHET, R. CADET, J.-P., CHARVET, J. & RAMPNOUX, J.-P. 1969. Sur l'existence d'un important dominae de flysch Tithonique-Créetacé inférieur en Yougoslavie: l'unité du flysch Bosniaque. *Bulletin de la Société géologique de France*, 7 (11): 871–880.

BRONNIMANN, P. & KOEHN-ZANINETTI, 1969. *Involutina hungarica* SIDO et *Involutina farinacciae*, n. sp., deux *Involutines* post-triasiques et remarque sur *Trocholina minima* HENSON. *Paleontologische Zietschrift*, 43 (1/2): 72–80.

CAFIERO, B. & DE CAPOA BONARDI, P. 1980a. Stratigraphy of the pelagic Triassic in the Budva–Kotor area (Crna Gora, Montenegro,Yugoslavia). *Bolletino della Societa Paleontologica Italiana*, 19 (2): 179–204.

CAFIERO, B. & DE CAPOA BONARDI, P. 1980b. I conodonti dei calcari ad *Halobia* del Trias superiore del Montenegro (Crna Gora, Yugoslavia). *Rivista Italiana Paleontologica*, 85 (3): 563–576.

CVIJIĆ, J. 1901. Die Dinarisch-albanische Scharung. *Sitzungsberichten der kaiser. Akademie der Wissenschaften in Wien, Mathematisch-Naturwassenschaftliche Klasse; Bd.CX, Abth. I*

CVIJIĆ, J. 1924. Geomorfologija, knjiga prva. Morphologie terrestre, tome premier. 1–588.

ČRNE, A.E. & GORIČAN, Š. 2008. The Dinaric Carbonate Platform margin in the Early Jurassic: A comparison between successions in Slovenia and Montenegro. *Bollettino della Societa Geologica Italiana,* 127 (2): 389–405.

ĆIRIĆ, A., OBRADINOVIĆ, Z., NOVAKOVIĆ, D., POPEVIĆ, A., KARAJIČIĆ, L., JOVIĆ, B. & SERDAR, R. 1977. Geological Map of sheet Prijepolje K34-16, 1:100 000. *Savezni geološki zavod.*

DE CAPOA-BONARDI, P. 1984. Halobia Zones in the pelagic Late Triassic sequences of the Central Mediterranean area (Greece, Yugoslavia, Southern Apennines, Sicily). *Bollettino della Societa Paleontologica Italiana*, 23, (1): 991–102.

DE CAPOA, P. & RADOIČIĆ, R. 1994. Calcareous Nannoplankton biostratigraphy of Tertiary sequences of the Cukali–Budva Basin (Montenegro, External Dinarides, Yugoslavia). *Rivista Espagnola de Micropaleontologia*, 26 (3): 101–116.

DE CAPOA, P., RADOIČIĆ R. & D'ARGENIO, B. 1995. Late Miocene deformation of the External Dinarides (Montenegro and Dalmatia). New biostratigraphic evidence. *Memorie di Scienze Geologiche*, 47: 157–172.

DIMITRIJEVIĆ, M.D. 1974. The Dinarides: A model based on the New Global Tectonics. Metalogenija i koncepcije geološkog razvoja Jugoslavije, Rudarsko-geološki fakultet u Beogradu, Katedra ekonomske geologije, 119–151. (in Serbian)

DIMITRIJEVIĆ, M.D. 1997. Geology of Yugoslavia. *Geological Institute Gemini, special publication*. p. 187.

DURMISHI, C., NAZAJ, S. & DAJA, S. 2010. Field trip in Albania. Polytechnic University of Tirana, Faculty of Geology and Mining, p. 66.

FARINACCI, A. 1967. La serie giurassico-neocomiana di Monte Lacerone (Sabina). Nuove vedute sull'interpretazione paleogeographica delle aree di facied umbro-marchigiana. *Geologia Romana*, 6: 421–480.

GORIČAN, Š. 1994. Jurassic and Cretaceous radiolarian biostratihraphy and sedimentary evolution of the Budva Zone (Dinarides, Montenegro). *Memoires de Geologie (Lausanne),* 18, 120 pp.

GUŠIĆ, I. 1969. Some new and inadequately known Jurassic foraminifers from central Croatia. *Geološki vjesnik*, 22: 55–88.

HOXHAJ, J. 1996. Discutim plotesues prerjen teresore stratigrafike rajonit Gashit. Buletin shkencave Gjeologjike, 30 (12): 15–18 (In Albanian, French summary).

JOVANOVIĆ, O., NOVKOVIĆ, M., & ČANOVIĆ, M. 1979. Lithobiofacial characteristics of Diabas-Chert Formation of the Sjenica Region. Zbornik radova, IV godišnji znanstveni skup sekcije za primjenu geologije, geofizike i geokemije (Stubičke Toplice, 1978). *Znanstveni savjet za naftu JAZU*, Serija A, 7: 147-154 (in Serbo-Croatian, English summary).

KISSEL, C., SPERANZZA, F. & MILIĆEVIĆ, V. 1995. Paleomagnetism of external southern and central Dinarides and northern Albanides: Implications for the Cenozoic activity of the Scutari-Peć transverse zone. *Journal of Geophysical Research, Solid Earth*, 100, B8: 14,999–15,07.

KOBER, L. 1929. Die Grossliederung der Dinariden. *Centralblat für Mineralogie*, Abh. B: 425–437.

LUBONJA, L., NISHANI, A., HYSENI, A., BUSHATI, S. & LECI, V. 1994. The position of Albanides in the Alpine-Mediterranean Orogenic Belt. *Buletoni i Shkencave Gjeologyke*, 1994/1: 9–13.

MAROVIĆ, M. & DJOKOVIĆ, I. 1995. Neotectonic activity of the Scutari-Peć general area. *Geološki anali Balkanskoga poluostrva*, 59 (2): 23–43.

MOJSILOVIĆ, S., BAKLAJIĆ, D. & DJOKOVIĆ, I. 1971. Geological Map of sheet Užice K34-4, 1:100 000. *Savezni geološki zavod.*

MOJSILOVIĆ, S., DJOKOVIĆ, I., BAKLAJIĆ, D. & RAKIĆ, B. 1973. Geological Map of sheet Sjenica K34-29, 1:100 000. *Savezni geološki zavod.*

PAMIĆ, J. & HRVATOVIĆ, H. 2003. Main large thrust structures in the Dinardes – a proposal for their classification. *Nafta*, 53 (12): 443–456.

PEZA, H.L., 1989. Outline of the Cretaceous of Albania. *In*: WIEDEMANN, J. (ed.), Cretaceous of the Western Tethys. *Proceedings 3rd international Cretaceous Symposium,* Tübingen, 1987, 483–504.

PEZA, L.H. & PEZA, E. 1994. The Mesozoic developmet of the Albanian Alps carbonate systems and its relationships with the Cukali and Kelmendi Troughs. *Geologie Mediterranienne*, 21 (3–4): 145–148.

RADOIČIĆ, R. 1961. Serie Flyschoide du Jurassique superieur au Montenegro du nord-ouest. *Vesnik,* ser. A, 19: 21–29.

RADOIČIĆ, R. 1966. O gornjoj juri sjeveroistočne Hercegovine / Uber den Oberen Jura in der Nordostlichen Herzegovina. *Zapisnici Srpskog geološkog društva.* (Zbor 11. 02. 1963) za 1963. godinu, 115–117.

RADOIČIĆ, R. 1984 Carbonate platforms of the Dinarides: the example of Montenegro – West Serbia sector. *Bulletin, T.80, de l'Academie Serbe des Sciences et des Arts, Classe des Sciences naturelles et mathematiques, Sciences naturalles*, 22: 35–46.

RADOIČIĆ, R. 1987. *Spraloconulus perconigi* ALLEMANNN & SCHROEDER (Foraminifera) u nekim jurskim serijama Jugoslavije, Grčke i Iraka. *Spiraloconulus perconigi* ALLEMANN & SCHROEDER (Foraminifera) in some Jurassic series of Yugoslavia,Greece and Iraq. *Geološki glasnik Zavoda za geološka istraživanja SR Crne Gore*, 12: 117–125.

RADOIČIĆ, R. & D'ARGENIO, B. 1999. An outline of the geology of External Dinarides and their Mesozoic – Early Tertiary facies. *Rendiconto dell'Accademia delle Scienze Fisiche e Matematiche, ser. IV, LXVI, Anno CXXXVIII.*

RADOIČIĆ, R., JOVANOVIĆ, D. & SUDAR, M., 2009. Stratigraphy of the Krš Gradac section (SW Serbia). *Geološki anali Balkanskoga poluostrva*, 70: 23–41

SILO, V., NISHANI, P. & SILO, E. 2010. Hydrocarbon exploration under Kruja zone in Tirana-Rodon area, Albania. *Journal of the Balkan Geophysical Socety*, 13 (1): 9–16.

THEODHORI, P., PEZA, L.H. & PIRDENI, A. 1993. Cretaceous pelagic and flysch facies of the Krasta-Cukali zone, Albania. *Cretaceous research*, 14: 199–209.

ZELILIDIS, A., PIPER, D.J., VAKALAS, I., AVRAMIDIS, P. & GETSOS, K. 2003. Oil and gas plays in Albania: do equivalent plays exist in Greece*? Journal of Petroleum Geology*, 26 (1): 29–48.

ZUCCARI, A.T. 1969. Due nuove specie di *Aulotortus* Weynschenk rinvenute nel Lias medio dei Monti di Spoleto (Prov. di Perugia). *Bollettino della Societa Italiana*, 88: 419–425.

Резиме

Involutina farinacciae BRONNIMANN & KOEHN-ZANINETTI маркер за средњи лијас басенских и неких платформних фација у областима Медитерана и Блиског Истока: дискусија о палеогеографији граничне области Црна Гора–Албанија (Скадар–Пећ линија)

Нову врсту *Involutina farinacciae* описали су BRONNIMANN & KUEHN-ZANINETTI на основу примјерака из средњег лијаса Умбрије (Италија), које је A. Farinacci приказала као врсту *Semiinvolutina clari* KRISTAN. Синоними ове нове врсте су *Aulotortus regularis* ZUCCARI и *Involutina scandonei* RADOIČIĆ, које су описане исте године, али у радовима који су доцније публиковани.

Ова ситна *Involutina* најчешће је слабо очувана, мање или више прекристалсала, а јавља се у реседиментним ооидно-пелоидним карбонатима поменутих басенских и платформних ареала.

Ирачки Кутрдистан: Карбонатно кластичне сукцесије јуре и креде Авроман области ирачког Курдистана, сличне су сукцесијама Будва и Пиндос Басена. *Involutina farinacciae* нађена је у лијаским секвенцама у пет локалитета.

У унутрашњим Динаридима лијаски седименти са *I. farinacciae* распрострањени су у СИ и ЈИ дијелу Офиолитског масива Златибора као и у области Сјенице и између Сјенице и Пријепоља. Ооидно-пелоидни кречњаци, дијелом силификовани и/или са рожнацима, у којима је јавља *I. farinacciae*, према геолошким картама листова Ужице, Сјеница и Пријепоље, припсани су "Дијабаз рожначкој формацији". Уствари, они претстављају само дио засада неименване вјероватно горњотријаско–лијаске формације.

Седименти са *I. farinacciae* на простору Динарске карбонатне платформе познати су у Словенији (СЗ сектор ДКП) и Црној Гори (ЈЗ сектор ДКП).

У Словенији, поред познатих локалитета Потпеч (RADOIČIĆ 1987) и Ковк (ČRNE & GORIČAN 2009) сада је забиљежен и налазак слојева са *I. farinacciae* у прелазним платформа–басен седиментима код жељежничке станице Авче.

У Црној Гори, слојеви са *I. farinacciae* депоновани су у благој депресији (источно и западно прелазе у слојеве са литиотисима) дуж трансверзалне линије Бока Которска–Гацко. У профилу између Грахова и Вилуса, *I. farinacciae* је нађена у неколико узорака у стубу од око 35 метара. Око 20 метара испод прве појаве *I. farinacciae* забиљежен је налазак доњолијаске врсте *Involutina turgida* KRISTAN.

Будва басен. У Црногрском приморју, између Динарске и Јадранске карбонатне платформе (ЈКП) прате се различите сукцесије интраконтиненталног Будва басена (горњи перм–горњи миоцен). То су различите сукцесје како интерног проксималног, аксијалног, субаксијалног и екстерног прокcдимално-субаксалног појаса.

У овим сукцесијама јасно се очитава интрабасенска и платформа-басен тектонска активност различитог степена и ефеката, која је, у неким интервалима интензивнија (средњи тријас, рето-лијас, кимериџ-беријас, средња креда, кампан и др). Западно од Боке Которске Будва басен се прати до Зубачког расједа, гдје се губи под Динарском карбонатном платформом ("Високи крш").

Секвенце лијаских седимената Будва басена са *Involutina jarinacciae* (око 20 до 30 m дебљине) засада су познате у сукцесијама Врмац–Вериге, Доња Ластва, Девесиље, Косљун, Мељине, Банићи и Буљарица–Чањ.

Палеогеографија граничне области Црна Гора–Албанија: ЦВИЈИЋ (1901, 1924) описао је скретање динарског правца набора код Скадра *"Scharung"*. Стога се дуго након ЦВИЈИЋА, а каткада и у новије вријеме, подручје Скадра узима као нуклеус трансверзале Скадар–Пећ. Према ЦВИЈИЋУ (1924, сл. 88: cups; сл. 3), ова трансверзална структура не обухвата двије палеогеографске јединице екстерних Динарида, сто се у бројним публикацијама игнорише.

Палеогеографија ове области Динарида формирана је на наслијеђеном тектонски потенцијално активном преалписком палеогеографском сценарију, што је условило различит распоред палеогеографских јединица западно и источно од палеоструктуре, која је контролисала геолошку историју региона. Значајна разлика је што се у СЗ Албанији завршава крупна палеогеографка јединца – Динарска карбонатна платформа.

Бројни радови претежно албанских аутора, геолошке карте и скице упућују на закључак да ова трансверзална палеоструктура подудара) са палеогеографским (а не тектонским) завршетком Динарске карбонатне платформе и б) западном границом навлаке и девијацијом навлаке Мирдита зоне која покрива знатан дио Цукали–Келменди басена (SILO *et al.* 2010; DURMISHI *et al.* 2010). Разлика у алпиској палеогеографској слици у продужењу од ДКП кроз Албанију, контролисана палеоструктуром, повод је сеизмицитета, ротације и девијације (ЈИ–СЗ у СИ) комплекске Мирдита Зоне.

PLATE 1

Liassic of the Zlatibor Mt. and Sjenica–Prijepolje area.

Figs. 1–5. *Involutina farinacciae* BRONNIMANN & KOEHN-ZANINETTI.
1. Drežnik, NE Zlatibor, Drežnik, thin section RR5090.
2, 3. S of Sjenica, on the road to gomila, thin section RR5094.
4. Duboki potok, between Aljivovići and Prijepolje, thin section RR5117.
5. Gomila, thin section RR5096 .

Figs. 6, 7. *Bosniella* cf. *oenensis* GUŠIĆ, Gomila, thin section RR5096; Vrelo, thin section RR5157.

Fig. 8. Genus?, Duboki potok–Aljinovići–Prijepolje, Lower Dogger?, thin section RR5126.

Fig. 9. *Mesoendothyra croatica* GUŠIĆ, Duboki potok, Aljinovići–Prijepolje, Dogger?, thin section RR5126.

Fig. 10. *Agerina martana* (FARINACCI), Vrelo, thin section RR5157.

Fig. 11. Genus?, Vrelo, thin section RR5157.

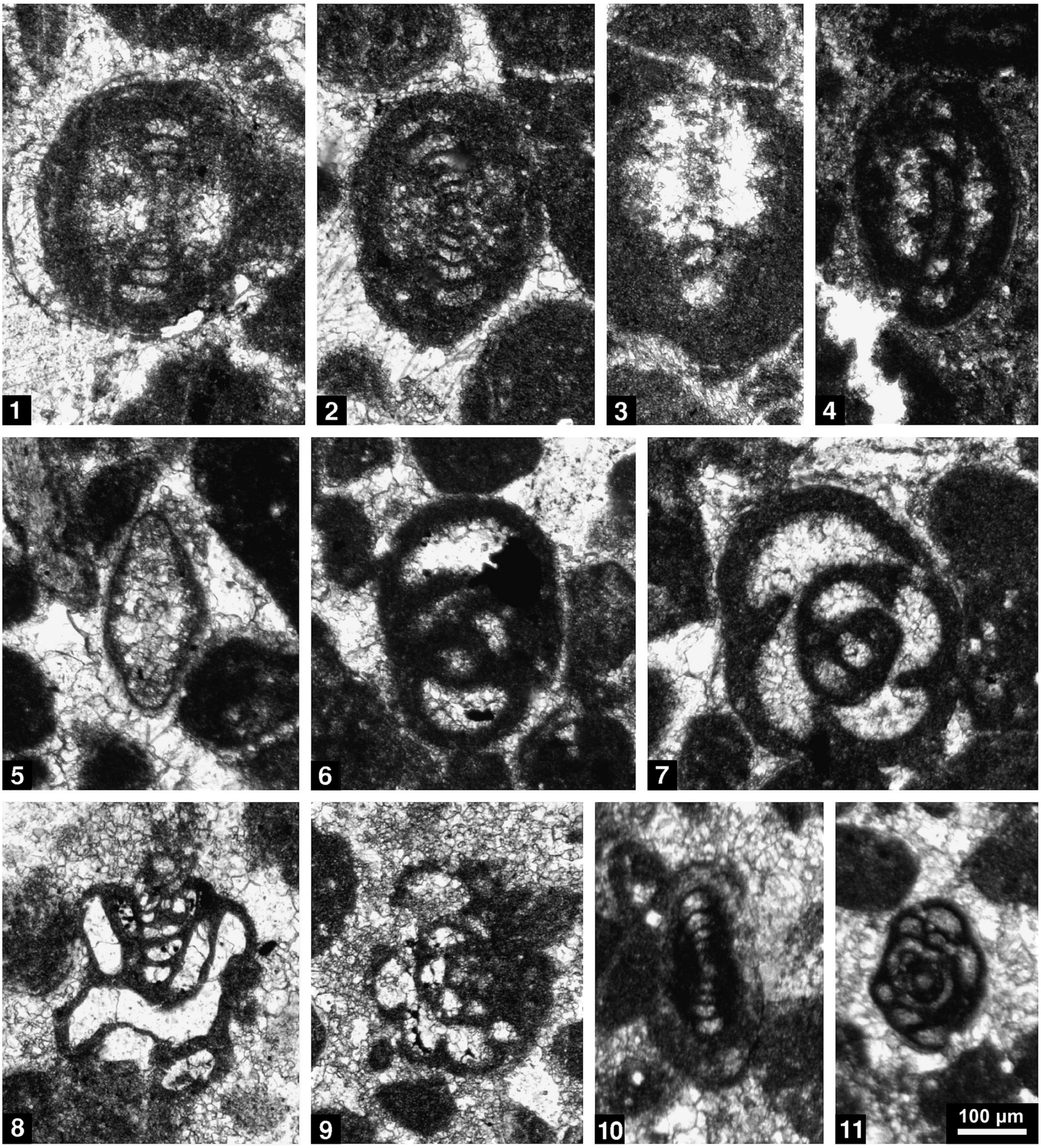

1
2
3
4
5
6
7
8
9
10
11
100 µm

PLATE 2

Figs. 1–11. Liassic of Avče, Slovenia,

Figs. 1–4. *Involutina farinacciae* BRONNIMANN & KOEHN-ZANINETTI, thin sections RR3230 and 3229.
Figs. 5–8. *Mesoendothyra croatica*, thin section RR 3230 and 3231.
Fig. 9. *Agerina martana* (FARINACCI), thin section RR3229.
Fig. 10. *Agerina martana* (FARINACCI), Verige, succession, thin section RR7293.
Fig. 11. Genus? "A1", thin section RR3231.
Fig. 12. Textulariformn foraminifer, thin sectiom RR3231.

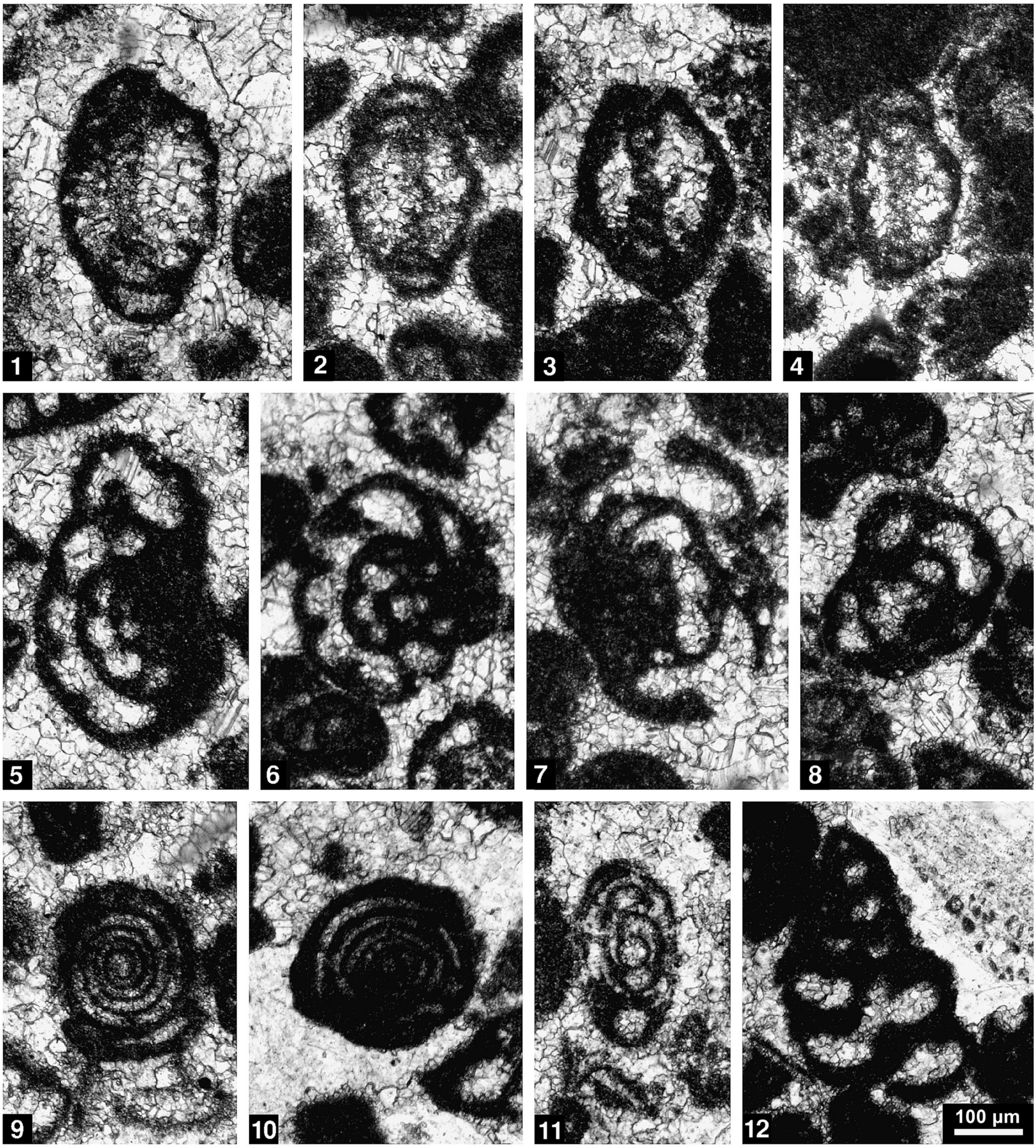

1
2
3
4
5
6
7
8
9
10
11
12
100 µm

PLATE 3

Figs. 1–9. Liasic of Viluse sequence, Dinaric Carbonate Platform, Montenegro.
1–6. *Involutina farincciae* BRONNIMANN & KOEHN-ZANINETTI, thin sections RR7233, 7234, 7234/1.
7. *Agerina martana* (FARINACCI), thin section RR 7234.
8. Sponge spicules, thin section 7231.
9. *Involutina turgida* KRISTAN, thin section RR7229.

Fig. 10. *Involutina liassica* (JONES) and lagenid from middle-upper Liassic of the Vojnik Mt. (some metres bellow limestone with *Hildoceras bifrons*), thin section RR 7245.

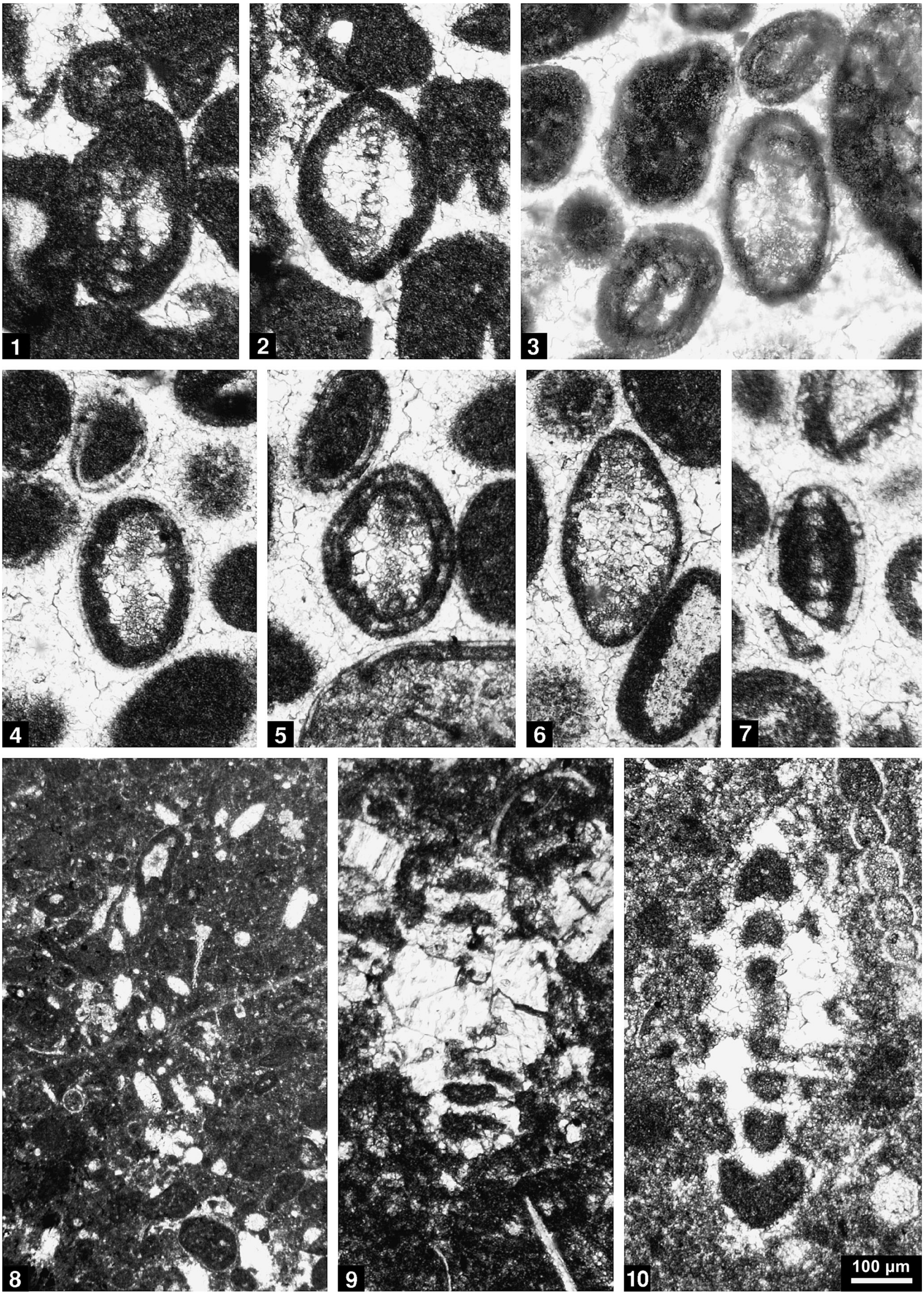
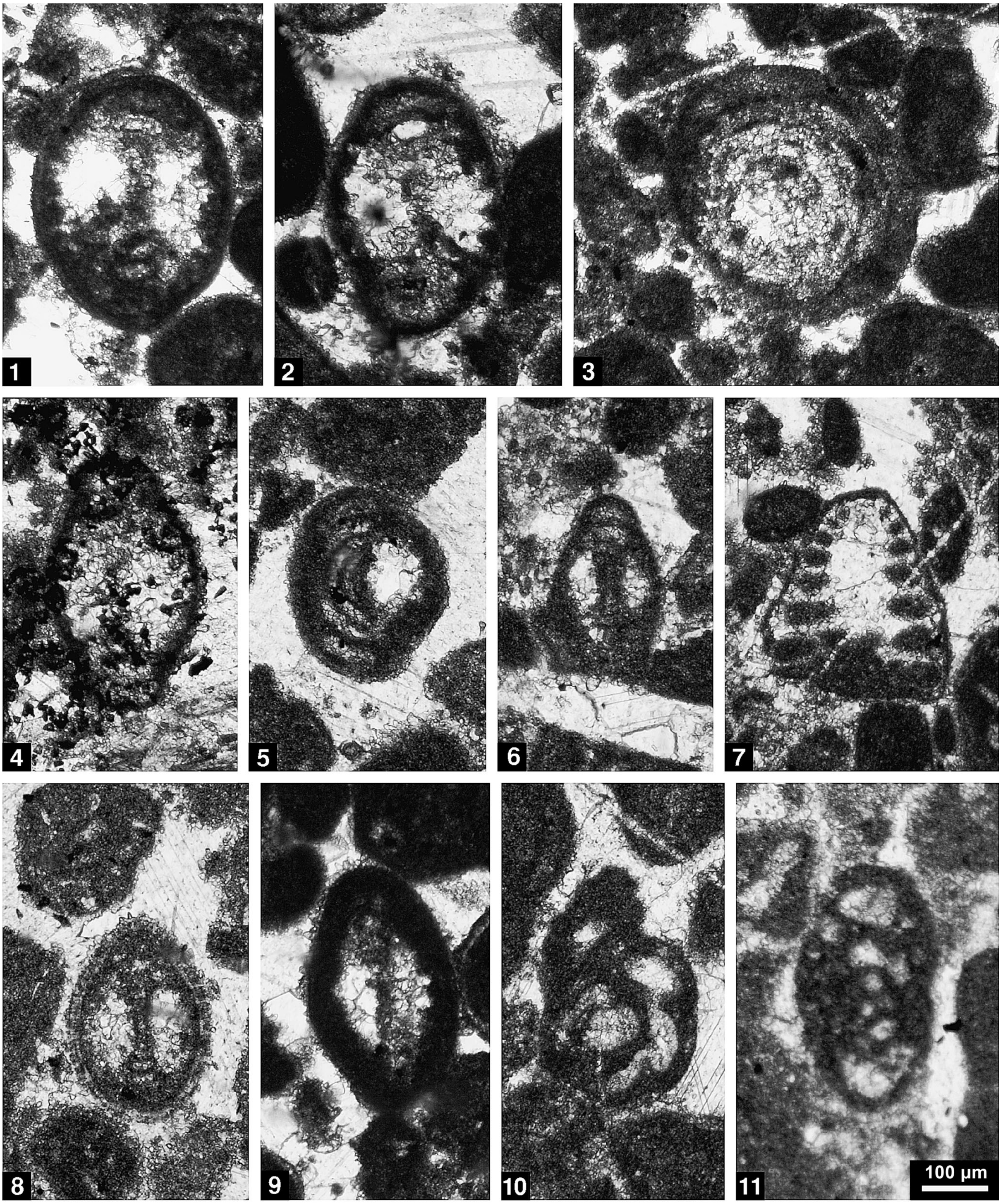

1
2
3
4
5
6
7
8
9
10
100 µm

PLATE 4

Figs. 1–11. Liassic sequence of the Verige succession.

Figs. 1–6, 8, 9.	*Involutina farinacciae*, thin sections RR7293 (1–4, 9), 7291 (5–6), 7294 (8).
Fig. 7.	*Trocholna* sp., thin section RR7291.
Fig. 10.	?*Mesoendothyra* sp., thin section RR7291.
Fig. 11.	*Mesoendothyra izjumiana* DAIN, thin section 7296.


1
2
3
4
5
6
7
8
9
10
11
100 µm

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	63–69	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172063B

Paraseqences in the Kotroman Formation, western Serbia

Nenad Banjac[1] & Divna Jovanović[2]

Abstract. An attempt was made to describe two parasequences separated within the sediments of the Kotroman Formation at the Mokra Gora Village in western Serbia. The whole formation, of Albian–Cenomanian age, in some general characteristics corresponds to tidal flats, some of which were described in the literature (Larsonneur 1975), and the sediments were compared with ones from recent tidal flat environments. The heterogeneous composition of the Kotroman Formation influenced different authors to describe several non-synchronous and incomparable superpositioned packages. The parasequences were investigated in the attempt to correlate them with the stratigraphic age of the members. The parasequences were formed during the Albian transgression and represent a gradual deepening of the wider area. Well-developed flooding surfaces with significant deepening indicated retrogradational stacking of certain transgressive system tracts and reflect landward movement of the shoreline, indicating a gradual sea level rise.

Key words: Parasequences, Kotroman Formation, palaeontology, sedimentology, Albian–Cenomanian, Mokra Gora, western Serbia.

Апстракт. У раду су описане две парасеквенце уочене у седиментима формације Котроман код Мокре горе у западној Србији. Цела формација, албско-ценоманске старости, у неким својим општим карактеритикама, одговара тајдалној равни, какве су већ описане у литератури (Larsonneur 1975), а њени седименти су упоредиви са творевинама рецентних тајдалних равни. Хетерогена грађа формације Котроман условила је да више аутора описује неколико различитих суперпозиционих пакета који се међусобно не могу поредити. У раду су описане парасеквенце и представљена је њихова стратиграфска припадност. Парасеквенце су формиране током албске трансгресије и настале су услед постепеног продубљавања на ширем простору. Површине плављења са маркатним продубљавањем указују на ретроградациони трансгресивни тракт и представљају последицу сталног издизања нивоа мора уз постепено померања обалске линије ка копну.

Кључне речи: Парасеквенце, Формација Котроман, палеонтологија, седиментологија, алб–ценоман, Мокра Гора, западна Србија.

Introduction

After a period of no deposition during the Aptian and the Albian, with a new transgressive cycle, land masses of Jurassic ophiolites (nowadays in western Serbia) were flooded with a shallow to moderately shallow sea. Although extensively eroded since, Cretaceous deposits that were formed during this transgressive cycle could be found on numerous outcrops in western Serbia. The most extensive exposure among these outcrops is located in the vicinity of Mokra Gora and occupies the Beli Rzav and Kamešina Valleys with their tributaries. The lower portion of these deposits near Mokra Gora Village was previously studied and described as the Kotroman Formation (Banjac *et al.* 2008 and references therein).

Previous Studies

The general consensus among the stratigraphic community was that the Mokra Gora deposits are Upper Cretaceous in age. However, much debate was involved to the question of the age of specific strati-

[1] Department of Geology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, P. O. Box 162, 11000 Belgrade, Serbia. E-mail: banjac@afrodita.rcub.bg.ac.rs

[2] Geological Institute of Serbia, Rovinjska 12, 11000 Belgrade, Serbia. E-mail: djdivna@gmail.com

graphic sections. The Mokra Gora deposits were first described by ŽUJOVIĆ (1893), as carbonates of Senonian age. The author sporadically mentioned numerous hippuritids and abundant fossil gastropod associations. The following works (ŽIVKOVIĆ 1905, 1907; PETKOVIĆ 1925; AMPFERER1928; MILOVANOVIĆ 1933) confirmed Mokra Gora deposits as Senonian in age, locating the whole sequence as analogues to the Gosau Beds in Austria. The determination was based on macrofossil fauna assemblages with: *Pyrgulifera pichleri, P. accinosa, P. lyra, P. striata, Glauconia kefersteini, G. renauxi, G. coquandi, Natica bulbiformis, N. lyrata, Hippurites gosaviensis, Radiolites lusitanicus*, etc. However, LÓCZY (1924) indicated that the sediments are Upper Cretaceous in age, more specifically Cenomanian, Turonian and Senonian, based on the macrofossil fauna: *Acanthoceras mantelli*, *Puzosia* aff. *gaudama*, *Biradiolites affilaensis*, etc. MILOVANOVIĆ (1935) just mentioned deposits from the Upper Cenomanian to the Upper Campanian age. MITROVIĆ (1966), MITROVIĆ *et al.* (1989), confirmed this age based on abundant echinid assemblages with numerous representatives of the *Epiaster* and *Hemiaster* genera.

PEJOVIĆ & RADOIČIĆ (1971, 1973, 1974) and RADOIČIĆ (1984), placed the whole Mokra Gora series as the Cenomanian, Turonian and older Senonian. According to these authors, the sandy and marly carbonate portion of the local stratigraphic column, "tens of meters above the weathering crust" RADOIČIĆ (1984, p. 136.), is characterized by mid-Cenomanian microfauna: *Aeolisacus inconstans, Ovalveolina maccagnae* and *Rhapidionina laurinensis*. Therefore, the authors concluded that the lower-most, palaeontologically sterile basal section can be recognized as the Albian stage. The upper portion of the local stratigraphic column is represented by marly limestone with abundant ostreids, grypheas and inoceramids, as well as pelagic microfossils of the *Pithonella ovalis*, *Hedbergella-Ticinella* group, which indicate the lower Turonian stage. However, upper Cenomanian age was accepted after later revision of the beds with *Cisalveolina fraasi*, (RADOIČIĆ 1984, 1995).

The uppermost member of the stratigraphic column is represented with massive limestone bearing hippurites and gastropods of Turonian age.

The Albian–Cenomanian age of the Mokra Gora Series was confirmed in the works of BANJAC (1994, 1994a, 2000). The author reported mollusc fauna of Albian–Cenomanian and Turonian age, although some of the specimens, e.g., *Paraglauconia lujani*, is known from Aptian deposits. DULIĆ (2003), described it as the Albian–Cenomanian palynomorph association from the Mokra Gora Series. The same age was confirmed by JOVANOVIĆ *et al*. (2004) based on the microfauna assemblage, as well as BANJAC *et al*. (2007) based on the gastropod assemblage. RADOIČIĆ & SCHLAGINTWEIT (2007) at the Mokra Gora Series established a new species *Neomeris mokragorensis* of Albian age. It must be noted that lower portion of the stratigraphic column is described as deposits of Barremian age (NIRTA *et al.* 2008; MENA *et al.* 2008).

Lithostratigraphic members

Due to heterogeneous composition of the Mokra Gora Series, authors described several non synchronous and incomparable superpositioned packages. LÓCZY (1924) differentiated five packages. (1) The first one consists of conglomerates and sandy horizons with oolith iron nodules, (2) the second with marly to sandy limestone, (3) the third with shaly and sandy limestone. The fourth package (4) is represented by greyish to yellowish fragile marl with large molluscs and bivalve fossil specimens, whereas the fifth package (5) is represented by massive reef limestone. MILOVANOVIĆ (1933) also differentiated 5 packages: (1) basal, represented by conglomerate, reddish quartzite and iron rich bearing schist; (2) tabular marl and limestone, which gradually become sandy limestone and sandstone; (3) lower package of sandstone, sandy limestone and marls with abundant associations of gastropods and most commonly the genus *Pyrgulifera* and (4) upper package of sandy limestone and marl with associations of gastropods, bivalves and echinoids. The uppermost package (5) is represented with massive reef limestone with abundant rudist fauna. This subdivision was generally accepted in the works of DRAKULIĆ & DEDIĆ (1963) and FOTIĆ (1965).

PEJOVIĆ & RADOIČIĆ (1971, 1973, 1974), RADOIČIĆ (1984) described the biostratigraphic characteristics of the Mokra Gora Series, with three main levels: (1) the basal clastites, (2) carbonates with marls and (3) shallow water reef limestone. The lowermost level (1), transgressively overlying serpentine or a weathering crust, is represented by conglomerate, conglomeratic sandstone and sandstone lacking any fauna. The overall height is around 50 m. The authors emphasized the extremely heterogeneous composition and thickness of this level. The following level (2) was named by the authors as Carbonaceous or Pelagic beds, and bears two members of lower rank, *i.e*., (2a) sandstone, marl and carbonaceous deposits (150–200 m thick) and (2b) marly-carbonaceous deposits (150–200 m. thick). The uppermost level (3) consists of massive limestone with hippurits of Turonian age. A similar partition with three principal units was presented by MOJSILOVIĆ *et al*. (1978) and OLUJIĆ *et al*. (1986). NIRTA *et al.* (2008) and MENA *et al* (2008) explained the lithologic characteristics of the Mokra Gora Series, describing two units (named A and B), which reflect two main deepening-shallowing cycles. These units correspond to the levels 1 and 2, respectively, suggested by PEJOVIĆ & RADOIČIĆ (1971, 1973, 1974) and RADOIČIĆ (1984). The authors also mentioned, but did not study, the third unit (named C), which corresponds to level 3 of massive limestone with hippurites suggested by PEJOVIĆ & RADOIČIĆ (1971, 1973, 1974).

Within an analysis of the Cretaceous deposits of western Serbia, JOVANOVIĆ *et al.* (2004) separated three levels.

The first is basal terrigenous sandy series with nodular biomicrite. The biocomponent is represented with rare fragments of microflora and microfauna in addition to mollusc detritus. The frequent charophyts and ostracods of the same age indicate the presence of an intermittent freshwater environment at the same period. Rich fossil assemblages can be found in the uppermost section of the Kotroman Formation.

The next level is the Pelagic Series, composed of thin-bedded marly limestone. These are fine laminated biomicrite with an abundant alevritic fraction and centimetre thick beds of bioclastic marl, bioclastic packstone, sometimes with accumulations of thin shell fragments. They are commonly alternating with thin marly layers.

The third level, uppermost portion of the Mokra Gora Series, consists of massive carbonates with hippurits and gastropods of Turonian age.

The first of the aforementioned, the so-called Basal terrigenous sandy series, was described by Banjac *et al.* (2008), and proposed as the Kotroman Formation. The Formation consists of clastic deposits in the lower part and limestone beds in the upper part of the stratigraphic column. The lower limit is a sharp transgressive boundary with serpentinite or a few meters thick weathering crust, while the upper limit is a blunt transition to the so-called Hemipelagic Series. Three separate members were distinguished in the Kotroman Fm.: the Kamišna Mb, the Uroševići Mb and the Jatare Mb. The whole Kotroman Fm. in some general way corresponds to a tidal flat, some of which were described in literature (LARSONNEUR 1975), and the sediments were compared with those from the environment of recent tidal flats. It must be noted that the low latitude (less than 30° N) position of the area during the Upper Cretaceous influenced not only the presence of siliciclasite, but also of carbonates with characteristics of the carbonate shelf system of the whole formation. The section with the described parasequences is shown in Fig. 1.

Kamišna Member

At the investigated locality, the Kamišna Member is not exposed at its whole thickness. In its lower segment, transgressive extra-formational oligomict conglomerate can be observed. Fragments of serpentinite and chert are deposited within a sandy or silty matrix.

Iron-rich, dark green chamosite ooides and serpentinite particles can be frequently found in the conglomerate fragments. The grains are cemented with calcareous or clay-ironstone cement. The described sediments correspond to the gravel initially deposited below the low-water tide level (LARSONNEUR 1975).

In the upper parts of the stratigraphic column, these sediments increasingly interchange with iron-rich sandstone characterized by well-rounded pyritised grains and fragments of serpentine, without any fossils. The deposits gradually transform to sandstone containing more than 25 % fine-grained rock fragments, predominantly pyroxene and spinel clasts. This coarse- to fine-grained loose dark grey sandstone is present in the main portion of the Basal Member. Small cherty fragments as well as sand particles of different sizes are bound by clayey or limonitic red or brown cement.

The described sediments correspond to gravelly sand which was deposited on about the low-water tide level (LARSONNEUR 1975).

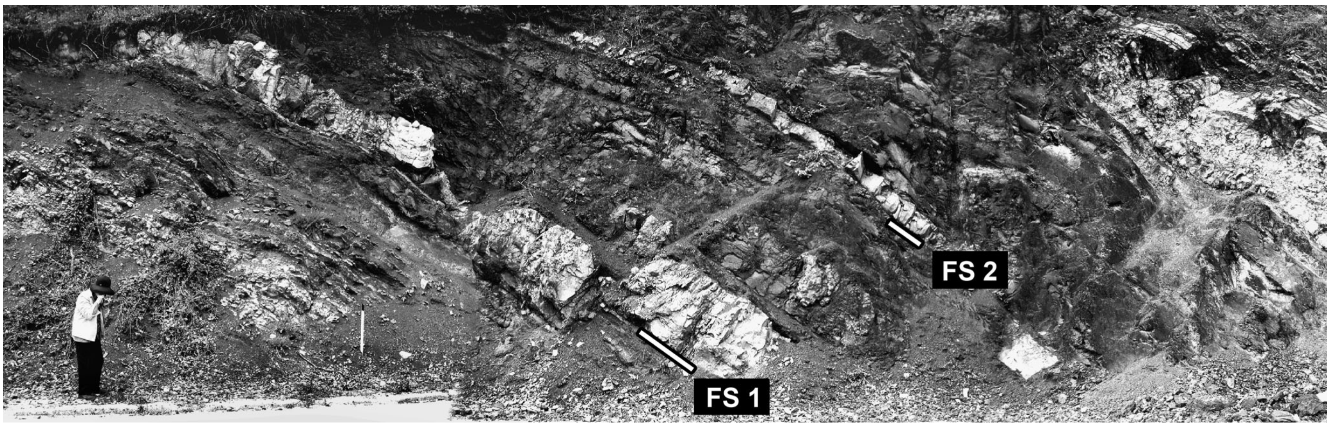


Fig. 1. Parasequences at the Kotroman locality. Legend: FS1 - Flooding surface 1, FS2 - Flooding surface 2.

Parasequences

An attempt was made to describe the two parasequences separated within the Uroševići Member of the Kotroman Fm. Their base is the upper portion of the Kamišna Mb. while they are overlain by the Jatare

The iron-rich sandstone dominates in the upper portion of the Kamišna Mb. However nodular clastic limestone interbedded with yellowish thin marl occurs in this portion. The nodular limestone is represented by biomicrite, floatstone and wackestone, enclosed in an intimate mixture of clay and carbonate. Clasts of serpentine, pyroxene and quartz mixed with scarce mollusc shell fragments are found in a fine grain microsparite and clayey matrix. Extremely small crystals of quartz, pyrite and hematite can frequently be found in these deposits.

The quantity of the bioclastic fragments increases in the upper horizons, and rock gradually changes to bioclastic wackestone, packestone and floatstone, with sometimes large clasts. The characteristics of the rock resemble storm beds. The bioclasts are represented with numerous fragments of gastropods, bivalvs, and ostracods. Floral remnants, such as fine dispersed plant particles and fragments of branches and tree trunks, are common. In addition, bisect particles of conifers, dominated by *Pinus* and rarely *Podocarpus* and *Cedrus* can be found.

The iron-rich sandstone of the upper portion of the Kamišna Mb. represents shallow water facies. It corresponds to biogenic sand and biogenic fine sand which was deposited about the high-water tide level (LARSONNEUR 1975).

Uroševići Member – Parasequence 1

Within the Uroševići Mb., two parasequences have been described, with an attempt to correlate them with stratigraphic age of the member (BANJAC *et al*. 2008).

The lowermost sediment of the Uroševići Mb. (within Kotroman Fm.) is represented with an almost one meter thick bed of sandy reddish nodular limestone with bivalve and gastropod shell fragments. Its lower boundary represents the flooding surface (FS1) that marks the base of a parasequence with abrupt contact. Sandy reddish nodular limestone lying directly on top of relatively shallow iron-rich sandstone located below the surface. The frequent appearance of small-scale erosion can be observed at this surface (Fig. 2).

In the following portion of the stratigraphic column, nodular limestone is frequently interbedded with thin layers of marl and siltstone.

The thin section of the reddish nodular limestone indicated bioclastic wackestone with frequent fossil shell fragments. Samples from the upper portion of these deposits revealed packestone, floatstone, rudstone and rarely fine-grained sandstone. The fossil content is represented with mollusc fragments, in some places with abundant gastropod and bivalve accumulations found in the cm-scale lenses of calcirudite and calcarenite. The mollusc shells frequently contain geopetal fillings. These beds also contain rare ostracode remnants, as well as gyrogonyts and charopohyte remnants, which indicate intermittent fresh water influxes. In addition, the algae *Radiocicelapses* sp. and *Hemicyclamina sigali* MAYNC can be found.

The microfauna assemblage consists of codiacean grains and *Radoicicelapses sterni* RADOIČIĆ, *Nezzazatinella* cf. *picardi* (HENSON), *Hemicyclamina sigali* MAYNC, *Salpingoporella urladanasi* CONRAD, PEYBERNES & RADOIČIĆ, *Aeolisacus* sp. and *Glomospira* sp. The macrofauna is represented by gastropod fragments (*Cassiope* sp.).

Samples from the upper portion of the parasequence revealed an increase of fine-grained sandstone, gradually transforming to lithic sandstone. Clasts are represented with quartz, chert, pyroxene, serpentine, peridotite and siliceous rocks in spary cement or a microsparitic matrix. Birds-eye structures as well as fenestrated fabrics, which can be observed in the thin section, indicate a shallow environment with sporadic exposure to open air, i.e., deposition at the high water tide level. The general characteristics of the fine-grained sandstone shows a gradual shallowing which is terminated with a sudden contact. Relatively deeper nodular limestone is situated on top of the shallow fine-grained sandstone located below the surface. Small scale erosion can be observed at this surface (FS2), similar to one at the previous flooding surface (FS1).

Fig. 2. Flooding surface at the top of the Kamišna Mb.

Uroševići Member – Parasequence 2

The lower portion of the second parasequence is represented with an approximately 20 cm thick bed of nodular limestone with mollusc shell fragments. Its lower boundary is designated as a second flooding surface (FS2) that marks the base of the second parasequence. The nodular limestone of this parasequence is fossiliferous packestone and wackestone with peloidal and biogenic intraclasts in a micritic and microsparitic matrix.

In the upper portion of the parasequence, the nodular limestone alternates with ophiolithic coarse-grained reddish sandstone.

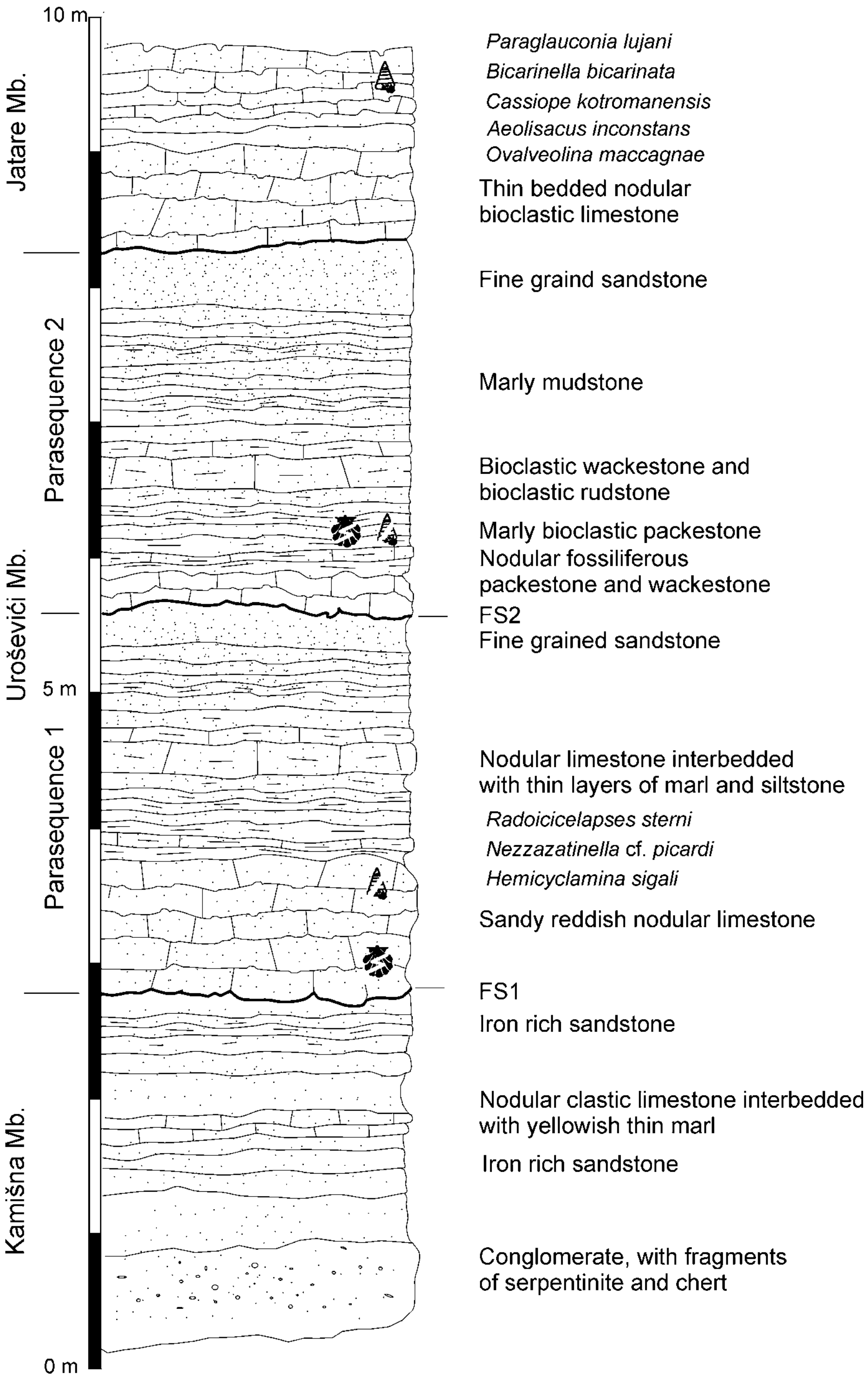


Fig. 3. Stratigraphic column with the described Parasequences.

Marly bioclastic packestone creates the next level in the parasequence. Gastropod or bivalve shells can frequently be found, especially in the marly beds between the thicker limestone beds. At some levels, there is a transition to wackestone, *i.e.*, biomicrite with unsorted angular shell fragments deposited within a microcrystalline calcite matrix. Besides shell fragments, charophyte girogonits and ostracods can be found, indicating intermittent fresh water influx. It is followed by decayed, lumpy limestone that is characterized by the presence of thin mollusc shell fragments. It is predominantly biomicrite with sporadic foraminifera and abundant iron matter. At some places within these limestone beds, the shell accumulations indicate storm beds. Bioclastic wackestone, as well as bioclastic rudstone can also be found at this portion of the parasequence. In the upper portion, a blunt transition to marly mudstone can be observed.

Fine-grained sandstone represents the uppermost portion of this parasequence. The described sediments correspond to biogenic gravelly sand to biogenic sand which was deposited between low and high water tide levels. (LARSONNEUR 1975).

Jatare Member

The fine-grained sandstone of the Uroševići Mb. is overlain by thin-bedded nodular bioclastic limestone belonging to the third member, the Jatare Mb. Calcareous and silty marlstones in some places contain abundant microfauna associations, which are represented by: *Aeolisacus inconstans* RADOIČIĆ, *Ovalveolina maccagnae* DE CASTRO and *Rhapidionina laurinensis* DE CASTRO. Macrofauna was discovered at numerous localities, sometimes forming coquina beds. It is represented by mollusc fragments: bivalvs *Amphidonte conicum* (SOWERBY), *Ostrea callimorphe* COQUAND and *O. cunabula* SEELEY, and the gastropods *Pseudomesalia teniucostata* (HACOBJAN), *P. multicostata* (HACOBJAN), *Pirenella* cf. *levadhiae* KOLLMANN, *Paraglauconia lujani* (DE VERNEUIL & COLOMB), *Bicarinella bicarinata* (PČELINCEV) and *Cassiope kotromanensis* BANJAC. Thin-bedded nodular bioclastic limestone with the aforementioned association of fauna corresponds to sediments deposited at a subtidal shelf or outer shelf with increased carbonate production. In the upper portion, they gradually transfer to the thin-bedded, marly limestone of the so-called hemipelagic series.

Conclusions

An attempt was made to investigate the presence of parasequences in the Cretaceous deposits known as the Kotroman Formation according to type locality and type section at the Kotroman Village in western Serbia.

The investigations of the sediments at the Kotroman locality imply two parasequences within the Uroševići Mb.: Parasequence 1 and Parasequence 2. The parasequences were formed during the Albian transgression and represent a gradual deepening of the wider area. Well-developed flooding surfaces with prominent deepening, indicated to retrogradational stacking of certain transgressive system tract and reflect the landward movement of a shoreline. The beds overlying the Uroševići Mb. indicate a new rise in the relative sea level. They are represented by thin-bedded nodular bioclastic limestone belonging to the Jatare Mb.

The insufficient data does not allow the results to be compared with the eustatic sea level curve (HAQ *et al.* 1987). It can only be approximately estimated (based on fossil age) that the described parasequences belong to the earliest Supercycle of the Upper Zuni A set (UZA 1).

Acknowledgments

We are very thankful to PLATON TCHOUMATCHENCO (Geological Institute, BAS, Sofia), as well as an anonymus critic who reviewed the paper. The work was supported by the Ministry of Education and Science of the Republic of Serbia (Project No. 176015).

References

AMPFERER, O. 1928. Zur Tektonik und Morphologie des Zlatibormassivs. *Denkschriften der kaiserlichen Akademie der Wissenschaften mathematisch-naturwissenschaftliche Klasse*, 101: 361–424.

BANJAC, N. 1994. Contribution to the study of the Upper Cretaceous fauna at Mokra Gora, western Serbia. *Radovi Geoinstituta*, 30: 167–171 (in Serbian).

BANJAC, N. 1994a. The Upper Cretaceous gastropod genus *Vernedia* from the Mokra Gora area, western Serbia. *Vesnik, Geologija, hidrogeologija i inženjerska geologija*, 45: 47–54.

BANJAC, N. 2000. Contribution to the Upper Cretaceous stratigraphy in western Serbia (Postenje Stream locality – Mokra Gora). *Vesnik, Geologija, hidrogeologija i inženjerska geologija*, 50: 75–82.

BANJAC, N., BANDEL, K. & KIEL, S. 2007. Cassiopid gastropods from the Cretaceous of western Serbia. *Geološki anali Balkanskoga poluostrva*, 68: 71–81.

BANJAC, N., JOVANOVIĆ, D., DULIĆ, I. & LJUBOVIĆ-OBRADOVIĆ, D. 2008. The Albian–Cenomanian Kotroman Formation of Mokra Gora (western Serbia). *Geološki anali Balkanskoga poluostrva*, 69: 31–38.

BORTOLOTTI, V., MARRONI, M., PANDOLFI, L. & PRINCIPI, G. 2005. Mesozoic to Tertiary tectonic history of the Mirdita ophiolites, northern Albania. *The Island Arc*, 14: 471–493.

DRAKULIĆ, D. & DEDIĆ, LJ. 1963. Structural composition of the Upper Cretaceous sediments of Mokra Gora and Beli Rzav. *Tehnika*, 18 (10): 230–236.

DULIĆ, I. 2003. *Palinomorphes from the Albian and Cenomanian deposits of Yugoslavia.* Unpublished Ph.D. dissertation. 231 pp. University of Belgrade, Faculty of Mining and Geology. (in Serbian).

FOTIĆ, V. 1965. Geological composition and tectonic structure of the Mokra Gora Basin with special regards to the oolitic iron ore. *Vesnik, Geologija* (A), 22 (23): 117–129 (in Serbian).

HAQ, B.U., HARDENBOL, J. & VAIL, P.R. 1987. Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). *Science*, 235: 1156–1167.

JOVANOVIĆ, D., LJUBOVIĆ-OBRADOVIĆ, D., DŽAJIĆ, S., STEVANOVIĆ, S., BANJAC, N. & BLAGOJEVIĆ, B., 2004. *Cretaceous formations of the western Serbia (Mokra Gora).* Geological Survey of Serbia, Internal report, 15 pp. (In Serbian).

LARSONNEUR, C. 1975. Tidal deposits, Mont Saint-Michel Bay, France. *In*: GINSBURG, R.N. (ed.), *Tidal Deposits – A casebook of recent examples and fossil counterparts*, 21–30. Springer Verlag, Berlin.

LÓCZY, L. sen. 1924. *Geologische Studien im westlichen Serbien*, 146 pp. Walter de Gruyter & Co., Berlin.

MENNA, F., NIRTA, G., BORTOLOTTI, V. CARRAS, N., FAZZUOLI, M., GARFAGNOLI, F. & PRINCIPI, G., 2008. Sedimentary Records of the Cretaceous Transgression in the Dinaric Orogen: The Mokra Gora Section (western Serbia) Preliminary data, *26th IAH Meeting of Sedimentology*, Poster, Bochum, Germany.

MILOVANOVIĆ, B. 1933. Contribution to the geology of western Serbia – Upper Cretaceous of the Mokra Gora Basin. *Geološki anali Balkanskoga poluostrva*, 11: 132–160 (in Serbian).

MILOVANOVIĆ, B. 1935. Zur Stratigraphie und Tektonik des Zlatibormassivs (Westserbien). *Mitteilungen der Geologischen Gesellschaft in Wien*, 28: 115–129.

MITROVIĆ-PETROVIĆ, J. 1966. Cretaceous and Miocene echinoids of Serbia. *Geološki anali Balkanskoga poluostrva*, 32: 87–164, (in Serbian).

MITROVIĆ-PETROVIĆ, J. & ANĐELKOVIĆ, M. 1989. *Paleoecology of Serbia – Cretaceous*. 158 pp. University of Belgrade, Faculty of Mining and Geology, Belgrade (in Serbian).

MOJSILOVIĆ, S., BAKLAJIĆ, D., ĐOKOVIĆ, I. & AVRAMOVIĆ, V. 1978. *Explanatory book for the basic geologic map, scale 1:100 000, sheet "Titovo Užice".* 50 pp. Federal Geologic Survey, Belgrade (in Serbian, English summary).

NIRTA, G., MENNA, F., FAZZUOLI, M., GARFAGNOLI, F., BORTOLOTTI, V. & PRINCIPI, G. 2008. Cretaceous transgressive deposits above an obducted ophiolitic nappe: The Mokra Gora sequence (western Serbia), *33rd International Geological Congress (HPS-01 General contributions to stratigraphy)*, Poster, Oslo, Norway

OLUJIĆ, J. & KAROVIĆ, J. 1986. *Explanatory book for the basic geologic map, scale 1:100 000, sheet "Višegrad".* 55 pp. Federal Geologic Survey, Belgrade (in Serbian, English summary).

PEJOVIĆ, D. & RADOIČIĆ, R. 1971. Über die Stratigraphie der Kreideserie der Mokra Gora. *Bulletin Scientifique du Conseil des Academies des Sciences et des arts de la RSF de Yugoslavie, Sect. A,* 16 (7–8), p. 138.

PEJOVIĆ, D. & RADOIČIĆ, R. 1973. Sratigraphy of the Vlasenica roof bauxite series. *II Jugoslovenski simpozijum o istraživanju i eksploataciji boksita*, 1–8, (in Serbian).

PEJOVIĆ, D. & RADOIČIĆ, R. 1974. *Biostratigraphic investigation of the Cretaceous of Mokra Gora*. Geological Survey of Serbia, Internal report, 13 pp. (in Serbian).

PETKOVIĆ, V. 1925. *Historical geology (Stratigraphy).* 365 pp. Državna štamparija Kraljevine Srba Hrvata i Slovenaca, Beograd (in Serbian).

RADOIČIĆ, R. 1984. The age of sediments overlaying Ni–Fe deposits in the Inner Dinarides (western Serbia, Kosovo, Macedonia). *Radovi Geoinstituta*, 17: 133–136 (in Serbian).

RADOIČIĆ, R. 1995. Contribution to the study of Cretaceous biostratigraphy of the Zlatibor Mountain. *Radovi Geoinstituta*, 31: 17–30 (in Serbian).

RADOIČIĆ, R. & SCHLAGINTWEIT, F., 2007. *Neomeris mokragorensis* sp. nov. (Calcareous alga, Dasycladales) from the Cretaceous of Serbia, Montenegro and the Northern Calcareous Alps, (Gosau Group, Austria). *Geološki anali Balkanskoga poluostrva*, 68: 39–51.

ŽIVKOVIĆ, M. 1905. About the genus *Pyrgulifera meek* in Serbia. *Comptes rendus des sèances de la Société Serbe de Géologie*, 7, p. 2, (in Serbian).

ŽIVKOVIĆ, M. 1908. Geology at the vicinity of Užice. *Izveštaj Užičke gimnazije za 1907–8.*, 24 pp. (in Serbian).

ŽUJOVIĆ J. 1893. *Geology of Serbia,* Part 1. 334 pp. Srpska Kraljevska akademija, Beograd (in Serbian).

Резиме

Парасеквенце формације Котроман, западна Србија

У седиментима формације Котроман код Мокре горе у западној Србији истражене су и описане две парасеквенце, формиране током албске трансгресије и настале услед постепеног продубљавања на ширем простору. Цела формација, албско ценоманске старости, по својим општим карактеристикама, одговара тајдалној равни, какве су већ описане у литератури (LARSONNEUR 1975), а њени седименти могу да се упореде са творевинама рецентних тајдалних равни.

Хетерогена грађа формације Котроман условила је да више аутора описује неколико различитих суперпозиционих пакета. У већем броју старијих радова (ŽIVKOVIĆ 1905, 1907; PETKOVIĆ 1925; AMPFERER 1928; MILOVANOVIĆ 1933) наводи се стратиграфска припадност сенону, док се касније јавља мишљење о припадности албу, ценоману и турону (MILOVANOVIĆ 1935; MITROVIĆ 1966; MITROVIĆ *et al.* 1989; PEJOVIĆ & RADOIČIĆ 1971, 1973, 1974; RADOIČIĆ 1984). У већини савремених радова наводи се припадност алб-ценоману (BANJAC 1994, 1994a, 2000; DULIĆ 2003; JOVANOVIĆ *et al.* 2004; BANJAC *et al.* 2007; RADOIČIĆ & SCHLAGINTWEIT 2007), а само изузетно и припадност старијим катовима (NIRTA *et al.* 2008; MENA *et al.* 2008).

У оквиру члана Урошевићи формације Котроман, издвојене су две парасеквенце формиране током албске трансгресије на ширем простору. Основу им чине пешчари и конгломерати члана Камешина, таложени у условима плитке воде. Изнад њих се запажа јасна површина плављења (FS1) која означава драстичан прекид у седиментацији и почетак прве парасеквенце.

Прва парасеквенца обележена је квргавим кречњацима, са честим фрагментима фосила, који се местимично смењују са финозрним пешчарима. Фрагменти љуштура мекушаца који се налазе у седименту често садрже геопеталне испуне. Понекад се у седименту налазе и фрагменти остракода као и гирогонити и остаци харофита.

Друга парасеквенца обележена је као и претходна, јасном површином плављења (FS2), изнад које се налазе квргави кречњаци, пакстон и вакстон са фрагментима фосилне фауне у микритској основи. У вишим деловима јавља се грубозрни црвенкасти пешчар. Парасеквенца се завршава јасном површином плављења којом је одвојена од танкослојевитих квргавих кречњака члана Јатаре.

Јасно дефинисане површине плављења на горњој и доњој граници сваке парасеквнце са маркатним продубљавањем током развоја парсеквенце указују на ретроградациони трансгресивни тракт и постепено померање обалске линије у правцу копна. Танкослојевити квргави кречњаци који леже преко горње границе члана Урошевићи, указују на ново издизање нивоа мора.

Скроман обим података није нам дозволио поређење резултата са кривом промене нивоа мора (HAQ *et al.* 1987). Могуће је само приближно предпоставити на основу старости детерминисане палеофауне да описане парасеквенце припадају најстаријем суперциклусу сета Upper Zuni A 1 (UZA 1).

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	71–85	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172071R

New data concerning the Early Middle Miocene on the southern slopes of Fruška Gora (northern Serbia): a case study from the Mutalj Quarry

Ljupko Rundić[1], Slobodan Knežević[1], Nebojša Vasić[2], Vesna Cvetkov[3] & Milovan Rakijaš[4]

Abstract. During the last few years, geological research at the southern slopes of Fruška Gora Mt.enabled the discovery of different Miocene units (undivided the Lower Miocene and Middle Miocene Badenian, predominantly). This is primarily thinking of the so-called Leitha limestone (Middle Miocene, Badenian), which is an important component in cement production (La Farge Co., Beočin). The high carbonate content (more than 98 %) allows it to be a very important raw material that is mixed with Pannonian marl in the process of cement manufacture. Continuous exploitation of this rock at the Mutalj Quarry enabled an insight into its structural, stratigraphic, sedimentological and hydrogeological features, as well as its relation to the other underlying/overlying units. Numerous fossils (*i.e.,* red algae, mollusks, corals, bryozoans, and foraminifers) and their biostratigraphic range indicate to Middle Miocene Badenian age. Based on data from different boreholes, structural and sedimentological characteristics, spatial distribution, *etc*., a relatively large rock body was discovered (approx. 0.3 km^2). Within these Leitha limestones, there are frequent cracks and caverns infilled with fine lateritic clays and alevrites. These clays were sampled for a paleomagnetic study. The carrier of the primary remanent magnetization (RM) is magnetite that has a primary origin. Lateritic clays are characterized by significant value of magnetic susceptibility. The degree of anisotropy of the magnetic susceptibility (AMS) is low with the dominant magnetic foliation.

Key words: Lower Middle Miocene, Badenian limestone, post-Badenian lateritic clays, paleomagnetism, Fruška Gora Mt.

Апстракт. Последњих неколико година, геолошка истраживања на јужним падинама Фрушке горе омогућила су увид у постојање различитих миоценских јединица (нерашчлањен доњи миоцен и првенствено, баденски кат средњег миоцена). Овде се говори пре свега о тзв. лајтовачким кречњацима (средњи миоцен, баден), важној компоненти у производњи цемента (Лафарж, Беочин). Висок садржаја карбоната (више од 98%) омогућава им да буду врло значајна сировина, те се додају панонском лапорцу у процесу производње цемента. Непрекидна експлоатација ових кречњака у каменолому Мутаљ, омогућила је увид у њихове структурне, стратиграфске, седиментолошке и хидрогеолошке карактеристике, као и њихов однос према другим, подинским односно повлатним јединицама. Бројни фосили (нпр. црвене алге, мекушци, корали, бриозое и фораминифери) и њихов биостратиграфски опсег упућују на млађе баденску старост. На основу података из различитих бушотина, структурних и седиментолошких карактеристика, као и просторне дистрибуције кречњака, утврђено је да се ради о релативно великој стенској маси (око 0,3 km^2). Унутар те кречњачке масе, честе су пукотине и каверне запуњене финим латеритским глинама и алевритима које су биле и предмет палеомагнетних испитивања. Но-

[1] Department of Geology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, 11000 Belgrade, Serbia. E-mail: rundic@rgf.bg.ac.rs; knezevic.slobodan@gmail.com

[2] Department of Mineralogy, Crystallography, Petrology and Geochemistry, Faculty of Mining and Geology, University of Belgrade, Studentski Trg 1, 11000 Belgrade, Serbia. E-mail: vasic.nebojsa@rgf.bg.ac.rs

[3] Department of Geophysics, Faculty of Mining and Geology, University of Belgrade, Đušina 7, 11000 Belgrade, Serbia. E-mail: cvetkov@rgf.bg.ac.rs

[4] Hidro-Geo Rad, Brankova 23, Belgrade, Serbia. E-mail: smrakijas@yahoo.com

силац примарне реманентне магнетизације (PM) је магнетит који је примарног порекла. Латеритске глине карактерише значајна вредност магнетне сусцептибилности. Степен анизотропије магнетне сусцептибилности (AMC) је мали са доминантном магнетном фолијацијом.

Кључне речи: Старији средњи миоцен, баденски кречњаци, пост-баденске латеритске глине, палеомагнетизам, Фрушка гора.

Introduction

The Pannonian Basin was formed as result of continental collision and subduction of the European Plate under the African Plate during the Late Early to Late Miocene (FODOR *et al*. 2005). The Late Early Miocene subsidence and sedimentation was an effect of the sin-rift extension phase that resulted in the formation of various grabens filled by thin sin-rift marine and brackish deposits (CLOETINGH *et al*. 2006; HORVÁTH *et al*. 2006; DOMBRÁDI *et al*. 2010). The tectonic events that formed the Pannonian Basin also affected the structure of the Neogene deposits of Fruška Gora (FG), which were deformed mainly by radial tectonics. Still, deformations that are more complex have been noted in the Upper Miocene and Pliocene nearer to the Danube, in the influence zone of the regional fault that separated large blocks: the uplifted structures of the FG horst from the southern Bačka depression (MAROVIĆ *et al*. 2007). FG was the focus of geological interest in the second half of the 19th century. LENZ (1874) and KOCH (1876) gave the first and original explanation of the geological record of FG. After the Second World War, ČIČULIĆ (1958), ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ (1971), PETKOVIĆ *et al*. (1976) wrote important contributions to the study of the stratigraphy of FG. In recent times, a few articles include different geological studies of FG (RUNDIĆ *et al*. 2005; GANIĆ *et al*. 2009, 2010; TER BORGH *et al*. 2011). All the mentioned authors noted the absence or minor occurrence of the Miocene at the southern flank of the mountain. Except for the Lower Miocene Vrdnik coal basin sediments and volcanites, which are transgressive over the basement rocks (PETKOVIĆ *et al*. 1976), there are no other significant occurrences of Miocene rocks at the southern slope of FG. Only two occurrences of the Miocene limestone were noted (the Mutalj and Beli Kamen Quarries near the Bešenovo village). The first paleomagnetic studies of lateritic clay from the Mutalj Quarry were performed to define the paleorotation pattern of FG during the Neogene. These investigations gave good results (LESIĆ *et al*. 2007; CVETKOV 2010). Afterwards, the lateritic clays from biogenic limestone were re-examined in detail in terms of their magnetic properties.

This work presents new structural, sedimentological, and paleontological data from Mutalj, the largest Middle Miocene quarry at the southern slope of FG (Fig. 1). Additionally, the post-Badenian clays were checked to determine the carrier of remanent magnetization (RM) and the anisotropy of magnetic susceptibility (AMS).

Materials and Methods

All the presented data were obtained on the surface at the Mutalj Quarry and from twelve boreholes (GB-1/10, GB-2/10, GB-3/10, B-16/05, BGMK-1/10, BGMO-3/10, IBMBK-1/10, IBMBK-2/10, IBMBK-4/10, IBMBK-5/10, IBMBK-6/10, IBMBK-7/10 – see Fig. 1; Table 1). Information was plotted on a geodetic plan on the scale 1:25 000, and three geological cross-sections drawn, to be reduced to the scale and prepared for print (Fig. 2).

A detailed sedimentological investigation was performed at the Mutalj Quarry during 2008. Additionally, different fossils were collected to date. For a more precise stratigraphic position, a few limestone samples were examined as thin-sections. All the mentioned material is stored in the Faculty of Mining and Geology, Belgrade as well as the Hidro-Geo Rad, Belgrade. Paleomagnetic measurements were conducted on the lateritic clays on three occasions. The first two times were to determine the paleodirections and the last one was to determine the carrier of the remanent magnetization (RM) and the anisotropy of the magnetic susceptibility (AMS). Samples of slightly different lithology were taken from two caverns. Clays from the first cavern (Mutalj 1) are reddish-brown, adhesive and compact while the clay from the second cavern (Mutalj 2) has a more sandy component. Paleomagnetic measurements were realized in the Paleomagnetic Laboratory of the Republic Geodetic Authority, Department for Geomagnetism and Aeronomy, Belgrade and the Etvös Lorand Geophysical Institute in Budapest, Hungary. For measurement of the initial magnetic susceptibility and the anisotropy of the susceptibility (AMS) in a low-intensity field (in fifteen positions) MFK1-A and KLY-2 Kappabridges were used. The direction and intensity of the remanent magnetization (RM) were measured using JR-5 and JR-5A spinner magnetometers within the domain of the natural remanent magnetization (NRM). A thermal demagnetizer MMTD80 and the pulse demagnetizer MMPM10 performed thermal demagnetization (TD) and isothermal remanent acquisition (IRM). For thermal demagnetization of specimens within the alternating field, an AFD300 and Schönstedt AF demagnetizers were used (max. field strength up to 0.23 T,

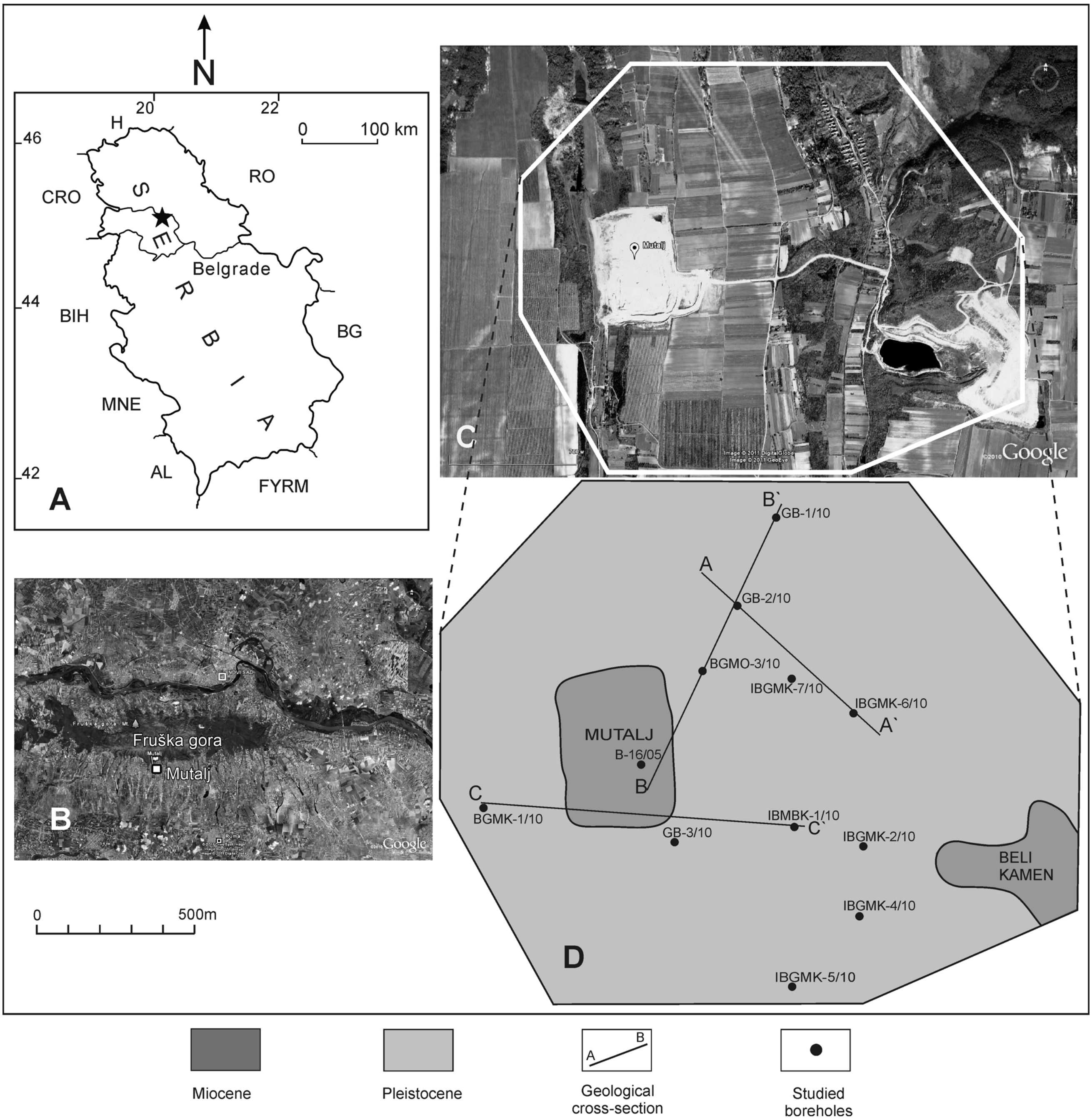


Fig. 1. Geographic position (A), satellite image of southern part of Fruška Gora Mt. (B) and satellite image of the Mutalj Quarry and its simplified geological map (C, D).

Technical University of Budapest). The demagnetization data were processed statistically following standard paleomagnetic procedures (KIRSCHVINK 1980; FISHER 1953).

Geology of the Mutalj Quarry

The Mutalj Quarry belongs to the village of Bešenovo on the southern slope of FG (N 45°6'29.24"; E 19°41'40.46" – Fig. 1). It is the largest open pit in this part of FG (approx. 295 000 m^2). Herein, Triassic and Jurassic rocks make the basement for the Neogene sediments that cover them on the southern side. Generally, the clastic–carbonate sediments of the Lower Triassic, the carbonate facies of the Middle Triassic and the igneous–sedimentary complex of the Middle and Upper Triassic represent the Triassic formations in FG. Tithonian-Berriasian sediments as well as an ophiolite complex represent the Jurassic age (Fig. 2, B–B'). The basement rocks form a very complex structural pattern with features of most diverse folding and radial deformation. In total, twelve exploration boreholes were investigated (Table 1).

Table 1. Geographic position of the investigated boreholes (WGS84).

No.	Borehole	North	East
1	IBMBK-1/10	45° 6' 22.25"	19° 42' 6.75"
2	IBMBK-2/10	45° 6' 20.36"	19° 42' 16.94"
3	IBMBK-4/10	45° 6' 12.94"	19° 42' 16.61"
4	IBMBK-5/10	45° 6' 5.44"	19° 42' 6.72"
5	IBMBK-6/10	45° 6' 34.21"	19° 42' 15.22"
6	IBMBK-7/10	45° 6' 37.73"	19° 42' 5.99"
7	BGMK - 1/10	45° 6' 23.69"	19° 41' 19.82"
8	BGMO -3/10	45° 6' 38.45"	19° 41' 52.74"
9	GB - 1/10	45° 6' 54.77"	19° 42' 3.45"
10	GB - 2/10	45° 6' 45.38"	19° 41' 57.62"
11	GB - 3/10	45° 6' 20.59"	19° 41' 48.90"
12	B-16/05	45° 6' 29.25"	19° 41' 44.35"

In the area of Bešenovo, the Miocene deposits are distributed along a narrow, discontinuous belt of E–W direction. The best exposure of these sediments is located at the Mutalj Quarry where Middle Miocene Badenian limestone appears. However, based on the exploratory drilling, it was determined that the basis of the Badenian sediments is composed of different rocks from an older Miocene continental series (Fig. 2. B–B', C–C'). It consists of multi-colored pebbly clays, sands, quartzites, older rock fragments, and conglomerates. Stratigraphically, these rocks correspond to the undivided Lower Miocene (Fig. 2). These sediments were best studied on the southern slopes of FG, near Vrdnik (the Vrdnik Coal-Bearing Basin); hence, they are known as "the Vrdnik Series" or the Vrdnik Formation (PETKOVIĆ *et al.* 1976; RUNDIĆ *et al.* 2005). They are transgressive and discordant over the various members of the basement rocks (Fig. 2. B–B'). In certain places, the relationship with the different older fragmented and reworked rocks is probably sharp (Fig. 2, A–A). Based on earlier data (RUNDIĆ *et al.* 2005), three litho-stratigraphic members within the Vrdnik Series are distinguished: a) at the base, there are various breccias, conglomerates and sandstones, rarely clays, 5–30 m thick; b) above the basis, there is a coal-bearing horizon. It is composed of 4–6 coal layers, 0.6–2.5 m thick, represented by intercalated layers of montmorionite clay (bentonite); c) the overburden of the coal layer is composed of a lower and upper overburden. However, based on the facts from the investigated boreholes, there are no coal seams at the Mutalj Quarry. Only a part of that lithological succession is determined. The varicolored terrigenous series contains brown clay, reddish sandy clay, grayish sand, and pebbles of different rocks (serpentinites, quartzites, diabases, different schist, *etc.*). It has a great distribution and makes the base for the different younger rocks (see cross-sections in Fig. 2). According to this, it can be supposed that the Lower Miocene sediments have a thickness of more than 100 m.

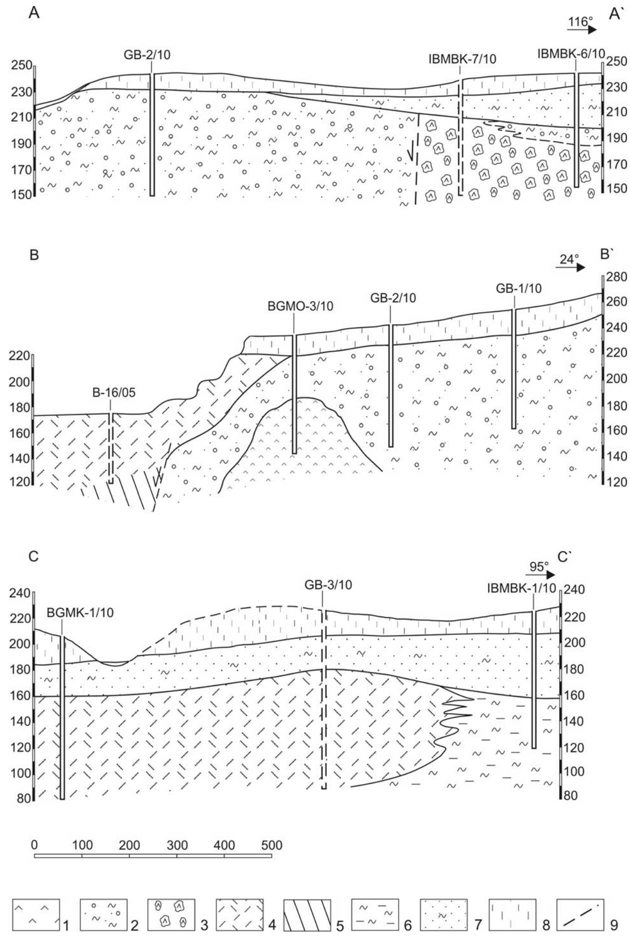


Fig. 2. Geological cross-sections across the Mutalj Quarry: A–A′, B–B′, and C–C′. Key: **1,** Jurassic diabases (only in cross section and boreholes); **2, 3,** Lower Miocene lacustrine deposits and volcanites (only in cross section and boreholes); **4,** Middle Miocene (Badenian) reef limestone; **5, 6,** Middle Miocene (Badenian) sandy marl and sandy clay; **7,** Pleistocene red beds – the Srem Formation; **8,** Pleistocene loess–paleosoil sequences; **9,** Fault.

The marine Badenian sediments have a relatively small distribution at the Mutalj Quarry. If compared to the northern parts of the mountain, there is a clear difference (PETKOVIĆ *et al.* 1976; RUNDIĆ *et al.* 2005). The Badenian sediments are present as an elongated, discontinuous rock body with E–W direction and they have much wider distribution on the northern slopes of FG. They are characterized by large diversity of the facies, which is a consequence of various conditions in the coastal area of the former island in the Paratethys Sea (conglomerates, sandstones, sandy marls and tuff-sandstones, clays and clayey marls, limestones, *etc*.). However, the Mutalj Quarry includes three lithostratigraphic members (Fig. 2. B–B'). Very rare grayish-green clay and sandy marl and the wider distributed biogenic limestones (the so-called Leitha limestone). They contain numerous fossils and several types of limestones could be distinguished: lithotamnian, amphistegin, bryozoan, *etc*. The limestone is massive, reefy, developed by the life activities of the red algae *Lithotamnion*, foraminifers and bryozoans, and including numerous fossil remains of mollusks, as well as scarce findings of sea urchins, corals and other organisms. Analyses of the sediment determined the dominance of algal and algal–foraminifer biomicsparite and biomicrudite (Figs. 3, 4). On the lateral sides, toward the E–NE periphery of the exploitation area, the limestones turn into marly limestones, sandy marl, and clay (Fig. 2. B–B', C–C').

The Badenian sediments at Mutalj Quarry are overlaid by Pleistocene red beds. Finally, Pleistocene loess–paleosoil sequences cover both of them (Fig. 2. B–B', C–C').

Based on data from the above-mentioned boreholes and from field observations, it can be concluded that there is no rock connection between the active Mutalj Open Pit and the abandoned one (the Beli Kamen Open Pit). This means that there are two independent limestone bodies, which belong to a narrow belt on the southern slope of FG.

Lithostratigraphy and sedimentology

A lithostratigraphic column of the Badenian limestone with a total thickness of more than 30 meters (2009) was recorded in the Mutalj Quarry (N 45°06'21.1", E 19°41'43.1"). Including the Pleistocene sediments of the Srem Formation and the loess–paleosoil sequences, the overall thickness of the whole section reaches up to 48 meters (Figs. 3, 4.). These are white biogenic limestones, very porous and poorly cemented. They have a general appearance of chalky carbonate and contain various fauna of mollusks (clams, snails), algae, and other reef builders. The thirty meters of the column appeared homogeneous without a clearly visible internal stratification or other structural features. At the top of the limestone, there are many emphasized cracks of meter dimensions that are filled by red clays and alevrites. The limestones are permeable and there is an accumulation in the deepest floor of the quarry (see Fig. 3A, B). The dark green water has a high content of carbonate. A typical example of Badenian biogenic limestone – biomicrudite is shown in Fig. 7.

The allochem contains primarily large algal remains. The fragments are rudites. Large pelagic and benthic foraminifers make a small percent of the allochem. Biogenic detritus is minimized. Ortochem is a micrite calcite. The Leitha limestone has an intergranular and intragranular porosity. The pores sporadically contain a sparite calcite. Non-carbonate ingredients are clay minerals that are either adhered to algal fragments or mixed with micrite. The total content of calcite ($CaCO_3$) is about 98 %.

Over the Badenian bioclastic limestone, there are breccias up to 2 meters thick (Fig. 3). One local phenomenon was noted, even in the realm of the quarry, which, regardless of their limited occurrence, we think consider very interesting. The phenomenon is constructed of a variety, both in size and form, of fragments that originated from the Badenian rocks (Fig. 5). The fragments can be observed macroscopically and they contain algal debris and large foraminifers (Fig. 7D). In some parts of the breccias, there was a significant transport of fragments, while in other parts, there was none at all. It is evident that there are polyphases of its making (Fig. 5). Vertically as well as laterally, there is black scree of black pebbles with centimeter dimensions. The cement of the breccias is carbonate, without fossil remains, painted in different shades of red. Given that, these breccias lie over "karstified" Badenian limestone and under the Srem Formation, their stratigraphic position for the time being, outstanding issues. A sample of the carbonate breccias (No. 33, Fig. 3), which overlies the Badenian biogenic limestone, is built from various, primarily in size, angular fragments. Smaller fragments may have rounded and dark brown to black membranes. These fragments may correspond to grain-type black pebbles. The Badenian algal limestone represents the source rock for the fragments. Each fragment represents the different microfacies. Most of the rudites contain algal fragments and other biogenic allochem similar to that of the Badenian limestone. In addition, as smaller fragments, independent algal grains are embedded in the matrix. The cement is a micrite pigmented with iron oxides. The terrigenous component is evenly distributed throughout the rock. Its content is up to 5 %. These are mainly angular quartz grains and fragments of metamorphic rocks. Present in the micrite matrix, there are an irregular cavities filled by sparite calcite which, together with micrite, correspond to a type of dismicrite.

A slightly different example is a sample of limestone breccias (No. 34, Fig. 3). A feature of the fragments is that they all have brown, ferrous membranes (black grains). The fragments do not touch; they are embedded in the matrix. The cement is a micrite pigmented with iron oxides. Within it, the terrigenous component reaches up to 2–3 %. The total content of calcite ($CaCO_3$) is about 97 %.

An important characteristic of the Leitha limestone is its high $CaCO_3$ content, which in certain samples reaches over 98 %. Therefore, it is used to enrich the main raw material (Pannonian marl) with carbonates

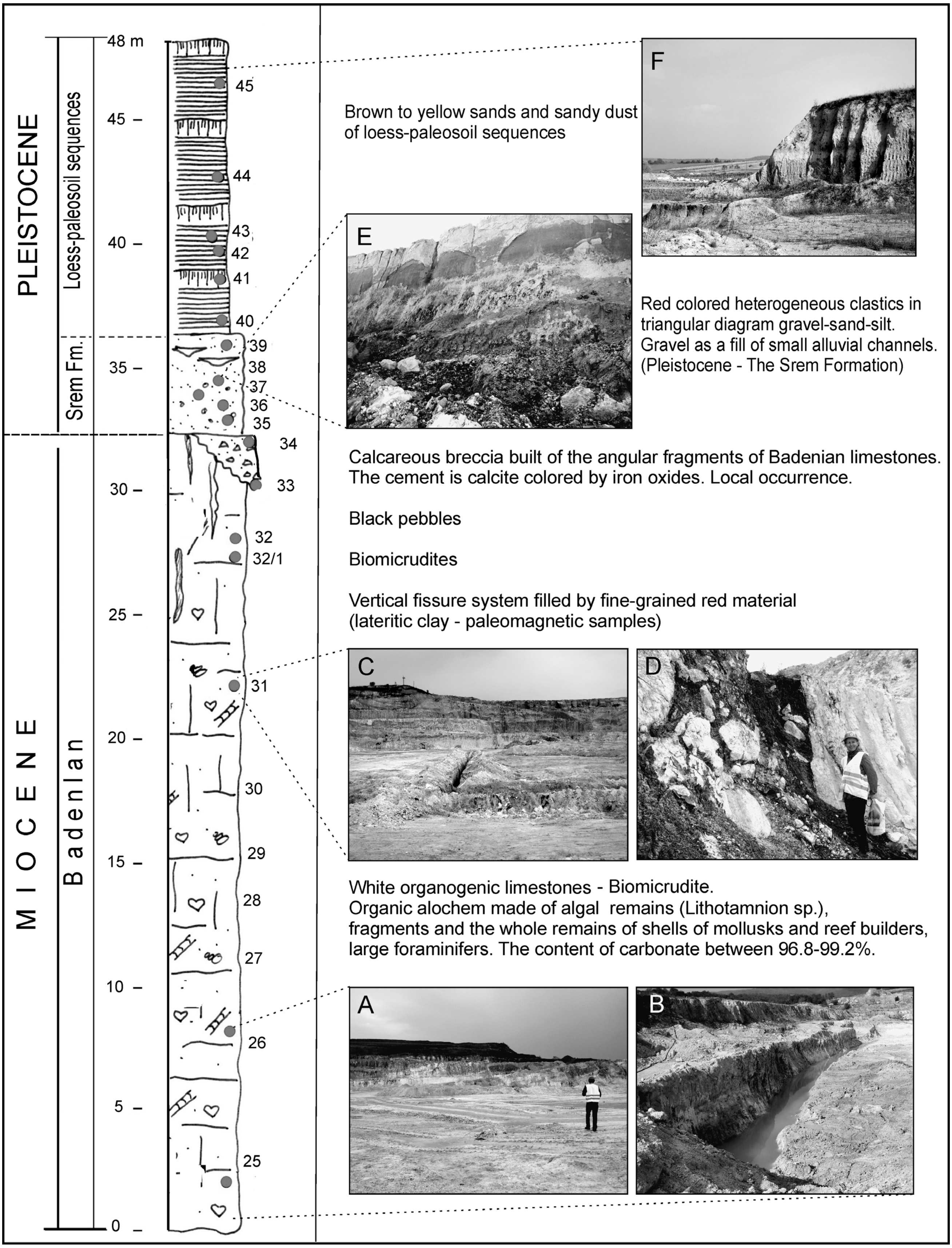


Fig. 3. Lithostratigraphic succession at the Mutalj Quarry and the main sedimentological features. The numbers from 25 to 45 show the position of the taken samples.

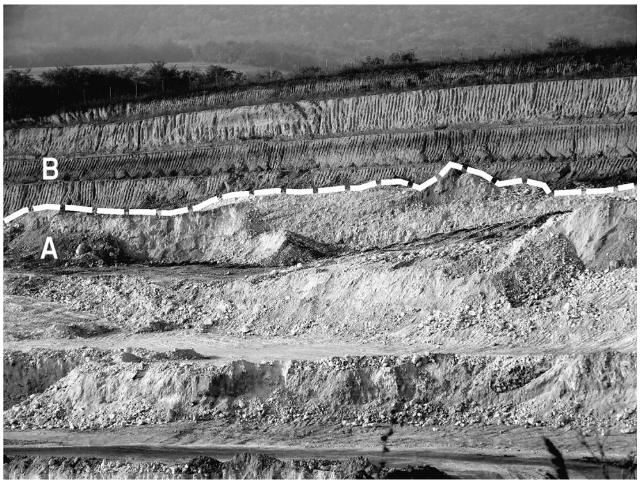


Fig. 4. Contact between Badenian limestones (A) and Pleistocene clastic sediments (B).

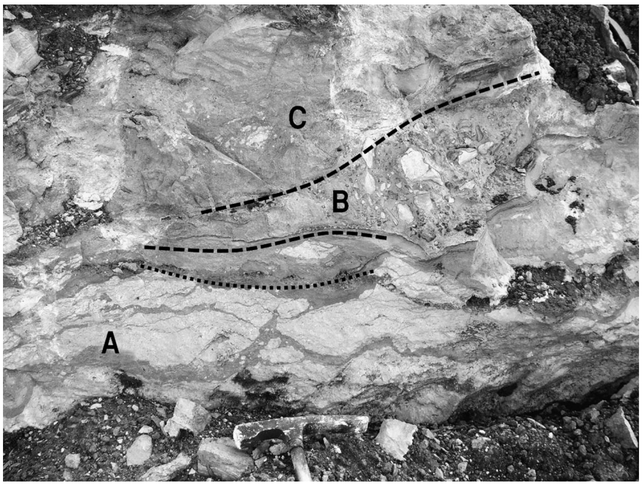


Fig. 5. Several stages in the creation of breccias. **A,** Fragmentation of the Badenian limestone without movement; **B,** Finer limestone fragments are transported; **C,** Large limestone fragments.

during cement production. In the paleogeographical sense, they were deposited during the Badenian, along the southern shore of the former Fruška Gora Island. Due to good insulation, the conditions needed for the development of red algae and other reef-forming organisms were more suitable here than on the northern coast; hence, the Badenian limestones on the southern slopes are richer in $CaCO_3$.

During the first phase of the limestone exploitation at the Mutalj Quarry, their total thickness was more than 100 meters.

Fossils in the Leitha limestone

The fossil macrofauna often contains large forms, such as: *Pecten aduncus*, *P. haueri*, *Chlamys latisimuss*, *Chlamys* sp., *Flabellipecten besseri*, *Glycimeris pilosus*, *Panopea menardi*, *Ostrea lamelosa*, *O. digitalina*, *Isocardia cor*, *Conus mercati*, *etc*. (Fig. 6). Foraminifers, ostracodes, as well as different algae and bryozoans, have also been recorded. Among the foraminifers, the genus *Amphistegina* is of particular importance and makes the microfacies specific. Following species were recognized: *Amphistegina haueri*, *Globigerina bulloides*, *G. bilobata*, *Asterigerina planorbis*, *Cibicides lobatulus*, *Ammonia ex gr. beccari*, *Elphidium crispum*, *Elphidium* sp., *Bolivina* sp., *Lithotamnion* sp. and *Lithophyllum* sp. Similarly, there are other types of these rocks based on the prevailing microfossils (Fig. 7). All the mentioned fossil species suggest the Upper Badenian, which is consistent with field observations and the position of similar sediments on the northern slope of the FG. However, a precise biostratigraphic determination will be realized later.

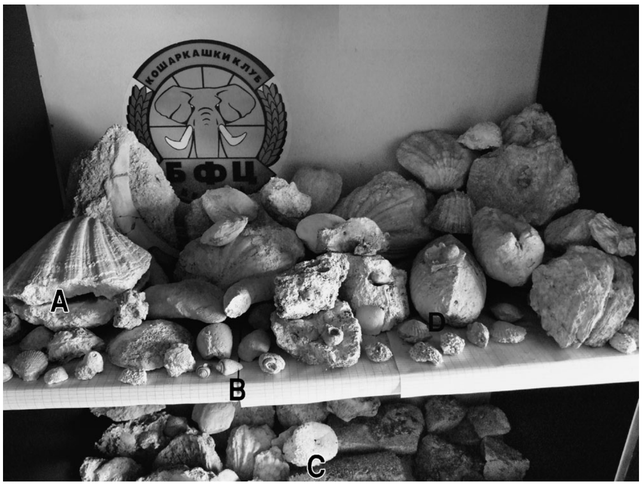


Fig. 6. Association of fossil mollusks extracted from the Leitha limestone: **A,** *Chlamys latissimus* Brocco.; **B,** *Conus* sp.; **C,** A fossil coral; and **D,** Shell molds of *Panopea* sp.

Hydrogeological features

From the hydrogeological point of view, the Middle Miocene Badenian limestones provide a good environment for the formation of karst aquifers. This was confirmed by geological exploration drilling and installation of piezometers, as well as other hydrogeological studies.

Analyses of hydrogeological mapping in the wider area of the Mutalj Open Pit, the bored cores and the infiltration tests determined the large permeability potential of this limestone as well as the overlying beds composed of loess sequences and different pebbly and sandy clay deposits of so-called the Srem Formation (Pleistocene). The results of the infiltration tests (*in situ*) showed that the coefficient of filtration in the Mutalj Open Pit limestone is about $K = 10^{-2}$ cm/s. Ac-

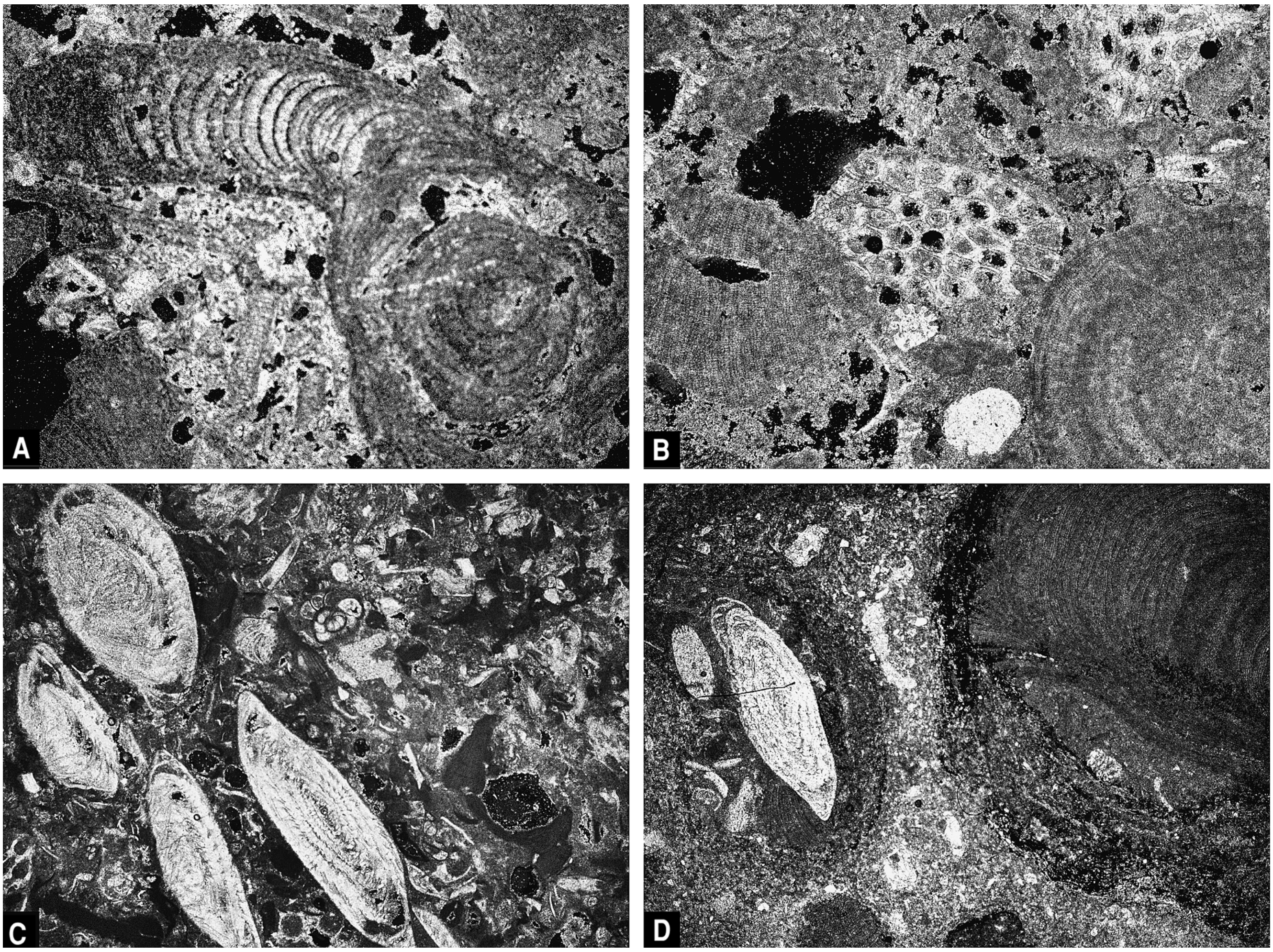


Fig. 7. Different microfacies of Badenian limestone: **A,** Lithotamnian limestone (Sample 32); **B,** Algal–bryozoan limestone (sample 32/1); **C,** Amphistegin limestone (sample 34/1); **D,** Algal and foraminifer fragments within the breccias (sample 34/2). Scale: length of pictures is 4 mm.

cording to these results, they belong to the highly permeable sediments. The coefficient of filtration for the overlying sediments is less than $K = 10^{-4}$ cm/s and they belong to the middle-permeable sediments. Based on these results, it can be concluded that the infiltration of atmospheric precipitation into the underground occurred very quickly and recharged the karst aquifer formed in the Badenian limestones. Drainage of the karst aquifer is towards the southwest, which is compatible with the dip direction of the Vrdnik Formation. This was concluded from the results of numerous measurements that were performed in the network of piezometers formed around the Mutalj Open Pit. During 2005, the limestone exploitation reached the ground water level at an elevation of from 175 m to 177 m and opened the karst aquifer within it.

The hydrogeological conditions and the relation between the Mutalj Open Pit and the abandoned neighboring limestone of the Beli Kamen Open Pit were the objects of detailed investigations during 2010. Main goal of these studies was to explain the geological conditions as well as their hydrogeological relations. Namely, during the past decades, it was not possible to determine whether there is a unique aquifer between these limestone quarries. In addition, there was doubt whether the karst aquifer in the Beli Kamen limestone and the artificial lake formed therein could affect the aquifer recharge in the Mutalj Open Pit. Finally, it could lead to an increased inflow of groundwater from this direction. However, further exploitation of the limestone from the Mutalj Open Pit, as well as its continual dewatering resulted in a lowering of the ground water level; the mirror of the water at level is now at 158.76 m (Table 2).

Table 2. Recent measurements of the elevation of the water mirror.

Open pit	Elevation	Date
Mutalj	158.76 m	19.11.2010.
Beli Kamen	173.10 m	17.01.2011.

All the mentioned geological and hydrogeological data obtained during 2010 show that the space between the pits is not constructed of marine limestone rock. It consists of Lower Miocene lacustrine deposits, dark, grayish-green siltstones, reworked blocks and fragments of diabases and schists, minor pebbles of carbonates, *etc*. (IBMBK-6/10, IBMBK/7/10). The exploration borehole BGMO-3/10, which was drilled with the purpose of determining of the absence of limestone, showed that there is a diabases block below the mentioned lacustrine sediments. From the hydrogeological point of view, the diabases are impermeable. These formations alternate with low-permeable sediments, such as gray–yellow marly clay, marly sandstone, poorly consolidated sandstone, gravel with lenses of sand, *etc*. These sediments represent a lateral facies of Badenian limestone (IBMBK-1/10, IBMBK-2/10). Similar geological successions were observed in boreholes IBMBK-4 and IBMBK-5. Different loess and paleosoil sequences form the cover of the mentioned Miocene sediments.

Paleomagnetic data

All samples in the NRM domain have measured values of initial magnetic susceptibility in the range 1.9–3.4 10^{-3} SI and remanent magnetization in the range 29.1–78.4 mA/m. The degree of AMS is low with the dominant magnetic foliation indicating remanent magnetization formed during compaction (Fig. 8). Correction for tectonics caused a slight change in the position of the anisotropy axis of the magnetic susceptibility (Fig. 9). Based on the acquisition of isothermal remanent magnetization experiment by the method of step-by-step thermal demagnetization three-component IRM (LOWRIE 1990) and the CISOWSKI test (1981), it was found that the primary carrier of natural remanent magnetization is magnetite (Fig. 10). To avoid cracking and loss of the samples during heating, it is planned to perform alternating field demagnetization. However, the presence of a "resistant" RM to the effect of an alternating field (AF) would require the use of thermal demagnetization (Fig. 11). The direction of the high-stability PRM component was determined by principal-component analysis (KIRSCHVINK 1980) and Fisher statistics (FISHER 1953). The isolated paleomagnetic directions are consistent not only within a cavern, but also between the cavities (Fig. 12).

Interpretation and Discussion

The Miocene epoch on the southern slope of FG is relatively unknown. Poor data were derived from the BGM 1: 100 000 sheet Novi Sad (ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1971). Therein, only a few "patches" indicate the presence of Miocene rocks. However, continual investment in the cement industry and the demand for good raw material resulted in numerous drilling in this area. Consequently, a completely different distribution pattern of the Miocene on the southern slope of FG to that on the northern slopes was established.

Lower Miocene undivided heterogeneous rocks have a relatively small distribution. Practically, they are confirmed only in the studied boreholes (see Fig. 2). However, based on core data, there is a clear signal for the continental development of the Lower Miocene there. The main characteristics of these deposits are as follows: variegated beds, lack of fauna, domination of coarse-grained clastics, very fast vertical and lateral alternation of facies, noticeable variations in grain size, *etc*. According to the early known facts regarding the geology of the Vrdnik coal-bearing basin (PETKOVIĆ *et al*. 1976; RUNDIĆ *et al*. 2005), these rocks correspond to the upper part of the Lower Miocene Vrdnik Formation. Up to the present, the age of these sediments is not clear. Comparable data comes from the neighboring Požeška Mt. (northern Croatia), where Lower Miocene alluvial deposits were discovered (PAVELIĆ & KOVAČIĆ 1999).

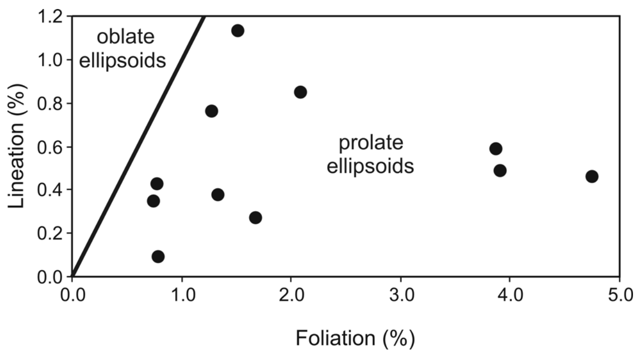


Fig. 8. Lineation *versus* Foliation (Flinn diagram), showing oblate shape for the AMS measurements, with the foliation coinciding with the bedding plane.

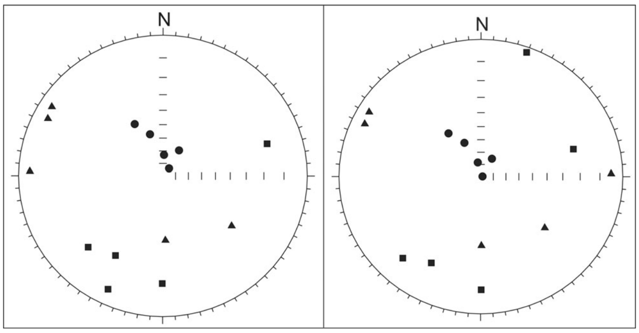


Fig. 9. Equatorial projection (on the lower hemisphere) k_{max} (square), k_{int} (triangle) and k_{min} (circle) of AMS ellipsoid axes for individual clay samples from the Mutalj Open Pit. Left: before correction for tectonics; right: after correction for tectonics.

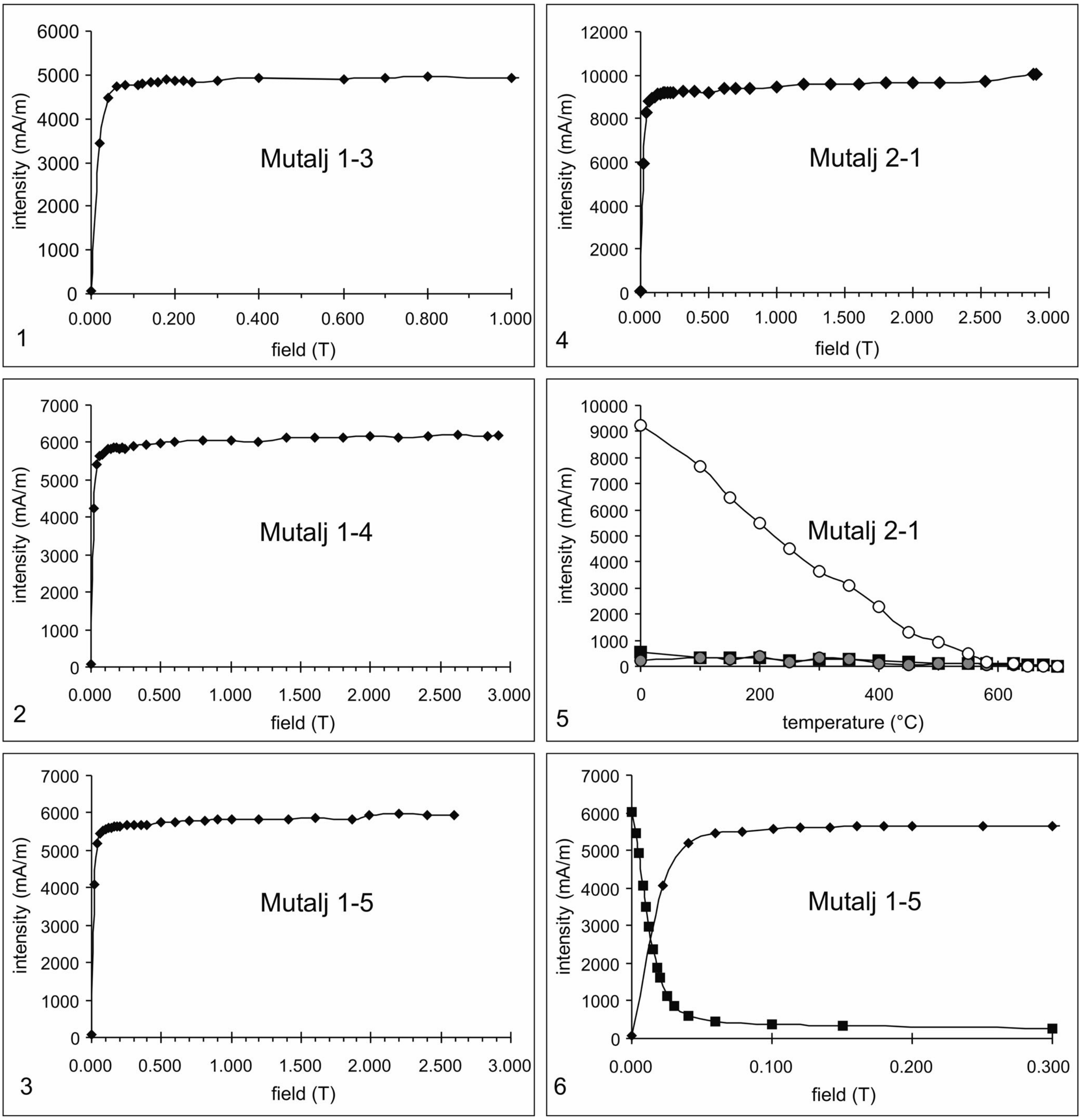


Fig. 10. Magnetic mineralogy. Diagrams of the behavior of the magnetization-bearing mineral during the magnetic field control and heating in the laboratory. Key: **1–4,** IRM acquisition behavior; **5,** The three-component IRM (LOWRIE 1990) behavior on thermal demagnetization. The hard (square), the medium hard (dots) and soft (circle) components of the composite IRM were acquired in fields of 2.91 T, 0.4 T and 0.121 T, respectively; **6,** Acquisition and AF demagnetization of IRM (CISOWSKI test, 1981).

A well-known fact is that the beginning of the Badenian age (Early Langhian, *ca*. 16.3 Ma) coincides with a marine transgression in the domain of the Central Paratethys (ĆORIĆ & RÖGL 2004; ĆORIĆ *et al*. 2004, 2009; HARZHAUSER & PILLER 2007; HOHENEGGER *et al*. 2009; PILLER *et al*. 2007; RÖGL *et al*. 2008). Such records, coupled with different tectonic, seismic and sequence stratigraphy data, indicate to a very powerful and important event (HORVÁTH *et al*. 2006; KOVÁČ *et al*. 2007; SCHMID *et al*. 2008). Generally, the Lower Badenian deposits discordantly overlie the older Miocene strata or the pre-Tertiary basement (e.g., the Vienna Basin, the Styrian Basin, the southern margin of the Pannonian Basin in Croatia, Bosnia,

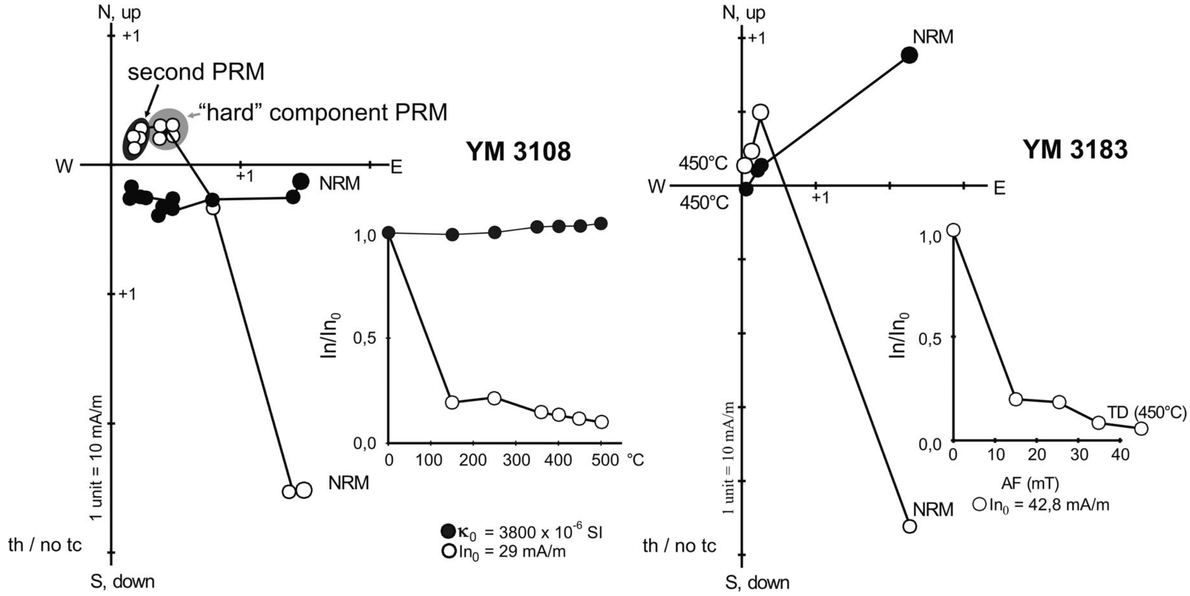


Fig. 11. Typical demagnetization curves for clay. Key: Zijderveld diagrams and intensity/susceptibility *versus* temperature curves. During thermal demagnetization, the remaining intensity of the NRM was measured after heating the specimen to a given temperature and cooling back to ambient. In the Zijderveld diagrams full/open circle: projection of the NRM in the horizontal/vertical plane; in the others susceptibility: dots, NRM intensity: circles. In_0 - initial intensity of the NRM, k_0 - initial susceptibility.

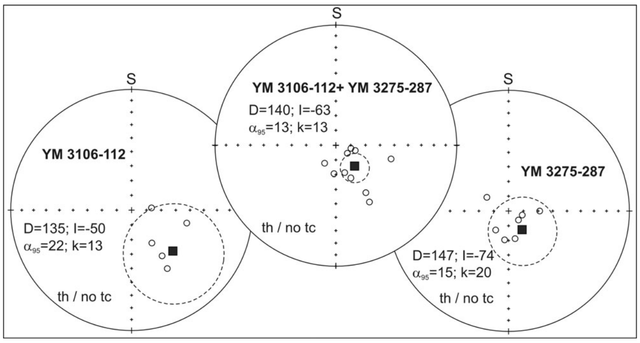


Fig. 12. Mutalj Open Pit, limestone with paleokarst. Paleomagnetic directions (open circles), locality mean paleomagnetic directions (squares) with statistical parameters a_{95} (interrupted line). Stereographic projection. Key: open circles - negative inclination.

Serbia – see Ćorić *et al*. 2009). All the collected facts from the Vojvodina Province and Fruška Gora Mt. indicate to a similar time event (Petković *et al*. 1976; Radivojević *et al*. 2010). It is considered that the marine transgression engulfed the Fruška Gora Island surrounded by the Central Paratethys Sea. On the southern flank of FG, there are no Lower Badenian rocks on the surface. The only evidence for them was found in borehole B-16/05, where sandy marl was drilled at a depth of 53 meters under the surface (see Fig. 2, B–B'). On the other hand, Lower Badenian marine deposits on the northern slopes of FG have a wider distribution (Petković *et al*. 1976). Nevertheless, younger Badenian sediments have a much wider distribution on FG. During the Late Badenian (Early Serravallian, *ca*. 13.6–12.7 Ma), algal–bryozoans, and coralline reefs built a distinct belt along both sides of the mountain (Erdelj, Ležimir, Mutalj, *etc*.). The main sedimentological feature is the enhanced carbonate production controlled by strong volcanism (tuffs, dacites, andesites, *etc*.). These Badenian limestones are not only high-quality raw materials, but also contain extremely fine association of fossil mollusks, algae, coral, bryozoans, foraminifers, ostracodes and other fauna. For example, warm-temperature pectinids and ostreids suggest a shallow-marine, sublittoral to littoral environment (Schmid *et al*. 2001). The mentioned biomicrudites with abundant reef-builders could be a part of a small carbonate platform that is existed in the area of FG. Similar records come from northern Croatia and Austria (Schmid *et al*. 2001; Vrsaljko *et al*. 2006). Temperature estimates for the Central Paratethys Miocene mostly rely on a comparison of the biota characteristic for a certain time interval with their present-day relatives. Additionally, a number of isotope and trace element studies are also available for the period considered (Báldi 2006; Kováčová *et al*. 2009). However, a direct interpretation of these records in terms of paleo-temperature without a consistent control based on faunal records is unsafe (Latal *et al*. 2006). The reason is that relatively small epicontinental seas, such as the Paratethys, can be strongly influenced by regional differences in seawater isotope composition (LATAL *et al.* 2006; HARZHAUSER *et al.* 2007). For this reason, some authors try to calculate the Paratethyan temperature record based on the open/closure position of the main gateways between the Mediterranean, the Indian Ocean, the Atlantic Ocean, and the Paratethys (KARAMI *et al.* 2011). They applied an oceanic 4-box model to determine the temperature, salinity and exchange flows for the Paratethys and the Mediterranean Sea before and after closure of the Indian Ocean gateways. They concluded that closure of the gateways connecting Paratethys and the Mediterranean to the Indian Ocean had a great impact on the temperature of the basin's temperature as well as on its salinity. Following this model, it seems that the Badenian predominantly algal and bryozoan limestone suggests warm-temperature conditions (17–21°C) in this period (KOVÁČ *et al.* 2007).

Based on the lithological succession, the geological and hydrogeological cross-sections and the results of the infiltration tests, it can be asserted with confidence that there is no hydraulic connection between the Mutalj and Beli Kamen Quarries that could have a significant impact on aquifer recharge.

The paleomagnetic study of the post-Badenian lateritic clays shows that biogenic limestones and their products should not be rejected *a priori* as unsuitable for paleomagnetism but should be viewed as potential carriers of the primary RM. The carrier of remanent magnetization in these clays is magnetite, which occurs in significant concentrations and probably has a primary origin. In relation to the Badenian sediments on the northern slope of FG, which have a positive RM polarity, they have the opposite RM polarity and, practically, same values of inclination (CVETKOV 2010; LESIĆ *et al.* 2007). The declination of the RM is counter-clockwise rotated, which is typical for Badenian deposits on FG (LESIĆ *et al.* 2007), as well as for other rock masses of the southern part of the Pannonian Basin (MARTON 2005). On the other hand, the extracted paleodirection is limited by the Late Pliocene rotation and the Badenian limestone underlying the Pontian sediments, hence, it can be concluded that the mentioned clays formed during the Middle–Late Miocene. This is contrary to common opinion that they belongs to the Pleistocene (the Srem Formation, see PETKOVIĆ *et al.* 1976)

Conclusions

The Mutalj Quarry is located on the southern slope of Fruška Gora. It is the largest Miocene quarry in this part of the mountain. It occupies of 0.3 square kilometer of a more or less rectangular area and the mean thickness is more than 40 meters (recent data). The high content of carbonate (more than 98 %) in the limestones allows them to be very important raw materials for cement production (La Farge Cement Factory, Beočin).

Core data, structural and stratigraphic measurements show that the whole limestone deposit on the southern slope of FG belongs to a narrow, discontinuous belt of Middle Miocene Badenian sediments with E–W extension. In the Mutalj Quarry, the limestone has the largest distribution and transgressively lies over the Lower Miocene Vrdnik Formation (up to date, there is no confident data regarding the precise stratigraphic position of these rocks). There are no other Miocene units there. This means that the Middle Miocene Sarmatian and the whole Upper Miocene are completely missing. Different Pleistocene sediments including the red continental beds (the Srem Formation) and the loess–paleosoil sequences form the cover of this limestone.

Sedimentological analyses as well as fossil remains from the limestone indicate to favorable conditions needed for development of marine, shallow-water assemblages (mollusks, foraminifers) and reef-forming organisms, such as red algae, bryozoans, corals, *etc*. This indicates to the Badenian marine transgression in this part of the Central Paratethys. The mostly algal and bryozoan limestone suggests warm-temperature conditions (17–21°C). This biogenic, shallow-water carbonate unit on the Mutalj Open Pit represents the best section of Leitha limestone on the investigated area. After the Badenian, a continental regime replaced this marine one. Due to the drier climate, red lateritic beds were formed upwards. Additionally, numerous cracks and caverns within the limestone were formed. Later, fine-grained prolluvial sediments infilled them.

The Middle Miocene Badenian limestone provides a good environment for the formation of karst aquifers. Analyses of hydrogeological mapping in the wider area of the Mutalj Open Pit, and data from boreholes and infiltration tests determined the large permeability potential of this limestone. The coefficient of filtration is about $K = 10^{-2}$ cm/s, thus they belong to the highly permeable sediments.

Based on paleomagnetic investigations, it was determined that the magnetite-bearing sediments deposited during the post-Badenian time mainly do not carry a coherent. In relation to the Badenian sediments on the northern slope of the FG that have a positive RM polarity, they have the opposite RM polarity. The declination of the RM is counter-clockwise rotated, which is a characteristic for Badenian Age (LESIĆ *et al.* 2007). However, the extracted paleodirection is limited by the well known the Late Pliocene rotation. Therefore, it can be concluded that the mentioned clays probably formed during the Middle–Late Miocene.

Acknowledgements

We would like to express gratitude to the La Farge Co. (Beočin, Serbia) for allowing access to their quarries. The authors wish to thank STJEPAN ĆORIĆ (GEOLOGICAL SURVEY, VIENNA) for useful comments that significantly improved the paper. In addition, thanks go to VIOLETA GAJIĆ (RGF, BELGRADE) and MARIJA ĐEDOVIĆ (HIDRO-GEO RAD, BELGRADE) for technical support. The Ministry of Education and Science of the Republic of Serbia, Project No. 176015, supported this study.

Reference

BÁLDI, K. 2006. Paleoceanography and climate of the Badenian (Middle Miocene, 16.4–13.0 Ma) in the Central Paratethys based on foraminifera and stable isotope (δ^{18}O and δ^{13}C) evidence. *International Journal of Earth Science*, 95: 119–142.

CISOWSKI, S. 1981. Interacting *vs*. non-interacting single domain behavior in natural and synthetic samples. *Physics of the Earth and Planetary Interiors*, 26: 56–62.

CLOETINGH, S., BADA, G., MATENCO, L., LANKREIJER, A., HORVÁTH, F. & DINU, C. 2006. Modes of basin (de)formation, lithospheric strength and vertical motions in the Pannonian–Carpathian system: inferences from thermomechanical modeling. *Geological Society of London*, 32: 207–221.

CVETKOV, V. 2010. Paleomagnetism of Fruška gora. 139 pp. Unpublished PhD Thesis, University of Belgrade, Faculty of Mining and Geology.

DOMBRÁDI, E., SOKOUTIS, D., BADA, G., CLOETINGH, S. & HORVÁTH, F. 2010. Modelling recent deformation of the Pannonian lithosphere: Lithospheric folding and tectonic topography. *Tectonophysics*, 484: 103–118.

ĆORIĆ, S. & RÖGL, F., 2004. Roggendorf-1 borehole, a key-section for Lower Badenian transgressions and the stratigraphic position of the Grund Formation (Molasse Basin, Lower Austria). *Geologica Carpathica*, 55 (2): 165–178.

ĆORIĆ, S., HARZHAUSER M., HOHENEGGER, J., MANDIC, O., PERVESLER, P., ROETZEL, R., RÖGL, F., SCHOLGER, R., SPEZZAFERRI, S., STINGL, K., ŠVÁBENICKÁ, L., ZORN, I. & ZUSCHIN, M. 2004. Stratigraphy and correlation of the Grund Formation in the Molasse Basin, northeastern Austria (Middle Miocene, Lower Badenian). *Geologica Carpathica*, 55 (2): 207–215.

ĆORIĆ, S., PAVELIĆ, D., RÖGL, F., MANDIC, O., VRABAC, S., AVANIĆ, R., JERKOVIĆ, L. & VRANJKOVIĆ, A. 2009. Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geologica Croatica*, 62: 31–43.

ČIČULIĆ, M. 1958. Oligocene and Miocene of Fruška Gora (Syrmien). *Bulletine Scientifiques*, Zagreb, 4 (2): 48–49 (in German).

ČIČULIĆ-TRIFUNOVIĆ, M. & RAKIĆ, M. 1971. Basic geological map 1:100,000, Sheet Novi Sad, with Explanatory book. 52 pp. *Savezni geološki zavod*, Beograd (in Serbian)

FISHER, R.A. 1953. Dispersion on a sphere. *Proceedings of the Royal Society of London, Series A*, 217: 295–305.

FODOR. L., BADA G., CSILLAG G., HORVÁT, E., RUSZKICZAY-RÜDIGER, Z., PALOTÁS, K., SÍKHEGYI, F., TIMÁR, G., CLOETING S. & HORVÁT, F. 2005. An outline of neotectonic structures and morphotectonics of the western and central Pannonian Basin. *Tectonophysics,* 410: 15–41

GANIĆ, M., RUNDIĆ, LJ., KNEŽEVIĆ, S., VASIĆ, N. & RADONJIĆ, M. 2009. Northern slopes of Fruska Gora Mountain, Beočin vicinity (southern part of the Central Paratethys) – a representative example of the Neogene succession. *3rd International Workshop Neogene of Central and South-Eastern Europe, Abstract volume*, 33–34, Cluj-Napoca.

GANIĆ M., RUNDIĆ LJ., KNEŽEVIĆ S. & CVETKOV V. 2010: Late Miocene Pannon marls from the Filijala Open Pit (Beocin, northern Serbia): new geological and paleomagnetic data. *Geološki anali Balkanskoga poluostrva,* 71: 95–108

HARZHAUSER, M. & PILLER, W.E. 2007. Benchmark data of a changing sea – Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 253: 8–31.

HARZHAUSER, M., PILLER, W. E. & LATAL, C. 2007. Geodynamic impact on the stable isotope signatures in a shallow epicontinental sea. *Terra Nova*, 19: 324–330.

HOHENEGGER, J., RÖGL, F., ĆORIĆ, S., PERVESLER, P., LIRER, F., ROETZEL, R., SCHOLGER, R. & STINGL, K. 2009. The Styrian Basin: A key to the Middle Miocene (Badenian/Langhian) Central Paratethys transgressions. *Austrian Journal of Earth Science,* 102: 102–132.

HORVÁTH, F., BADA, G., SZAFIÁN, P., TARI, G., ÁDÁM, A. & CLOETINGH, S. 2006. Formation and deformation of the Pannonian Basin. *In*: GEE, D.G. & STEPHENSON, R.A. (eds.), European lithosphere dynamics. *Geological Society of London,* 32: 191–207.

KARAMI, M.P., DE LEEUW, A., KRIJGSMAN, W., MEIJER, P.Th. & WORTEL, M.J.R. 2011. The role of gateways in the evolution of temperature and salinity of semi-enclosed basins: An oceanic box model for the Miocene Mediterranean Sea and Paratethys. *Global and Planetary Change*, 79: 73–88.

KIRSCHVINK, J.L. 1980. The least-square line and plane and the analysis of paleomagnetic data. *Geophysical Journal of the Royal Astronomical Society*, 62: 699–718.

KOCH, A. 1876. Neue Beiträge zur Geologie der Fruška Gora in Ostslavonien. *Jahrbuch der Kaiserlich-Königlichen Geologischen Reichsanstalt,* 26: 1–48.

KOVÁČ, M., ANDREYEVA-GRIGOROVICH, A., BARJAKTEREVIĆ, Z., BRZOBOHATY, R., FILIPESCU, S., FODOR, L., HARZHAUSER, M., NAGYMAROSY, A., OSZCZYPKO, N., PAVELIĆ, D., RÖGL, F., SAFTIĆ, B., SLIVA, L. & STUDENCKA, B. 2007. Badenian evolution of the Central Paratethys Sea: paleogeography, climate and eustatic sea-level changes. *Geologica Carpathica*, 58 (6): 579–606.

KOVÁČOVÁ, P., EMMANUEL, L., HUDÁČKOVÁ, N. & RENARD, M. 2009. Central Paratethys paleoenvironment during the Badenian (Middle Miocene): evidence from foraminifera and stable isotope (δ^{13}C and δ^{18}O) study in the

Vienna Basin (Slovakia). *International Journal of Earth Science*, 98: 1109–1127.

LATAL, C., PILLER, W. E. & HARZHAUSER, M. 2006. Shifts in oxygen and carbon signals in marine molluscs from the Central Paratethys (Europe) around the Lower/Middle Miocene transition. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 231: 347–360.

LENZ, O. 1874. Beitrage zur Geologie der Fruska Gora in Syrmien. *Jahrbuch der Kaiserlich-Königlichen Geologischen Reichsanstalt,* 24: 325–332.

LESIĆ, V., MARTON, E. & CVETKOV, V. 2007. Paleomagnetic detection of Tertiary rotations in the Southern Pannonian Basin (Fruška Gora). *Geologica Carpathica*, 58 (2): 185–193.

LOWRIE, W. 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophysical Research Letters,* 17 (2): 159–162.

MAROVIĆ, M., TOLJIĆ, M., RUNDIĆ, LJ. & MILIVOJEVIĆ, J. 2007. Neoalpine tectonics of Serbia. *Serbian Geological Society*, series Monographs, 87 pp., Belgrade.

MÁRTON, E. 2005. Post-Badenian Horizontal Movements in the Pannonian Basin as Indicated by Paleomagnetic Data. *GeoLines*, 19: 82–84.

PAVELIĆ, D. & KOVAČIĆ, M. 1999. Lower Miocene Alluvial Deposits of the Požeška Mt. (Pannonian Basin, Northern Croatia): Cycles, Megacycles and Tectonic Implications. *Geologica Croatica*, 52 (1): 67–76.

PETKOVIĆ, K., ČIČULIĆ-TRIFUNOVIĆ, M., PAŠIĆ, M. & RAKIĆ, M. 1976. Fruška Gora – Monographic review of geological materials and tectonic assembly. 267 pp. *Matica srpska*, Novi Sad (in Serbian with French summary).

PILLER, W.E., HARZHAUSER, M. & MANDIC, O. 2007. Miocene Central Paratethys stratigraphy – current status and future directions. *Stratigraphy*, 4: 71–88.

RADIVOJEVIĆ, D., RUNDIĆ, Lj. & KNEŽEVIĆ, S. 2010. Geology of the Čoka structure in northern Banat (Central Paratethys, Serbia). *Geologica Carpathica*, 61: 341–352.

RÖGL, F., ĆORIĆ, S., HARZHAUSER, M., JIMENEZ-MORENO, G., KROHN, A., SCHULTZ, O., WESSELY, G. & ZORN, I. 2008. The Middle Miocene Badenian stratotype at Baden-Sooss (Lower Austria). *Geologica Carpathica*., 59: 367–374.

RUNDIĆ, LJ. DULIĆ, I., KNEŽEVIĆ, S., BOGIĆEVIĆ, G., GAJIĆ, V. & CVIJIĆ, P. (eds.). 2005. The First International Workshop on Neogene of Central and South-Eastern Europe, Fruška Gora - Field Guide. *Serbian Geological Society*, 1–31, Novi Sad.

SCHMID, S., BERNOULLI, D., FÜGENSCHUH, B., MATENCO, L., SCHEFER, S., SCHUSTER, R., TISCHLER, M. & USTASZEWSKI, K. 2008. The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences*, 101: 139–183.

SCHMID, H. P., HARZHAUSER, M. & KROH, A., 2001. Hypoxic Events on a middle Miocene Carbonate Platform of the Central Paratethys (Austria, Badenian, 14 Ma). *Annales Naturhistorische Museum Wien*, 102A: 1–50.

TER BORGH, M., VASILIEV, I., STOICA, M., KNEŽEVIĆ, S., MATENCO, L., KRIJGSMAN, W., RUNDIĆ, Lj. & CLOETINGH, S. 2011: The age of the isolation and evolution of the sedimentary infill of the Pannonian Basin. Geophysical Research Abstracts, vol. 13, EGU 2011-6492.

VRSALJKO, D., PAVELIĆ, D., MIKNIĆ, M., BRKIĆ, M., KOVAČIĆ, M., HEĆIMOVIĆ, I., HAJEK-TADESSE, V., AVANIĆ, R. & KURTANJEK, N. 2006. Middle Miocene (Upper Badenian/Sarmatian) Palaeoecology and Evolution of the Environments in the Area of Medvednica Mt. (North Croatia). *Geologica Croatica*, 59: 51–63.

Резиме

Нови подаци о старијем средњем миоцену на јужним падинама Фрушке Горе (северна Србија): пример каменолома Мутаљ

Током последњих неколико година, истраживања која је на јужним падинама Фрушке горе спровела компанија ЛАФАРЖ, омогућила су откриће значајних наслага средње миоценских кречњака. Ту се пре свега мисли на тзв. баденски лајтовац који представља важну компоненту у производњи цемента. Висок садржај карбоната (преко 98%), омогућује им да буду важна сировина која се додаје лапорцу у процесу стварања цементног клинкера. Стална експлоатација овог камена на каменолому Мутаљ, омогућила је увид у његове структурно-тектонске, стратиграфске и седиментолошке и хидрогеолошке карактеристике. Скоро по правилу, баденски кречњаци леже дискордантно преко различитих кластичних творевина тзв. Врдничке серије (формације). С друге стране, углавном су покривени неколико метара дебелим серијама тзв. Сремске серије и лесно-палеоземљишних секвенци. Бројни фосилни докази (алге, мекушци, корали, бриозое и фораминифере) указују да кречњаци припадају млађим еквивалентима баденског ката. Њихове литолошке и седиментолошке особине указују на плитку, субспрудну морску средину. Бројне истражне бушотине, анализа њихових језгара и интерпретација структурних профила указују на испрекидан појас пружања ових седимената на јужним падинама Фрушке горе (са запада ка истоку). Експанзивна експлоатација кречњака са површине од око 0,3 km^2 брзо мења и њихове техничке карактеристике (сада је просечна дебљина преко 40 m у односу на раније године кад је била преко 100 m).

Са хидрогеолошког аспекта гледано, баденски кречњаци представљају добру средину за формирање карстне издани што је истражним бушењем, уградњом пиезометара и осталим хидрогеолошким испитивањима и потврђено. Коефицијент филтрације баденских кречњака указује на добро пропустљиве седименте (K=10^{-2} cm/s). Новим истраживањима (2010) је утврђено да не постоји хидраулична веза (нема јединствене карстне издани) између Мутаља и напуштеног оближњег каменолома Бели Камен. Висинска разлика између кота водених огледала на та два копа износи око 15 m. Палеомагнетна истраживања пост-баденских латеритских глина показују да се биогени кречњаци не смеју априори одбацити као неподобне стене за палеомагнетна мерења, и треба их посматрати као потенцијалне носиоце примарне магнетизације. Носилац реманентне магнетизације у овим глина је магнетит, који се јавља у великом концентрацијама и вероватно има примарно порекло. У односу на баденске седименте на северним падинама Фрушке Горе који имају позитиван поларитет реманентне магнетизације, ове глине на Мутаљу имају супротан поларитет и практично, исте вредности инклинације (LESIĆ *et al*. 2007; CVETKOV 2010). Деклинација реманентне магнетизације показује ротацију у смеру супротно кретању казаљке на сату што је типично за баден Фрушке горе (LESIĆ *et al*. 2007) као и за остале стене у јужном делу Панонског басена (MARTON 2005). С друге стране, издвојени палеоправац је ограничен млађе плиоценском ротацијом те се може закључити да су поменуте глине формиране у периоду средњи–горњи миоцен.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	87–100	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172087G

Petrophysical and mechanical properties of the Struganik limestone (Vardar Zone, western Serbia)

Violeta Gajić[1], Vesna Matović[1],
Nebojša Vasić[1] & Danica Srećković-Batoćanin[1]

Abstract. The Struganik limestone has been increasingly popular in recent years for interior and exterior building applications, due to easy workability, low cost and multi purpose suitability. The quality of limestone is determined by its mineralogical and textural characteristics and physico-mechanical properties. The Struganik stone corresponds to marl, clayey limestone and limestone (micritic and allochemical). The limestone is commonly layered, either thinly bedded or banked. Chert concretions are present in all varieties. The Upper and the Lower Campanian age were deduced by the abundant foraminifers. Micrite limestone is an autochthonous rock generated in a deep marine environment, whereas allochemical limestone is related to a shallow marine environment but subsequently brought into a deep-water system.

The mass quality of the Struganik limestone is controlled by variability of lithology and layering. The values of physico-mechanical properties, such as density, porosity, water absorption and strength, were statistically analyzed and the obtained data were used to assess the rock quality in the quarry. The relationship among the quantified properties is described by regression analyses and the equations of the best-fit line.

The Struganik limestone was qualified by its petrological and engineering properties coupled with statistical analysis. It satisfies the majority of the requirements of the Main National Standard as a decorative stone, but with a limiting factor regarding abrasive resistance.

Key words: Struganik limestone, western Serbia, petrology, physico-mechanical properties, correlation, rock quality.

Апстракт. Интересовање и примена струганичких кречњака како у екстеријеру, тако и у ентеријеру је у порасту последњих година, посебно у западној Србији, због њихове лаке обраде, ниске цене и могућности различите примене. Квалитет кречњака зависи од његових минералошких и текстурних, као и физичко-механичких својстава. Петролошки, струганички кречњаци одговарају лапорцима, глиновитим кречњацима и кречњацима (микритски и алохемијски). Обично су слојевити, танкоплочасти или банковити. У свим варијететима јављају се конкрециони рожнаци. На основу бројних фораминифера ови седименти су сврстани у доњи и горњи кампан. Микритски кречњаци су аутохтоне стене настале у дубоководној маринској средини, док је порекло алохемијских кречњака везано за плитку морску средину, одакле су принети у дубоководни систем.

Квалитет струганичких кречњака је условљен литолошким саставом и типом слојевитости. Вредности физичко-механичких својстава, као што су густина, порозност, упијање влаге и чврстоћа, статистички су анализирани, а добијени резултати су коришћени као показатељи квалитета стенске масе каменолома. Односи између испитиваних својстава су испитани регресионом анализом и изражени једначином “best-fit line”. Петрографска и техничка својства заједно са резултатима статистичке регресионе анализе која је примењена у овом раду, указују да струганички кречњаци по свом квалитету испуњавају већину захтева сходно главном националном стандарду за примену архитектонског камена, а да је ограничавајући фактор њихова отпорност према хабању.

Кључне речи: струганички кречњак, западна Србија, петрологија, физичко-механичке особине, корелација, квалитет кречњака.

[1] Department of Petrology and Geochemistry, Faculty of Mining and Geology, University of Belgrade, Djušina 7, 11000 Belgrade, Serbia. E-mails: violeta.gajic@rgf.bg.ac.rs; vesna.matovic@rgf.bg.ac.rs; nebojsa.vasic@rgf.bg.ac.rs; danica.sreckovic@rgf.bg.ac.rs

Introduction

Natural stone is one of the most common construction materials. Dimension stone is used in areas where the aesthetical properties (color, design), soundness of the deposit and market demand are crucial factors (LUODES *et al*. 2000). To be used for the interior and exterior of buildings, a natural stone must satisfy standardized physical and mechanical requirements strictly (YAGIZ 2010). Petrophysical and mechanical properties of sedimentary rocks are influenced by the size, shape, packing of grains, porosity, cement and matrix content, depending strongly on depositional fabric and post-depositional processes (ANDRIANI & WALSH 2002). These properties are measured in laboratories by standardized, relatively simple methods but they are time consuming and expensive and require a well-prepared rock sample. For this reason, the modern world trend in geological and civil engineering practice is the investigation of the relationship between complex mechanical and simple physical properties. The equations for estimating mechanical properties on the base of simpler, faster and more economical indirect tests have been presented by a great number of authors (HANDLIN & HAGER 1957; D'ANDREA *et. al*. 1964; DEER & MILLER 1966; BROCH & FRANKLIN 1972; OLLSON 1974; BIENIAWSKI 1967, 1975; HUGMAN & FREIDMAN 1979; GUNSALLUS & KULHAWY 1984; FREDRICH *et al*. 1990; WONG *et. al*. 1996; HOFFMAN & NIESEL 1996; HATZOR *et al*. 1997, 1998; TURGUL & ZARIF 1999; PALCHIK *et al*. 2000, 2002).

Carbonate deposits with different lithology, age and quality are widespread in Serbia, making limestone the most excavated stone for building purposes. In the western part of Serbia, particularly in the Mionica area (Fig. 1), there are more than 70 quarries excavating limestone known as Struganik stone. The first written data related to the exploitation of this stone dates back to 1737. In 1861, Struganik stone was used for the building of the Vienna Opera House.

In the last two decades, the popularity of this limestone and its use as an architectural stone has increased rapidly due to its cost coupled with aesthetic value, quality and available reserves. It is still the main building material in this area, used for exterior and interior cladding but with limited application mainly due to insufficient investigations from geological and engineering aspects. Many authors investigated the stratigraphy of this area (*e.g*., ANĐELKOVIĆ 1978), paleontological assemblages (*e.g*., FILIPOVIĆ *et al*. 1978) and tectonic features (KARAMATA *et al*. 1994, 2000; DIMITRIJEVIĆ 2001; GERZINA 2002; ROBERTSON *et al*. 2009). Only a small number of recently published papers provide general information on the stratigraphy and lithology of stone in the Struganik area (VASIĆ *et al*. 2001; RABRENOVIĆ *et al*. 2002; VASIĆ *et al*. 2005; GAJIĆ 2007; DJERIĆ *et al*. 2009; GAJIĆ & VASIĆ 2011). Unfortunately, petrological and technical features of the Struganik limestone, data of the depositional processes and problems of the quality and assortment of use have not yet been studied in detail. Insufficient data raised a necessity for an improvement of the exploration methodology of the Struganik limestone. Therefore, studies concerning the fabric of the Struganik limestone and its quality as a building stone have not only theoretical significance, but also practical importance for civil engineering.

The object of the present investigation was the oldest and largest quarry in the Struganik area, with the same name (Fig. 2), located about 100 km southwest of Belgrade (Fig. 1).

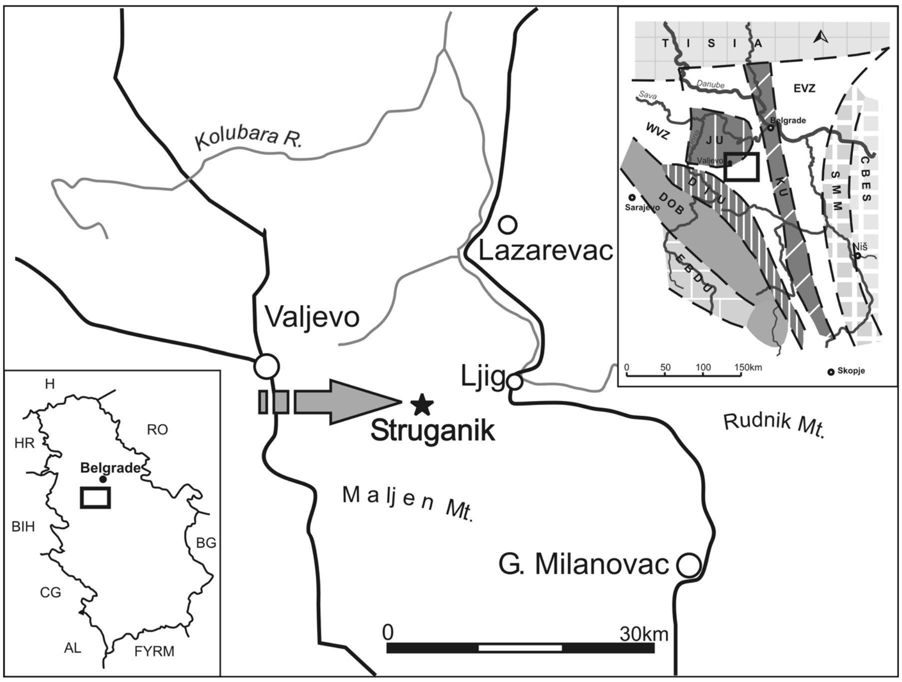


Fig. 1. Location of the Struganik limestone in western Serbia, central part of the Vardar Zone. Right: Terranes of the central part of the Balkan Peninsula (According to KARAMATA & KRSTIĆ 1996; KARAMATA 2006 and ROBERTSON *et al*. 2009). Key (in alphabetic order): **CBES,** Eastern Serbian Carpatho–Balkanides; **DIU,** Drina–Ivanjica Unit; **DOB,** Dinaride Ophiolite Belt; **EVZ,** Eastern Vardar Ophiolitic Zone; **JU,** Jadar Unit; **KU,** Kopaonik Unit; **SMM,** Serbo–Macedonian Massif; **WVZ,** Western Vardar Ophiolitic Zone.

This quarry is irregular in shape, elongated in the NW–SE direction and opened at approximately 0.32 km^2 (KIJANOVIĆ 2007). The extraction in it, 30 years old, is constrained by bedding planes in limestone (Fig. 2). The extraction comprises the removal of large tiles and their cutting into natural-faced slabs usually 2–3 cm thick using a circular blade saw or hand tools. These products, with natural appearance, are packed on a palette and ready for use as external and interior cladding. Their limited application is mainly caused by insufficient investigations of their properties needed to meet the requirements of architectural stone.

Fig. 2. The "Struganik" quarry in the Struganik area.

The purpose of this study was a detail determination of the lithological, structural and textural properties, and the depositional processes and their link with physical and mechanical properties. This work provides new geological data for the Struganik limestone based on petrological field observations, optical and chemical analysis of the collected samples, as well as on results of a statistical analysis of the geomechanical characteristics and, finally, an assessment of the limestone quality as a building stone.

Geological setting

Geological setting of the Struganik area consists of Mesozoic formations of Triassic, Jurassic and Cretaceous age, and of Quaternary sediments to a lesser extent. According to ANĐELKOVIĆ (1978), the shallow Triassic sediments were deposited over the Permian. Complex and geotectonic processes during the Jurassic led to the formation of the ophiolite mélange (SCHMID *et al*., 2008). The Struganik area is part of the northern rim of the Maljen ophiolitic massif. This region is in the Vardar Zone Western Belt (Fig. 1; KARAMATA & KRSTIĆ 1996; KARAMATA 2006; ROBERTSON *et al*. 2009).

In the wider area, Cretaceous sedimentation commenced with the Albian transgression. Terrigenous-carbonate and carbonate sedimentation continued from the Albian to the Maastrichtian, while flysch ("Ljig flysch") sediments were deposited in the latest Senonian (FILIPOVIĆ *et al*. 1978).

According to data obtained during geological studies in the villages Osečenica, Brežđe and Struganik, MARKOVIĆ & ANĐELKOVIĆ (1953) considered the Struganik limestones as Senonian, *i.e*., as the latest Cretaceous products in this area. The Cretaceous sediments in the broader Struganik area were studied recently by VASIĆ *et al*. (2001), RABRENOVIĆ *et al*. (2002), GERZINA (2002), VASIĆ *et al*. (2005), GAJIĆ (2007), DJERIĆ *et al*. (2009), GAJIĆ & VASIĆ (2011). FILIPOVIĆ *et al*. (1978) distinguished within the Cretaceous sediments the following members: detrital limestones, claystones and sandy marlstones of Albian age, conglomerates and limestones of Albian–Cenomanian age, Cenomanian conglomerates, limestones, marlstones and sandstones, organogenic-detrital limestones and marlstones of the Cenomanian–Turonian, a limestone and limestone–marlstone series of Turonian–Senonian age and Campanian–Maastrichtian flysch (Fig. 3).

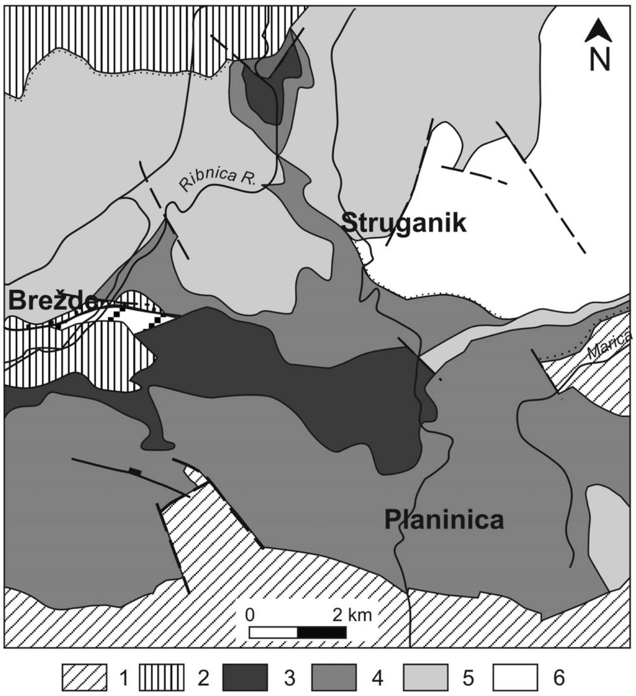


Fig. 3. Simplified geological map of the Struganik area based on the Basic Geological map sheet Gornji Milanovac 1:100000 (FILIPOVIĆ *et al*. 1976). Legend: **1,** Jurassic ophiolite mélange; **2,** Triassic shallow sediments; **3,** Conglomerate and limestone of Albian–Cenomanian age; **4,** Cenomanian sediments; **5,** Limestone and limestone–marlstone series of Turonian–Senonian age; **6,** Campanian–Maastrichtian flysch.

The Turonian–Senonian age of the Struganik limestone is documented by the microfossils: *Praeglobotruncana helvetica*, *Rotalipora sp*., *Globotruncana lapparenti coronata*, *etc*. (FILIPOVIĆ *et al*. 1978). A recent micropaleontological analysis, *i.e.,* the association of pelagic globotruncanas, indicates that these sediments are of Campanian age (GAJIĆ 2007). The age of radiolarians from the layer of smectite clay within the micrite limestone of the Struganik was defined as the Coniacian (VASIĆ *et al*. 2005; DJERIĆ *et al*. 2009).

Material and methods

Determination of petrological properties of the Struganik limestone commenced with field observations in the quarry and preparation of a detailed lithological column. A total of 33 samples were collected from the lowest level of the quarry for further laboratory testing in order to assess the structural and chemical composition of the limestone (Fig. 2). A microscopic analysis of thin sections by optical microscopy was used to characterize the mineral composition, microtextural features (size and kind of allochem, grain orientation, *etc*.), and content and type of microfossils. Based on the field inspection and the results of a petrographic (optical) investigation, the rock samples were classified according to the FOLK (1959) and DUNHAM (1962) classification scheme. In the same samples, the contents of CaO and MgO were determined by the complexometric method (EDTA titration) using a standardized solution of 1 M EDTA as the titrant.

In order to examine the quality of the Struganik limestone as a building stone, the physical (bulk and apparent density, porosity, water absorption, frost resistance) and mechanical properties (compressive strength, abrasive resistance) of a total of 18 samples from the quarry were determined. The laboratory tests were performed according to the national standards (Unification of Serbian Standards) at the Laboratory of the Highway Institute of in Belgrade. The bulk density is given as mass per unit of apparent volume. The volume was determined by hydrostatic weighing of the specimens soaked and suspended in water under atmospheric pressure (according to SRPS B.B8.032). On powdery samples, the real densities were determined using a pycnometer with water as the displacement fluid. From the values for real and bulk density, the total porosity was calculated (according to SRPS B.B8.032).

The specimens that were used for the determination of the bulk density were also used for the determination of the water absorption, which was determined by measurement of the mass of water absorbed by the sample after immersion for 48 h at atmospheric pressure. It is expressed as a percentage of the initial mass of the sample previously dried at 105 °C to constant weight (SRPS B.B8.010). The resistance to frost was determined by 25 cycles of freezing to –25 °C and thawing according to SRPS B.B8.001. The freeze–thaw tests were performed on cubic samples to assess the durability of the limestone samples by determining their strength and mass loss after 25 freeze–thaw cycles. The test procedure involved repeating of cycles where one cycle involved placing a water-saturated sample in a freezing chamber for 4 h, after which the sample was totally immersed in water in a thawing tank for 2 h.

The limestone samples were tested for their mechanical properties (compressive strength and abrasion resistance). The uniaxial compressive strength tests (SRPS B.B8.012) were performed on both dry and water-saturated limestone samples (5×5×5 cm cube) and on samples that had been subjected to the freeze–thaw test. According to SRPS B.B8.015, cubic samples of 7 cm in size were used for determination of the Böhme abrasion resistance. The test procedure involved 440 cycles of sample abrasion using abrasion dust (crystalline corundum) on a rotating steel disc under an applied stress of 300 N.

In order to evaluate the relationships between the physical and mechanical properties, different statistical analysis techniques (basic descriptive statistics, correlation, bivariant regression analysis, *etc.*) were performed using the SPSS computer program. All the measured values of the technical properties were statistical analyzed at the level of significance (α) of 0.05. The descriptive statistical parameters included the mean, minimum and maximum value, standard deviation, median, standard error, range, quartiles, standardized skewness, kurtosis, *etc*. The Kolmogorov-Smirnov (non-parametric test for normality) was used with the level of significance set at 0.2.

Subsequently, the results of the laboratory measurements were correlated using the method of least squares regression. Linear regression ($y = ax+b$) were performed and the equations of the best-fit line, the regression coefficient (R^2) and the 95 % confidence limit were determined for the regressions.

Validation of the regression analyses was confirmed by the Student *t*-test and by the test of variant analysis (the *F*-test).

Petrological properties of the Struganik limestones

Struganik limestones are the latest Upper Cretaceous sediments in this part of western Serbia. The limestones are best uncovered in the village Struganik. Exploration were performed in the "Struganik" quarry and a lithological column about 10 m tall was constructed (Fig. 4).

The limestones are massive and compact. Their uniform grayish color throughout the entire deposit is

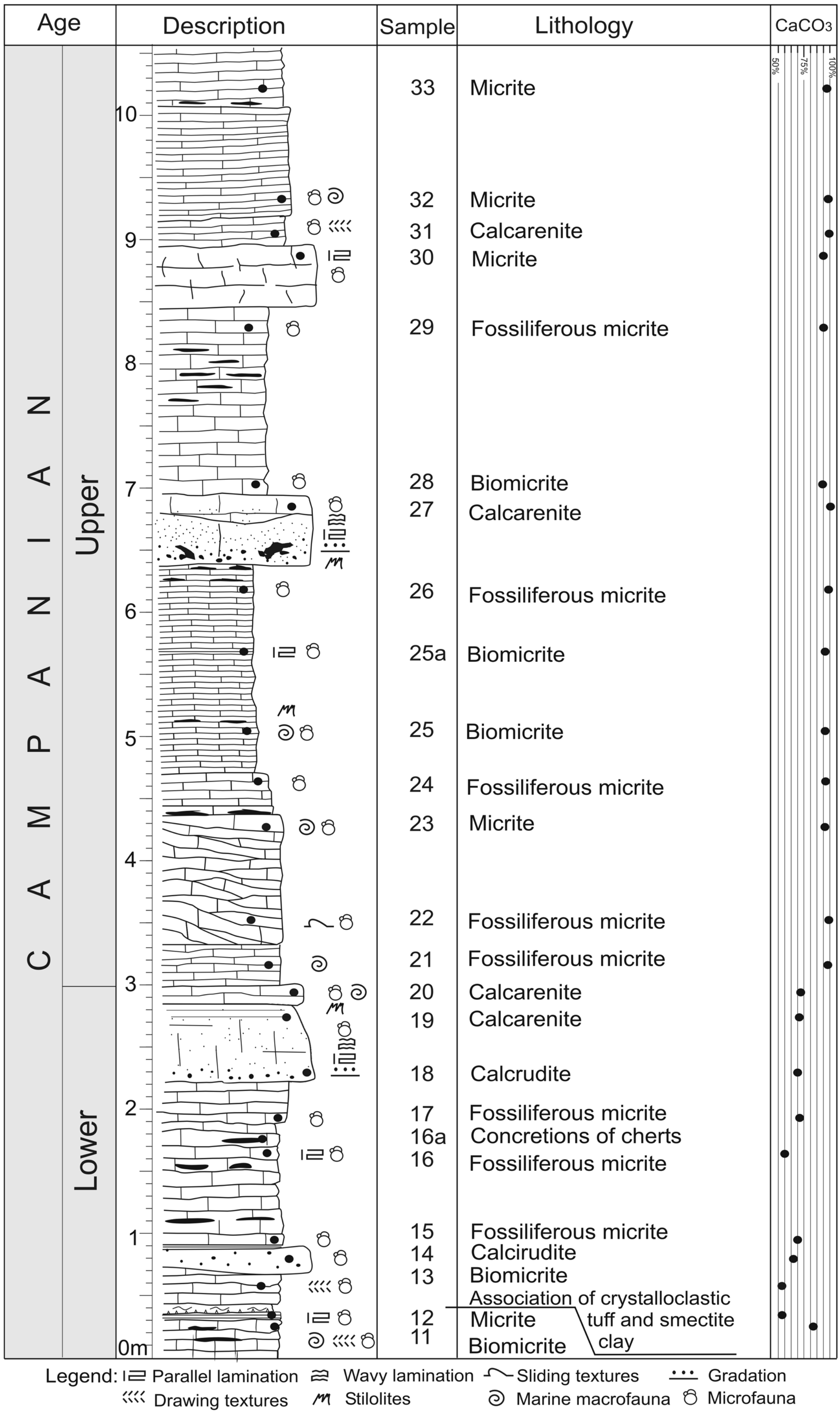


Fig. 4. Local lithological column of the lowest level in the “Struganik”quarry.

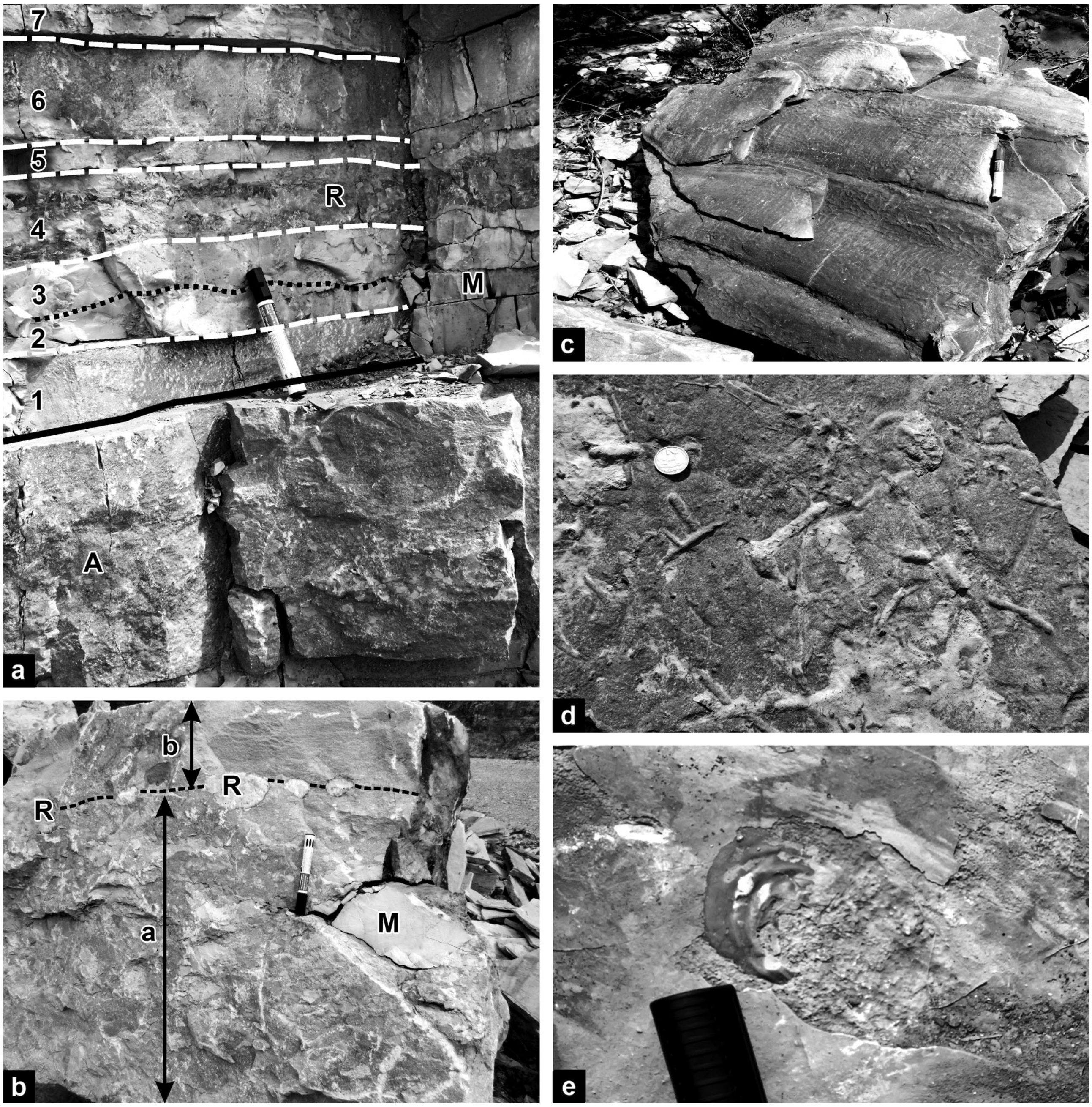


Fig. 5. The appearance of the Struganik limestone. **a,** Beds of Struganik limestone. Thick bed of the allochemical-sparite limestone with gradation (A). Beds of the micrite limestone (1, 2, 3, 4, 5, 6 and 7). Stylolitic boundary surface between beds 2 and 3. Concretional interlayer of black chert in bed 4; **b,** Bank of the allochemical limestone with well-developed Bouma intervals a & b. Interval "a" is calcrudite with fragments of the micrite limestone (caught by turbidity flow). Interval "b" is calcarenite. Along the boundary between a & b whitish concretional chert is developed; **c,** Upper bedding plane with ripple marks in fine-grained calcarenite; **d,** Grouped tracks of life activities on the lower bedding plane in the Struganik limestone (obscured origin); **e,** Test of Inoceramus in the micrite limestone.

sporadically disturbed by the presence of dark gray, grayish blue or whitish chert concretions.

The main lithological member is micrite limestone, which represents the autochthonous rock of deep water, marine carbonate sedimentation (Fig. 5). Micrite limestones are layered in thick beds (Fig. 5a). The distinctive beds display notable horizontal lamination. Allochemical limestone, the second lithological member, is related to a shallow marine environment. Subsequently, the shallow water allochems were transported into a deep-water environment by turbidity currents to produce either beds or banks (Fig. 5a) or sporadic packages composed of two or three beds. Allochem limestone carries textures that are characteristic for the turbulent transport (particular intervals of the Bouma Sequence within the layers, Fig. 5b).

Mechanical and biogenic textures are common on the bedding planes in the Struganik limestone (Fig. 5c, Fig. 5d). Bedding planes in both of the mentioned limestones are often stylolitic (Fig. 5a). On the upper bedding planes in micrite limestones, Inoceramus can be found abundantly (Fig. 5e).

The third lithological member, concretional cherts, was produced by silification during diagenesis. The chert concretions are notable textural, as well as being a petrological feature of the Struganik limestone. The chert concretions are uniformly distributed throughout the whole column in both micrite and allochem-sparite limestone (Fig. 5a, Fig. 5b).

The paleontological study of the microfauna (many foraminifers) indicates to Campanian age of the Struganik limestone (GAJIĆ 2007). According to the observed association, the first three meters of the column correspond to the Lower Campanian, whereas the remaining 7 m of the column corresponds to the Upper Campanian.

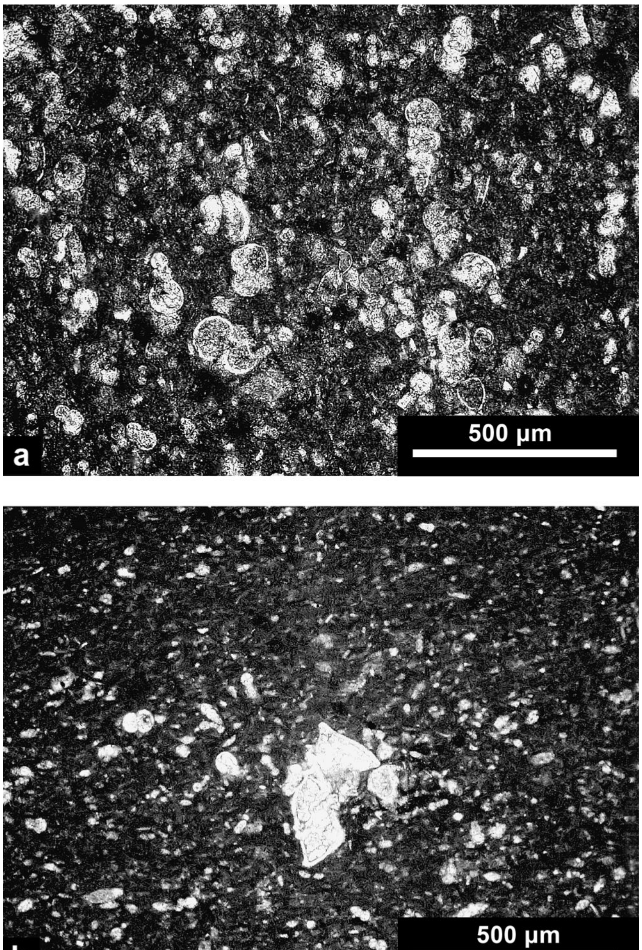


Fig. 6. Photomicrographs of the micrite limestone: **a,** Biomicrite; **b,** Fossiliferous micrite with globotruncana in the middle.

Micrite (orthochemical) limestone

The micrite limestone is mainly composed of microcrystalline calcite – micrite. Non-carbonaceous compounds are clay minerals, organic matter and subordinated silty material. According to the $CaCO_3$ content, micrite limestone refers to pure limestone, clayey limestone and marlstone (Fig. 4). The least amounts of $CaCO_3$ were determined inside the Lower Campanian rocks (marlstone - 55–60 % and clayey limestone - 70–85 %). This is, beside their micro paleontological characteristics, identifiable feature in respect to the Upper Campanian rocks (86–94 %). The allochem (biogenic) component is represented by well-preserved moulds of microorganisms. Pelagic foraminifers (globotruncana) are prevailing, but some calcispheres and radiolarians were also registered. The micrite limestone could be defined by the amount of biogenic component, defined either as micrite and fossiliferous micrite (less than 10 % of biogenic allochem, Fig. 6a), or as biomicrite (biogenic allochem exceeding 10 %, Fig. 6b). According to the DUNHAM classification (1962), the micrite limestone belongs to Mudstone and Wackestone.

Allochemical limestone

The allochemical limestones are represented by alternation of very coarse-grained rudites to fine-grained calcarenites, regarding their textural features, *i.e.*, the coarseness of the particles and the allochem component.

The allochem and orthochem types, the bio-intraspar varieties are the commonest (Fig. 7.). Among the sparry varieties, intrasparrudite, biosparrudite, intrabiosparrudite, biosparite and intrabiosparite may be distinguished.

The biogenic allochem compounds include fragmented moulds of shallow-water organisms (mollusks), moulds of benthos and planktonic microorganisms as well as algal fragments (Fig. 7.a.). Intraclasts might be simple or composite. The simple intraclasts usually occur within the medium and fine-grained calcarenite varieties (Fig. 7.b), while the latter were registered in the coarse-grained varieties of calcarenite of the allochemical limestone. The amount of $CaCO_3$ (calcite) in these limestones is in general higher than in the micrite varieties (Fig. 4), attaining from 67 to 96 %.

Depositional environmental

The Pelagic sediments, represented by marlstone, clayey limestone and limestone, were deposited in the deeper parts of an Upper Cretaceous sea. All the mentioned sediments contain chert concretions, just like the Struganik limestone. The autochthonous sedi-

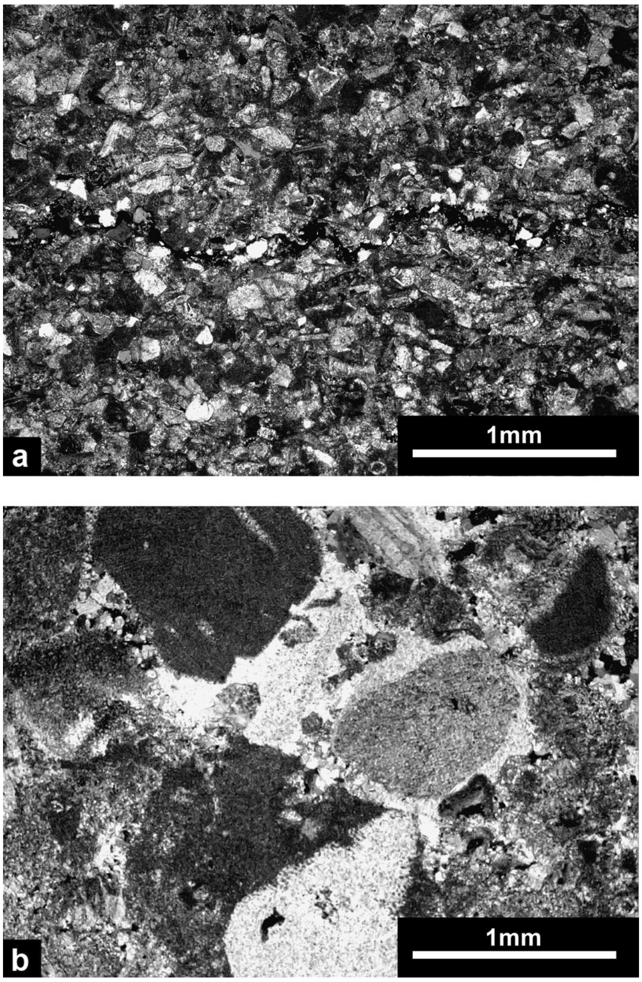


Fig. 7. Photomicrographs of the allochemical limestone: **a,** Fine-grained intrabiosparite. In the middle of the photo is a stylolite seam marked with the accumulation of a sandy component; **b,** Coarse-grained biosparite.

ments are marly limestone and marlstone of micrite and biomicrite composition. The presence of weakly preserved radiolarians and silica sponges in these rocks indicates to their formation at depths deeper than 200 m, while the partial replacement of the siliceous skeletons with calcite implies an alkaline environment, most probably with pH 8 during diagenesis. The presence of concretional cherts indicates the presence of organogenic siliceous remains. The association of rocks and fossil remains is indicative of sedimentation related to a deep marine environment. The presence of layers and banks of allochemsparite, calcarenite and calcrudite with characteristic textures from the Bouma sequence suggests an intermittent supply of shallow-water material by turbid flows along the continental slope, *i.e.*, through the Bathyal Zone.

It could be concluded that the Struganik limestone was derived in a deep marine environment, through deposition on a continental slope.

Physico-mechanical properties of the Struganik limestone

The results obtained from the statistical analyses of the physico-mechanical values of the Struganik limestone are given in Table 1. The real density of a rock is one of its basic properties. It is influenced primarily by the density of the minerals, their content and amount of void space inside the rock (BELL & LINDSAY 1999). In the investigated samples of Struganik limestone, the real density displayed little variation and range from 2700 to 2720 kg/m^3, with a mean value of 2710 kg/m^3. The bulk density also varied slightly due to the low amount of void space and was in range 2610 to 2680 kg/m^3, with a mean value of 2650 kg/m^3. All of the tested samples had a moderate density according to BILBIJA & MATOVIĆ (2009). The values of the absolute porosity varied from 1.10 to 3.30 %. Central tendency parameters indicated a negative asymmetrical unimodal distribution of the porosity, with the most frequency class (1.0–1.5 %) of 43 %. According to the mean value of 2.0 %, these limestones generally have a low porosity, although in some samples a moderate porosity was detected (BILBIJA & MATOVIĆ 2009). The obtained values of water absorption (from 0.17 to 0.67 % with an average value of 0.4 %) indicate a very low water absorption by the Struganik limestone. All the investigated limestone samples were resistance to frost. The mass loss after freezing and thawing was low due to the low porosity of the Struganik limestone.

The values of the central tendency for all the physical parameters were similar and indicate to a symmetric, unimodal distribution conforming closely to a Gauss curve. The statistical parameters of the Kolmogorov-Smirnov test confirmed that all the tested samples had a normal distribution of the measured values of the physical properties ($D_{max} > D_{cr}$, Table 1).

The dry unconfined compressive strength values of the limestones varied between 48 and 189 MPa, with a mean value of 134 MPa (Table 2). Most of the tested samples were very strong (strength > 150 MPa), while over a quarter of the samples were moderately strong according to the proposed strength classification of BILBIJA & MATOVIĆ (2009). The values of the saturated compressive compression strength were between 41 to 177 MPa, with an average value of 120 MPa. The mean of the water saturated samples was 10 % lower than that in the dry state, while after 25 freeze–thaw cycles, it had decreased by 4 % to 129 MPa (mean value), indicating that the Struganik limestone is durable to freezing and thawing. The negligible decrease in the unconfined compressive strength reflects that the amount of saturated water is not an important factor for the strength reduction. A significant reduction in the strength appeared when the porosity of the limestone exceeds 3 % (the reduction was about 30 %). The values of volume loss on wear (Böhme abrasion value) varied from 13.5 to 23.2 cm^3 per 50 cm^2. In terms of the mean value, this limestone is a hard to moderately hard rock (BILBIJA & MATOVIĆ 2009).

The results of regression analysis indicate to a prominent relationship between the dry compressive strength (σ_s) and the water equivalent (σ_v). The trend

Table 1. Statistical parameters of physico-mechanical properties of the Struganik limestone. Legend: n, number of samples; $\bar{X}$, mean; V_{min}, Minimum values; V_{max}, maximum value; $PX_{-95\%}$, confidence intervals for the mean; M, median; Md, Mod; R, range; Q_i, quartile range; Q_1, lower quartile; Q_2, upper quartile; S^2, variance; S, standard deviation; As, Skewness; Kt, Kurtosis; SE, standard error; D_{max}, value of the largest absolute difference between the observed and the expected cumulative distributions; p, confidence interval; D_{cr}, critical value; α, probability level.

Technical properties								
statistical parameters	Bulk density (ZSP)	Real density (ZBP)	Porosity (P)	Water absorption (Uv)	Strength dry (σ_s)	Strength water (σ_v)	Strength frost (σ_m)	Wear abrasive (H_b)
n	18	7	7	16	18	18	7	18
$\bar{X}$	2650	2710	2,0	0,40	134	120	129	19,36
V_{min}	2610	2700	1,1	0,17	48	41	52	13,5
V_{max}	2680	2720	3,3	0,67	189	177	174	23,15
$PX_{-95\%}$	2640	2700	1,35	0,32	109	96	91	17,9
	-2660	-2720	-2,78	-0,48	-159	-144	-168	-20
M	2650	2700	2,3	0,40	152	138	148	19,29
Md	2650	2700	2,3	0,50	156*	146*	148	22,2
R_i	70	20	2,2	0,50	141	136	122	10
Q_1	30	20	1,17	0,21	99,75	88	58	3,55
Q_2	2640	2700	1,4	0,28	85	68	102	18,22
Q^2	2670	2720	2,57	0,50	181	156	160	21,77
S	365	114,28	0,59	0,02	2503	2323	1729	7,637
S	19,11	10,69	0,77	0,14	50,03	48,20	41,58	2,76
As	-0,60	0,37	0,32	0,02	-0,626	-0,477	-1,19	-0,74
Kt	0,05	-28	-0,74	-0,59	-1,181	-1,355	1,18	-0,06
SE	4,50	4,04	0,29	0,03	11,79	11,36	15,71	0,65
Kolmogorov-Smirnov test of normal distribution (D_{max}) α=0.20								
D_{max}	0,135	0,360	0,197	0,077	0,166	0,184	0,240	0,168
p	0.893	0.324	0.949	0.996	0.699	0.571	0.814	0.683
D_{cr}	0,244	0,381	0,381	0,258	0,244	0,244	0,381	0,244
Distrib.	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal

Regression analysis

Regression analysis was applied to obtain relationships between the mechanical and physical properties of the Struganik limestone. Some of these relationships and the best-fit curves between the different parameters are shown in Fig. 8. The relationships show fairly higher correlations between the bulk density (*ZSP*) and the porosity (*P*). The relationship between them is highly significant with a correlation coefficient of –0.929 and a Students t-value of –5.598 ($p < 0.05$; Fig. 8a). The cross plot of porosity and bulk density shows a general trend of increasing bulk density with decreasing absolute porosity. The plot suggests that the bulk density may be used to obtain the value of the porosity.

is positive and clearly linear with a regression coefficient R^2 = 93 % and a Students t-value of 14.717 (Fig. 8b). Comparing the value of the dry strength (σ_s) and that after the freeze–thaw cycles (σ_m), the correlation is positive and high statistically significant with a regression coefficient R^2 = 78 % (t = 4.159; Fig. 8c). Low correlations with no significant Pearson coefficients were obtained for all the other physico-mechanical properties.

Validation of this model was confirmed by the t-test and analysis of the variance (Table 2). As can be seen in Table 2, all the regression coefficients are significant at the 95 % confidence level. The computed t-values are greater than the tabulated critical t-values of ±2.36 and ±2.10 for the obtained models. The analysis of variance follows an F-distribution with degrees

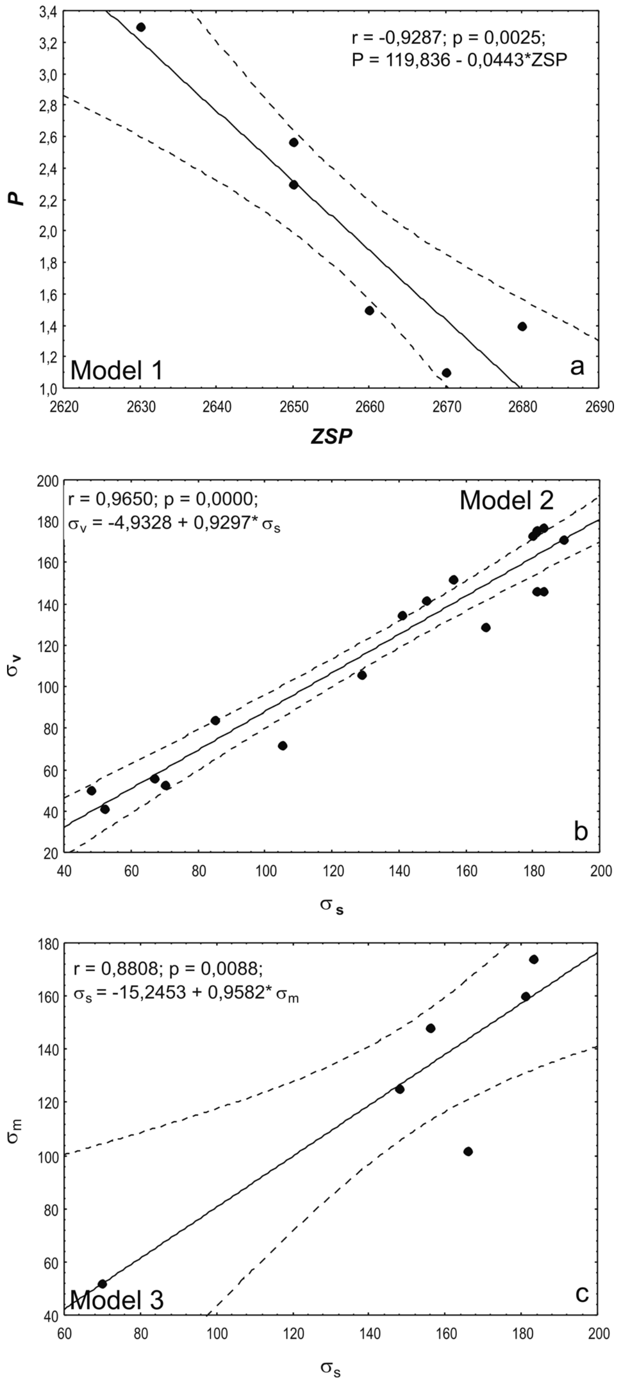


Fig. 8. Relationship between physico-mechanical properties: bulk density *vs*. porosity (a); compressive strength dry *vs*. water equivalent (b); compressive strength dry *vs*. the after freezing equivalent (c).

of freedom $df_1 = 1$ and $df_2 = 5$ for models with samples number of 7, therefore the critical region consists of values exceeding 6.61. For the model with a sample number of 18 ($df_1 = 1$ and $df_2 = 16$), the corresponding critical F value is 4.49. All the computed F values were greater than those tabulated; thus, the null hypothesis can be rejected and it can be concluded that all equations are significant according to the F-test.

Discussion and conclusions

The presence of two lithological types of limestone, *i.e.*, micrite and allochemical, was emphasized. Micrite limestone is the autochthonous rock of a deep water, marine environment. In the original terminology (FOLK 1959), these limestones are considered as orthochemical. The allochemical limestones were derived from shallow-water material that was brought by turbidity currents into the system. The Struganik limestone represents a series of marlstone, clayey limestone and limestone. Concretional cherts and many microfauna are present in all the distinguished varieties. Among the macrofaunal remains, inoceramus is the most frequent.

Generally, the values of physico-mechanical properties indicate the good quality of Struganik limestone as a dimensional stone. Their quality and way of exploitation are directly governed by their petrological properties. Pronounced layering in the micrite varieties results in their exploitation in the form of thin plates and simultaneously determines the dimensions of the final products. As Struganik limestone is used as natural-faced slabs, this texture is undoubtedly a significant economic factor in that it simplifies the process of final shaping. Allochemical, banked limestone, is used to a lesser extent due to its mode of appearance and economic interests. The petrological heterogeneity of the Struganik limestone, including its textural and structural characteristics, has an impact on the numerical values of its physico-mechanical properties. Statistical analysis showed notable variation in important mechanical parameters, *i.e.*, in major criteria, for the application of the stone. This is the consequence of not only the natural heterogeneity of the rock mass, but also probably partially of the fabric and structural differences between the investigated samples. The results of the regression analysis presented in this paper imply that the porosity could be deduced from the bulk density values. Similarly, using the regression equation, the values of the strength of a water-saturated sample or a sample after freezing could be accurately determined using values of the strength in the dry state that was estimated in the laboratory.

However, other properties cannot be estimate with any confidence due to low regression coefficient. It should be emphasized that the analysis was performed on a statistically small number of sample, which additionally affected the obtained results. The real density of limestone is relatively constant as was to be expected due to the uniform mineral composition. The bulk density had a value range of 70 kg/m^3, which is probably related to small range in the porosity of this limestone. However, the inverse relationship between the porosity and the bulk density was predicted. Generally, these limestones have low interparticle and intraframe (intraskeletal) porosity, which results from

Table 2. Data on validation of regression models.

Model	*t* -test	*t*-critical	degree of freedom		***F*-test**	*p* (α=0.05)	*F*-critical
			df_1	df_2			
1	-5.598	±2.36	1	5	31.33	0.003	6.61
2	14.717	±2.10	1	16	216.18	0.000	4.49
3	4.160	±2.36	1	5	17.30	0.009	6.61

the depositional process. However, some higher values of porosity (secondary type: stylolite and micro fissures) are probably caused by post depositional processes. The very low value of water absorption is in agreement with that of their porosity. Even in samples with a porosity value of 3 % or higher, the water absorption was very low (under 0.4 %). This means that these rocks contain isolated, unconnected pores or micro-cracks unable to receive and retain water. The low values of water absorption indirectly imply limestone resistance to frost.

The mechanical properties data of the Struganik limestone point to its variable quality, which is in accordance with the petrological heterogeneity of the rock mass. The same part of the rock mass is strong to moderately strong regarding the unconfined compressive strength. Simultaneously, it is hard to moderately hard rock concerning its wear abrasive. Samples with high values of strength (over 150 MPa) and lower values of abrasive resistance (below 18 cm^3 per 50 cm^2) probably correspond to micrite, fossiliferous micrite or biomicrite. On the other hand, layers/banks of bio-intra-spar varieties as well as layers with a higher clay content (marly limestone and marlstone) are present in the quarry. This may be the main cause for the very low strength values (below 70 MPa) and poor resistance to wear (over 22 cm^3 per 50 cm^2). Additionally, the presence of chert concretions, variable layer thickness, lamination, stylolite and other textural forms are reasons for the variable technical properties.

All the mentioned parameters are limiting factors for the use of the Struganik limestone as a dimension stone. Namely, the thickness of the final slabs is naturally defined by the layering, whereas the pronounced petrological heterogeneity requires selective exploitation. The statistically analyzed data confirmed that the average values of the technical properties satisfy the majority of the requirements of the national standard for stone slabs (SRPS B.B3.200 national standard without obligatory use). Unfortunately, the average value of the abrasive wear is higher than the limit for some applications of building stone and actually represents the main limiting factor. According to this standard, in the case that the tensile strength has been previously determined, the Struganik limestone may be used for:

– Pavement of interior vertical surfaces and horizontal surfaces with intensive and moderate trailer traffic;

– Pavement of exterior vertical surfaces up to 30 m in height in objects;

– Pavement of exterior horizontal surfaces with moderate trailer traffic (if the value of the wear abrasive is max. 18 cm^3 per 50 cm^2 or lower).

Compact, thinly bedded micrite varieties of chemically pure limestones entirely fulfill the requirements for the above-listed purposes, whereas the banked allochemsparite varieties or beds with an elevated content of clayey components should be avoid as dimensional stone.

Acknowledgements

Authors would like to thank Elena Koleva-Rekalova (Bulgaria) and Ladislav Palinkaš (Croatia) for their very helpful and much appreciated comments and suggestions for the improvement of the manuscript. We are grateful to the "GABP" Editor in Chief Vladan Radulović (Serbia) for his help. This work was supported by the Ministry of Education and Science of the Republic of Serbia, Project No. 176019 and 176016.

References

Andriani, G.F. & Walsh, N. 2002. Physical properties and textural parameters of calcarenitic rocks: qualitative and quantitative evaluation. *Engineering Geology*, 67: 5–15.

Anđelković, M. 1978. Stratigrafija Jugoslavije – paleozoik i mezozoik. 1017 pp. Univerzitet u Beogradu, Beograd (in Serbian).

Bell, F.G. & Lindsay, P. 1999. The petrographic and geomechanical properties of some sandstones from the Newspaper Member of the Natal Group near Durban, South Africa. *Engineering Geology*, 53: 57–81.

Bieniawski, Z.T. 1967. Mechanism of brittle rock fracture: Part I. Theory of the fracture process. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 4: 395–406.

Bilbija, N. & Matović, V. 2009. Primenjena petrografija, svojstva i primena kamena. 417 pp. Građevinska knjiga, Beograd (in Serbian).

Broch, E. & Franklin, J.A. 1972. The point-load strength test. I*nternational Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 9: 669–697.

D'Andrea, D.V., Fischer R.L. & Fogelson, D.E. 1964. Prediction of compressive strength from other rock properties. Colorado School of Mines Quarterly, 59: 623–640.

Deere, D.U. & Miller, R.P. 1966. Engineering classification and index properties for intact rocks. *Technical Report Air Force Weapons Laboratory*, New Mexico, No. AFNL-TR, 65–116.

DIMITRIJEVIĆ, M.D. 2001. Dinarides and the Vardar Zone: a short review of the geology. *Acta Vulcanologica*, 13: 1–8.

DUNHAM, R.J. 1962. Classification of carbonate rocks according to depositional texture. *In*: HAM, W.E (ed.), Classification of Carbonate Rocks. *American Association of Petroleum Geologists Memoir*, 1: 108–121.

DJERIĆ, N., GERZINA, N., GAJIĆ, V. & VASIĆ, N. 2009. Early Senonian radiolarian microfauna and biostratigraphy from the Western Vardar Zone (Western Serbia). *Geologica Carpathica*, 60: 35–41.

FILIPOVIĆ, I., PAVLOVIĆ, Z., MARKOVIĆ, B., RODIN, V., MARKOVIĆ, O., GAGIĆ, N., ANTIN, B. & MILIĆEVIĆ, M. 1976. Basic geological map 1:100 000, Sheet Gornji Milanovac. Federal Geological Survey, Belgrade.

FILIPOVIĆ, I., MARKOVIĆ, B., PAVLOVIĆ, Z., RODIN, V. & MARKOVIĆ, O. 1978. Explanatory booklet for the Sheet Gornji Milanovac (Basic Geological map of Former Yugoslavia 1:100 000). Federal Geological Survey, 71 pp., Belgrade.

FOLK, R.L. 1959. Practical petrographic classification of limestone. *American Association of Petroleum Geologists Bulletin*, 43, 1–38.

FREDRICH, J.T., EVANS, B. & WONG T.F. 1990. Effect of grain size on brittle and semibrittle strength: implications for micromechanical modelling of failure in compression. *Journal Geophysics Research*, 95: 10907–10920

GAJIĆ, V. 2007. Petrology of Upper Cretaceous sedimentary rocks in the area Struganik–Planinica (Western Serbia). Unpublished MSc thesis, 108 pp. Faculty of Mining and Geology, University of Belgrade (in Serbian, English abstract).

GAJIĆ, V. & VASIĆ, N. 2011. Structures of the Struganik limestones. 1st International Conference: "Harmony of nature and spirituality in stone". Kragujevac, Serbia, 63–74.

GERZINA, N. 2002. Geological setting of the Vardar Zone between Struganik and Divčibare. Unpublished MSc thesis, 93 p.p. Faculty of Mining and Geology, University of Belgrade (in Serbian, English abstract).

GUNNSALLUS, K. L. & KULHAWY, F. H. 1984. A comparative evaluation of rock strength measures. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 16: 233–248.

HANDLIN, J. & HAGER, R.V. 1957. Experimental deformation of sedimentary rock under a confining pressure. *Journal of the American Association for Petroleum Geology*, 41: 1–50.

HATZOR, Y. H. & PALCHIK, V. 1997. The influence of grain size and porosity on crack initiation stress and critical flaw length in the Dolomites. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 34: 805–816.

HATZOR, Y.H. & PALCHIK, V. 1998. A microstructure-based failure criterion for Aminadav Dolomites. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 35: 797–805.

HOFFMAN, D. & NIESEL, K. 1996. Relationship between pore structure and other physico-technical characteristics of stone. Proceedings 8th Internationl Congress on deterioration and conservation of stone, 461–472. Berlin, Germany.

HUGMAN, R. H. H. & FRIEDMAN, M. 1979. Effects of texture and composition on mechanical behavior of experimentally deformed carbonate rocks. *American Association of Petroleum Geologists Bulletin*, 63: 1478–1489.

KARAMATA, S. 2006. The geological development of the Balkan Peninsula related to the approach, collision and compression of the Gondwanan and Eurasian Units. *In*: ROBERTSON, A.H.F. & MOUNTRAKIS, D. (eds.), *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, Special Publications, 260: 155–178, London.

KARAMATA, S., KNEŽEVIĆ, V., MEMOVIĆ, E. & POPEVIĆ, A. 1994. The evolution of the Northern Part of the Vardar Zone in Mesozoic. *Bulletin of the Geological Society of Greece*, 30: 479–486.

KARAMATA, S. & KRSTIĆ, B. 1996. Terranes of Serbia and neighboring areas. In: KNEŽEVIĆ, V., ĐORĐEVIĆ, P. & KRSTIĆ, B. (eds.), *Terranes of Serbia*, 25–40. Belgrade University and Serbian Academy of Science and Art, Belgrade.

KARAMATA, S., OLUJIĆ J., PROTIĆ LJ., MILOVANOVIĆ, D., VUJINOVIĆ L., POPEVIĆ A., MEMOVIĆ, E., RADOVANOVIĆ, Z. & RESIMIĆ-ŠARIĆ, K. 2000. The Western Belt of the Vardar Zone – the remnant of a marginal sea. *In*: KARAMATA, S. & JANKOVIĆ, S. (eds.), *Proceedings of the International Symposium "Geology and Metallogeny of the Dinarides and the Vardar Zone"*, 1: 131–135. Academy of Sciences and Arts of the Republic of Srpska, Collections and Monogrphs 1, Department of natural, Mathematical and Technical Sciences.

KIJANOVIĆ, V. 2007. Elaborat o rezervama krečnjaka kao TGK i AGK u ležištu "Struganik" kod Mionice. Fond stručne dokumentacije Geološkog instituta Srbije, 86 pp, Beograd (in Serbian).

LUODES, H., SELONEN, O. & PÄÄKKONEN, K. 2002. Evaluation of dimension stone in gneissic rocks – A case history from southern Finland. *Engineering Geology*, 52: 209–223

MARKOVIĆ, O. & ANĐELKOVIĆ, M. 1953. Geological composition and tectonics of wider surroundings of villages Osečenica, Brežđe and Struganik (Western Serbia). *Zbornik radova Srpske akademije nauka*, 33 (5): 111–150 (in Serbian, summary in French)

OLSSON, W.A. 1974. Grain size dependence of yield stress in marble. *Journal of Geophysical Research*, 32: 4859–4862.

PALCHIK, V. & HATZOR, Y.H. 2000. Correlation between mechanical strength and microstructural parameters of dolomites and limestones in the Judea Group, Israel. *Israel Journal of Earth Science*, 49 (2): 65– 79.

PALCHIK, V. & HATZOR, Y.H. 2002. Crack damage stress as a composite function of porosity and elastic matrix stiffness in dolomite and limestones. *Engineering Geology*, 63: 233–245.

RABRENOVIĆ, D., VASIĆ, N., MITROVIĆ-PETROVIĆ, J., RADULOVIĆ, V., RADULOVIĆ, B. & SREĆKOVIĆ-BATOĆANIN, D.

2002. The Middle Cenomanian basal series of Planinica, Western Serbia. *Geološki anali Balkanskoga poluostrva*, 64: 13–43.

ROBERTSON, A., KARAMATA, S. & ŠARIĆ, K. 2009. Overview of ophiolites and related units in the Late Paleozoic–Early Cenozoic magmatic and tectonic development of Tethys in the nothern part of the Balkan region. *Lithos*, 108: 1–36.

SCHMID, M. S., BERNOULLI, D., FÜGENSCHUH, B., MATENCO, L., SCHEFER, S., SCHUSTER, R., TISCHLER, M. & USTASZEWSKI, K. 2008. The Alpine-Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences*, 101: 139–183.

TUGRUL, A. & ZARIF, I.H. 1999. Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. *Engineering Geology*, 51: 303–317.

VASIĆ, N., KOSTIĆ, M., ĐURIĆ, S. & RABRENOVIĆ, D. 2001. Highly magnesian smectite clay in the basal series of the Albian–Cenomanian of Planinica (Western Serbia). *Mineralogy, Godišnjak jugoslovenske asocijacije za mineralogiju*, 3: 78–85.

VASIĆ, N., GAJIĆ, V., RABRENOVIĆ, D., MILOVANOVIĆ, D., ĐERIĆ, N. & KOSTIĆ, M. 2005. Pyroclastic rock in the Upper Cretaceous carbonaceous sediments from Struganik. 14th Geological Congress of Serbia and Montenegro, 113–114, Novi Sad.

WONG, R.H.C., CHAU, K.T. & WANG, P. 1996. Microcracking and grain size effect in Yuen Long marbles. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 33: 479–485.

YAGIZ, S. 2010. Geomechanical properties of construction stones quarried in south-western Turkey. *Scientific research and essays*, 750–757.

Резиме

Петрофизичке и механичке особине струганичких кречњака (Вардарска зоне, западна Србија)

Природни камен је највише коришћен грађевински материјал на свету, како за унутрашња тако и за спољашња зидања. Да би се користио у грађевинарству, камен треба да поседује добар квалитет односно физичко-механичка својства која задовољавају захтеве стандарда у грађевинарству. Карбонатне наслаге различите литологије, старости и квалитета су широко распрострањене у Србији па су и кречњаци најчешће коришћен грађевински камен. У индустрији архитектонског камена значајно место заузима струганички кречњак, најпознатији украсни камен западне Србије чија је експлоатација започела још у 18. веку. Данас, више од 70 каменолома обавља активну експлоатацију кречњака у области Струганика и шире, али услед недовољне геотехничке истражености ове стене имају још увек ограничену примену у грађевинарству. Рад представља синтезу резултата детаљних петролошких и технички испитивања кречњака из најстаријег и највећег површинског копа „Струганик“, интерперетацију депозиционе средине стварања кречњака, као корелацију физичко-механичких карактеристика тј. утицај петролошких карактеристика на квалитет стенске масе.

Према петрлошким карактеристикама, минералном и хемијском саставу, стенску масу површинског копа „Струганик“ граде лапорци, глиновити кречњаци и кречњаци. Стратиграфски они припадају доњем и горњем кампану, а нова открића асоцијације пелашких глоботрунканида потврђују њихову кампанску старост (ГАЈИЋ 2007). Кречњаци су једри, компактни са хомогеном сивом бојом коју делимично нарушава присуство тамносивих конкреција рожнаца. Основни текстурни облик појављивања кречњака је слојевитост са доминантном дебљином од 5–15 cm. Слојне површи су равне или стилолитске, а на горњим површинама се налазе и бројни биогени текстурни облици и трагови богате животне активности. Од интерних текстурних облика јављају се хоризонтална ламинација, стилолитски шавови и веома карактерстична конкрециона тела рожнаца. Палеонтолошка анализа микрофауне показала су да доњи део литолошког стуба стратиграфски припада доњем кампану а преосталих седам метара – горњем кампану. Према структурним карактеристикама издвајују се два основна литотипа кречњака: микритски – ортохемијски, аутохтони кречњаци (Mudstone, Wackestone) и алохемијски кречњаци, био-интра-спар варијетети (Grainstone, ретко Rudstone). Основу микритских кречњака гради микрокристаласти калцит док некарбонатни део чине минерали глина, органска материја и алевритска компонента. Биогена компонента је представљена добро очуваним љуштурицама пелашких фораминифера *(Globotrunkanide)* и у зависности од њиховог садржаја разликују се микрити, фосилиферни микрити и биомикрити. Садржај $CaCO_3$ у овим стенама варира од 55 до 94 %. Банковити био-интра-спар варијетети (интраспаррудити, биоспаррудити, биоспарити, интрабиоспарити) су изграђени од разноврсног биогеног алохема (фрагменти љуштура плитководних организама, љуштурице бентоских и планктонских микроорганизама, фрагменти алги) и простих до сложених интракласта. Природа транспорта којим је материјал принешен у басен омогућила је развој интерних текстура карактерстичних за Боумину секвенцу. Садржај $CaCO_3$ у овим стенама варира од 86 до 98 %.

На основу петролошких показатеља утврђено је да су аутохтони микритски варијетети пелашки седименти таложени на континенталној падини у

дубоководној средини горњокредног мора, док присуство слојева и банака алохемоспаритских калкаренита и калкрудита указују на повремени принос плитководног материјала турбидитним токовима низ континенталну падину.

Квалитет струганичког кречњака као украсног камена у функцији је његовог минералног састава, склопа и физичко-механичких својстава. Према статистичким показатељима испитивани кречњак припада категорији умерено тешког, компактног и тврдог камена са врло малим упијањем воде, средње до високе чврстоће према притиску. Квалитет и начин експлоатације предодређени су екстерним и интерним текстурним облицима. Изражена слојевитост микритских варијетета условила је: експлоатацију у облику танких плоча, димензије готових производа; равни слојевитости су природне, али и финалне површи ове врсте архитектонског камена. Петролошка хетерогеност стенске масе условила је велику варијабилност нумеричких вредности физичко-механичких карактеристика тј. главних критеријума за примену камена. Густина кречњака је релативно константна што је и очекивано с обзиром на уједначени минерални састав. Запреминска маса показује мали опсег варирања – последица релативно уједначене порозности. Струганички кречњак има ниску интерпартикуларну и интерскелетну порозност која је резултат депозиционих процеса. Ниске вредности упијања воде индиректно указују на отпорност кречњака на агресивно дејство мраза што је потврђено и лабораторијским анализама. Чврстоћа на притисак и отпорност на хабање су технички параметри са највећим варирањем вредности. Узорци кречњака са високим вредностима чврстоће на притисак (изнад 150 MPa) и високом отпорношћу према хабању брушењем (<18 $cm^3/50cm^2$) одговарају микритским варијететима док био-интра-спар варијетети и варијетети са високим садржајем глиновите компоненте одговарају стенама умерене чврстоће, а њихова нижа абразивна отпорност је и главни ограничавајући фактор примене. Резултати регресионе анализе приказани у раду, показују да су порозност и запреминска маса у директној линераној зависности са високим статистички поузданим коефицијентом регресије. Високу међусобну линеарну зависност показују и параметри чврстоће на притисак у сувом, водозасићеном стању у после дејства мраза. Остала физичко-механичка својства, услед ниског регресионог коефицијента немају статистички значајне функције зависности.

На основу резултата статистичке анализе физичко-механичких својстава може се закључити да квалитет струганичког кречњака задовољава већину захтева националног стандарда за примену плоча за унутрашња и спољашња, вертикална и хоризонтална облагања. Отпорност на хабање је једини фактор који лимитира примену кречњака као украсног камена.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	101–109	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172101A

The Novo Okno copper deposit of olistostrome origin (Bor, eastern Serbia)

Ivan Antonijević[1]

Abstract. The copper deposit Novo Okno, uncovered at present, with non-ore and ore clasts of massive sulphides (from 0.5 to 50 m^3 in size), has many distinctive features that indicate its olistostrome origin. The deposit is chaotic in structure, unstratified, with the lower surface unconformable over the underlying parent rock of the basin. It is a lens-like body, with the longer axis directed east and west, variable in thickness from 15 to 28 metres, about 335 metres long and less than 140 metres wide. These and other characteristics of the body indicate a unified, reworked, olistostrome copper deposit formed from primary ore bodies of the Bor mineral deposit and vulcanite, destroyed by volcanic explosion into blocks and rocks of Turonian age and extrusion and concurrent deposition on the land surface. Gravitational massive sliding of the consolidated rocks down the slopes of the volcanic relief and chaotic accumulation of ore and non-ore clasts (olistoliths) in a marine basin evolved in the Upper Turonian and the Lower Senonian.

Key words: Olistostrome, copper ore, mineral deposit, ore-clast, olistolith, origin.

Апстракт: Данас већ откопано лежиште бакра „Ново Окно“, са нерудним и рудним кластима масивних сулфида (величине 0,5–50 m^3), одликује се низом специфичних особености које указују на његову олистостромску генезу. Има хаотичну геолошку грађу, без слојевитости и доњи неравни контакт са подинским матичним стенама басена. Генерално је сочивастог облика. Издужено је по оси исток–запад. Промењљиве је дебљине 15–28 m, дужине око 335 m, а ширине до 140 m. По тим, као и другим особинама представља јединствено, редепоновано, олистостромско лежиште бакра. Настало је вулканским експлозивним разарањем примарно образованих рудних тела борског лежишта и вулканита у блокове и комаде туронске старости, њиховим изношењем на површину и синхроним депоновањем на копну. У горњем турону и доњем сенону долази до гравитационог клижења консолидоване стенске масе путем одрона и клизишта низ падине вулканског рељефа и хаотичне акумулације рудних и нерудних класта (олистолита) у морском басену.

Кључне речи: олистостроме, лежиште бакра, рудокласти, олистолити, генеза.

Introduction

The copper deposit Novo Okno at Bor, uncovered at present, is an uncommon type of chaotic assemblage of ore and non-ore fragments, the geology in general and origin in particular of which have not been addressed adequately.

It lies on the “threshold” of the primary massive copper sulphide deposit Jugoistok, near Bor (ore bodies H, J and others). While nearly identical paragenetically to these deposits, particularly to the massive copper sulphide in the central ore zone from which it originates, it differs essentially in being a reworked copper or body of olistostrome origin.

The deposit was discovered in 1979/80 by a local positive gravimetric anomaly in the first exploratory borehole, B 128, in a Senonian epiclastic deposit of hornblende andesite at a depth of about 270 metres.

Concept and definition of an olistostrome

An olistostrome is a sedimentary chaotic formation lacking bedding, composed of cm^3-clasts or m^3-olistoliths in a matrix. It is formed by mechanical accumulation of clasts and gravity sliding of semi-fluid rock material down land and submarine slopes (Extra-olistostrome/Intraolistostrome).

[1] Vjekoslava Kovača 14, Belgrade, Serbia.

An olistostrome body has distinct and uneven lower and comparatively even and regular upper boundaries. The bodies vary in size from 0.5 to 100 km or more in length (DIMITRIJEVIĆ 1975; NACHEV 1977).

Olistoliths are rock masses (blocks) or elements of an olistostrome, which vary in size and shape, being mainly oval, ellipsoid to irregular. Classified by dimensions, there are: macro- (over 1000 m^3), meso- (under 1000 m^3) and micro-olistoliths (tens of m^3) (RIGO DE RIGHI 1956). Note that olistostrome is a generic concept (NACHEV 1977).

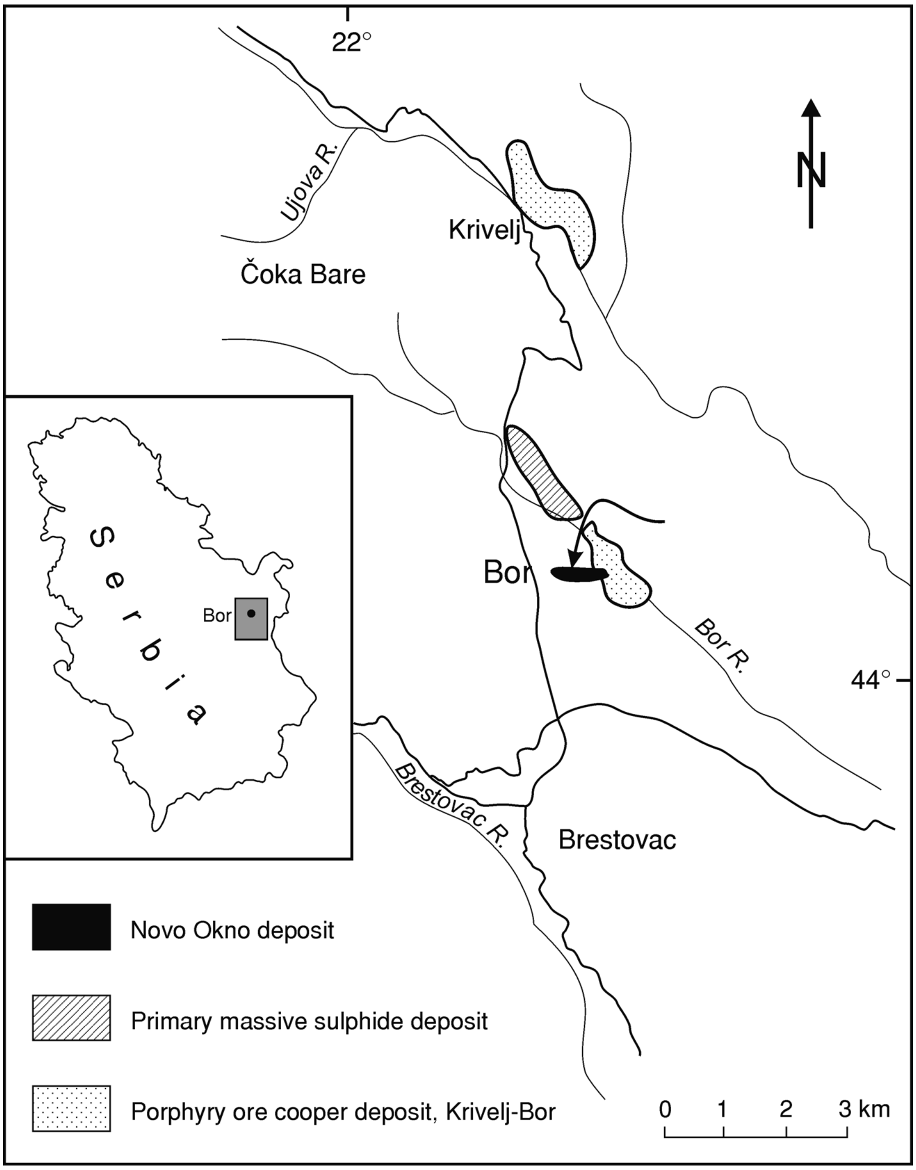


Fig. 1. Geographical location of the Novo Okno copper deposit of olistostrome origin.

Olistostromes in Serbia were mentioned mainly in flysch sequences of different ages, and were recognized and described by GRUBIĆ (1975, 1976), DIMITRIJEVIĆ & DIMITRIJEVIĆ (1973), BOGDANOVIĆ (1975), *etc*.

Mineral olistostrome deposits and occurrences of only non-metals?, building materials and ornamental stone, such as Ropočevo decorative breccias, are known in Serbia (GRUBIĆ 1975).

Olistostrome characteristics of the Novo Okno copper deposit

Contrary to previous interpretations in the mentioned references, this work presents the geology of the Novo Okno copper deposit, mechanism and formational processes of ore and non-ore clasts, volcanism, and so forth in terms of the olistostrome origin of the deposit, based on available geological publications (MIŠKOVIĆ 1989, 1995; JANKOVIĆ 1990; DROVENIK 1982, 2005, *etc.*), drilling and mining records and own investigations.

The deposit Novo Okno is characterized by a chaotic structure of rocks and concentration of ore and non-ore clasts in a volcaniclastic matrix. Some clasts (from 0.5 to 50 m^3 in size) shape extraordinary examples of olistoliths.

This deposit includes two classes of ore-clasts (olistoliths A and B). Olistoliths A and B (in MIŠKOVIĆ 1989, 1995) correspond to ore-clasts of mineral associations A and B, respectively.

Mixed olistolith classes A and B are local occurrences, because the lighter and smaller Class B are mixed in almost every interval of the olistostrome ore body.

The deposit is elongated east to west, 335 m long, up to 140 m wide and about 25 m thick, embedded in a heterogeneous unstratified mass of rocks. This morphogenetic characteristic indicates a typical development of a mineralized olistostrome in epiclastics of the parent Metovnica Formation.

A basic feature of the Novo Okno olistostrome body is the lower irregular, deformed surface over the source rocks. It was observed many years ago by Mišković in the northern incline drift (el. 45). "A large ore-clast (olistolith Class A) fell and deformed the underlying grey pelite" (MIŠKOVIĆ 1989).

Mechanism and processes of the olistostrome formation

The relation in time and space of the Novo Okno olistostrome deposit, the environment and formational processes indicate two different geochronologic phases:

– Turonian preolistostrome (volcanogenic) and
– Senonian olistostrome (submarine) phases.

Preolistostrome volcanogenic phase

This was a phase of subaerial eruption and explosion of the central Bor edifice; destruction of primary massive sulphide ore bodies into fragments and blocks (ore and non-ore clasts), their ejection and deposition on land.

Volcaniclastics and ore-clasts, while being ejected on the land surface, formed the initial contour of the subsequent slide or the Novo Okno ore body with its mineral distribution.

Heterogeneous rock mass of ore and non-ore clasts in a matrix cooled and consolidated epigene in the subaerial phase. While still semi-fluid, however, fragments of similar size or gravity separated and sorted:

– Heavy and large blocks (olistoliths) Class A, 1.0–50 m^3, on the lower, and
– Light blocks Class B, 0.3–0.5 m^3, on the upper part of the slopes.

This distribution and vertical (gravitational) zonation of the ore-bearing materials on land, in the preolistostrome phase, persisted through the subsequent submarine olistostrome phase of the formation of the deposit.

In a similar consideration of this issue, JANKOVIĆ (2002) writes as follows: "Formation of the Novo Okno ore body through mechanical accumulation of massive sulphide fragments, produced by destruction of the already formed ore bodies, indicates a polyphase activity that affected the environment of the already formed sulphide ore bodies and impregnated stockwork before Bor pelite had been deposited." He continues: "It would be difficult, however, to be more precise about the origin of ore-clasts in the epiclastics and the copper deposit of Novo Okno." (JANKOVIĆ 2002).

Drovenik studied the genetic aspect of the Bor mineral deposits, ore-clasts and the newly found copper deposit Novo Okno, and as early as in 1966 invented bonanzas, rich bodies of copper ore, somewhere in the Upper Cretaceous?, far from the Bor deposits, the likely primary material of the massive sulphide ore-clasts and the Novo Okno copper deposit. In order to maintain the untenable but prevailing concept of the Laramian (post-Senonian) formation of the Bor copper deposit, in association with structural geology, he repeated the same in 1982 and 2005 (DROVENIK 2005, p. 34).

MIŠKOVIĆ (1989, 1995) interpreted the Novo Okno ore-clasts as material of the primary deposits destroyed by Senonian volcanic explosion and projected into Senonian marine environment.

ĐORĐEVIĆ (1977), however, mentions the lack of evidence of Senonian volcanic activity in the Novo Okno deposit, or in the Bor area proper. All ore-clasts are indeed angular to subangular pebbles and likely blocks moved by gravity, and the rocks bearing them are epiclastics of the Senonian Metovnica Formation.

It follows from the above that these are sedimentary copper ore occurrences in pebbles (or olistolithic or bodies in a sedimentary, olistostrome environment).

The olistostrome submarine phase

Invasion of the Senonian Sea over the volcanic landscape created conditions for the onset of the submarine olistostrome phase. Erosion and deposition of the reworked Turonian volcaniclastics formed new, Senonian epiclastic deposits on land and in the sea, including olistostrome sequences and ore-clasts.

Gravity sliding of the mineralized material down the volcanic relief and accumulation of fragments in the marine environment produced the authentic olistostrome copper deposit of Novo Okno (Table 1), although in the group of primary copper deposits Jugoistok (ore bodies H, J, *etc*.), after which it was given the attribute "distal" (MIŠKOVIĆ 1995), Novo Okno differs in being a particular copper deposit of olistostrome origin.

Unlike nearly all more or less rounded olistolith ore-clasts, andesite clasts, fresh or hydrothermally altered, are mostly angular (JANKOVIĆ 1990).

Mineralized olistostrome was found underlain by laminated pelitomorph and some other rocks, often over homogeneous Turonian andesite. The underlying pelite or the parent epiclastic association is dated the uppermost Turonian and the lowermost Senonian using a microfossil assemblage of *Marginotruncana coronata*, *Globotruncana linneinana*, *G.* sp. *arca*, *Hedbergela* sp., *etc*. (SLADIĆ-TRIFUNOVIĆ & GAKOVIĆ 1988).

Some thirty metres above "the main ore layer" in the olistostrome sequence of Novo Okno, JANKOVIĆ (1990) reports "a second layer" of epiclastics and small ore and non-ore clasts as a likely unit of a new olistostrome sequence. This layer consists of pelite and sandy tuffite embedding fragments of hornblende andesite, hydrothermally altered, and pyrite and chalcopyrite ore-clasts. JANKOVIĆ assigns it to the mineral association C.

Larger ore-clasts overlying epiclastics are scarce or not mentioned.

The mentioned olistostrome character of the Novo Okno copper deposit, the processes and mechanism of development, indicate that it was a sedimentary reworked deposit.

phase of the Timok eruption area. The formation is built of well-stratified clastic, epiclastic beds, dominantly of hornblende andesite (breccia, conglomerate), fresh and altered angular fragments of psammite, subordinately pelite, ore-clasts, matrix, hydrothermally altered epiclastics, *etc*.

Table 1. Metallogenetic model of the Novo Okno olistostrome copper deposit.

<table>
<tr><th colspan="3">Model Phase</th><th>Geology</th><th colspan="2">Genetic process</th><th>Metallogeny</th><th></th><th>Epoch</th></tr>
<tr><td rowspan="3">Submarine</td><td>Olistostrome (Sec. II)</td><td rowspan="3">Epiclastic</td><td>Epiclastics, ore and non-ore clasts</td><td colspan="2">Gravity downslope sliding in volcanic relief</td><td>Min. ass. C
pyrite, chalcopyrite</td><td rowspan="6">Massive copper sulphide mineralization</td><td rowspan="3">Senonian</td></tr>
<tr><td></td><td>(0.5-10 m^3) Cl.B
OLISTOLITHS
(1-50 m^3) Cl.A</td><td colspan="2">OLISTOSTROME</td><td>Min. ass. B
chalcopyrite, bornite, Au, Ag, etc.
OLISTOLITHS</td></tr>
<tr><td>Olistostrome (Sec. I)</td><td>Chaotic heterogeneous epiclastic rocks in pelite matrix</td><td colspan="2">Sliding into sea basin; accumulation</td><td>Min. ass. A
pyrite, covellite, chalcocite, Au, Ag</td></tr>
<tr><td rowspan="4">Volcanigenic subaerial</td><td>Preolistostrome</td><td>Pyroclastic</td><td>Volcaniclastics, v. bombs in ore-clast matrix, tuff, v. agglomerate, v. Breccia</td><td colspan="2">Mechanical subaerial accumulation on land</td><td>Min. ass. B
ORE-CLASTS
Min. ass. A</td><td rowspan="4">Turonian</td></tr>
<tr><td>Volcanigenic explosive</td><td rowspan="2">Edifice</td><td>Volcanic breccia, hornblende, biotite andesite</td><td>Explosive polyphase volcanism</td><td rowspan="3">Hydrothermal alteration</td><td>Massive copper sulphide paragenese (Bor)</td></tr>
<tr><td>Volcanigenic</td><td>Homogeneous andesite flows</td><td>Volcanics</td><td>Stockwork impregnation</td></tr>
<tr><td>Subvolcanigenic intrusive</td><td></td><td>Amphibole andesite, diorite, quartz diorite</td><td>Hypabysal consolidation</td><td colspan="2">Porphyry mineralization (Bor River, Krivelj)</td></tr>
</table>

The olistostrome parent rocks

Large amounts of Senonian epiclastic rocks under, over and around the Novo Okno olistostrome deposit are the source-formational unit of the olistostrome and ore-clasts of massive copper sulphides. The unit is similar to Turonian pyroclastic rocks of the first volcanic phase, the Timok Association, from which it derives. It was not treated in previous research.

The unit, classified as formation, was recognized and investigated in detail south of Bor and Novo Okno as an epiclastic rock mass that deposited in the sea (ĐORĐEVIĆ 1994, 1997, 2005). It formed over the volcanic Turonian, precisely over the first volcanic

The major parent rocks of the epiclastics include the Novo Okno olistostrome copper deposit and many individual ore-clasts in the greater Bor area.

The source rocks have a variable thickness from a few to hundreds of metres and include fragments of all pre-existing Turonian rocks, mainly pyroclastics, ore and non-ore clasts (olistoliths) and some erosional remnants of destroyed olistostromes (Čoka Bare, Metovnica).

This body of rocks formed in the late Upper Turonian and the Lower Senonian (Coniacian–Santonian) by filling depressions in the rugged Turonian volcanic relief. The formation is not recognized in Bor, although, like in Novo Okno, a large part of the Timok

Formation volcaniclastics (timocite) corresponds to epiclastics of the Metovnica Formation. A recent reference (ANTONIJEVIĆ 2010) to the formation reads: “for further copper investigation and targeting of the exploration works in Bor, the potentially different epiclastic Senonian and volcaniclastic, or volcanigenic, Turonian lithogenetic units must be separated”.

Pelitomorphic rocks in the lower part of the primary epiclastic formation have a microfaunal content identical to that in pelite under the Novo Okno olistostrome. These are Coniacian-Santonian foraminifera from the Lower Senonian and the uppermost Turonian (ĐORĐEVIĆ *et al.* 1997).

A section of the Novo Okno deposit (MIŠKOVIĆ 1989) shows the underlying hornblende andesite as the oldest Turonian rocks (±90 m.y., K/Ar method). Epiclastics of the source formation and laminated pelite of the lower Senonian and the uppermost Turonian are transgressive and unconformable over the deposit.

The deductions based on the deposit section are the following:

– Turonian amphibole andesite basement is underlying the Novo Okno olistostrome parent rocks, and

– Laminated pelite of the olistostrome parent rocks, immediately over them, is part of the epiclastic Lower Senonian–Upper Turonian formation.

Massive sulphide ore-clasts

Many ore-clasts of massive copper sulphide are notable in the epiclastics of the Metovnica Formation, excluding the Novo Okno deposit. DROVENIK (1966) studied some forty of the more than hundred mentioned ore-clasts on the margin of the primary ore bodies from which they derive.

The exposure of ore-clasts of about 25 km^2 surface area extends north to south from Kriveljski Kamen to Metovnica, with the largest olistostrome copper body of Novo Okno between them. The ore-clasts are isolated blocks, 15×25 cm in size, mostly in Senonian epiclastics of amphibole andesite, the products of destroyed ore bodies from the older Turonian copper deposits in the central mineral zone of Bor.

Agglomerations of ore fragments in a nearly defined set of epiclastic hornblende andesite deposits are also known on the slopes of Čoka Bare and at Metovnica south of Bor (DROVENIK 1966; ĐORĐEVIĆ 1977; MIŠKOVIĆ 1989).

This does not rule out the possibility that the occurrences of Čoka Bare and Metovnica ore-clast were erosional remnants of the destroyed olistostromes, like the economic ore-clast bodies in the Novo Okno olistostrome copper deposit. Physically, they are identical with the mineral parageneses of the primary deposits and, naturally, with ore-clasts of the massive copper sulphide deposit of Novo Okno, formed on land during explosions of the volcanic structure (from plugs in channels), probably in the preolistostrome Turonian phase.

The ore-clasts are coated with iron oxides or copper carbonates (azurite, malachite, *etc.*). MIŠKOVIĆ (1989) studied only partly the ore-clasts near Novo Okno and Metovnica, mainly citing the results and conclusions of DROVENIK (1966).

Drovenik is still the most informative about ore-clasts in the Bor area, and far less ĐORĐEVIĆ (1977) *etc.* Ore-clasts of the epiclastic deposits will be presented for several major locations, based on the available sources (DROVENIK 1966, 1982; ĐORĐEVIĆ 1977; *etc.*) and some own observations.

Čoka Bare ore-clasts

Remnants of the chaotic, destroyed olistostrome? A high proportion of massive sulphide ore-clasts are preserved on Čoka Bare and Ujova some 4–5 km NW of Bor. These are probably the next largest exposures of massive sulphide ore-clasts after Novo Okno, explored before Drovenik but the exploration results were not available to this author.

Ore-clasts of Čoka Bare are useful for correlation with those of the Novo Okno olistostrome mineral deposit. Whether outcrops *in situ* or erosional remnants of the olistostrome, the ore-clasts should be verified by evidence of their structural elements and strike and dip, in view of the olistostrome zone length of about 400 metres (DROVENIK 1966).

The ore-clasts are subrounded or rounded, 1–30 cm in size, mostly 3–8 cm. Olistoliths of 0.3 m^3 are rare. They are emplaced in hornblende-biotite andesite epiclastics [DROVENIK (1966, 1992), takes them for volcanic breccia of amphibole-biotite andesite from the first volcanic phase, *i.e.*, the Timocite association.] that form an east to west zone about 400 metres long, like the Novo Okno deposit, and less than 100 metres wide. The thickness of the ore zone is not known, because it is wholly covered, but the given morphogenetic parameters are sufficient for a comparison with the Novo Okno ore body.

Ore-clasts of massive sulphides are located in the Ujova Valley and on the Krivelj Kamen Hills, “on the other side” of the Bor volcanic structure, some 8 km north of Novo Okno.

According to DROVENIK (1966), the Čoka Bare and other ore-clasts consist of pyrite, chalcopyrite, bornite, digenite and chalcocite, similar to the Novo Okno mineral parageneses of associations A and B.

The ore-clasts rich in massive sulphides have appreciable amounts of gold and silver. Fragments with 42.61 % Cu contain Au 105.6 g/t and Ag 544 g/t (DROVENIK 1992).

For the genetic and other aspects of the Čoka Bare ore-clasts in the Novo Okno deposit, the opinion of Drovenik is cited previously.

Ore-clasts of Metovnica–Nikoličevo

Massive copper sulphide ore-clasts of Metovnica, south of Bor and Novo Okno, were recognized and investigated before the Novo Okno deposit was uncovered. These ore-clasts were found in association with fresh epiclastic breccia of hornblende-biotite andesite and Timok andesite and subvolcanic rocks of the Borska River.

Large chaotic accumulations of ore-clastic rocks near Metovnica were identified as hydrothermal ore occurrences on the banks of the Brestovačka and Suva Rivers. The presence of hydrothermally altered rock fragments and matrix was notable. The rock fragments varied in size from a few to 25 cm and were angular, coated by malachite or azurite, but including no olistolith habit.

Pyritized rocks with chalcopyrite and chalcocite were most abundant in the examined fragments (DROVENIK 1966; ĐORĐEVIĆ 1977); there were also fragments of the primary massive sulphides (bornite, chalcopyrite).

MIŠKOVIĆ (1989, p. 167) explored the area of the Novo Okno copper deposit and reported ore-clasts from "several" intervals, the lowest of which had a somewhat higher concentration, in the Jasenovo Brdo and the Suva Reka locations, similar to that of Novo Okno [sic.].

Pyrite fragments were more abundant than fragments containing chalcopyrite, bornite, and especially low chalcocite. The occurrences of ore fragments in the epiclastics of the Grlište–Lenovac eruption area are the least known.

The potential mineral resource of Metovnica ore-clasts has not been ascertained even though the occurrences were explored by trial adits and test wells before the First World War.

A general metallogenic map of Serbia on the scale 1:200,000 (JANKOVIĆ & JELENKOVIĆ 1994) shows ore-clasts as the occurrences of copper ore. ĐORĐEVIĆ (1997), however, takes Metovnica occurrences (Jovanovo Brdo, Kameni Potok, *etc.*) to be pebbles or ore-clasts in epiclastic rocks of the Metovnica Formation, like other similar occurrences, only without an economic concentration of ore as in Novo Okno.

Metallogeny of the deposit

This section, including isotopic analysis of sulphur, is an integral interpretation of the exploration data from the mentioned published sources, in the measure necessary for a better understanding of this concept of the genesis the Novo Okno olistostrome mineral deposit.

All mineralization processes in the Novo Okno copper deposit virtually ended in the pre-olistostrome phase on land, subaerially, through long gradual cooling of the volcaniclastic and mineral ore materials extruded from the primary copper deposits of the central Bor Zone.

It probably was the time when the structure of chalcopyrite and other sulphides changed ("internal concentric structure") to which DROVENIK (1992) referred.

Slides of consolidated rocks with massive sulphide ore-clasts into the sea basin finally shaped the lens-like ore body, or the Novo Okno olistostrome. Vertical disposition of ore-clasts, while still on land, was completed in the submarine phase of the deposit development; coarse olistoliths Class A concentrated in the lower and finer olistoliths Class B in the upper parts of the deposit (Table 1).

Material in the olistostrome is sorted to a variable degree, chaotic, but there is no break in the arrangement of the olistoliths and matrix.

Based on detailed laboratory examinations, the mineral parageneses of the massive sulphide deposits in the olistoliths and accessories in particular, MIŠKOVIĆ (1989), CVETKOVIĆ (1989), JANKOVIĆ *et al.* (1990) distinguished three mineral associations of ore-clasts:

A. Pyrite-covellite-chalcocite,
B. Chalcopyrite-bornite and
C. Pyrite-chalcopyrite.

A. The pyrite-covellite association

Blocks (olistoliths) of the pyrite-covellite association prevail in the lower-central part of the olistostrome. The association in ore-clasts (olistoliths Class A) was also denoted A by MIŠKOVIĆ (1989).

Class A olistoliths (pyrite-covellite-chalcocite association), commonly large, even 30–50 m^3, and with high concentrations of Cu, Au, Ag, *etc.* were probably ejected on land in the preolistostrome phase and deposited in the basin as the lower part of the deposit.

The mineral constituents in the Class A olistoliths, low-lying in the deposit, are copper from 1.9 % to 13.7 %, gold from 0.6 g/t to 30.5 g/t, locally much higher, and silver from 0.4 g/t to 40 g/t (JANKOVIĆ 1990, p. 308).

B. The chalcopyrite-bornite association

MIŠKOVIĆ (1989) takes that the mineral association B is largely related to ore-clasts, or to Class B olistoliths. The association is located in the upper part of the olistostrome body without breaks in the development of either association. The boundary between ore-clasts of Class A and Class B is gradual.

Ore-clasts of the chalcopyrite-bornite association differ from those of association A not only in their mineral composition, but also in the size of the fragments. Fragments prevailing in the higher part of olistostrome, or in the ore body intervals, are smaller, 0.3–10 m^3, according to Mišković (1989) than the ore-clasts (olistoliths) of the pyrite-covellite-chalcocite association.

Some sulphides in the deposit show internal structure (Cvetković 1989) of alternating thin zones of chalcopyrite and pyrite, a likely consequence of epigenetic consolidation and cooling on land, during the preolistostrome phase, not in a marine environment.

The mean amounts of the main constituents: copper, gold, silver and other minerals in olistoliths depend on the ore body (olistostrome) thickness and varies, according to Janković (1990, p. 312), from 1.9 % to 8.48 % Cu, 2.5 to 24.5 g/t Au and from 2 to 40 g/t Ag.

C. The pyrite-chalcopyrite association

The association was recognized by Janković (1990, p. 312). It is aligned with fragments of hydrothermally altered andesite with chalcopyrite and pyrite over the chalcopyrite-bornite association some 30 m above "the main orebody" that includes Class B olistoliths.

The assemblage is widespread on the Novo Okno periphery, being undoubtedly marginal on a younger olistostrome sequence. The rock fragments are smaller and the copper content in them ranges from 0.05 % to 0.22 %, rarely higher (Janković 1990). It formed probably in the closing phase of the sedimentation basin filling.

The ore body Novo Okno was wholly uncovered in 1988/89. It was a small deposit of massive copper sulphides of high economic value, up to two million tons?, with the mean copper content of about 3% and Au+Ag more than 5 g/t (Mišković 1995).

Sulphur isotopes in the Novo Okno deposit

Isotopic analysis of the S^{34} content of the massive copper sulphide in pyrite, covellite, chalcocite, chalcopyrite and bornite was performed for Mišković (1989) in order to establish the source of sulphur and minerals in the Novo Okno copper deposit. The analysis of a total of 22 samples indicated a uniform S^{34} content (from 1.8 to 3.8 parts per thousand) in the pyrites of the mineral association B (Table 2).

The sulphur isotope composition in covellite and chalcocite (Mineral Association. A) suggests some depletion of the light isotope, but S^{34} is uniform as in pyrite, and indicates magmatic origin of the ore minerals (Mišković 1989; Janković 1990).

The amounts of S^{34} in the chalcopyrite and bornite of Association B are similar to those in other copper sulphides. Differences in some sulphides may be explained by fractional crystallization as a function of the precipitation temperature (Janković 1990).

Geophysical information

The ore body or mineral deposit of Novo Okno was indicated by a local, positive gravimetric anomaly in the first exploratory borehole B 128, in 1979/80 (Bilibajkić 1985, personal communication; Partly confirmed by Mišković (1989) who wrote: "I discovered by drilling the copper deposit Novo Okno in late 1978).

Certain disagreement or discrepancy in the gravimetric anomalies between the Novo Okno and the primary massive sulphide copper (ore bodies H, Jugoistok, Kraku Bugaresku and Severozapad) is a consequence, according to Bilibajkić (1985), of the shape and heterogeneous structural pattern of the mineral ores in the Novo Okno deposit.

An explanation of "the cause" of the anomaly, Bilibajkić (1985, personal communication) continues, should be looked for deeper in the Novo Okno ore body, in the particular configuration of the ore mass and the chaotic structural pattern of the deposit and the surrounding rocks.

The gravimetric (geophysical) interpretation of Bilibajkić was not controversial at the time with the current geological interpretation of the deposit's olistostrome origin. On the contrary, the chaotic heterogeneous structure, including olistoliths mineralized to various degrees, the size and shape, and other characteristics express faithfully the geophysical description of the cause of gravimetric anomaly that indicated the presence of the Novo Okno olistostrome copper deposit.

Table 2. Sulphur isotope S^{34} in the massive sulphide of the Novo Okno copper deposit (amounts from Janković 1990).

<table>
<tr><th>Sulphide</th><th>Amount (‰)</th><th>Mineral Assoc.</th><th>Olistoliths</th></tr>
<tr><td>Pyrite</td><td>from 1.8 to 3.8</td><td rowspan="2">A</td><td rowspan="2">Class A</td></tr>
<tr><td>Covellite</td><td>from 4.1 to 4.3</td></tr>
<tr><td>Chalcocite</td><td>from 2.6 to 5.2</td><td>A</td><td rowspan="3">Class B</td></tr>
<tr><td>Chalcopyrite</td><td>from 3.5 to 4.8</td><td rowspan="2">B</td></tr>
<tr><td>Bornite</td><td></td></tr>
</table>

Conclusions

The copper ore deposit Novo Okno, uncovered at present, consists of massive copper sulphide ore and non-ore clasts (olistoliths from 0.5 to 50 m^3 in size) and has many distinctive features characteristic of chaotic sedimentary products of the olistostrome origin.

The mineral deposit is heterogeneous in structure without bedding and has a lower surface unconformable on the basin bedrock. It is a lens-like, "trough-shaped" body elongated on the olistostrome axis in the east and west direction, variable in thickness from 15 m to 28 m, about 335 m long and less than 140 m wide. These and other attributes of the body indicate a unified, reworked, and essentially extraolistostrome deposit of copper minerals.

The ore body was discovered in 1978 at a depth of about 270 m on the basis of a local positive gravimetric anomaly in Senonian epiclastic rocks of amphibole andesite.

The genetic and spatial relationships of the mineralized olistostrome indicate two synchronous (genetic) phases of the deposit formation, *viz*.:

– Turonian (volcanigenic) preolistostrome and

– Senonian submarine olistostrome phase.

The former phase includes volcanic explosion of the central Bor edifice and the breaking of the primary ore bodies and volcanic rocks into blocks and fragments, their emergence and deposition on land.

The latter phase, much later, embraced downslope sliding of consolidated rocks in the volcanic relief and chaotic accumulation of ore and non-ore clasts (olistoliths) in the sea basin.

Not all ore-clasts reached the sea basin, but were reworked and scattered in epiclastic rocks on the margin of the orebody, north and south of Bor. Major concentrations of ore-clasts in Čoka Bara and Metovnica may indicate remnants of destroyed olistostromes that resembled the Novo Okno orebody.

Vertical zonation of ore-clasts and other materials in the mineral deposit (matrix, cm-clasts) arranged on land remained unchanged in the aquatic environment. Coarser and heavier olistoliths Class A are always concentrated in the lower and lighter olistoliths Class B in the upper and middle parts of the olistostrome body.

The olistolithic ore-clasts of the deposit are characterized by complex mineral parageneses of massive copper sulphides:

A. The Pyrite-Covellite-Chalcocite Association of olistolith dimensions;

B. The Chalcopyrite-Bornite Association of olistolith dimensions; and

C. The Pyrite-Chalcopyrite Association (clasts, ore-clasts).

The mineral association of the Novo Okno is very similar to the primary massive sulphide minerals in individual bodies (Tilva Mika, Čoka Dulkan) of the central Bor ore deposit from which they originate, and to the Jugoistok (J and H) ore bodies.

Isotopic analysis of the S^{34} content confirmed the magmatic derivation of sulphur and the ore minerals.

The geophysical interpretation of the Novo Okno geology expresses a true olistostrome structure and the cause of the gravimetric anomaly.

Genetic aspects of the primary copper deposits of Bor, the mineral parageneses, absolute age, and so forth confirm a pre-Senonian age of the deposits, their formation in the preolistostrome Turonian phase. The Novo Okno mineral deposit, formed in the olistostrome Senonian phase, is accommodated in epiclastics and pelites of the Upper Turonian and the Lower Senonian as determined from palaeontological evidence.

The olistostrome interpretation of the Novo Okno copper deposit therefore indirectly proves that the age of the ore bodies, the massive copper sulphides in the Bor ore deposit, is virtually determined as the Turonian.

Acknowledgement

I wish to acknowledge gratitude to ALEKSANDAR GRUBIĆ (Faculty of Mining and Geology, University of Belgrade) and RADE JELENKOVIĆ (Faculty of Mining and Geology, University of Belgrade) for critical reading of the manuscript and useful suggestions.

References

ANTONIJEVIĆ, I. 2010. Formational base of the Bor copper deposit. Proceedings of the 15th Congress of Geologists of Serbia, 177–180, Belgrade (in Serbian).

BOGDANOVIĆ, P. 1977. Upper Cretaceous (Senonian) Olistostrome Mélange in the Kozarčevo-Grđevci Zone of Kosovo, *Glasnik Prirodnjačkog muzeja*, Serija A, 32: 119–127 (in Serbian).

CVETKOVIĆ, Lj. 1989. Minerals of Cu_3 (As, Sa, V, Sn, Ge, W)S_4 System in copper deposits of eastern Serbia. Unpublished PhD dissertation. 161 pp., Faculty of Mining and Geology, University of Belgrade (in Serbian).

DIMITRIJEVIĆ, M.D. & DIMITRIJEVIĆ, M.N. 1973. Olistostrome mélange in the Yugoslavian Dinarides and Late Mesozoic plate tectonics. *Journal of Geology*, 81 (3): 328–340.

DIMITRIJEVIĆ, M. 1975. Olistolith. Olistostrome. *In*: PETKOVIĆ, K. (ed.), *Geological Terminology and Nomenclature, Petrology*. 4. 109 pp.. Zavod za regionalnu geologiju i paleontologiju Rudarsko-geološkog fakulteta (in Serbian).

DROVENIK, M. 1993. Contribution to the knowledge of the ore clasts from the Novo Okno orebody in the Bor copper deposit. *Geologija,* 35: 287–318.

DROVENIK, M. 2005. Origin of the Bor and Other Copper Deposits in the Surroundings, Eastern Serbia. *Razprave IV razreda SAZU*, 46: 5–81.

ĐORĐEVIĆ, M. 1994. Pyroclastic and epiclastic in "the first volcanic phase" of the Timok eruptive area. *Geološki Vesnik*, Serija A, B, Geology, 46: 291–311 (in Serbian).

ĐORĐEVIĆ, M. & BANJEŠEVIĆ, M. 1997. *Geology of the Timok Eruptive Region South*. 171 pp. Savezno Ministarstvo za privredu, Beograd (in Serbian).

ĐORĐEVIĆ, M. 2005. Volcanigenic Turonian and epiclastic Senonian in the Timok Magmatic Complex between Bor and Tupižnica Mountain, eastern Serbia. *Geološki anali Balkanskoga poluostrva,* 66: 63–71.

GRUBIĆ, A. 1975. *Sedimentologija*. 67 pp. University of Belgrade, Građevinska knjiga, Beograd (in Serbian).

GRUBIĆ, A. & ANTONIJEVIĆ, I. 1976. Olistolith near Mokranje and Rajac (Timočka Krajina). II Skup sedimentologa

Jugoslavije, Rudarsko-geološki fakultet, 51–57, Beograd (in Serbian).

JANKOVIĆ, S. 1990. *Ore deposits of Serbia. Ore field Bor "Novo Okno"*. 307 pp. Republički društveni fond za geološka istraživanja, Rudarsko-geološki fakultet, Beograd, Ekonomska geologija (in Serbian).

JANKOVIĆ, S. & JELENKOVIĆ, R. 1994. Metalogenetic map of Serbia, 1:200 000. Unpublished, Republički društveni fond za geološka istraživanja, Beograd.

JANKOVIĆ, S., JELENKOVIĆ, R. & KOŽELJ, D. 2002. *The Bor Copper and Gold Deposit*. 298 pp., Mining and Smelting Basen Bor (RTB Bor), Copper Institute Bor (CIB), Bor.

MIŠKOVIĆ, V. 1989. Genesis of the copper deposits "Novo Okno" and metalogenetic correlation with the oreclast in the Bor area, eastern Serbia. Unpublished PhD dissertation, 189 pp., Faculty of Mining and Geology, University of Belgrade. (in Serbian).

MIŠKOVIĆ, V. 1995. Distal Copper Deposit „Novo Okno": A Special Type of the Massive Sulfide Deposit in the Carpatho-Balkan Metallogenic Belt. XV Congress of the Carpatho-Balkan Geological Association, 4 (2): 789–793, Athens.

NACHEV, I. 1977. Olistostromes in the Tithonian Flysch of Bulgaria. *Review of the Bulgarian Geological Society*, 37 (1): 43–52 (in Bulgarian, English summary).

RIGO, DE RIGHI, 1956. Olistostromi neogenici in Sicilia. *Bolletino della Societa Geologica Italia*, 75/3: 185–215.

Резиме

Лежиште бакра „Ново окно" (Бор) олистостромске генезе

Данас већ откопано лежиште бакра „Ново окно" састоји се од нерудних и рудних класта масивних сулфида бакра (олистолити величине 0,5–50 m^3) и одликује се низом особености карактеристичних за хаотичне седиментне творевине олистостромске генезе.

Лежиште је хетерогене геолошке грађе и без слојевитости са доњим неравним контактом према подинским матичним стенама морског басена. Има сочиваст „коритасти" облик и издужено је по оси олистостроме исток–запад. Промењљиве је дебљине од 15–28 m, дужине око 335 m и ширине до 140 m. По тим и другим особинама представља јединствено, редепоновано и у суштини екстраолистостромско лежиште бакра.

Откривено је 1978. године на дубини око 270 m на основу локалне позитивне гравиметријске аномалије у матичним сенонским епикластичним стенама амфибол-андезита.

Генетски и просторни односи рудоносне олистостроме указују на две синхроне хронолошке (генетске) фазе настанка лежишта. То су:

– туронска (вулканогена) преолистостромска фаза и

– сенонска субмаринска олистостромска фаза.

Прва фаза обухвата експлозију вулканског апарата централне борске структуре и разарање туронских примарних рудних тела и вулканита у блокове и комаде, затим њихово изношење на површину и синхроно депоновање на копну.

У другој фази, временски знатно касније, извршено је клижење консолидоване стенске масе у виду одрона и клизишта низ падине вулканског рељефа и хаотична акумулација рудних и нерудних класта (олистолита) у морском басену.

Сви рудокласти, међутим, нису доспели у морски басен. Значајан део њих је преталожаван и расејан у епикластитима по ободу примарних рудних тела северно и јужно од Бора. Веће концентрације рудокласта у Чока бари и Метовници указују, можда, на остатке разорених олистострома које су биле сличне лежишту „Ново окно".

Вертикална зоналност рудокласта и другог материјала у лежишту (матрикс, сантиметарски класти), остварена још на копну, задржала се и касније у воденој средини. Крупнији и специфично тежи олистолити класе А, по правилу су концентрисани у нижим, а ситнији, лакши, класе Б, у вишем и средњем делу олистостромског тела.

Олистолитски рудокласти лежишта се одликују сложеним минералним парагенезама масивних сулфида бакра:

А. Пиритско-ковелинско-халкозинска асоцијација олистолитских димензија;

Б. Халкопиритско-борнитска асоцијација олистолитских димензија;

В. Пиритско-халкопиритска асоцијација (класти, рудокласти).

Минералне асоцијације лежишта „Ново окно" показују веома велику сличност са примарним рудама масивних сулфида појединих рудних тела централног борског рудишта (Тилва мика, Чока дулкан) од којих воде порекло и са рудним телима лежишта „Југоисток" („Ј" и „Н").

Изотопска испитивања садржаја сумпора S^{34} потврдила су магматско порекло сумпора и рудне минерализације.

Гравиметријска геофизичка интерпретација геолошке грађе лежишта „Ново окно" верно одражава грађу олистостроме и узроке аномалије.

Генетски аспекти примарних борских лежишта бакра, менералне парагенезе, апсолутна старост и др. потврђују да су та лежишта старија, стварана пре сенона у преолистостромској туронској фази. Новообразовано лежиште „Ново окно", настало у олистостромској сенонској фази, смештено је у епикластитима и пелитима горњег турона и доњег сенона, чија је старост палеонтолошки доказана.

Олистостромска интерпретација лежишта бакра „Ново окно", према томе, посредно доказује да је старост рудних тела масивних сулфида бакра у борским рудиштима практично решена, односно да је туронска.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	111–117	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172111I

Magnesite-bearing fracture zones of the Zlatibor ultrabasic massif (Serbia) as a discrete structural–morphological type of magnesite deposits in ultrabasites

Miloje Ilić[1], Zoran Pavlović[2] & Zoran Miladinović[3]

Abstract: In this paper, a discrete structural–morphological type of magnesite deposits in ultrabasites, i.e., in magnesite-bearing fracture zones, is presented. The most prominent occurrences of such zones in Serbia are in the Zlatibor ultrabasic massif and they are economically very significant because they contain large reserves of high-quality magnesite, as well as of the accompanying sepiolite.

Key words: Magnesite-bearing fracture zones, structural–morphological type, magnesite, deposits, Zlatibor ultrabasites, Serbia.

Апстракт: У раду су приказане магнезитоносне разломне зоне које представљају посебан структурно-морфолошки тип магнезитских лежишта у ултрабазитима. Ове зоне најбоље су изражене у златиборском ултрабазитском масиву и економски су врло значајне јер садрже велике резерве квалитетног магнезита, као и пратећег сепиолита.

Кључне речи: магнезитоносне разломне зоне, структурно-морфолошки тип, магнезит, лежишта, златиборски ултрабазити, Србија.

Introduction

A discrete structural–morphological type of vein magnesite deposits, magnesite-bearing fracture zones, which has not hitherto been recognized, is presented in this paper. It should be added to the already known types: magnesite veins – single or systems; brecciated veins, both lenticular and irregular magnesite bodies, and magnesite stockwork (Ilić 1969a; Ilić & Rubežanin 1978; Popević *et al*. 1996). These zones occur at numerous locations in Serbia, the most prominent ones being in the Zlatibor ultrabasic massif (Fig. 1) (Ilić *et al.* 2005). Thus, they will be the topic of further consideration.

Magnesite-bearing fracture zones

Magnesite-bearing fracture zones are complex disjunctive deformations in ultrabasites (Ilić 1969b; Karamata & Popević 1996), having hectometre to kilometre length, mineralized by magnesite (and often by accompanying sepiolite; Figs. 1 and 2). Although, considered partially, they contain all the above-mentioned known structural–morphological types of magnesite deposits (and constitutive orebodies) in ultrabasites, they can be recognized, integrally considered, as a discrete complex structural–morphological type, based on their particular structural, morphological, mineragenetic and economic–geological features.

So far, seven magnesite-bearing fracture zones have been discovered in the Zlatibor ultrabasic massif: four in the Ribnica–Donja Jablanica ore field (Čavlovac, Masnica II, Masnica III and Rasevac), one in the Stublo ore field (Marin Izvor), one in the Slovići ore field (Slovići), and one in the Gola Brda ore field (Rasadnik) (Fig. 1). Their general strike is W–E (up to WNW–ESE) and dip towards S (up to SSW) at 20–50°.

The length of these zones ranges from several hundred metres to about two kilometres; their width ranges from several metres to several dozen metres (Figs.

[1] 27. Marta 27, 11000 Belgrade, Serbia. E-mail: milojeilic@yahoo.com

[2] Geosfera d.o.o., Kosmajska 47a, 11000 Belgrade, Serbia. E-mail: geosfera.bg@gmail.com

[3] Department of Economic Geology, Faculty of Mining and Geology, University of Belgrade, Đušina 7, 11000 Belgrade, Serbia. E-mail: zoran.mi@gmail.com.

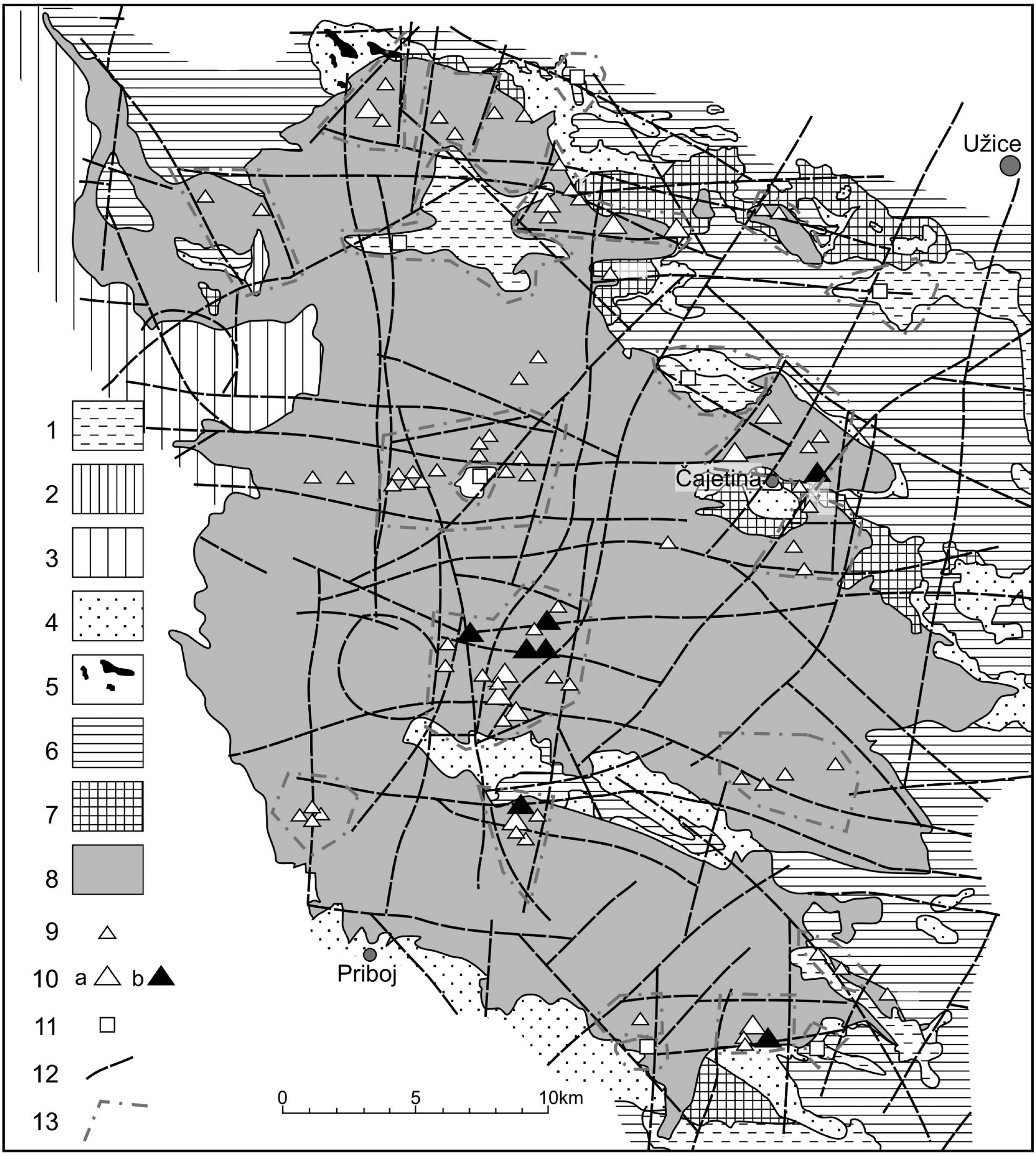


Fig. 1. A synoptic geological map of the Zlatibor ultrabasic massif and the neighbouring formations with the patterning of the distribution of the magnesite deposits. **1,** The freshwater Neogene (Miocene); **2,** limestone of Santonian– Maastrichtian age; **3,** the Upper Cretaceous undivided; **4,** volcanic–sedimentary formation of Jurassic age ("Diabase-chert formation"); **5,** bigger masses of Jurassic basic magmatic rocks (diabase, spilite, dolerite and melaphyre); **6,** the Middle and Upper Triassic undivided (limestone and dolomite); **7,** amphibolite; **8,** ultramafic rocks; **9,** occurrences of vein magnesite; **10,** deposits of vein magnesite (a) and magnesite-bearing fracture zones (b); **11,** deposits of sedimentary magnesite; **12,** regional ruptures; **13,** boundaries of ore (magnesite) fields.

2a and b), while the extension to depth along the dip ranges from 100 m to 300 m (Fig. 3). They pinch out gradually along the strike and dip, but there are also transitions into magnesite veins. They usually have clear salbands (on the footwall and/or hanging wall) towards the neighbouring ultrabasites, while, in their

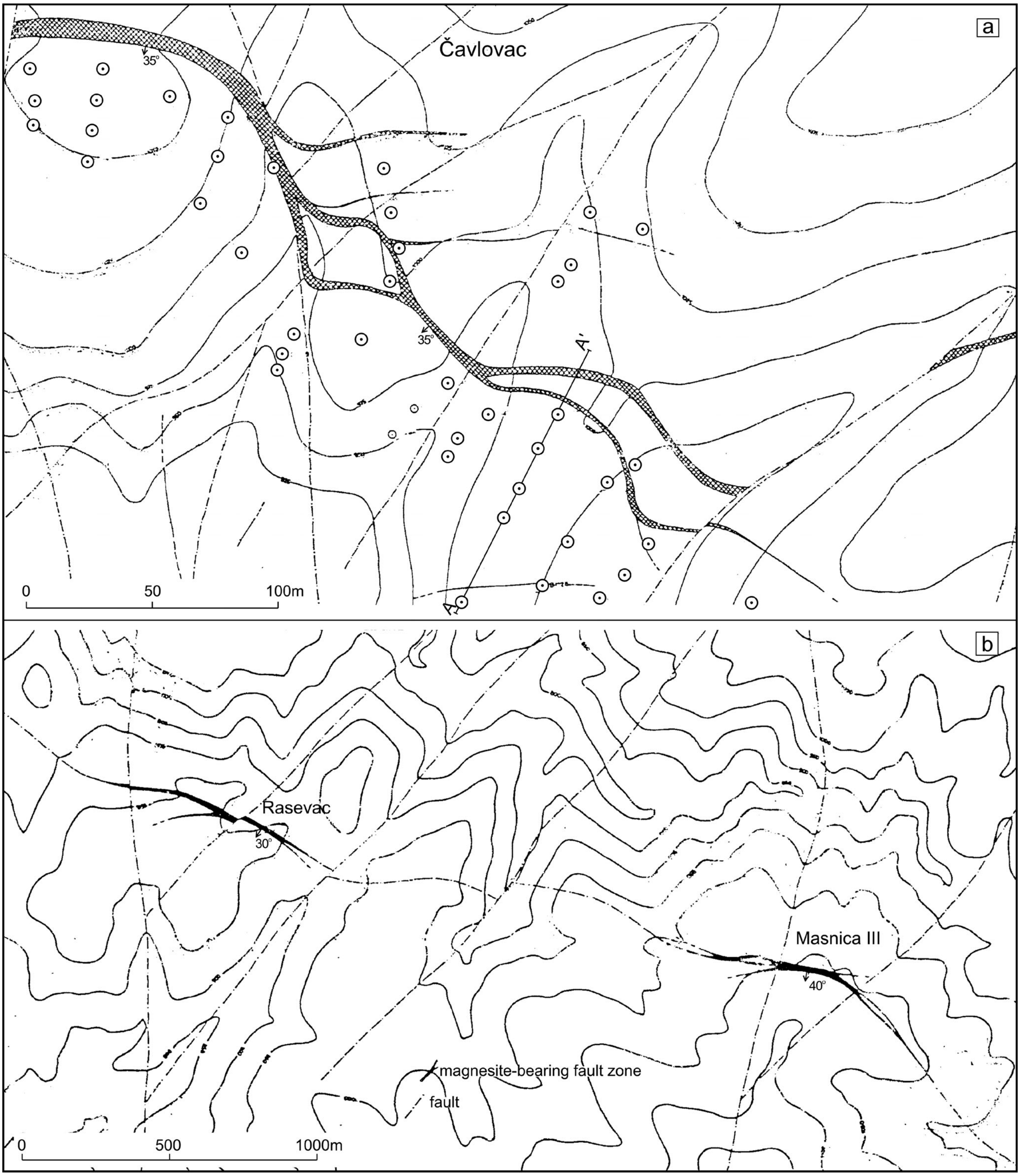


Fig. 2. Sketch showing magnesite-bearing fracture zones of Čavlovac (a) and Masnica III and Rasevac (b).

interior, ultrabasites are intensively cataclased, serpentinized, nontronized and limonitized (Figs. 3 and 4). The magnesite in them most often occurs in the form of parallel or sub-parallel veins (simple or complex ones – with apophyses, locally brecciated), of the same orientation as the whole zone, of lenticular and irregular bodies, and stockwork. The degree of mineralization of these zones by magnesite substance ranges from 30 to 40 %. In addition to magnesite, sepiolite also occurs in these zones in the form of veins in magnesite or discrete veins, and as cement in magnesite breccias (Figs. 3 and 4).

Magnesite either follows the whole dislocation or occurs only in some of its parts. The former is the

Čavlovac magnesite-bearing fracture zone (Fig. 2a), and the latter is the Donja Jablanica–Bakića Kolibe dislocation, in which magnesite accumulation occurs in its two parts (which are treated as separate magnesite-bearing fracture zones): Masnica III and Rasevac (Fig. 2b). Partial accumulation of magnesite within some dislocations can be explained by specific features of pre-mineralization and mineralization tectonics; post-mineralization tectonics, which however, led only to a change of the position of particular parts of the zone (owing to differential movement of separate blocks).

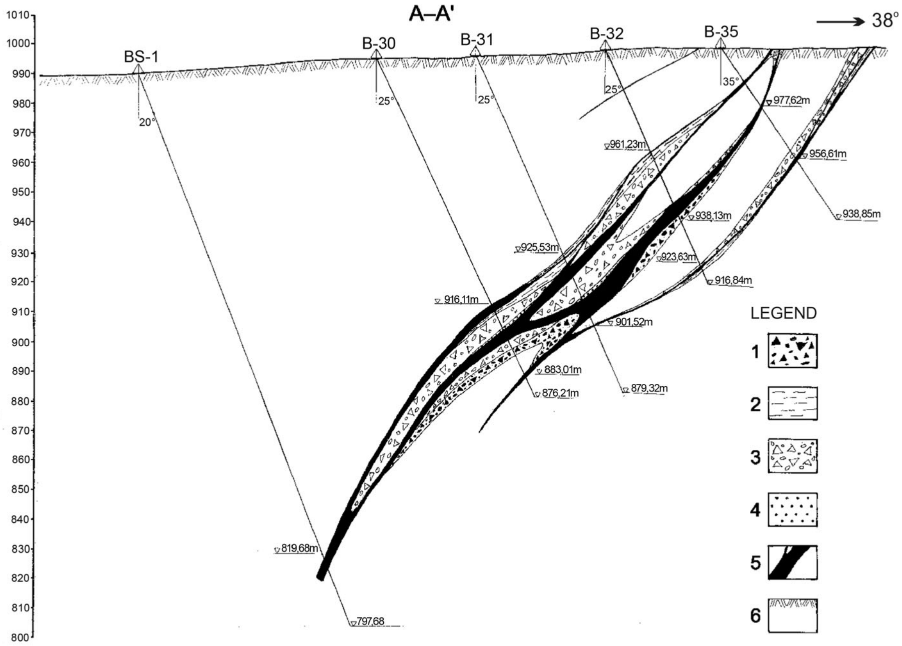


Fig. 3. Geological cross-section A–A' through the magnesite-bearing fracture zone of Čavlovac. **1,** Magnesite–serpentinite breccia; **2,** non-tronite clay; **3,** serpentinite–magnesite breccia; **4,** sepiolite–magnesite breccia; **5,** magnesite; **6,** humus.

Structurologically considered, the magnesite-bearing fracture zones and the fractures where the largest independent magnesite veins occur represent shear fractures, namely h0l ruptures. Thus, magnesite veins, within magnesite-bearing fracture zones (which have the same position as the zones, but are of smaller size), and independent magnesite veins (in other parts of the Zlatibor ultrabasic massif) have mainly similar elements of dip; the statistical maximum of the dip elements of magnesite-bearing fracture zones is 178/22, while in case of independent magnesite veins there are two maxima of dip elements, *i.e.*, 14/82 and 183/68. The apophyses of magnesite veins (both those in magnesite-bearing fracture zones and in independent ones) mainly represents mineralized feather fissures accompanying the main h0l ore-bearing ruptures.

The rupture structure, formed in the pre-mineralization period, impacted decisively magnesite mineralization, which occurred in the Upper Oligocene–Miocene (related to strong disjunctive tectonics and accompanying hydrothermal activity). These ruptures served both for introduction of hydrothermal solutions and for localization of magnesite mineralization. In the mineralization period, the existing fissures were activated many times, there were movements in various directions along them and they were opened and closed periodically, in accordance with the development of regional tectonic movements. These movements caused shattering and crushing of the magnesite substance and neighbouring rocks, while the magnesite and accompanying minerals (dolomite, calcite, quartz, chalcedony, opal and sepiolite) of younger generations were deposited in the newly formed empty spaces.

In the post-mineralization period, strong tectonic movements occurred, finally forming magnesite orebodies, including their fragmentation and differential movement of separate blocks along fault systems.

From a mineralogical point of view, the magnesite from the magnesite-bearing fracture zones is identical to the magnesite from independent veins: it is dense (microcrystalline to cryptocrystalline), white, and exhibits conchoidal fracture. With regards to the magnesite from independent veins, it differs only in a somewhat higher content of other carbonates (dolomite, calcite), while the content of other accompanying minerals, mainly silica (quartz, chalcedony, opal), is very similar.

In accordance with its mineral composition, the magnesite from the magnesite–bearing fracture zones differs from the magnesite from independent veins in a higher content of lime (CaO), *i.e.*, 1.5–3 % in the former and less than 1 % in the latter.

From a mineragenetic point of view, the magnesite-bearing fracture zones and the independent magnesite veins are syngenetic and synchronous formations. Both these structural–morphologic types of magnesite deposits occur in ultrabasites as host rocks and were formed in the same mineralization cycle bound to the Upper Oligocene–Miocene fracture tectonics and accompanying intermediate volcanism, namely its hydrothermal activity. Then hydrothermal solutions (which, in fact, represented a mixture of genuine juvenile solutions and prevailing ground waters of meteoric origin, heated by volcanic chamber), rich in CO_2, on their ascending movement leached magnesium out of

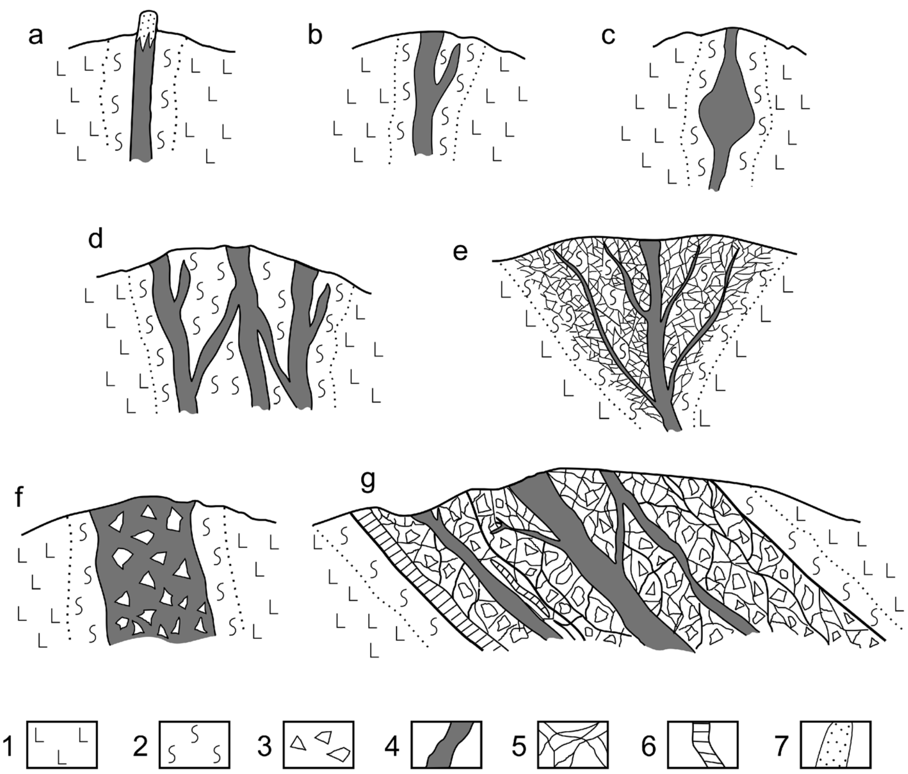


Fig. 4. Structural–morphological types of vein magnesite deposits: **a,** vein with a silica “hat”; **b,** vein with apophysis; **c,** lenticular orebody; **d,** system of veins with apophyses; **e,** vein with apophyses and accompanying stockwork; **f,** brecciated vein; **g,** magnesite-bearing fracture zone. **1,** peridotite; **2,** serpentinite (predominantly schistose with striae); **3,** fragments of serpentinites; **4,** magnesite vein; **5,** magnesite stockwork; **6,** sepiolite veins; **7,** silica “hat” (reef).

deeper lying ultrabasites, transported it in the form of bicarbonate and deposited it in the form of magnesite in ruptures (fracture zones, faults, fissures) in higher parts of the ultrabasite massifs (ILIĆ 1969a). Differences between these two types, thus, are only related to some structural and morphological features, but not to their genesis.

From an economic–geological point of view, magnesite-bearing fracture zones are large deposits of magnesite and accompanying sepiolite, having a complex constitution. In them are magnesite orebodies of varied structural–morphological types (veins, brecciated veins, lenticular and irregular bodies and stockwork), as well as accompanying sepiolite orebodies, which altogether, from an economic–geological point of view, form deposits. These deposits contain significant reserves (from several dozen thousand tonnes to several hundred thousand tonnes) of magnesite substance of good quality for application in the fireproof materials industry, as well as significant reserves of accompanying sepiolite, which has wide industrial application based on its sorbent and catalytic properties. Mining of such large and complex deposits should be preformed on the whole and completely (of all magnesite and accompanying sepiolite orebodies), not only of the largest and high-quality magnesite orebodies.

The Čavlovac, Rasevac, and Masnice III zones in the Zlatibor ultrabasite massif (Figs. 1, 2 and 3) can be considered as typical examples of magnesite-bearing fracture zones. The zones have been noticed in some other ultrabasite massifs (*e.g.*, in the Goleš and Maljen–Suvobor ones) but they have not been sufficiently explored.

Conclusions

Magnesite-bearing fracture zones represent specific dislocations in ultrabasites, mineralized by magnesite (and often accompanied by sepiolite), having hectometre to kilometre length. Although, they contain all known structural–morphological types of magnesite deposits (and constitutive orebodies) in ultrabasites (veins – single or systems, brecciated veins, lenticular and irregular bodies and stockwork – ILIĆ 1969a), they can be classified into a discrete complex structural–morphologic type, based on their distinct structural, morphological, mineragenetic and economic–geological features. These zones are the most prominent in the Zlatibor ultrabasite massif and economically very significant, as they contain large reserves of high quality magnesite, as well as of the accompanying sepiolite.

Acknowledgments

The authors are grateful to the reviewers: RUSLAN KOSTOV (University of Mining and Geology “St. Ivan Rilski”, Sofia, Bulgaria), RADE JELENKOVIĆ (Faculty of Mining and Geology, Belgrade, Serbia), and MIRA MILIĆ (Faculty of Forestry, Banja Luka, Bosnia and Herzegovina)

REFERENCES

ILIĆ, M. 1969a. Genesis and genethic types of magnesite deposits of the Balkan Peninsula. *Acta geologica JAZU VI, Prirodoslovna istraživanja*, 36: 67–102, Zagreb (in Croatian, English summary).

ILIĆ, M. 1969b. On the stratigraphic position and tectonic characteristics of the ultrabasic massifs of the Dinarides. *Geološki anali Balkanskoga poluostrva*, 34: 519–541, Beograd (in Serbian, English summary).

ILIĆ, M., PAVLOVIĆ, Z. & MILADINOVIĆ, Z. 2005. Results of exploration of magnesites in the area of Zlatibor ultrabasic massif in the period of 2002–2004. *6. Međunarodna izložba i savetovanje „Kamen 2005"*, 32–40, Aranđelovac (in Serbian, English summary).

ILIĆ, M. & RUBEŽANIN, D. 1978. On the origin of magnesite deposits of the Zlatibor ultrabasic massif. *Zbornik radova IX kongresa geologa Jugoslavije*, 539–554, Sarajevo (in Serbian, English summary).

KARAMATA, S. & POPEVIĆ, A. 1996. Ultramafites of Mt. Zlatibor. *In*: DIMITRIJEVIĆ M.D. (ed.), *Geology of Zlatibor Mt.*, Geoinstitut, monografija, posebna izdanja 18: 31–36, Beograd (in Serbian, English summary).

POPEVIĆ, A., JOKSIMOVIĆ, D. & KARAMATA, S. 1996. The Magnesites of Zlatibor. *In*: DIMITRIJEVIĆ M.D. (ed.), *Geology of Zlatibor Mt.*, Geoinstitut, monografija, posebna izdanja 18: 69–74, Beograd (in Serbian, English summary).

Резиме

Магнезитоносне разломне зоне у златиборском ултрабазитском масиву (Србија) као посебан изолован структурно-морфолошки тип магнезитских лежишта у ултрабазитима

У овом раду је приказан један посебан, до сада неиздвојен, структурно-морфолошки тип жичних магнезитских лежишта: *магнезитоносне разломне зоне*, који треба прикључити до сада познатим типовима (то су: магнезитске жице – појединачне или системи, бречасте жице, сочиваста и неправилна магнезитска тела и магнезитски штокверк ; Илић 1969а; Илић и Рубежанин 1978; Поповић *и др.* 1996). Ове зоне се јављају на више места у Србији, а најбоље су изражене у златиборском ултрабазитском масиву (сл. 1) (Илић *и др.* 2005), што је предмет овог рада.

Магнезитоносне разломне зоне представљају сложене дисјунктивне деформације у ултрабазитима (Илић 1969б; Карамата и Поповић 1996), хектометарске до километарске дужине, које су орудњене магнезитом (а често и пратећим сепиолитом) (сл. 1 и 2). Иако оне, парцијално посматрано, садрже све познате, горе наведене структурно-морфолошке типове магнезитских лежишта (односно конститутивних рудних тела) у ултрабазитима, оне се, на основу својих посебних структурних, морфолошких, минерагенетских и економско-геолошких карактеристика, интегрално посматрано, могу издвојити као посебан, комплексан структурно-морфолошки тип.

У златиборском ултрабазитском масиву до сада је откривено седам магнезитоносних разломних зона: четири у рудном пољу Рибница–Доња Јабланица (Чавловац, Масница II, Масница III и Расевац), једна у рудном пољу Стубло (Марин Извор), једна у рудном пољу Словићи (Словићи) и једна у рудном пољу Гола брда (Расадник) (сл. 1). Оне имају генерално пружање З–И до ЗСЗ–ИЈИ, а пад према Ј односно ЈЈЗ под 20–50°.

Ове зоне имају дужину од пар стотина метара до око 2 km, ширину од неколико метара до неколико десетина метара (сл. 2а и б), а простирање по паду им износи 100–300 m (сл. 3). По пружању и паду оне постепено исклињавају, а постоје и прелази у магнезитске жице. Према околним ултрабазитима оне обично имају јасне салбанде (на лежећем и/или висећем боку), а унутар њих ултрабазити су интензивно катаклазирани, серпентинисани, нонтронитисани и лимонитисани (сл. 3 и 4). Магнезит се у њима најчешће јавља у виду паралелних или субпаралелних жица (простих или сложених – са апофизама, местимично бречастих), истог залегања као и читава зона, сочивастих и неправилних тела и штокверка. Степен орудњености ових зона магнезитском супстанцом износи 30–40 %). Поред магнезита, у овим зонама се јавља и сепиолит у виду жица у магнезиту или посебних жица и као везиво у магнезитским бречама (сл. 3 и 4).

Магнезитско орудњење или прати целокупну дислокацију или се пак јавља само у појединим њеним деловима. Првонаведени пример представља магнезитоносна разломна зона Чавловац (сл. 2а), а другонаведени пример је дислокација Доња Јабланица – Бакића Колибе у којој се магнезитско орудњење јавља у два њена дела (који се третирају као посебне магнезитоносне разломне зоне): Масница III и Расевац (сл. 2б). Делимична орудњеност неких дислокација може се објаснити специфичностима прерудне и рудне тектонике; пострудна тектоника је, међутим, само доводила до промена просторног положаја појединих делова зоне (услед диференцијалног кретања оделитих блокова).

Структуролошки посматрано, магнезитоносне разломне зоне, исто као и разломи у којима се налазе највеће самосталне магнезитске жице, представљају раседе смицања, односно h0l руптуре. Стога магнезитске жице у оквиру магнезитоносних разломних зона (које имају исто залегање као и зоне, само са мањих димензија) и самосталне магнезитске жице (у другим деловима златиборског ултрабазитског масива) већином имају сличне елементе пада; статистички максимум елемената пада магнезитоносних разломних зона износи 178/22, а код самосталних магнезитских жица постоје два максимума елемената пада 14/82 и 183/68. Апофизе магнезитских жица (како оних у магнезитоносним разломним зонама тако и оних самосталних) већином представљају оруднене тензионе (перасте) пукотине које прате главне h0l рудоносне руптуре.

За магнезитску минерализацију, која је извршена у периоду горњи олигоцен–миоцен (у вези са снажним дисјунктивном тектоником и пратећом хидротермалном активношћу), пресудан значај је имао руптурни склоп образован у прерудном периоду: ове руптуре су послужиле и за привођење хидротермалних раствора и за локализацију магнезитског орудњења. У рудном периоду постојећи разломи били су вишекратно активирани, дуж њих су вршена кретања у разним правцима, периодично су отварани и затварани, у складу са развојем регионалних тектонских покрета. Ова кретања проузроковала су ломљење и дробљење магнезитске супстанце и околних стена, а у новообразованим празним просторима депонован је магнезит и пратећи минерали (доломит, калцит, кварц, калцедон, опал, сепиолит) млађих генерација, у више фаза.

У пострудном периоду такође су деловали снажни тектонски покрети који су финално уобличили магнезитска рудна тела, укључујући њихово разламање и диференцијално кретање оделитих блокова дуж система раседа.

У минералошком погледу магнезит из магнезитоносних разломних зона је идентичан магнезиту из самосталних жица једар (микрокристаласт до криптокристаласт), беле боје, шкољкастог прелома. Од магнезита из самосталних жица разликује се само по нешто вишем садржају других карбоната (доломита, калцита), док су остали пратећи минерали, пре свега силицијски (кварц, калцедон, опал), приближно једнако заступљени.

У складу са својим минералним саставом, магнезит из магнезитоносних разломних зона се од магнезита из самосталних жица разликује по повећаном садржају калције (CaO): 1,5–3 % код првопоменутих, а испод 1 % код другопоменутих.

У минерагенетском погледу магнезитоносне разломне зоне и самосталне манезитске жице представљају сингенетске и синхроничне творевине. Оба ова структурно-морфолошка типа магнезитских лежишта налазе се у ултрабазитима као околним стенама и образована су у истом минерализационом циклусу везаном за горњоолигоценско-миоценску разломну тектонику и пратећи интермедијарни вулканизам, односно за његову хидротермалну активност. Тада су хидротермални раствори (који су заправо представљали мешавину правих јувенилних раствора и од стране вулканског огњишта загрејаних подземних вода метеорског порекла), богати садржајем CO_2, при свом асцедентном кретању, вршили излуживање магнезијума из дубље лежећих ултрабазита, транспортовали га у виду бикарбоната, а обарали га у виду магнезита у разломима (разломним зонама, раседима, пукотинама) у вишим деловима ултрабазитских масива (Илић 1969a). Разлике између њих, дакле, постоје само у погледу неких структурних и морфолошких карактеристика, али не и погледу њихове генезе.

Са економско-геолошког аспекта магнезитоносне разломне зоне представљају велика лежишта магнезита и пратећег сепиолита, сложене грађе.

Магнезитоносне разломне зоне се, осим напред описаних у златиборском ултрабазитском масиву, јављају и у неким другим ултрабазитским масивима Србије (нпр. голешком, маљенско-сувоборском) али нису довољно истражене.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	119–129	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172119J

Vertical mineralization interval and forecast of the position of an ore-body in the Alšar Sb–As–Tl deposit, FYR Macedonia

Rade Jelenković[1] & Blažo Boev[2]

Abstract. Establishing a vertical interval of mineralization is a complex geological task based on the knowledge of many parameters and quantities that describe the genesis of an ore deposit. It is particularly important to know the time and the primary depth of the formation of an ore-body and its recent position.

The establishment of the vertical mineralization interval is considered in this work on the example of the Alšar Sb–As–Tl mineral deposit. The research methods used were geomorphological analysis (the principal exploration method), measurement of cosmogenic radioactive (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides to determine the erosion velocity (control method) and comparison of the obtained results with the geological exploration data from operative mine workings. A detailed geological study of the formation of the Alšar deposit preceded the research.

The research data are the following: depth interval of the ore-body is 10–50 m below the present ground surface; average level of erosion in the Alšar deposit area is 20–80 m over a period of 10^6 years (Ma), or about 100–400 m from the beginning of the volcanic activity to the present day (≈5 Ma); thickness of the eroded rock complex over the ore bodies from the beginning of the hydrothermal alteration and the formation of ore bodies (4.31 Ma) to the present is ≥150 m (Crven dol), or ≥230 m (central deposit); the palaeointerval of the formation of the ore-body is 230 m (200–430 m); and, finally, the potentially mineralized interval is deep, from 10 m to 280 m below the surface.

Key words: vertical mineralization interval, geomorphology, cosmogenic nuclides, erosion rate, genesis, Alšar, Macedonia.

Апстракт. Одређивање вертикалног интервала распрострањења рудне минерализације је сложен геолошки задатак који подразумева познавање бројних параметара и величина које описују генезу лежишта. Од посебног значаја међу њима су познавање времена и примарне дубине стварања рудних тела, као и одређивање дубине њиховог данашњег положаја у простору.

Одређивање вертикалног интервала распрострањења рудне минерализације у овом раду, показано је на примеру Sb–As–Tl лежишта Алшар. Истраживања су извршена применом више метода: геоморфолошке анализе (основна метода истраживања), мерењем космогених радиоактивних (^{10}Be, ^{26}Al) и стабилних нуклида (^{3}He, ^{21}Ne) за одређивање брзине ерозије (контролна метода) и поређењем добијених резултата са подацима оперативних геолошких истраживања из рударских радова. Истраживањима су претходила детаљна студијска изучавања геолошке грађе и генезе лежишта Алшар.

Истраживањима су добијени следећи резултати: одређен је горњи интервал распрострањења рудних тела на дубини од 10–50 m од данашње површине терена; утврђен је просечни ниво ерозије терена за шире подручје лежишта Алшар у износу од 20–80 m за период од 10^6 година (Ma), односно ≈100–400 m за период од почетка вулканске активности на подручју лежишта до данас (≈5 Ma); утврђена је дебљина еродованог комплекса стена из повлатног дела рудних тела у периоду од почетка хидротермалне алтерације и стварања рудних тела (4,31 Ma) до данас, и износу ≥150 m (локалитет Црвен дол), односно ≥230 m (Централни део лежишта); утврђен је вертикални палеоинтервал стварања рудних тела у износу од 230 m (200–430 m) и, на крају, констатовано је да се потенцијално рудоносни хоризонт налази на дубини од 10–280 m од данашње површине терена.

Кључне речи: вертикални интервал минерализације, геоморфологија, космогени нуклиди, ниво ерозије, генеза лежишта, Алшар, Македонија.

[1] Department of Economic Geology, Faculty of Mining and Geology, University of Belgrade, Đušina 7, 11000 Belgrade, Serbia. E-mail: radej@rgf.bg.ac.rs

[2] Faculty of Natural and Technical Science, "Goce Delčev" University of Štip, Goce Delčev 89, 92000 Štip, FYR Macedonia.

Introduction

Knowledge of the vertical mineralization interval is important for scientific research and for economic geology. Scientific research of an interval is necessary for the correct interpretation of the deposit formation, and economic geology for geological prediction of the spatial position of an ore body, rational design of exploratory work at the stage of detailed prospecting, possible delineation of ore bodies using a small volume of field work, high efficiency, and geological and cost-effective exploration.

How well a vertical mineralization interval is defined and the position of an ore-body is predicted depends on many geological attributes of the primary ore-body environment and the genetic model of its formation. Particularly important are the geology and structural geology of the region, the age of mineralization and the geological unit to which it is related in space and origin, the shapes of ore bodies and factors that controlled their spatial position, the mineral composition, the lateral and vertical zones of the distribution of the ore elements, the types of alteration, time and conditions of formation, *etc*.

Basically, the vertical interval of an ore body is established when its upper and lower boundaries are located in an explored mineral deposit, whereas its prediction requires knowledge of its formational palaeodepth, and velocity and level of erosion in the region. The prospecting activities include geological, geochemical, petrological and some other research, the commonest being the method of quantitative geomorphological analysis.

The primary depth of an ore-body formation and the depth of its recent interval are difficult to establish for hydrothermal mineral deposits that are spatially and genetically associated with the products of extensive and intensive volcanic processes in an environment heterogeneous in lithology and age. The Alšar Sb–As–Tl deposit in the FYR Macedonia is this type of mineral deposit.

The Alšar deposit was explored in detail from 1986 to 2011 under the LOREX Project (FREEDMAN *et al.* 1976; PAVIĆEVIĆ & AMTHAUER 1994; PAVIĆEVIĆ *et al.* 2004). A significant segment of exploration under the Project was the depth of thallium mineralization (primary lorandite) and its extraction from ore bodies in the Crven dol and Central part. The vertical interval of Sb–As–Tl mineralization in the Alšar deposit, the palaeodepths of the known ore bodies and potential environments of mineral ore localization were explored in 2011 under the LOREX Project, and under the Projects 176016 and 176019 financed by the Ministry of Education and Science of the Republic of Serbia. The basic search method used under the Projects was quantitative geomorphological analysis (GMA). For control and correction of the obtained results, the velocity and level of erosion were calculated through measurement of cosmogenic radioactive (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides.

Metallogenic position and basic geologic characteristics of the Alšar Sb–As–Tl deposit

The hydrothermal-volcanogenic Sb–As–Tl deposit Alšar is located on the NW slope of the Kožuf Mountain, FYR Macedonia, near the Greek border, which is a part of the Serbian–Macedonian metallogenic province, or the Kožuf ore assemblages (JANKOVIĆ & JELENKOVIĆ 1994; JANKOVIĆ *et al.* 1997; VOLKOV *et al*. 2006). The formation of the deposit is associated with the evolution of a complex intrusive volcanic structure of Pliocene age and the concomitant activity of hydrothermal ore-bearing systems.

The geology of the Alšar deposit has been studied in detail since 1960. The oldest lithologic members in the wider area of the deposit are dated Precambrian (albite gneiss, marble and mica schist) and the youngest geologic units are the Pliocene clastics, tufa, volcanic and pyroclastic rocks, and recent Quaternary deposits. Magmatism evolved in stages. Volcanism was central, developed over the intersection of regional-scale faults at the contact of Pelagonian Block and the Vardar Zone (BOEV 1988; KARAMATA *et al.* 1994; JANKOVIĆ *et al.* 1997; DUMURDZANOV *et al.* 2005; DIMANATOPULOS 2006; VOLKOV *et al.* 2006; BURCHFIEL *et al*. 2008).

The structural pattern of the Alšar deposit area is complex, composed of many ring structures and related fracture systems in different directions alongside regional faults of dominantly NW–SE to N–S (the Vardar direction) and E–W (Kožuf-Kukuš) trends.

Establishing the primary depth of the formation of the Sb–As–Tl ore bodies in the Alšar deposit was preceded by a study of its geology, identification of the primary and additional controls of the spatial position, shape, textural ore varieties, mineral composition and association of essential and minor elements of the ore-body. The age of volcanism, time of hydrothermal solution control, facies of hydrothermal alteration, time and order of their formation and dating the ore mineralization were given particular consideration. This was the basic information for establishing the primary formational depth of the ore bodies, which has been addressed since 1988.

The mentioned explorations determined Palaeozoic age of the schist, the oldest geologic unit in the Alšar deposit, and Triassic age of the silicified dolomite and marble. Geological and trial excavation prospecting in parts of the deposit revealed some sub-volcanic latite intrusions and sporadic presence of quartz latite, trachyte, andesite and dacite (Fig. 1). Most of the mentioned geologic units were covered by tuff and other pyroclastic materials in the closing phase of the geologic history (IVANOV 1965, 1986; KARAMATA *et al.* 1994; PERCIVAL & RADTKE 1994; JANKOVIĆ & JELENKOVIĆ 1994; JANKOVIĆ *et al.* 1997; VOLKOV *et al.* 2006).

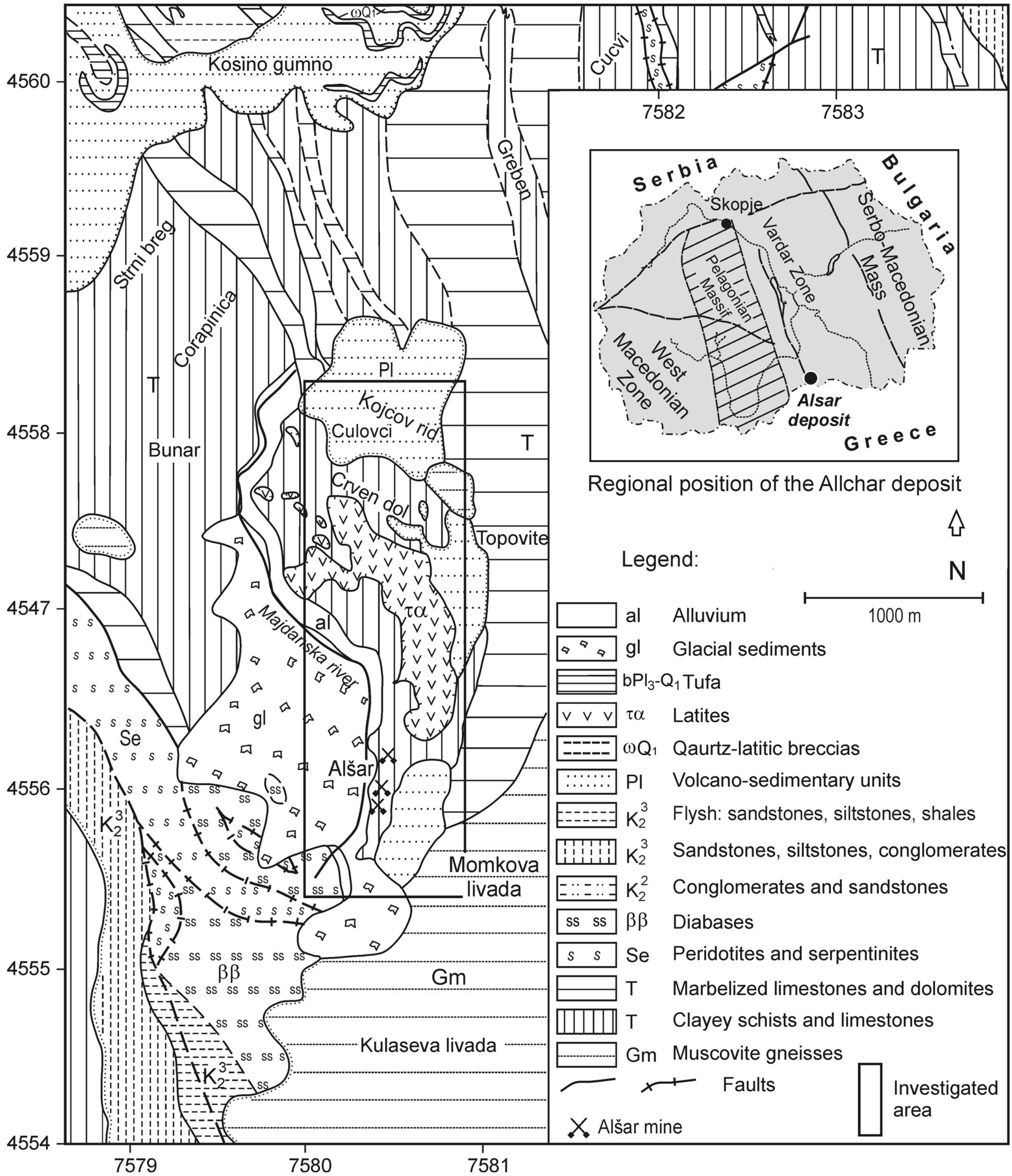


Fig. 1. Simplified geological map of the Alšar mineral deposit area (JANKOVIĆ *et al.* 1997).

The volcanic rocks of the Alšar deposit were dated using various methods on different minerals. The K/Ar method applied on sanidine from andesite and tuff dated it from 6.5 ± 0.2 Ma to 1.8 ± 0.2 Ma (BOEV 1988; TROESCH & FRANTZ 1992). The ages of biotite and feldspar from tuff at Vitačevo and Rudina were determined by the same method to be 5.1±0.1 to 4.31 ± 0.2 Ma and those of biotite, feldspar and pyroxene from andesite at Crven dol to be 6.5 ± 4.3 Ma to 3.9 ± 0.2 Ma (LIPPOLT & FUHRMANN 1986). The Ar/Ar method determined the age of biotite (5.78 ± 0.12 Ma), amphibole (4.8 ± 0.2–3.3 Ma) and K-feldspar (3.3–4.0 ± 0.2 Ma) from latite at Kojčov Rid (northern part of the Alšar deposit). In addition, crystallization temperatures were established for amphibole (550–500°C), biotite (300°C) and K-feldspar (250–160°C) (NEUBAUER *et al.* 2009).

Hydrothermal alterations of the rocks surrounding the ore bodies in the Alšar deposit indicated two main places of hydrothermal activity, one at a temperature of ≈400°C that ankeritised dolomite, and the other at temperatures from 280–250°C to ≈120°C when neighbouring rocks were intensively silicified, argillitised, decalcified and dolomitised. Ore minerals were deposited in the latter phase of the hydrothermal activity, during the intensive rock alteration before 4.31 ± 0.02 Ma (Rudina location) (JANKOVIĆ *et al.* 1997; VOLKOV *et al.* 2006).

The primary source of ore elements building the Alšar deposit was the continental crust. Most of the mineral elements were primarily associated with calc-alkali magmatic rocks of Pliocene age. A far smaller proportion of ore elements originated from the surrounding geologic formations. Sulphur was derived from a heterogeneous source; in the Alšar sulphide minerals, it was mainly of volcanic origin, from some magma chamber. However, the values of $\delta^{34}S$ vary within a range from +2.03 ‰ to +3.93 ‰, mean +2.92, whereas the isotope $\delta^{18}O$ was between +14.92 ‰ and 28.72 ‰. The fluid salinity is fairly low (7.9–12.9 wt. % NaCl). Ore elements were transported in the form of complex ions (bisulphides) from the primary sources to the locations of deposition or of ore-body formation by acidic to mildly alkaline hydrothermal brines in an oxidizing environment, partly also as colloids in weakly reducing conditions. The temperature range for most ore minerals was 120–200°C (SERAFIMOVSKI 1990; BALIĆ-ŽUNIĆ *et al.* 1993; BERAN *et al.* 1994; JANKOVIĆ & JELENKOVIĆ 1994; JANKOVIĆ *et al.* 1997; VOLKOV *et al.* 2006).

The principal factors controlling the positions of the Alšar ore bodies were lithology and structure. The lithologic controlling factors includes heavily crushed and hydrothermally altered Triassic dolomites and marbles and contact zones of carbonate with volcanic rocks (andesite, latite, quartz latite) and the associated Pliocene volcanogenic–sedimentary products (tuffaceous dolomite). Faults and secondary fracture systems, bedding planes in carbonate rocks and their contacts with volcanic rocks were the structural controlling factors.

The varied and eventful geohistory of the Alšar deposit region and its complex geology controlled by polyphase magmatism and recurring pulsation of mineral-bearing fluids led to the formation of ore bodies different in morphology, texture and mineral composition.

Massive realgar bodies emplaced in dolomites, ore bodies of similar textural features in dolomite contact zones with sub-volcanic intrusions and zones of brecciation, and impregnations of Tl–As minerals localized in carbonate rocks, all complex in morphology, are prevailing in the northern part of the deposit (Crven dol).

Centrally located in the Alšar deposit are ore lenses in carbonate rocks and associated stockwork impregnations (dominantly ore of the realgar type), elongate-lenticular to vein-like pyrite/marcasite or bodies and antimonite-prevailing ore bodies, then complex, irregular lens-like and columnar antimonite ore bodies and accessory pyrite, marcasite and gold (at contacts of basal tuffaceous dolomite and tuff with carbonate rocks that include silicified and argillitised volcanic rocks), and pyrite–marcasite and stibnite bodies with accessory As–Tl sulphides localized in silicified dolomite.

The Alšar deposit has a complex mineral composition. Pyrite with marcasite formed in an early stage of the deposit; then followed hydrothermal activity that produced arsenopyrite, antimonite and sulphosalt Sb–Pb, and the process of mineral deposition ended with the formation of realgar, orpiment and Tl-sulphosalt (PAVIĆEVIĆ & El GORESY 1988; SERAFIMOVSKI *et al.* 1990; BALIĆ-ŽUNIĆ *et al.* 1993; JANKOVIĆ 1993; BERAN *et al.* 1994; FRANTZ 1994). The identified group of ore minerals was used to determine geochemical associations of elements in the Alšar deposit. The main ore elements were found to be Sb, As, Tl and Au, and minor elements were Hg and Ba. In addition, there are Pb, Zn and Cu in traces. The elevated Tl concentration is related to parts of the deposit where As, Sb and Hg are elevated (JANKOVIĆ 1960; PALME *et al.* 1988; JANKOVIĆ 1993; PAVIĆEVIĆ *et al.* 2010). All the aforementioned associations of ore elements characteristically have a lateral zonal distribution. Thus, As–Tl, less Sb, locally Hg and Au are prevalent in the north; Sb–Au, less As, Tl, locally Ba, Hg and Pb traces in the central, and Au and minor Sb are dominant in the southern parts of the deposit (IVANOV 1965; JANKOVIĆ *et al.* 1997).

The vertical interval of the mineral ore in the Alšar deposit is widely variable. It is comparatively short in the reactive environment of dolomite and its contact zone with volcanic rocks. In a weakly reactive geological environment, however, such as silicified dolomite, tuffaceous dolomite, felsitic tuff and argillitisation zones, the interval is ≈150–200 m. The determined vertical ore body interval is ≈50–100 m (depth ≈840–760 m) in the north and ≈75 m (depth ≈850–775 m) in the central Alšar (IVANOV 1965; JANKOVIĆ *et al.* 1997).

Determination methods of the vertical mineralization interval

The vertical interval of the Alšar Sb–As–Tl mineralization was determined through three steps. The first two steps were establishing the base level of erosion, first by geomorphological analysis (GMA) and second by cosmogenic radiation (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides. In the last step, the obtained results were correlated and refined with the ore-body depth data from underground mining. The internal activity of data interpretation and drawing was performed alongside extramural explorations.

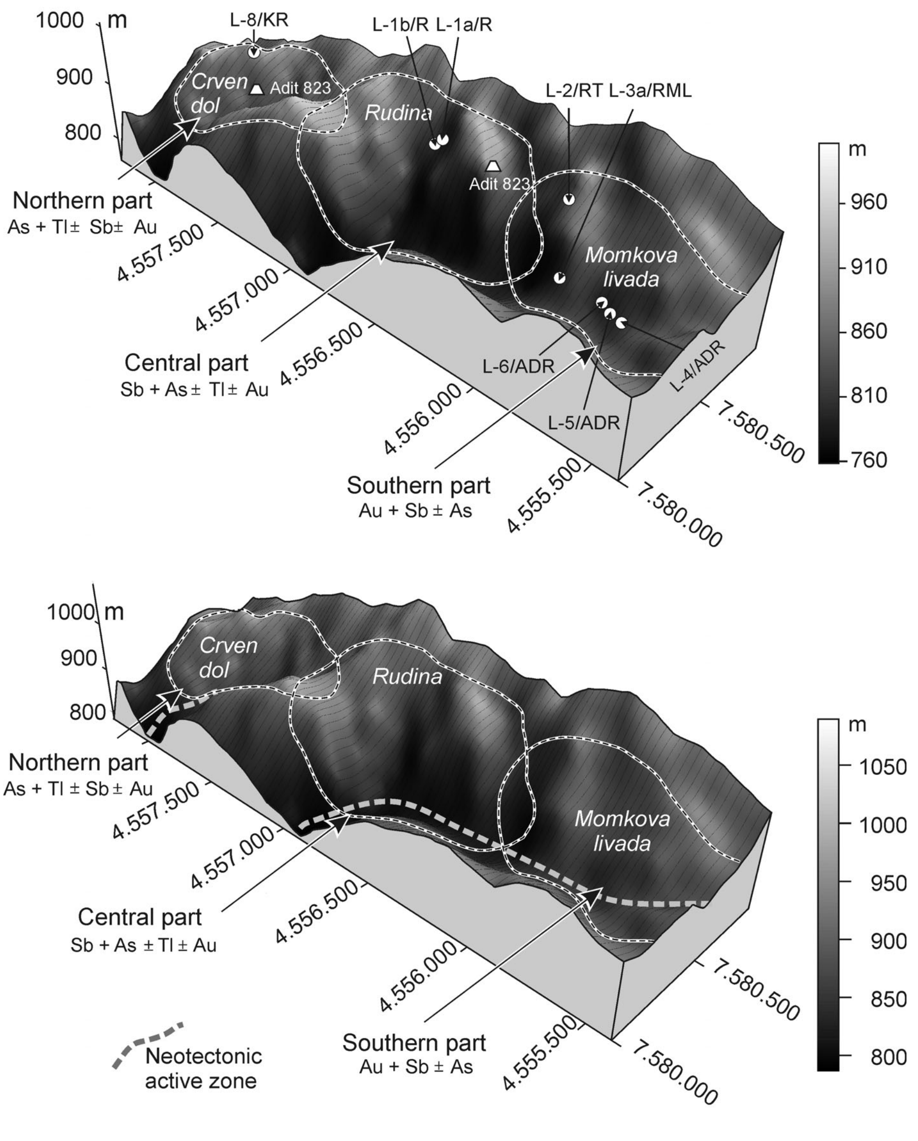


Fig. 2. Upper: 3D representation of the Alšar deposit area proper with delineated northern, central and southern parts, ore element associations, locations of Crven dol and Central part, sampling places and sample symbols for 2nd stage of the exploration. Lower: 3D palaeorelief of the Alšar deposit proper.

The first step methods and results

Several methods of qualitative and quantitative geomorphological analysis were employed in the first stage of determining the vertical interval of ore mineralization in the Alšar mineral deposit.

A qualitative geomorphological analysis of the Alšar region included interpretation of topographical and geological maps at the scales 1:100,000 and 1:25,000. The quantitative geomorphological analysis embraced treatments of the following: potential relief intensity, land slopes, comparison of the actual state of relief to the theoretical model, theoretical analogue of longitudinal stream sections, theoretical model of relief change in time and analysis of the erosion integral. The two substage research was realised in an area of 6 km^2.

In view of the previously determined age of volcanic activity in the Alšar region, the onset of the hydrothermal activity and the age of ore mineralization, the level of erosion was established for a period of 5 Ma. The unit field area, from which topographical and geological information was collected and further prospected, was 1 km^2. A detailed quantitative geomorphological analysis was made for the northern (Crven dol) and central (Central part) parts of the Alšar deposit, the locations in which Sb–As–Tl ore bodies were explored earlier in boreholes and adit excavations under the LOREX project. Since the morphology of the ore bodies, the recent interval of the ore bodies and controlling factors of their spatial position were determined in the two locations, they were used in the third step as gauges for amendment of geomorphological data. The level of erosion was established for the mentioned locations for the periods of five and one million years. The unit area for the calculation was 0.25 km^2 for the latter period (JELENKOVIĆ & PAVIĆEVIĆ 1994). Upon thorough consideration of all data, or geological and geostatistical processing, and reference to the elevation differences of the land surface, further analysis in either case used the potential energy of relief, the first trend of the height and slope variation.

A potential energy relief map was constructed and, using the method of current mean values, translated into a map of the first trend vertical breakdown of the relief. Based on this map, areas of positive and negative elevations, or parts of the considered space in which ground is slowly rising or sinking, were denoted on a topographical map. Comparison of the topographical and geological maps revealed that the sinking parts of the terrain were bounded by large faults, or were the geomorphologic features suitable for accumulation of waste materials, located in the catchment of the Majdanska River and its major tributaries.

The rising part of the terrain WSW and ESE in the research area is interpreted as landforms of intensive erosion, and the land between the rising and the features of waste accumulation are interpreted as active neotectonic structures. A map of the surface slope angles was prepared to determine the potential erosion. The level of erosion was established by deducting the recent land surface area from the palaeorelief applying the software package Surfer 9. The resulting surface is graphically represented in Fig. 2.

The mean level of erosion, indicated by the data obtained for the greater Alšar deposit for a period of five million years is ≈250 m, or within the interval from ≈100 m to 400 m, locally higher. Mean velocities of erosion were 37 m/Ma and 54 m/Ma at Crven Dol (northern part of the deposit) where the As–Tl ore bodies were well explored and in the old mine workings over the Sb–As–Tl ore bodies, respectively.

Second stage - methods and results

The levels of erosion were determined in the second stage of this research by application of cosmogenic radioactive (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides. Two methods of research were employed: first, AMS or accelerated mass spectrometry of the long-life radioactive cosmogenic nuclides ^{10}Be and ^{26}Al (PRIME Lab – Purdue Rare Isotope Measurement Laboratory, Purdue University) and second, MS or mass spectrometry of the noble gases or stable cosmogenic nuclides ^{3}He and ^{21}Ne (Geoforschungs Zentrum, Potsdam). The laboratory measurements were preceded by field sampling of silicified rocks (enriched by hydrothermal metasomatic quartz) from several places in the Alšar deposit and of sanidine and diopside, and their detailed petrological and mineralogical examinations by optical microscopy, X-ray diffraction and SEM–EDX. The methods for producing pure stoichiometric quartz were described by PAVIĆEVIĆ *et al.* (2006), whereas analytical MS treatments and methods for the isotopes ^{3}He and ^{21}Ne were described by NIEDERMANN *et al.* (1997) and NIEDERMANN (2002). The results of the AMS and MS measurements were further mathematically treated to estimate the erosion velocity or its level for a period of 10^6 years, and the conclusions are summarized in Table 1.

The isotope ^{10}Be and the ratio ^{10}Be/Be in BeO (1σ = 3–5 %) were determined in sixteen samples by AMS. The spectroscopy results were used to calculate the velocity and thickness of the eroded overburden, which varied within the range from 3.4 ± 0.5 m/Ma to 14.7 ± 1.8 m/Ma and were lower than the corresponding values determined by other methods.

The isotope ^{26}Al and the ratio ^{26}Al/^{27}Al in Al_2O_3 (1σ = 26–87 %) were determined in 21 samples. The erosion level of the rock complex overlying the Sb–As–Tl ore bodies was estimated to vary from a minimum of 67 ± 24 m/Ma to a maximum of 640 ± 150 m/Ma. These values are higher in relation to the erosion intensity obtained from the quantitative geomorphological analysis and from other analytical treatments in the study of cosmogenic radioactive and stable nuclides.

The isotopes ^{21}Ne and ^{3}He were measured in quartz by the NG MS method (samples from three different locations), in sanidine (one location) and in diopside (two locations). The results were similar, in some instances two-times higher than those resulting from the quantitative geomorphological analysis, For example, the erosion velocity determined by quartz sample analysis was ≥22–51 m/Ma, for ^{21}Ne in sanidine ≥69 (1σ = 10 % – 60 %), and ≥15 m/Ma for ^{3}He in diopside.

Discussion

The conclusions based on an analysis of the information presented above are the following:

1. The level and velocity of soil erosion in the greater Alšar deposit, in the past 5 Ma, the period from the onset of the volcanic activity and hydrothermal-mineralization activity to the present, were not uniform over the study area. The qualitative and quantitative geomorphological analyses revealed that the eroded overlying rocks were ≈100–400 m thick in the northern and central Alšar deposit containing economic ore bodies, and that average erosion velocity range was 20–80 m/Ma.
2. A study of the cosmogenic radioactive and stable nuclides indicated some similarities between them, but also certain dissimilarities. A high agreement was noted in of the data produced by the quantitative geomorphological analysis and the study of the isotopes ^{10}Be, ^{3}He and ^{21}Ne. The isotope ^{26}Al, however, demonstrated significant difference from the results obtained by other employed methods.
3. Further interpretation and metallogenetic analyses gave different GMA and AMS data that resulted from the following factors: (1) the high ^{27}Al concentration in hydrothermal quartz, associated with the formational conditions, type of volcanism and hydrothermal activity; (2) limitations of the applied analytical method, or the high threshold of its sensitivity (1×10^{-15}), and (3) different lengths of time for which the level of erosion was calculated (≈40,000 years) in re-

Table 1. Signs, locations and types of materials sampled for the study of cosmogenic nuclides and the determined erosion velocities (sample position denoted in Fig. 2). Abbreviations: al - albite; ap - orpiment; ba - barite; D - hydrothermally altered dolomite; di - diopside; Feh - Fe-hydroxide; ja - jarosite; M - hydrothermally altered and mineralized rocks without visible relics of their primary texture; mr - marcasite; py - pyrite; q - hydrothermal quartz; re - realgar; sa - sanidine; sc - scorodite; se - sericite; st - stishovite; V - hydrothermally altered and mineralized volcanoclastics; GMA - geomorphological analysis; S-1, S-2, S-3 - sample numbers; na - not analysed.

Location	Sampled materials	Thickness of the eroded rocks + / – error of determination (m/Ma)				
		^{10}Be	^{26}Al	^{21}Ne	^{3}He	GMA
L-1a/R	S-1: D, q, py, mr, sa, Feh. S-2: V, q, ja, mr.	na	na	= 69 +145/28	na	50 ± 10
L-1ba/R	q	14.7 ± 1.8	400 +120	51 +99/21	na	50 ± 10
L-2/RT	S-1: M, q, sc, re, ba, Feh. S-2: V, q, re, ap, sc, se, Feh. S-3: q.	5.4 ± 0.6	na	41 +24/14	na	46 ± 9
L3a/RML	V, q, se, ja, Feh.	5.1 ± 0.7	67 ± 24	39.4 +16/9	na	28 ± 6
L-4/ADR	S-1: V, q, se, mr, ba, ja, Feh. S-2: q.	4.2 ± 0.5	94 ± 19	40.8 +22/11	na	27 ± 5
L-5/ADR	V, q, se, mr, ba, Feh.	5.6 ± 0.7	345 ± 100	22 +2.6/2.1	na	30 ± 6
L-6/ADR	V, q, se, mr, ja, sc, Feh.	3.4 ± 0.5	640 ± 150	na	na	27 ± 5
L-8/KR	V, al, di, st.	na	na	na	≥15	40 ± 8

lation to the method of geomorphological analysis (5 Ma and 1 Ma).

4. The differences in the ^{26}Al/^{10}Be value as a function of ^{10}Be may be explained as being the consequence of any of the following: (1) linear erosion (steady-state irradiation history); (2) the presence of overlying rocks above the productive mineral-bearing interval with hydrothermal quartz that shielded it from radiation for a period of time (shielding from radiation); and (3) the complex history of the erosion processes (complex irradiation history). In view of the complexity of geohistory and metallogenic evolution, or the complexity of geology and evolution of the given region, case (3) seems to be the most likely event. Although the cosmogenic radionuclides ^{26}Al and ^{10}Be are the interaction products between cosmic radiation and hydrothermal quartz, their relationship (^{26}Al/^{10}Be) changed over time. Besides the dependence expressed by their different half-life (0.71 Ma for ^{26}Al and 1.36 Ma for ^{10}Be), this is also a consequence of the facts that sampling places from the time of hydrothermal quartz formation (4.31 Ma) to the present were repeatedly covered with pyroclastic materials, erosion rock debris from higher elevations and, later, with ice. When the ice melted, probably some 12,000 years ago, the sampled rocks were exposed to cosmogenic radionuclides and to intensive erosion which was determined using ^{26}Al and ^{10}Be. Different reference data and moraines in the immediate proximity of the Alšar deposit suggest that the rocks above an elevation of 1800 m were ice-covered. In view of the level of erosion determined by the quantitative geomorphological analysis for a period of 5 Ma, and of the calculated exposure period of the sample rocks to cosmic radiation of 10,000–85,000 years and the ≥2 Ma ground coverage with pyroclastic materials, the error of most the erosion level values is of the order of that for the quantitative geomorphological analysis (25 %).

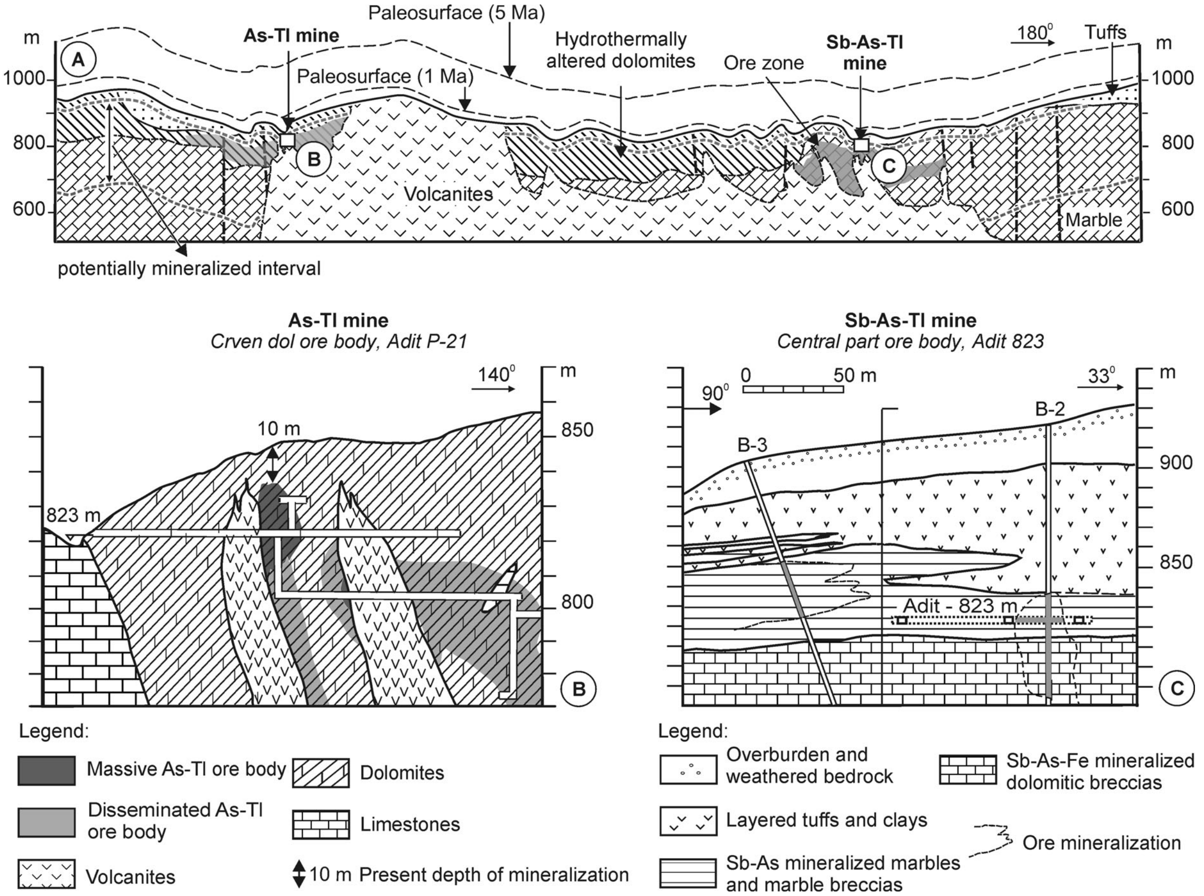


Fig. 3. A: Simplified geologic cross-section of the Alšar Sb–As–Tl deposit showing palaeosurfaces for different periods (5 Ma and 1 Ma), positions of the ore bodies and potentially mineralized rocks in the As–Tl mine (Crven dol) and the Sb–As–Tl mine (Central) locations. B: Characteristic geological cross-section at Crven dol (adit 823 m) and C: Characteristic geological cross-section at the Central part (adit 823 m) showing the positions of the identified ore bodies and the vertical intervals of ore mineralization verified in underground workings.

5. The average depth of erosion over the As–Tl ore bodies (Crven Dol) in the northern Alšar deposit was calculated to be 36 m for a period of million years (Fig. 3). The average depth of erosion in the Central area of the Sb–As–Tl ore bodies, where the old mine workings are located, was 54 m. Since the deposition of the minerals is associated with a period 4.31 ± 0.02 Ma and was concomitant with the onset of intensive hydrothermal alteration of the rocks surrounding the ore bodies, the average thickness of the eroded overlying rock complex should be ≈150–230 m.
6. The upper contour of the ore bodies in Crven dol, northern Alšar, is ≈10 m below the land surface. The mean depth of the ore bodies in the Central area is ≈50 m at present. In view of the abovementioned thickness of the overlying eroded rocks, the palaeodepth of the Sb–As–Tl ore-body formation in the Alšar deposit varied from 165 m to 380 m.
7. Vertical interval of the Alšar ore minerals was found by geological prospecting and excavations to be ≈80 m thick (depth interval 760–840 m) in Crven dol and ≈75 m (depth interval 775–850 m) in the Central area. The palaeointerval of their formation varied from 200 m to 430 m, or was ≈230 m. This value agrees with the vertical mineralization interval of most of the low- to medium-temperature hydrothermal mineral deposits, the duration of which is associated with young volcanogenic-intrusive complexes of calc-alkali magma (interval 200–300 m in length).
8. The position of a potentially mineral-bearing interval to be searched geologically is located at depths from 10 m to 280 m from the ground surface (Fig. 3).

Conclusions

The presented data may lead to the conclusion that the method of quantitative geomorphological analysis gives reliable information on the level and velocity of erosion used in preliminary and detailed prospecting for mineral resources, and for their geological exploration. Compared to the methods of the erosion level and velocity study by measurement of stable and radioactive cosmogenic nuclides, GMA has many advantages, such as comparatively simple application, fast operation and low cost.

The limitations of quantitative geomorphological analysis are many compared to other methods for the determination of the velocity and level of land erosion. Unlike other methods that give fairly reliable information on the erosion levels for geographically well-defined sampling microlocations, the GMA data are approximations, interpretations of the statistically processed information drawn on corresponding maps. For this reason, the level of erosion determined by GMA for accurately defined geographical locations mainly differs from the actual erosion values. Another group of limitations is related to the personal attitude of the researcher using GMA, or the subjective approach to the interpretation of the geologic evolution of the region. Additional factors affecting the accuracy of the calculation the level and velocity of erosion by GMA are: the scales of the geological and topographical maps used, the surface areas of the individual blocks from which data were collected for calculation of the erosion level and the calculation time interval. The quantity of the calculation error increases with increasing scale of the maps employed and the period for which the erosion is determined. For the scales of the maps used and the time interval for which the erosion level was determined, the mean calculation error empirically determined for the Alšar deposit area was ±25 %. The palaeodepth of the ore body formation was accordingly defined as an interval ≈120–350 m below the ground surface.

Acknowledgements

The authors gratefully acknowledge the reviewer VESELIN KOVACHEV (University of Sofia) for his constructive comments on the manuscript and an anonymous reviewer for the critical comments and helpful suggestions. The work was supported by the Ministry of Education and Science of the Republic of Serbia (Projects Nos. 176016 and 176019) and FWF der Wissenschaftsfonds, Austria, Project P20594-N16. Our gratitude is due to MIODRAG PAVIĆEVIĆ (University of Salzburg) who gave us his assistance in processing the results of the research under the LOREX Project and for the laboratory analyses of the stable and radioactive cosmogenic nuclides.

References

BALIĆ-ŽUNIĆ, T., STAFILOV, T. & TIBLJAS, D. 1993. Distribution of thallium and the genesis at Crven dol locality in Alšar. *Geologica Macedonica*, 7 (1): 45–52.

BERAN, A., GOTZINGER, M. & RIECK, B. 1994. A Fluid Inclusion study of Realgar from Allchar deposit, FYR Macedonia. *Neues Jahrbuch für Mineralogie*, 167 (2/3): 345–348.

BOEV, B. 1988. Petrological, geochemical and volcanic features of volcanic rocks of the Kožuf Mountain. Unpublished PhD dissertation, 195 pp., Faculty of Mining and Geology, Štip (in Macedonian).

BURCHFIEL, B.C., NAKOV, R., DUMURDZANOV, N., PAPANIKOLAOU, D., TZANKOV, T., SERAFIMOVSKI, T., KING, R.W., KOTZEV, V., TODOSOV, A. & NURCE, B. 2008. Evolution and dynamics of the Cenozoic tectonics of the South Balkan extensional system. *Geosphere*, 4 (6): 919–938.

DIMANATOPULOS, A. 2006. Plio–Quaternary Geometry and Kinematics of Ptolemais Basin (Northern Greece): Implications for the Intra-Plate Tectonics in western Macedonia. *Geologia Croatica*, 59/1: 85–96.

DUMURDZANOV, N., SERAFIMOVSKI, T. & BURCHFIEL, C. 2005. Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime. *Geosphere*, 1 (1): 1–22.

FRANTZ, E., PALME, H., TODT, W., EL GORESY, A. & PAVIĆEVIĆ, M. 1994. Geochemistry of Tl–As minerals and host rocks at Allchar (FYR Macedonia). *Neues Jahrbuch für Mineralogie*, 167 (2/3): 359–399.

FREEDMAN, M.S., STEVENS, C., HORWITZ, P., FUCHS, L., LERNER, L., GOODMAN L., CHILDS W. & HESSLER J. 1976. Solar Neutrinos: Proposal for a New Test. *Science*, 193 (4258): 1117–1119.

IVANOV, T. 1965. Zonal distribution of elements and minerals in the deposit Alshar. *Symposium Problems of Postagmatic Ore Deposition*, *In*: ŠTEMPROK, M. & RIEDER, M. (eds.), II, 186–191, Prague (in Russian).

IVANOV, T. 1986. Allchar the richest ore deposit of Tl in the world. *In*: NOLTE, E. (ed.), *GSI-report* 86–9: 9. Darmstadt.

JANKOVIĆ, S. 1960. Allgemeine Charakteristika der Antimonit Erzlagerstätten Jugoslawiens. *Neues Jahrbuch für Mineralogie*, 94: 506–538.

JANKOVIĆ, S. 1993. Metallogenic features of the Alshar epithermal Sb–As–Tl deposit (the Serbo–Macedonian Metallogenic Province). *Neues Jahrbuch für Mineralogie*, 166 (1): 25–41.

JANKOVIĆ, S. & JELENKOVIĆ, R. 1994. Thallium mineralization in the Allchar Sb–As–Tl–Au deposit. *Neues Jahrbuch für Mineralogie*, 167 (2/3): 283–297.

JANKOVIĆ, S., BOEV, B. & SERAFIMOVSKI T. 1997. Magmatism and Tertiary Mineralization of the Kozuf Metallogenic district with Particular Reference to the Alšar District. 262 pp. Monograph, Special Issue No. 5, Faculty of Mining and Geology, Štip.

JELENKOVIĆ, R. & PAVIĆEVIĆ, M.K. 1994. Erosion investigation of Allchar district based on the applied geomorphological and structuro-geological methods. *Neues Jahrbuch für Mineralogie*, 167 (2/3): 299–309.

KARAMATA, S., PAVIĆEVIĆ, M.K., KORIKOVSKIJ, S.K., BORONIHIN, V.A. &. AMTHAUER, G. 1994. Petrology and mineralogy of Neogene volcanic rocks from the Allchar area, the FY Republic of Macedonia. *Neues Jahrbuch für Mineralogie*, 167 (2/3): 317–328.

LIPPOLT, H.J. & FUHRMANN, U. 1986. K–Ar age determinations on volcanics of the Alshar Mine (Yugoslavia). *In*: NOLTE, E. (ed.), *GSI-report* 86–9. Darmstadt.

NIEDERMANN, S., BACH W. & ERZINGER, J. 1997. Noble gas evidence for a lower mantle component in MORBs from the southern East Pacific Rise: Decoupling of helium and neon isotope systematics. *Geochimica and Cosmochimica Acta*, 61, 2697–2715.

NIEDERMANN, S. 2002. Cosmic-ray-produced noble gases in terrestrial rocks: Dating tools for surface processes. *Reviews in Mineralogy and Geochemistry*, 47, 731–784.

NEUBAUER, F. PAVIĆEVIĆ, M.K., GENSER, J., JELENKOVIĆ, R., BOEV, B. & AMTHAUER, G. 2009. $^{40}Ar/^{39}Ar$ dating of geological events of the Allchar deposit and its host rock. *Geochimica and Cosmochimica Acta*, 73 (13): A938.

PALME, H., PAVIĆEVIĆ, M.K. & SPETTEL, B. 1988. Major and trace elements in some minerals and ore from Crven dol, Allchar. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 271 (2): 314–319.

PAVIĆEVIĆ, M.K. & AMTHAUER, G. 1994. Solar neutrino detection with Tl-205 – The LOREX Project. *Neues Jahrbuch für Mineralogie*, 167 [Supplement]: 125–426.

PAVIĆEVIĆ, M.K. & El GORESY, A. 1988. Crven dol Tl deposit in Allchar: Mineralogical investigation, chemical composition of Tl minerals and genetic implications. *Neues Jahrbuch für Mineralogie*, 167: 297–300.

PAVIĆEVIĆ, M.K., WILD, E.M., PRILLER, A., KUTSCHERA, W., BOEV, B., PROHASKA, T., BERGER, M. & STEFFAN, I., 2004. AMS measurements of ^{26}Al in quartz to assess the cosmic ray background for the geochemical solar neutrino experiment LOREX. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 223–224: 660–667.

PAVIĆEVIĆ, M.K., CVETKOVIĆ, V., AMTHAUER, G., BIENIOK, A., BRADSTATTER, F., GOTZINGER, M., JELENKOVIĆ, R., PRELEVIĆ, D. & PROHASKA, T. 2006. Quartz from Allchar as monitor for cosmogenic ^{26}Al: Geochemical and petrogenetic constraints. *Mineralogy and Petrology*, 88 (3/4): 527–550.

PAVIĆEVIĆ, M.K., BOSCH, F., AMTHAUER, G., ANIČIN, I., BOEV, B., BRUCHLE, W., ĐURIČIĆ, Z., FAESTERMANN, T., HENNING, W.F., JELENKOVIĆ, R. & PEJOVIĆ, V. 2010. New data for the geochemical determination of the solar pp-neutrino flux by means of lorandite mineral. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 621: 278–285.

PERCIVAL, J.C. & RADTKE, A.S. 1994. Sedimentary-rock-hosted disseminated gold mineralization in the Alsar District, Macedonia. *Canadian Mineralogist*, 32: 649–665.

SERAFIMOVSKI, T. 1990: Isotopic Composition of the Sulphur in the Sulphides from Alshar. *Geologica Macedonica*, 5 (1): 165–172.

TROESCH, M. & FRANTZ, E. 1992. $^{40}Ar/^{39}Ar$ Alter der Tl–As Mine von Crven Dol, Allchar (Macedonia). *European Journal of Mineralogy*, 4: 276.

VOLKOV, A.V., SERAFIMOVSKI, T., KOCHNEVA, N.T., TOMSON, I.N. & TASEV, G. 2006. The Alshar epithermal Au–As–Sb–Tl deposit, Southern Macedonia. *Geology of Ore Deposits*, 48 (3): 175–192.

Резиме

Вертикални интервал минерализације и прогноза положаја рудоносног нивоа у Sb–As–Tl лежишту Алшар (БЈР Македонија)

Одређивање вертикалног интервала распрострањења рудне минерализације је везано са бројним питањима генезе лежишта, и посебно, одредбом времена и палеодубине стварања рудних тела. У овом раду, извршено је на примеру Sb–As–Tl лежишта Алшар применом комплекса метода геоморфолошке анализе као основних метода истраживања, изучавањем радиоактивних (^{10}Be, ^{26}Al) и стабилних (^{3}He, ^{21}Ne) космогених нуклида (контролна метода) и поређењем добијених резултата са подацима оперативних геолошких истраживања из рударских радова. Истраживањима су претходила детаљна студијска изучавања геолошке грађе и генезе лежишта Алшар на основи којих је оно сврстано у класу сложених хидротермално-вулканогених лежишта плиоценске старости изграђених од више морфоструктурних типова рудних тела, комплексног минералног састава. Утврђена је старост вулканске активности, старост доминантних фација хидротермалних алтерација и рудне минерализације.

Квантитативна геоморфолошка анализа ширег простора лежишта Алшар обухватила је примену више поступака: поступак анализе енергије рељефа терена, анализу нагиба падина терена, поступак поређења реалног стања рељефа са теоријским моделом, поступак теоријског аналогона уздужног профила водотока, теоријски модел развоја рељефа у времену и анализу ерозионог интеграла. Истраживања су спроведена у две подфазе, на површини од 56 km^2, на ширем простору лежишта и на површини од 6 km^2 (ужи простор лежишта).

Ниво ерозије је одређен за период од 5 милиона година. Површина јединичног прорачунског поља износила је 1 km^2 и 0,25 km^2. Детаљна квантитативна геоморфолошка анализа је спроведена у локалитетима Црвен дол и Централни део у којима су претходних година истражним бушењем и рударским истражним радовима вршена детаљна геолошка истраживања Sb–As–Tl рудних тела. Будући да су у поменутим локалитетима детаљно утврђене морфолошке карактеристике рудних тела, вертикални интервал распрострањења рудне минерализације и контролни фактори њиховог положаја у простору, она су у трећој фази рада коришћена као

еталони за корекцију података геоморфолошке анализе. После детаљног сагледавања, геолошке и геостатистичке обраде улазних података праћене анализом вертикалне расчлањености рељефа, даља анализа терена у оба случаја извршена је применом поступака енергије рељефа терена, првог тренда енергије рељефа терена и нагиба падина терена.

У даљем току рада, конструисана карта енергије рељефа је методом текућих средњих вредности преведена у карту првог тренда вертикалне расчлањености рељефа. На основу ње су затим, на топографској основи издвојени простори са позитивним и негативним вредностима изолинија, односно делови анализираног простора у којима је вршено лагано издизање или спуштање терена. Зоне издизања терена су интерпретиране као простори интезивније ерозије, док су делови терена који се налазе између зона издизања и зона акумулације еродованог материјала, интерпретирани као неотектонски активне структуре. Одређивање нивоа ерозије терена извршено је одузимањем површи савременог рељефа од површи палеорељефа терена применом софтверског пакета Surfer 9.

Друга фаза рада је подразумевала одређивање нивоа ерозије применом космогених радиоактивних (^{10}Be, ^{26}Al) и стабилних (^{3}He, ^{21}Ne) нуклида применом метода акцелераторске масене спектрометрије дугоживећих радиоактивних космогених нуклида ^{10}Be и ^{26}Al и масене спектрометрије племенитих гасова или стабилних космогених нуклида ^{3}He и ^{21}Ne. Лабораторијским испитивањима су претходила теренска узорковања хидротермалног кварца са више локалитета лежишта Алшар, њихова детаљна петролошка и минералошка испитивања применом метода оптичке микроскопије, X-ray дифракције и SEM-EDX.

Изучавање изотопа ^{10}Be и односа ^{10}Be/^{9}Be у BeO (1σ = 3–5%), извршено је на 16 узорака применом AMS методе. На основи добијених података, срачунати су брзина и дебљина еродованог повлатног комплекса стена рудних тела у износу од 11–31 m/Ma. Изучавање изотопа ^{26}Al и односа ^{26}Al/^{27}Al у Al_2O_3 (1σ = 26–87%), извршено је на 21 узорку. Процењен је ниво ерозије у износу од минимум 67 ± 24 m/Ma до максимум 640 ± 150 m/Ma, што је знатно више у односу на вредности које су добијене применом квантитативне геоморфолошке анализе. Мерења изотопа ^{21}Ne и ^{3}He извршена су у хидротермалном кварцу применом MS методе (пробе са три различита локалитета), у санидину (једна локација) и у диопсиду (две локације). Добијени резултати се крећу у распону ≥22–51 m/Ma за ^{21}Ne у кварцу, ≥69 за ^{21}Ne у санидину (1σ = 10–60%), и ≥15 m/Ma за ^{3}He у диопсиду.

На основу претходно изложених података закључено је да су ниво и брзина ерозије терена на ширем подручју лежишта Алшар, у протеклих 5 Ma у периоду од почетка вулканске и хидротермално-минерализационе активности до данас, били су различити у различитим деловима анализираног простора. У северном и централном делу Sb–As–Tl лежишта Алшар у коме се налазе економски најзначајнија рудна тела са повишеним концентрацијама талијума, применом метода квалитативне и квантитативне геоморфолошке анализе утврђено је да дебљина еродованог комплекса повлатних стена износи ≈100–400 m. Просечна брзина ерозије терена кретала се од 20–80 m/Ma.

Поређењем добијених података са резултатима изучавања космогених радиоактивних и стабилних нуклида, уочене су одређене сличности али и разлике. Висок степен подударности података уочен је између резултата који су добијени применом методе квантитативне геоморфолошке анализе и резултата изучавања изотопа ^{10}Be, ^{3}He и ^{21}Ne. У случају изотопа ^{26}Al, међутим, одступања од резултата других метода су значајна.

Коначни закључци примењених истраживања су следећи: *а-* горњи интервал распрострањења рудних тела налази се на дубини од 10–50 m од савремене површине терена, *б-* просечни ниво ерозије терена на ширем подручју лежишта Алшар износи 20–80 m за период од 1 Ma, односно ≈100–400 m за период од времена почетка вулканске активности до данас (≈5 Ma); *в-* дебљина еродованог комплекса стена из повлатног дела рудних тела у периоду од почетка хидротермалне алтерације и стварања рудних тела (4,31 Ma) до данас износи ≥150 m за локалитет Црвен дол, односно 230 m за централни део лежишта; *г-* вертикални палеоинтервал стварања рудних тела износи ≈230 m (200–430 m) и *д-* потенцијално рудоносни хоризонт налази се на дубини од ≈10–280 m од савремене површине терена.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	131–141	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172131S

Prospects for wider energetic utilization of subgeothermal water resources: eastern Serbia case study

Zoran Stevanović[1], Aleksandar Saljnikov[2], Dejan Milenić[1], †Mića Martinović[1], Darko Goričanec[3], Mirko Komatina[2], Petar Dokmanović[1], Dragi Antonijević[4], Ana Vranješ[1] & Sava Magazinović[1]

Abstract. Extensive worldwide usage of fossil energy sources causes high pollution and contributes to global warming. Hence, achieving energy independence by stimulating efficient use of energy and environmentally friendly exploitation of renewable sources is a main orientation of European countries.

Geothermal energy is generally treated as a renewable and inexhaustible energy source. Nonetheless, direct use of low enthalpy subgeothermal resources, i.e. groundwater of 30ºC or lower, for heating is commonly viewed as economically unjustified. To enable its usage, large panel surfaces or a high-temperature heat pump with excellent efficiency is required. The development of a cascade type heat pump and its wide application would enable more efficient utilization of widely available and easy replenished groundwater sources with temperatures of 10–30ºC.

The hydrogeological conditions in eastern Serbia are particularly favourable for exploitation of subgeothermal resources due to rich aquifer systems and notable terrestrial heat flow formed into the main geo-structures of the region (Carpathian-Balkan arch and Dachian basin). More intensive exploitation of subgeothermal sources additionally justifies the existence of a number of urbanized small and medium-size cities with a heating infrastructure already developed and centralized. Sustainable use of groundwater resources should be followed by thermal reconstruction of the previously constructed buildings as well as new legislation which supports and encourages development of renewable energy sources. It is estimated that the total potential thermal power which can be generated from subgeothermal waters in the study area is around 33 MWt, which corresponds to some 16 % of the total heat requirements.

Key words: subgeothermal source, groundwater, heat pump, energy efficiency, eastern Serbia.

Апстракт. Интензивно коришћење фосилних горива широм света узрок је озбиљних загађења природе и утиче на глобално загревање. Отуда је један од главних циљева енергетске политике европских земаља коришћење ефикасније "зелене" енергије из обновљивих и сопствених извора.

Генерално, геотермална енергија представља вид обновљивих извора енергије. Ипак, и даље се сматра да коришћење субгеотермалне енергије ниске енталпије (температуре подземних вода од 30°C и ниже) за потребе грејања није у потпуности економски оправдано. Стандардна технологија за примену овог вида енергије захтева велике површине под панелима са цевима које проводе топлу воду и/или употребу топлотних пумпи са високим степеном искоришћења. Развој каскадне топлотне пумпе и њена шира примена омогућила би далеко ефикаснију употребу "лако" доступних подземних водних ресурса температуре између 10–30°C и стога је у више пројеката реализованих последњих година анализирана и развијана ова технологија.

Хидрогеолошки услови у теренима источне Србије, су веома повољни са аспекта експлоатације субгеотермалних ресурса. Подручје се одликује значајним количинама подземних вода и терестичним

[1] Department of Hydrogeology, Faculty of Mining & Geology, University of Belgrade, Djusina 7, Belgrade, Serbia, E-mail: zstev@eunet.rs

[2] Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, Belgrade, Serbia.

[3] Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, Maribor, Slovenia.

[4] Faculty of Applied Ecology, Singidunum University, Bul. M. Pupina 12a, Belgrade, Serbia.

топлотним током у оквиру геолошких формација у основним гео-структурним јединицама овог региона (Карпато-Балканиди и Дакијски басен). Близина урбанизованих насеља и мањих градова и постојање развијеног и централизованог грејања су чињенице које повољно утичу на могућност експлоатације субгеотермалних водних ресурса. Одрживо коришћење подземних водних ресурса подразумевало би и потребну термалну реконструкцију и бољу изолацију постојећих грађевинских објеката, као и доношење нових законских прописа у Србији у циљу подстицаја коришћења обновљивих извора енергије. У подручју источне Србије, процењене количине енергије које се могу добити из субгеотермалних вода износе око 33 MWt, што би представљало око 16% укупних енергетских потреба неколико одабраних већих насеља за које је ова анализа вршена. И поред чињенице да се не очекује потпуно искоришћење овог потенцијала, евидентно је да је он далеко већи од 4 % колико је у плановима енергетског развоја предвиђено да би могло износити учешће геотермалних водних ресурса на нивоу целе Србије.

Кључне речи: субгеотермални извори, подземне воде, топлотне пумпе, енергетска ефикасност, источна Србија.

Introduction

The utilisation of low-enthalpy ground source heat for space-heating (or cooling) is widespread in the USA and in Canada, with recent growing interest throughout Europe (BANKS 2008). The heat pump technology which supports low-enthalpy sources would help to achieve the objectives of the Kyoto protocols on "greenhouse" gas emissions. The thermal input for those pumps can be provided either directly by groundwater extracted from wells or tapped springs, or indirectly by water injected into the ground and then pumped out (rock and soil heat release) afterwards. Ground source heat pumps (GSHP) can be regarded as complementary technology inasmuch as they require a "driving" mechanical or thermal power input (commonly, electrical power to a compressor) that is used to extract renewable heat from the ground.

The heat effect delivered by a GSHP is typically 3–4 times the electrical power input. This means that it delivers heat 3–4 times more cheaply, with up to 75 % less CO_2 emission, than direct use of electrical resistance elements. This, in turn, allows GSHPs to deliver more CO_2-efficient space-heating than even the most efficient combustion of fossil fuels. Fossil energy sources are especially limited in European countries, and their dependence on import will be even more critical in the near future. Moreover, ground source heat can also compete effectively in terms of marginal costs with coal or gas (YOUNGER *et al*. 2007). The energy of the geothermal water could be exploited to the maximum before it is returned to the ground through a reinjection well (as already required by legislation of the European Union). With reinjection an ecological problem is also minimized, as utilized geothermal water must not be released into local water courses.

Although the initial high capital cost of GSHP schemes is a potential weakness, within the European Union the uptake of ground source heat technology has dramatically increased (ALLEN *et al.* 2003). In Sweden, for example, which has few native fossil fuel resources and an energy economy that is founded on nuclear/hydroelectric electricity, there has been a strong political motivation to develop technologies that utilise electrical energy as efficiently as possible. Moreover, the strong environmental and centralist traditions of the Swedish government have stimulated the uptake of technology since the early 1990s by a generous subsidy programme. In 2007, it was assumed that 185,000 GSHPs were installed in Sweden, providing some 1700 MW of power (BOUMA 2002; YOUNGER *et al*. 2007; BANKS 2008).

In central and SE Europe there is also growing interest in introducing, widely applying and promoting this kind of "green energy". In 2000, fewer than 1000 GSHP were functional within Czech Republic or Poland, while just five years later the number of procured and installed systems had increased tenfold. Rapidly growing interest in GSHPs is also noticed in Italy and in Slovenia, but the less powerful economies of the Balkan countries are still waiting for the encouraged legislation and the deduction of fees for their wider application. However, concerning groundwater resources and availability most of the countries that belong to the Balkan region are strong prospects. The efficient use of thermal potential of existing fluids would thus prevail over the possible alternative i.e. exploitation of rock and soil petrothermal resources.

Subgeothermal water sources

In most relevant references the geothermal fluids with a temperature lower than 100º C are classified as "low enthalpy": only the direct generation of electrical energy from water heat at a temperature higher than 100º C is considered to be fully feasible (NICHOLSON 1993; LUND & FREESTON 2001; HUTTRER 2001).

Due primarily to the "young Alpine geology" of the Balkan countries, there are insufficient geothermal fields to generate electrical power under existing technologies. However, the number of thermal occurrences is very large. For example, in Serbia alone over 230 springs or wells with thermal or mineral waters are registered, 2/3 of them with water temperatures over 20ºC. Most of the thermal waters are used for balneology and just a few for heating purposes. In contrast, in neighboring Hungary thermal flows are tapped for heating purposes in many locations. A good example is Hodmezovasarhely where 50000 inhabitants get their heat from the thermal waters at 80ºC, tapped at a depth of 2000 m (75 % of utilized waters are reinjected into the ground).

Recently conducted studies aiming to assess the thermal potential of lower temperature ground sources in Serbia introduced the term "subgeothermal resources" (STEVANOVIĆ *et al.* 2008). It has been proposed that waters with a temperature of 30ºC or lower are to be classified in this group whereas those with a temperature of 30–100ºC belong to "geothermal resources". One of the explanations is very practical: although GSHP is necessary for water with lower temperatures, the panel radiator systems allow direct use of water with a temperature of 30ºC or more without GSHP. However, as temperatures are lower, heating panels with larger surfaces are required.

Subgeothermal fluids in the territory of Serbia are typical of complex geology as well as of a moderate continental climate. They are classified as follows (Table 1):

Table 1. Energetic potential of subgeothermal sources.

Group	Temperature (°C)	Average depth (m)	Energetic potential
1	>10	0–20	None
2	10–16	20–75	Small
3	16–22	75–135	Moderate
4	22–30	135–200	High

Brief physio geography, geology and hydrogeology of the study area

There were several reasons to choose the Carpathian region in eastern Serbia (Fig. 1) as a study area: abundant groundwater reserves, considerable subgeothermal flow, a good number of small industrial towns with developed centralized heating infrstructure, and moderate continental climate. The northern boundary is the Danube River, the eastern/northeastern boundary is the state border with Bulgaria (toward which the Carpathian-Balkan mountain range continues), and its western border runs along the edges of the Velika Morava and Južna Morava valleys (Fig. 2). The main settlements are (from north to south): Donji Milanovac, Kladovo, Negotin, Majdanpek, Bor, Zaječar, Sokobanja, Knjaževac, Pirot (all with between 10000–60000 citizens). Further west in an adjacent area of central Serbia (Velika Morava valley) there are several large cities such as Niš, Paraćin, Ćuprija, Požarevac and others that are also envisaged as possible consumers of geothermal energy produced either from local sources or from eastern Serbia (MILIVOJEVIĆ & MARTINOVIĆ 2005; MARTINOVIĆ *et al.* 2008).

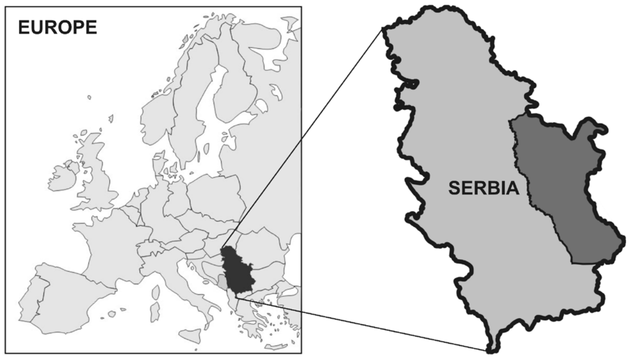


Fig. 1. Location maps of eastern Serbia.

The mountains of the Carpathian-Balkan arch are mostly unpopulated and used by the local villagers for specific crop cultivation or grassland during the summer months. Most of the hills are covered by forests or pastures. The demographic trend in the region is negative: the younger population is gravitating towards nearby industrial centers such as Bor or Zaječar.

The area is a prospect for the development of tourism. It is unpolluted and accessible by many roads, is rich in clean waters, and boasts beautiful landscapes and features such as caves, waterfalls and springs, including several spa and medical centers.

Annual average rainfall ranges from 600 mm to 750 mm for most of the cities, while the annual average air temperature for the entire region is around + 9ºC.

The complex geology of eastern Serbia comprises two main geo-structures: the Carpathian-Balkan arch and the Dachian basin, both characterized by hydrogeological heterogeneity and a variety in aquifer systems and groundwater distribution. Thus, the region is characterized by the presence of formations with small groundwater reserves but also Mesozoic carbonate rocks, Tertiary or Quaternary alluvial and terrace deposits that could be very rich in groundwater (STEVANOVIĆ 1994).

The study area consists of several mountain massifs, the majority of which are built from carbonate rocks (Fig. 2). Precambrian rocks are not often exposed to the surface and can be found in anticline cores, often corresponding with mountain central parts and peaks. They are commonly overlaid by Paleozoic rocks (Ordovician, Silurian and Devonian age). Paleozoic formations, magmatic and metamorphic rocks are mostly aquitards or aquifuges.

The major part of the study area was invaded by the Middle Jurassic marine transgression, and the sedimentation cycle continued until the end of the Lower

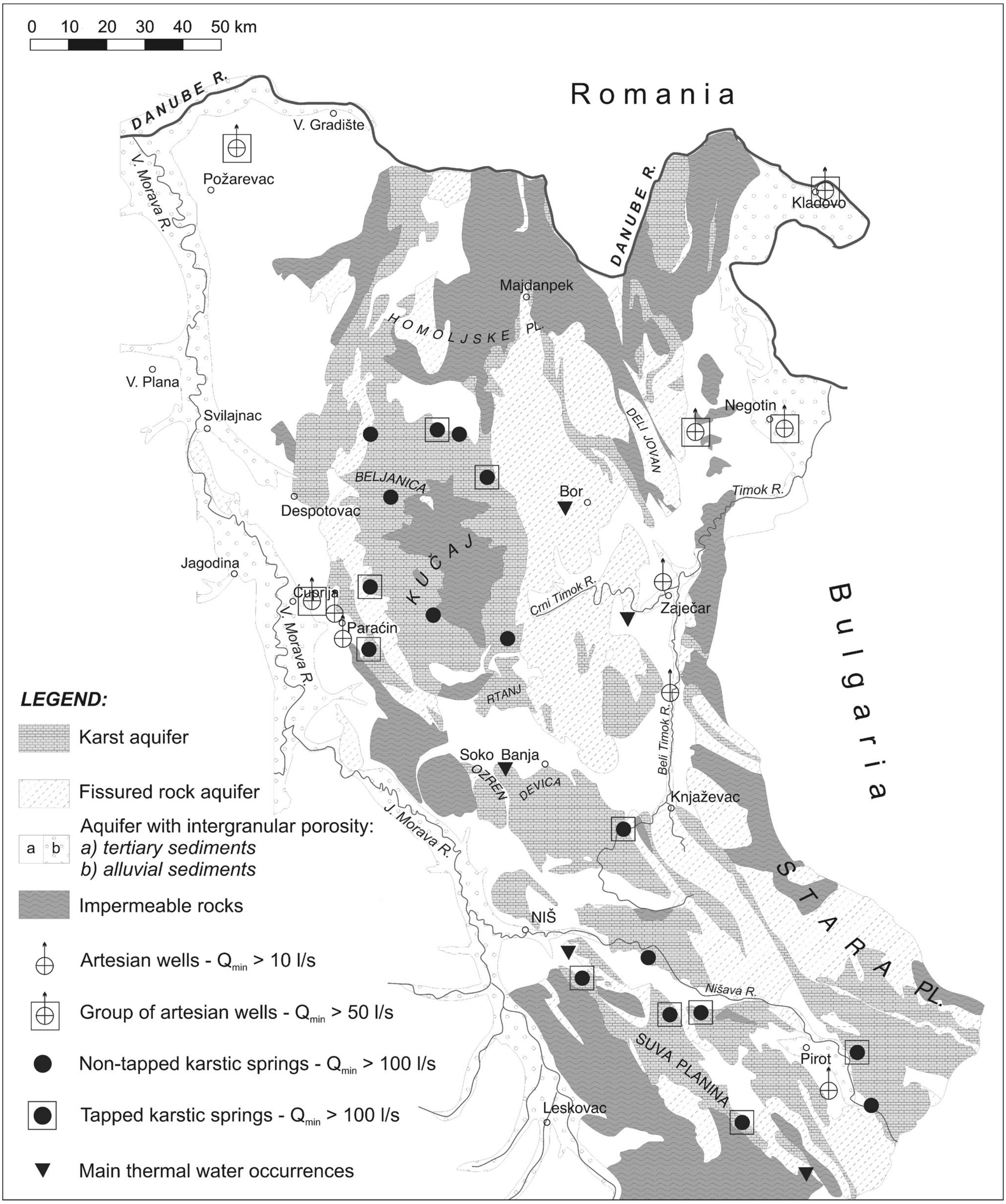


Fig. 2. Hydrogeological sketch map of eastern Serbia and main groundwater sources (based on Hydrogeological digital map of Serbia, Stevanovic & Jemcov 1995).

Cretaceous (Albian). Throughout this period, thick deposits, primarily of carbonate rocks, were formed to a total thickness of about 1300 metres. Carbonate rocks are characterized by the non-uniformity of the facies with prevalent limestone but also by ”impure” varieties in lower sections, such as sandy limestones of the Dogger, or Oxfordian-Kimeridgian chert limestones. The carbonate complex was formed mostly during the Tithonian, Valanginian, Hauterivian, Barremian and Aptian and it contains predominantly pure carbonates or magnesium carbonates.

The karst aquifer formed in carbonate rocks is rich in groundwater, and is recharged mainly from rainfall and from sinking flows which gravitate from impermeable rocks at higher altitudes. Carbonate rocks are well-karstified and contain very large groundwater reserves (STEVANOVIĆ 1994, 2009).

The karstic groundwater is used mostly for drinking purposes or for small industry supply; almost all the cities in the region are consumers. Although the total dynamic reserves in karst often surpass by far the exploitation capacities, most of the tapping structures are constructed simply to tap the natural discharge of the springs and thus depend solely on the natural flow regime. Aiming to overcome this problem, during the last three decades several successful aquifer control projects have been completed (STEVANOVIĆ *et al.* 2007). Karstic groundwater is extracted in a very small amount for irrigation purposes.

In the Timok tectonic trough on the eastern part of Carpathian arch, a volcanogenic-sedimentary series over 2000 meters thick (andesites, pyroclastics, tuffa) was formed during the Senonian and the Paleogene (Fig. 2). Fissured aquifer of this complex contains several important thermal and thermomineral occurrences with the water temperature ranging from 30–40ºC (Brestovačka spa, Gamzigradska spa, Sokobanja, Nikoličevo, Šarbanovac).

Clastic sediments, marls, clays, and sands were deposited in a number of the intermountain depressions filled with lake waters during the Neogene (e.g. Žagubica, Bogovina, Sokobanja, Babušnica, Pirot). The sandy water-bearing layers could have an artesian pressure (confined aquifers) and are tapped in several locations (e.g. Negotin, Zaječar).

Most recent are alluvial sediments which follow major streams in the region (Nišava, Timok, Resava etc.) and are used mostly to supply local villages. The exception is Niš where a large amount of alluvial water is tapped (Mediana source) for Niš itself, the third largest city in the country.

Utilizing geothermics by cascade heat pump - Discussion

For heating purposes three basic types of heat pumps are used (GORIČANEC *et al.* 2008):

– a single stage heat pump,
– a two stage heat pump with a flash vessel,
– a two stage heat pump with a heat transmitter.

Using a single stage heat pump for heating buildings, the temperature of the secondary carrier can reach 55°C maximum, which is quite a bit too low for the heating of buildings with a "classical" radiator heating system. Therefore, single stage heat pumps are primarily used for low-temperature heating systems, with the temperature of the secondary carrier up to 45°C. In high temperature heating systems, the temperature of the secondary carrier must be even higher than 60°C. With an appropriate refrigerant, a two stage heat pump with a flash vessel could be used for high temperature heating systems. But it is difficult to find a refrigerant which allows the exploitation of the temperature of geothermal water by cooling it to 10° C and at the same time reach a high temperature in the condenser of the second stage in the heat pump (GORIČANEC *et al.* 2009).

This problem has initiated research for a two stage heat pump with a heat transmitter (heat exchanger), schematically shown in Figure 3. The heat pump in fact consists of the two single stage heat pumps which are connected by a heat transmitter. The advantage of such a cascade heat pump is that, according to their physical-chemical characteristics, different refrigerants can be used at each stage. In choosing the refrigerant considerable attention must be paid to its physical-chemical characteristics, ecological acceptability, and use of recognized brands.

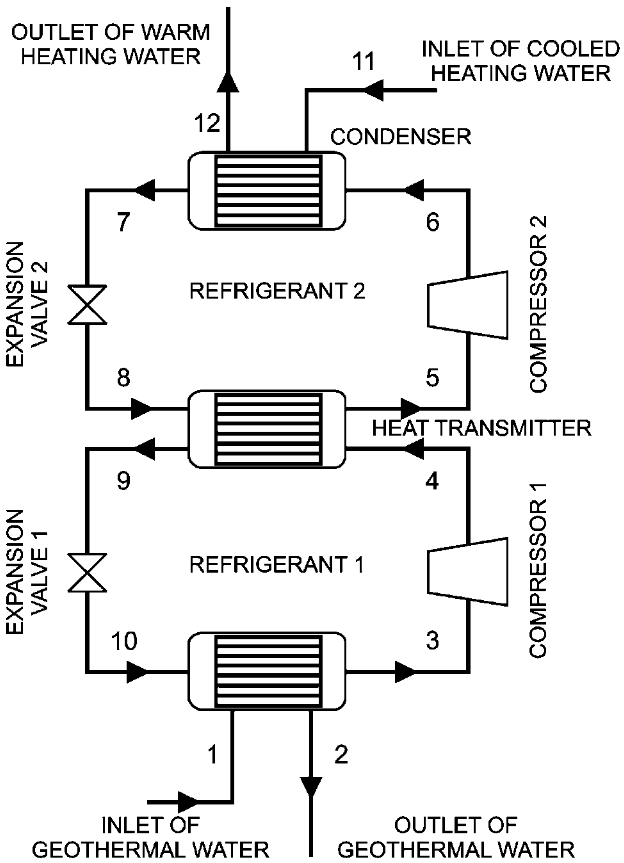


Fig. 3. Scheme of two stage heat pump with a heat transmitter (Goričanec *et al.* 2009)

The heat transmitter between the two stages represents a condenser for the first stage and an evaporator for the second (GORIČANEC *et al.* 2008). The use of two stage heat pumps with a heat transmitter is suggested in the existing district heating system of buildings in the city of Lendava in Slovenia (TORHAČ *et al.* 2005). The heat source for the heat pumps is geothermal water of 42°C. The principle of exploiting heat from geothermal water in an individual facility is shown in Figure 4. With such a system it would be possible to exploit the heating of geothermal water to a temperature of even 10°C.

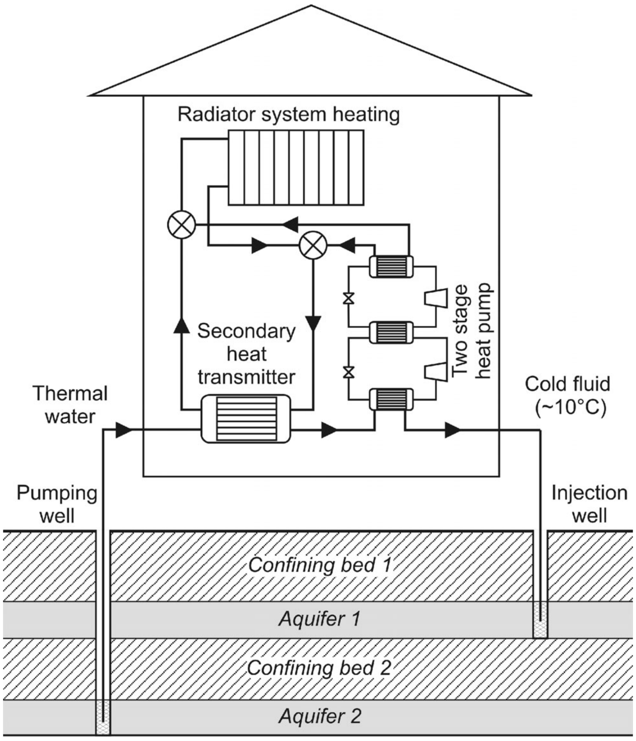


Fig. 4. Scheme of heating of building by a two stage heat pump and reinjection of utilized waters

The coefficient of profitability of a two stage heat pump and the period of time for the investment to be recovered show these to be good prospective solutions. In the case of the Lendava thermal source, the coefficient of profitability has been calculated on 1.19, and the investment will be returned in 3.2 years (KOZIĆ *et al.* 1994; TORHAČ *et al.* 2005). The coefficient of performance (COP) of a heat pump is between 3.5 and 4.4. Tests and calculations for water at lower temperatures, different refrigerants and equipment used resulted in a longer period for investment recovery, but still justifiable in terms of both economy and ecology.

At present, almost 50 % of total energy production in EU countries is spent in buildings. In Serbia even more, almost 2/3 of the energy is utilized for domestic heating, which is quite logical given that more than 50 % of buildings in Serbia were built before 1970. when application of thermal insulation was not obligatory. According to some estimates, the annual energy output is in the range of 150 to 250 kWh/m^2. This is 2–3 times more than optimal.

Moreover, the application of active and passive renewable energy for space and water heating is still not properly regulated in Serbia: it is only recommended in different state or local government strategies. However, central heating systems exist in numerous cities and can be used for conveying energy from alternative thermal sources.

Eastern Serbia - subgeothermal potential and prospect

Several conducted studies (STEVANOVIĆ 1994, 2009; MILIVOJEVIĆ & MARTINOVIĆ 2005, 2010; MARTINOVIĆ *et al.* 2008; STEVANOVIĆ et al. 2008) have concluded that eastern Serbia is one of the regions in the country with the greatest prospect for groundwater and subgeothermal energy extraction due to: richness of the aquifer, developed heating infrastructure within moderately populated cities, proximity of the sources to the end-users.

In practical terms, most important is the karstic type of aquifer in Jurassic and Cretaceous limestones, which covers about 30 % of this region. The region features a considerable number of karstic springs, of which 16 have a minimum yield of more than 0.1 m^3/s (STEVANOVIĆ 1995). All major cities use water from karstic aquifers; however, available reserves are several times higher than the water demand of this and neighboring regions, and will remain so for a long time to come. There is also good potential for groundwater utilization from alluvial sediments and Neogene formations in Intra-Carpathian basins. Regarding the total groundwater resources available there are some contradictions in their estimates. The Water Master Plan of Serbia from the year 2000 indicated dynamic groundwater reserves in the amount of 4.27 m^3/s, while some other studies found that even the reserves of karst aquifers are considerably higher, reaching 12.6 m^3/s. The karst and fissured aquifers are also rich in thermal water occurrences: there are 6 registered with temperatures over 30°C and some 20 with temperatures over 20°C. In addition, average water temperatures of artesian and subartesian waters from Neogene sediments are in the range of 10–18°C which also classifies those aquifers as ones with high potential for geothermics utilization (Table 2).

According to the preliminary assessment, some 1.7 m^3/s of groundwater in eastern Serbia can be extracted and sustainably used for heating/cooling systems (STEVANOVIĆ *et al*. 2008). This potential flow resulted from the calculation which took into consideration prioritized water utilization for drinking and industrial water supply, ecological flow for downstream water dependent eco-systems, and the average water temperature ranging from 10–30° C. The subthermal flow

Table 2. Available subgeothermal resources and calculated heat power in the Eastern Serbia.
* = Temperature of groundwater resources: 10–30°C

Aquifer system	Total groundwater resources (l/s) *	Total heat potential capacity (Mwt)	Available subgeothermal water resources (l/s)			Available heat power (Mwt)
			Temperature 10–16° C	Temperature 16–22° C	Temperature 22–30° C	
Alluvial aquifer	1750	43.9	610	0	0	15.3
Neogene artesian aquifer	730	26.8	170	55	45	10.4
Karstic and fissured aquifer	5310	140.0	730	55	30	23.5
TOTAL	7790	210.8	1510	110	75	49.2

ΔT = 6° C – temperature 10–16° C
ΔT = 12° C – temperature 16–22° C
ΔT = 18° C – temperature 22–30° C

can be separated into three categories as presented in Table 1. Total potential heat capacity is calculated by the formula:

$$Q = m * c * \Delta T$$

where,

Q – total potential heat capacity (MWt),
m – mass (kg),
c – specific water thermal capacity J/(kg°C) i.e. 0.004184,
ΔT – differential temperature (°C).

Differential temperatures are in the range of 6–18°C depending on geothermal categories (e.g. ΔT = 18°C for the waters with T 22–30°C). Available heat power is based on available water resources and tolerable COP, and is assumed to be around 49.20 MWt (Table 2).

The next step in the calculations considered the thermal heat power from sources which are located in the vicinity of the urban areas. Most of the water resources are at a viable distance from the consumers. The calculation is based on apartments with an average surface of 60 m^2 and required average heat of 100 kWh/m^2. The latter figure takes into consideration the implementation of some other energy efficiency measures to be implemented at the same time (thermal reconstruction and insulation of the buildings). Complete and systematic insulation would additionaly improve the situation and reduce required heat, but at this stage just part of these activities are envisaged. Table 3 contains data concerning the total power required to heat the apartments in major towns, the potential subgeothermal flow available in their vicinity (for each of defined three categories), the potential thermal power which can be produced by heat pumps, and the percentage of heat demands that can be met by heat power generated in such a way.

The total potential thermal power which can be generated from subgeothermal waters for large settlements is assumed to be around 33 MWt, which corresponds to some 16 % of their total heat demands. While it is clear that not all potential energy can be efficiently exploited, this figure indicates that the

Table 3. Potential of subgeothermal water resources and heat power in vicinity of urban areas of Eastern Serbia.
* = Flow of subgeothermal categories: 10–16 / 16–22 / 22–30°C.

No	Main towns	Number of house holds in urban area	Total surface for heating (m^2)	Required heat power (Mwt)	Available subthermal flow (l/s)*	Potential thermal power supported by heat pumps (Mwt)	Cover of required heat (%)
1	Kladovo	5,016	300,900	30.1	110/20/10*	4.5	15
2	Negotin	2,739	164,300	16.4	120/20/10	4.7	29
3	Majdanpek	2,563	153,700	15.4	120/10/5	4.3	28
4	Zaječar	6,812	408,700	40.9	160/10/10	5.3	13
5	Bor	5,736	344,100	34.4	130/10/10	4.5	13
6	Knjaževac	4,015	240,800	24.1	150/10/10	5.0	21
7	Pirot	6,728	403,600	40.4	140/10/5	4.4	11
	TOTAL	33,600	2,016,100	201.7	930/90/60	32.7	

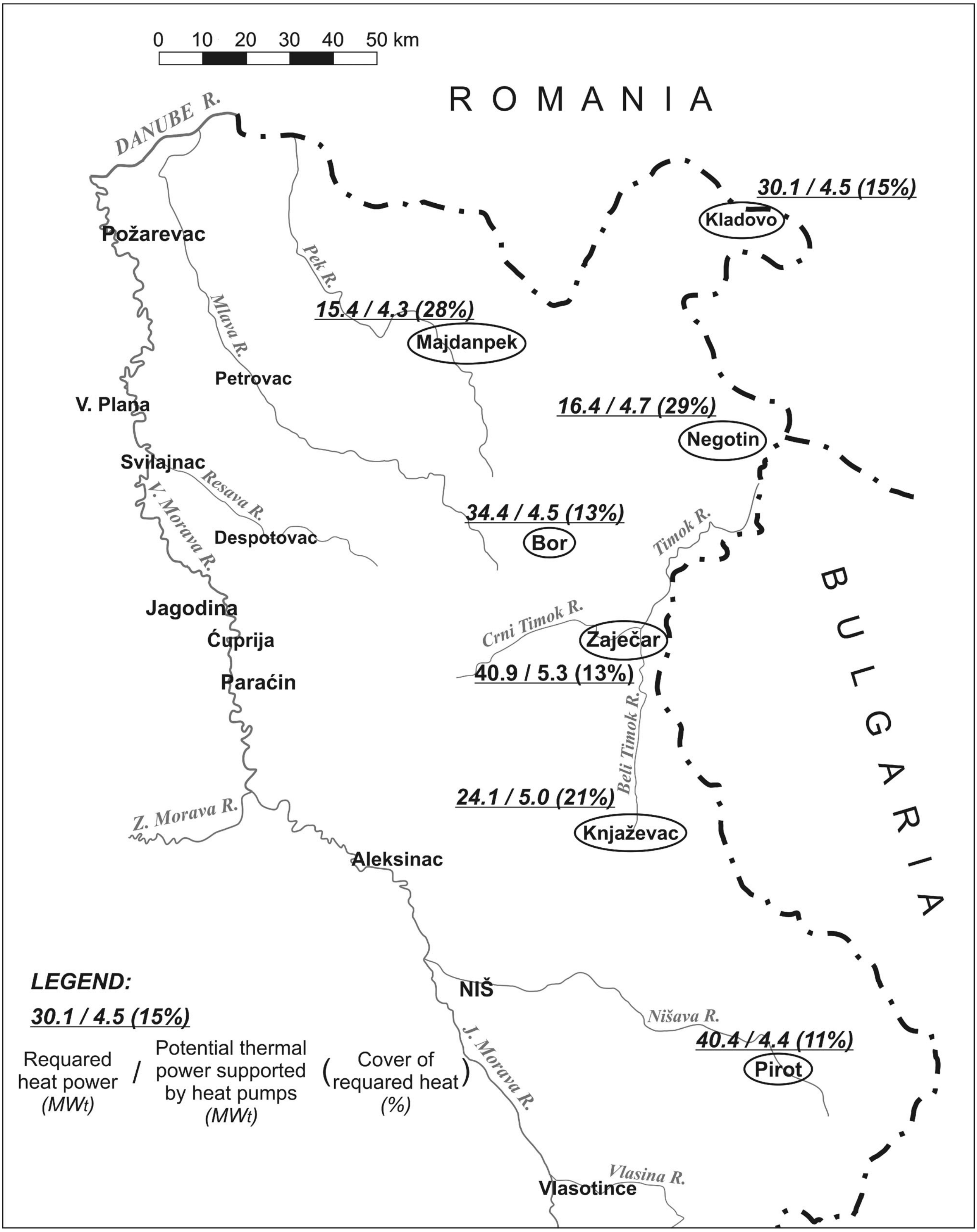


Fig. 5. The settlements - Main potential consumers of subgeothermal energy in eastern Serbia, their heat demands and possible cover

potential of subgeothermal energy in this region is much higher than the 4 % contribution from that kind of energy source to the Serbian energy balance recently announced in the national energy plans.

Between 11 % and 29 % of heat demands of selected towns are covered (Fig. 5). The latter figure characterizes the town of Negotin where a relatively large groundwater resource is located near a small urban settlement.

Such promising geothermal potential requires further systematic research as well as the development of a new strategy and legislation. Therefore, greater governmental support for "green" energy production is expected. Sustainable groundwater extraction should also be followed by controlled extraction (by the provision of permits for exploitation rights) as well as permanent monitoring aiming to prevent over-exploitation and potential technogenic processes.

The implementation of new legislation similar to that of the European Union is also required particularly for utilized waters which have to be regularly reinjected into the ground. A sound practice applied in developed countries suggests that reinjection should take place in the layers regularly overlying the main aquifer (Fig. 4) in order not to cool the existing temperature of the tapped waters [The heat pumps produce thermal energy by significantly decreasing initial water temperature (ΔT)]. A new approach also requires intensive public promotion of energy efficiency demands and achievements. And last but not least, the reconstruction of old buildings and thermal insulation should systematically be undertaken.

Conclusions

Among the main advantages of subgeothermal energy extraction from groundwater (temperature 30°C or less) are:

- Easy tapping (once the groundwater resource is properly explored and defined);
- Renewable energy resource which is cheap to develop;
- Inexpensive heating pumps and equipment (will be even less costly with wider application and further commercialization);
- Conservation and guarding non-renewable energy sources for future generations (in accordance with sustainable development principles);
- Energy independence of the country;
- Lesser emission of CO_2, CO, along with numerous other ecological benefits;
- Prospect for alternative economic development including tourism, recreation and the development of spa centers.

The two stages (cascade) heating pumps enable the exploitation of low enthalpy sources with temperatures over 10°C. However, every additional temperature degree makes this exploitation more feasible. Some regions such as eastern Serbia are a good example to demonstrate the feasibility and advantages of the development of subgeothermal resources and wider application of cascade heat pumps. One of the main advantages is the existence of a centralized heating infrastructure in most of the small or medium sized cities in the region.

Acknowledgements

The authors gratefully acknowledge the financial and administrative support provided by EUREKA Programme of the European Union and the Ministry of Science and Technological Development of Serbia for the implementation of the R&D projects !EUREKA 4117, SGTE 18008, and OI 176022. We are also acknowledging valuable comments provided by the reviewers Dr Hans Zojer (WATERPOLL, Graz) and Dr Aleksey Benderev (Geological Institute of Bulgarian Academy od Science, Sofia) which helped to improve quality of our work.

References

Allen, A., Milenić, D. & Sikora, P. 2003. Shallow groundwater aquifers and the urban 'Heat Island' effect: a source of low enthalpy geothermal energy. *Geothermics,* 32: 569–578

Banks, D. 2008. *An introduction to thermogeology: ground source heating and cooling.* 339 pp. Blackwell Scientific Publication, Oxford.

Bouma, J. 2002. Heat pumps – better by nature. *Newsletter*, 2 (20): 10–27

Goričanec, D., Saljnikov, A., Krope, J., Stevanović, Z. & Rudonja, N. 2008. Economic and environmental sustainability of geothermal cascade heat pump. *Proceedings of Conference Sustainable development and climatic changes*. Niš (in Serbian, English summary).

Goričanec, D., Saljnikov, A., Antonijević, D., Krope, J. & Komatina, M. 2009. Hydrogeothermal cascade heat pump – Economic and ecologic appropriacy. *Proceedings of International Conference on Renewable Energies and Power Quality (ICREPQ'09)*, Valencia.

Huttrer, G.W. 2001. Status of world geothermal power generation 1995-2000. *Geothermics*, 30: 7–27.

Kozić, D., Krope, J. & Goričanec, D., 1994. Optimization of large heat pumps in long distance transit heat transportation. *International Journal of Power & Energy Systems*, 14: 1: 5–8.

Lund, J.W. & Freeston, D.H., 2001. Worldwide direct use of geothermal energy, *Geothermics*, 30: 29–68.

Martinović, M., Stevanović, Z., Saljnikov A. & Andrejević S. 2008. Hydrogeothermal resources of Serbia – An energetic alternative. *Proceedings of Conference Sustainable development and climatic changes*. Niš (in Serbian, English summary).

Milivojević, M. & Martinović, M., 2005. Geothermal energy possibilities, exploration and future prospects in Serbia. *Proceedings of the World Geothermal Congress 2005*, Antalya.

MILIVOJEVIĆ, M. & MARTINOVIĆ, M., 2010. Serbia Country Update. *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia.

NICHOLSON, K. 1993. *Geothermal fluids: Chemistry and Exploration Techniques*. 268 pp. Springer-Verlag, Berlin.

STEVANOVIĆ, Z. 1994. Karst groundwater of Carpatho-Balkanides in Eastern Serbia. *In:* STEVANOVIĆ, Z. & FILIPOVIĆ, B. (eds.), *Ground waters in carbonate rocks of the Carpathian – Balkan mountain range*, 203–237, Allston Hold. Jersey.

STEVANOVIĆ, Z. 1995. Karst ground waters of Serbia. Present and potential uses in regional water suplly. *Lithospheric water mineral resources of Serbia*. 77–119, Speccial edition of Faculty of Mining and Geology, Belgrade.

STEVANOVIĆ, Z., JEMCOV, I. & MILANOVIĆ, S. 2007. Management of karst aquifers in Serbia for water supply. *Environmental Geology*, 51 (5): 743–748

STEVANOVIĆ, Z., SALJNIKOV, A., MILENIĆ, D., MARTINOVIĆ, M., ANTONIJEVIĆ, D., DOKMANOVIĆ, P. & GOJAK, M., 2008. Optimization of energetic utilization of subgeothermal water resources (in Serbian). Report on technological development project no. 18008, Ministry of Science and Technology Develelopment of Serbia, Archive of Faculty of Mining and Geology, Belgrade (in Serbian).

STEVANOVIĆ, Z. 2009. Karst groundwater use in the Carpathian-Balkan region. *In:* PALIWAL, B. (ed.), *Global Groundwater resources and management*, 26, 429–442, Scientific Publishers, Jodhpur.

TORHAČ, E., CREPINSK, L., KROPE, J., GORIČANEC, D., SALJNIKOV, A., STIPIĆ, R. & KOZIĆ, Dj. 2005. Profitability evaluation of the heating system using borehole heat exchanger and heat pump. *IASME Transactions*, 2 (8): 1381–1388.

YOUNGER, P., 2007. THORA project proposal - Thermogeological outreach activity: Transfer of ground source heating and cooling technology beyond the European Union. Archive of University Newcastle upon Tyne, Newcastle.

Резиме

Потенцијал субгеотермалних водних ресурса за шире енергетско искоришћавање - пример источне Србије

Геолошки услови на подручју Србије и балканских земаља не омогућују формирање хипертермалних вода у плићим структурама (до 2000 m), самим тим ни постојање геотермалне енергије која би се могла користити за производњу електричне енергије. Међутим, потенцијал за коришћење термалних вода и водних ресурса различите температуре за грејање је велики. Само у Србији регистровано је преко 230 извора и бунара са термалним и минералним водама. Од тога 2/3 ових вода су са температуром већом од 20°C. Већина термалних вода се користи у балнеологији, а само мањи број појава за потребе грејања. Насупрот томе, у суседној Мађарској геотемална енергија се користи за потребе грејања у многим местима. У суседном Ходмезовасархелу, преко 50 000 становника добија топлотну енергију из термалних вода температуре од 80°C, захваћене на дубини од 2000 m (75 % искоришћене воде се реињектира назад у геолошку средину).

Спроведене новије анализе усмерене на процену потенцијала субгеотермалних водних ресурса у Србији, увеле су термин „субгеотермални ресурси" (СТЕВАНОВИЋ *и др.* 2008). Овој категорији би припадале воде температуре 30°C или ниже, док би воде температуре од 30 до 100°C представљале "геотермалне ресурсе". Док су геотермалне топлотне пумпе (ГТП) неопходне за подизање температуре хладније воде, панелни систем грејања дозвољава директно коришћење вода температура 30°C или више, и то без употребе пумпи. Наравно, површина панела за грејање мора бити већа што су температуре ниже.

Коришћење геотермалне енергије ниске енталпије за потребе грејања (или хлађења) простора је широко распрострањено у САД и Канади, а од недавно је приметан пораст интересовања и широм Европе (BANKS 2008). ГТП се могу сматрати алтернативном технологијом, пошто им је потребно довођење механичке или топлотне енергије (обично електричне енергије до компресора), како би се геотемална енергија "извукла" за коришћење. При том, топлотни ефекат добијен радом ГТП је обично 3–4 пута већи од утрошене електричне енергије потребне за њен рад. Произведена топлота је уједно и 3–4 пута јефтинија, са до 75 % мање емисије CO_2, у односу на најефикасније системе за грејање са сагоревањем фосилних горива.

Иако су почетна инвестициона улагања у ГТП висока, касније уштеде и еколошке предности условиле су да посебно у земљама Европске Уније значајно порасте интерес за коришћење овог вида "зелене" енергије. Илустративни пример су Чешка и Пољска у којима је током 2000. године било нешто мање од 1000 оперативних ГТП, а само пет година касније број инсталираних система се повећао десетоструко.

Тренутно, у земљама ЕУ скоро 50 % укупне производње енергије троши се на стамбене објекте. У Србији је овај проценат знатно већи, готово 2/3 целокупне потребне енергије се користи за грејање домаћинстава. То је и логично ако се има у виду да је више од 50 % стамбених објекта у Србији изграђено пре 1970, када термоизолација у становградњи није била обавезна. Према неким проценама, годишњи утрошак енергије је у распону од 150 до 250 kWh/m^2, што је 2–3 пута више од оптималног.

Постоји неколико разлога због чега је област Карпато-балканида источне Србије разматрана као подручје у коме би се могли активније користити

ресурси субгеотермалне енергије: обилује значајним резервама подземних вода које нису у потпуности искоришћене за друге намене, има значајан број термалних и субгеотермалних природних водних појава, у овој области се налази и значајан број мањих индустријских градова са развијеном инфраструктуром централног грејања, и има релативно специфичан умерено-континетални тип климата. Ова област је перспективна и за развој туризма. Природни амбијент је релативно очуван, богата је чистом водом, и разноврсним природним појавама (пећине, водопади, извори), укључујући неколико бања и медицинских центара. Све то је потенцијал чијој би већој валоризацији могли допринети и ефикаснији системи грејања.

У неколико раније спроведених студија (Stevanović 1994, 2009; Milivojević & Martinović 2005, 2010; Мартиновић *и др.* 2008; Стевановић *и др.* 2008) закључено је да је источна Србија један од региона у земљи са највећим потенцијалом за експлоатацију подземних вода и субгеотермалне енергије. У практичном смислу, најзначајнији је карстни тип издани формиран у оквиру јурских и кредних кречњака, који заузимају око 30 % ове области и у којима су акумулиране резерве вода процењене на преко 12 m^3/s.

Према прелиминарној процени, око 1,7 m^3/s подземних вода источне Србије из различитих геолошких средина, могло би се експлоатисати и одрживо користи за потребе система за грејање/хлађење (Стевановић *и др.* 2008). Тај потенцијални капацитет резултат је прорачуна који је узео у обзир да су приоритет воде које се користе за пиће и индустријско водоснабдевање, као и да се мора обезбедити и еколошки проток воде за низводне екосистеме. Субгеотермални ресурси су подељени у три категорије (табела 1).

Процењено је да је укупни потенцијал термалне енергије, која се може добити из субгеотермалних вода око 33 MWt за већа насеља. То би представљало око 16 % њихових укупних енергетских потреба. Проценат покривености топлотног конзума за одабране градове се креће између 11 и 29 %. Највеће учешће субгеотермалних вода за грејање могло би се остварити у Неготину, где су релативно значајни ресурси подземних вода у близини нешто мањег урбаног насеља.

Иако је познато да се субгеотермални потенцијал не може практично никада искористити у потпуности, анализа указује и да је потенцијал субгеотермалне енергије у источној Србији далеко већи од 4%, колико је у плановима енергетског развоја предвиђено да би могло износити укупно учешће геотермалних ресурса на нивоу Србије.

Табела 1. Енергетски потенцијал субгеотермалних извора

Група	**Температура (°C)**	**Просечна дубина (m)**	**Енергетски потенцијал**
1	>10	0–20	занемарљив
2	10–16	20–75	мали
3	16–22	75–135	средњи
4	22–30	135–200	већи

Значајан геотермални потенцијал захтева даља систематска истраживања, као и развој нове стратегије и законодавства у енергетици. Према томе, очекује се већа државна подршка за производњу “зелене” енергије. Одрживо коришћење подземних вода треба да буде праћено и контролисаном експлоатацијом (обезбеђивањем експлоатационих дозвола), као и сталним мониторингом, са циљем да се спречава прецрпљивање издани и могућа појава пратећих техногених процеса.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	143–157	Београд, децембар 2011 Belgrade, December 2011

DOI: 10.2298/GABP1172143P

Hydrogeological and hydrodynamic characteristics of groundwater sources for the public water supply of Bečej (northern Serbia)

Dušan Polomčić[1], Olivera Krunić[1] & Vesna Ristić-Vakanjac[1]

Abstract. The existing groundwater source for the public water supply of Bečej City in Serbia is tapping groundwater from three water-bearing horizons over 15 wells with a summary capacity over 100 l/s. It is one of the characteristics of sources that several water-bearing layers are most frequently tapped simultaneously by wells. Two layers are tapped simultaneously by 12 wells; all three layers are tapped by ten wells, while one water-bearing layer is tapped by only three wells. The groundwater table at the source was recorded for a period of 30 years. In the conducted hydrodynamic analysis of the groundwater regime, it was concluded that in the mentioned period, a relatively low fall of the water table occurred, far lower than the previously predicted values. The results of a simulation of the exploitation regime of both the town and surrounding sources are presented in this paper for a period of more than two and a half years and the results of the identification of the basic hydrogeological parameters of the tapped water-bearing layers are presented in this paper. In addition, a balance for each element in the water-bearing layers exploited as sources of tapped water for the town are presented.

Key words: water-bearing layer, groundwater source, rheometric measurements, groundwater modeling, groundwater balance.

Апстракт. Постојеће извориште подземних вода за водоснабдевање становништва у Бечеју (Србија) захвата подземне воде из три водоносна слоја преко 15 бунара сумарног капацитета од преко 100 l/s. Једна од карактеристика изворишта је да су бунарима најчешће истовремено каптирано више водоносних слојева. Два слоја су истовремено каптирана на 12 бунара, сва три на 10, а три бунара каптирају само један водоносни слој. Током периода од 30 година регистрован је ниво подземних вода на изворишту. У спроведеној хидродинамичкој анализи режима подземних вода закључено је да је у поменутом периоду дошло до релативно малог опадања нивоа, далеко мање од раније прогнозираних вредности.У раду су презентирани резултати симулације експлоатационог режима градског и околних изворишта у периоду од преко две и по године и резултати идентификације основних хидрогеолошких параметара каптираних водоносних слојева. Такође, презентовани су елементи биланса градског изворишта на нивоу сваког каптираног водоносног слоја.

Кључне речи: водоносни слој, извориште подземних вода, реометријска мерења, моделирање подземних вода, биланс подземних вода.

Introduction

The studied terrain on which the public groundwater source lies is located west of Bečej, north of Novi Sad (Vojvodina). The terrain considered in the research and mathematical model takes the form of a rectangle with sides of 12.8 ×13.2 km and covers an area of 168.96 km^2 (Polomčić *et al*. 2011) (Fig. 1).

To meet the water supply requirements of the population and industry of the wider area of Bečej, the groundwater is tapped from three water-bearing layers located at depths from 60 to 13 meters. The town source of Bečej (Vodokanal–Bečej) comprises about 15 exploitation wells tapping the three mentioned water-bearing layers. The source is characterized by a relatively rapid ageing of the wells and relatively low

[1] Department of Hydrogeology, Faculty of Mining and Geology, University of Belgrade, Djušina 7, Belgrade, Serbia. E-mails: dupol2@gmail.com; krunico@yubc.net; vesna.risticvakanjac@gmail.com

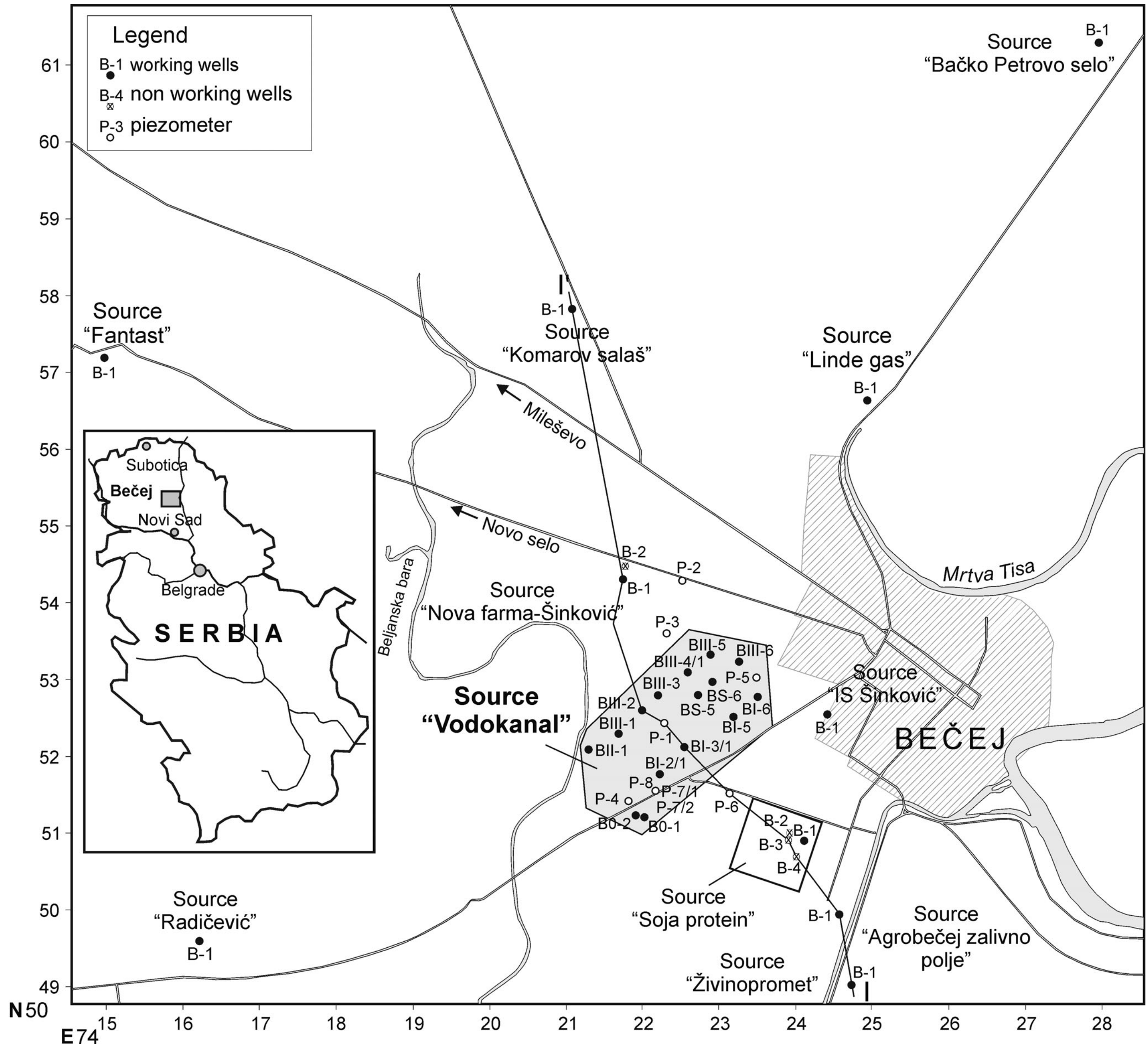


Fig. 1. Geographical location and positions of the groundwater sources.

head losses, being far lower than the predicted values. Several water-bearing layers are most frequently tapped by wells: two layers are tapped simultaneously by 12 wells, and all three by 10 wells, while one layer is tapped by three wells. In order to determine the hydrogeological parameters for each of the water-bearing layers, as well as the ground water balance of the Vodokanal–Bečej Source, a hydrodynamic model for each of the tapped water-bearing layers was developed. During the exploitation regime, a simulation of both the town and surrounding sources for a period of more than two and a half years and an identification of the basic parameters of the hydrogeological environment were performed and the balance of the groundwater elements was also determined.

Geologic setting of the wider surroundings of the Vodokanal–Bečej Source

From a geological point of view, the study area belongs to the large Pannonian Plain. The stratigraphical column in the study area is made of rocks of Precambrian–Palaeozoic, Mesozoic, Miocene, Pliocene and Quaternary age. The oldest rocks in the study area are comprised of crystalline shale, most likely of Precambrian–Palaeozoic age. The crystalline shale is found at depths between 1424 m and 1528 m in deep boreholes in Bečej itself and its surroundings. Discordant sediments of the Upper Jurassic and the Upper Cretaceous overlie the crystalline shale. Among the Mesozoic members, the Upper Cretaceous, comprised of carbonate and flysh sediments, is the most widely distributed. Upper Cretaceous formations in the Bečej area are found at depths from 1357 m to 1900 m.

The thickness of the overall Neogene series is about 1250 m. This series most frequently overlies transgressively Upper Cretaceous, Sennonian, flysh and carbonate formations. Sediments of Miocene age are represented by sandstone, reef limestone, marl, clayey marl, and Badenian conglomerates, while the formations of Pannonian age are comprised of clayey marl, marl, sandy–clayey marl and sandstone. Badenian sediments are not of high thickness but are very good aquifers in which a carbon dioxide deposit was discovered. Unlike them, Pannonian sediments are typical aquifuges. Sediments of Pliocene age are represented by Upper Pontian sandy–marly clay, marl, sandstone and clayey marl, and by Paludina deposits comprised of clay, sand, sandy coal-bearing clay and lignite. The thickness of the Upper Pontian sediments is estimated to be 400–450 m, and the thickness of sandy layers within them ranges from several meters to about 250–300 m. These layers are significant aquifers. It is thermo-mineral water with the presence of dissolved gases that occurs in the deep regions.

Quaternary deposits cover the whole surface of the study area. The thickness of the Quaternary deposits ranges from about 130–140 m. Generally, the Quaternary, in relation to Paludina deposits, is characterized by a higher content of the Psammite component and more frequent alternation of sand and clay. Tapped water-bearing layers in the Bečej town source belong to the Quaternary, predominantly the Upper and partly the Middle Pleistocene, deposited under river-lake and river-marsh conditions.

Hydrogeological characteristics of the wider area of Bečej town source

In the study area, there have been developed five water-bearing layers were developed in a vertical profile to a depth of about 170 m.

The shallowest water-bearing layer lies to a depth of 30 m (Fig. 2). Its horizontal distribution is significant. Lithologically, its composition is not homogenous. It is comprised of loess sediments in the upper part and fine-grained, locally clayey sand, in the lower one. An unconfined aquifer, the water of which is used neither for the public water supply nor for industrial needs, formed in these heterogeneous sediments.

Three deeper water-bearing layers lying at depths of 60 m to 130 m are comprised of fine-grained to medium-grained sand and are used for domestic and industrial water supplies. All three layers are distributed regionally extending beyond the study area. These three deeper water-bearing layers represent a hydrogeological complex formed under similar sedimentary river-lake and river-marsh conditions during the Lower and the Middle Pleistocene. From the surface of the terrain, these layers are marked by Roman numbers I, II

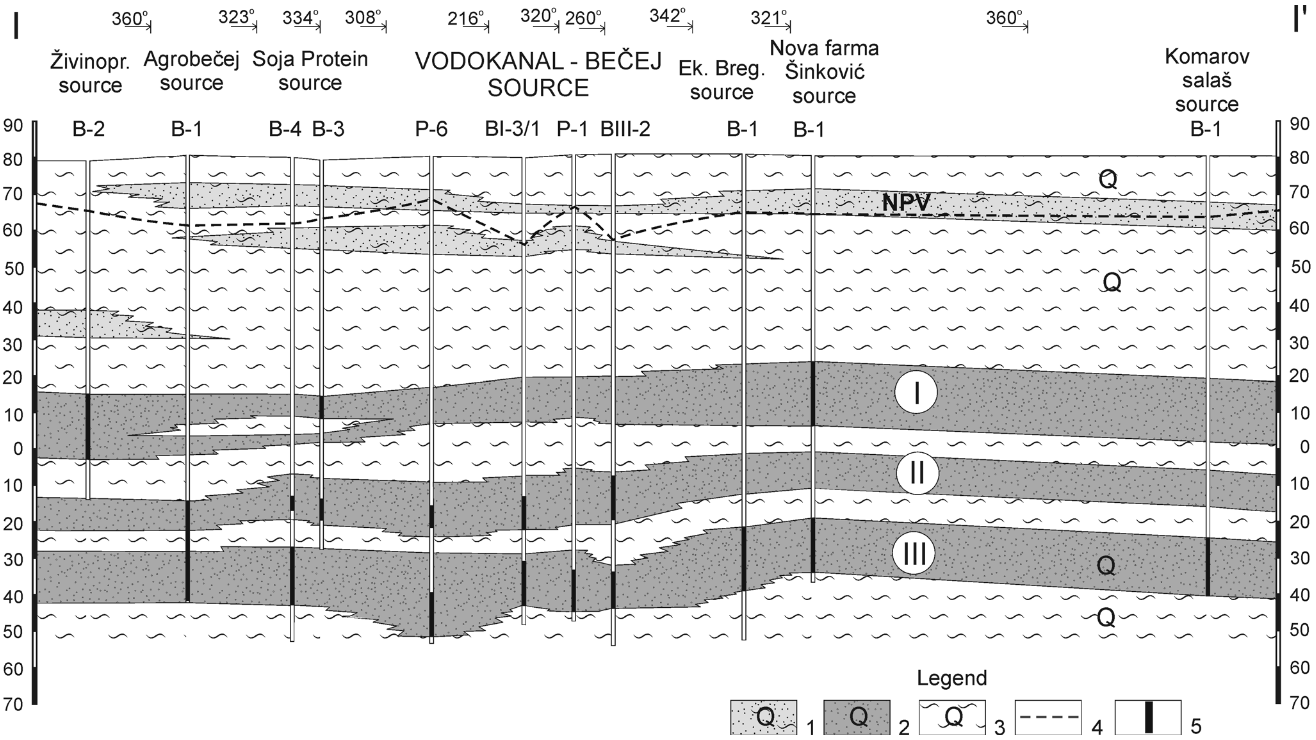


Fig. 2. Hydrogeological profile across the Vodokanal–Bečej Source. Legend: **1,** unconfined aquifer; **2,** confined aquifer; **3,** conditionally waterless sediments; **4,** head of the confined aquifer; **5.** position of the well screen.

and III (Fig. 2). The thickness and depth of some water-bearing layers were determined based on data obtained by well drilling and logging measurements in the majority of the wells and are presented in Table 1.

Table. 1. Thickness of water-bearing layers in wider study area.

Groundwater Source	Water- bearing layer		
	I Thickness (m)	II Thickness (m)	III Thickness (m)
"Vodokanal" - Bečej	9.1–16.1	6.6–18.1	7.0–23.0
"Soja Protein"	6.0–8.7	12.5–12.9	16.2–16.5
"Linde Gas"	23		14.6
"Nova farma - Šinković"	17.6	7.69	15
"Inkubatorska stanica - Šinković"	17	11	14.3
Komarov salaš	17.7	10	16
"Hotel Fantast"			
"Zalivno polje Agrobečej"	13.8	27.4	
Radičević	26	11	20
"Svinjogojstvo"	16.9	11.5	21
Bačko Petrovo Selo			
"Živinopromet"	18	10	14.6

The water-bearing layers I, II and III are separated by packages of clay and sandy clay with the thickness of 5–20 m. This insulation is not complete and allows partial hydraulic communication and the construction of an aquifer with the table under pressure. Additionally, northwest in the area of the Linde Gas Source, the water-bearing horizons of I and II merge into one. All this indicates a complex hydrodynamic whole.

It was perceived by analysis of logging diagrams that interlayers and lenses of clay material with a thickness of 2–6 m occur within some water-bearing layers (MILOSAVLJEVIĆ & POLOMČIĆ 2010). The distribution zones of the clayey interlayers in the water-bearing layers are presented in Figure 3. The significance of these intercalations of clay is that the thickness of the water-bearing layers of the city sources is really smaller, by the thickness of the clay intercalations. In order to simulate the real hydrogeological conditions in the exploratory area, these interbeds were later included in the hydrodynamic model, which resulted in increase of number of the model layers from 7 to 13.

The water-bearing layer IV, tapped under pressure only by the piezometer P7/1, was recorded in the underlying layer of the water-bearing layer III, at depths of about 149–155 m, and 161–167 m, but owing to the unfavorable quality of the groundwater, it is not used as a water supply.

The way of recharging the complex aquifer tapped in sources in the wider area of Bečej has not been studied especially and it can be discussed only based on general knowledge of the geological and hydrogeological features of the terrain and head loss analysis over a long period of time. The overlying layer of the water-bearing layer I is comprised of loess, sand, clayey sand and sandy clay. Partial precipitation infiltration into the water-bearing layer I is allowed by such a lithological composition. Infiltration certainly occurs very slowly and in complex ways. As the aquifer is distributed regionally, recharging occurs over a wider area where water permeable sediments prevail in the overlying layer or in zones where the aquifer communicates directly with the surface of the terrain or river flows.

The aquifer is drained by about 70 wells distributed over the area with a diameter of 15–20 km: by the town source in Bečej, Novi Bečej, Bačko Petrovo Selo, Veliko Gradište and other minor settlements, as well as by the factories: Sojaprotein, Linde–Gas, Agricultural Industrial Company Bečej and the companies: Agroprodukt Šinković, *etc.*

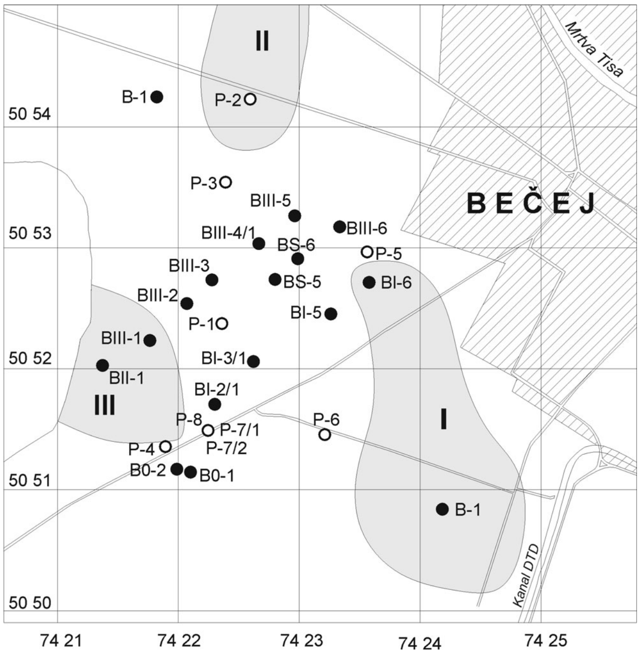


Fig. 3. Distribution of clayey interlayers (I to III) within the tapped water-bearing layers of the town source.

Physico-chemical characteristics of the groundwater

In the past, numerous chemical analyses of the town source were conducted in order to determine physico-chemical characteristics of the groundwater. As the largest number of wells tap water from two or three water-bearing layers simultaneously, only a common mixed water type could be determined. Only in a few cases were the conditions given for groundwater sampling from only one water-bearing layer (Table 2).

Table 2. Comparative analysis of physico-chemical characteristics of some water-bearing layers.

Parameter	Mark of water-bearing layer			
	II, III	I, II, III	III	IV
Electrical conductivity (μS/cm)	699–808	785–832	792	1.133
Evaporation residue (mg/l)	440–501	450–526	499	702.5
Total Hardness (°dH)	13.5	17.6–18.6	–	3.8
Consumption $KMnO_4$ (mg/l)	3.5–6.1	2.4–5.5	4.5	24.2
Ammonia (mg/l)	2.2-2.8	1.6–3.4	3.5	3.0
Sodium (mg/l)	86.1	83.9–108.1	–	243.0
Magnesium (mg/l)	36.5	43.3–50.0	–	13.1
Total Iron (mg/l)	0.4–0.8	0.2–0.5	0.4	0.1
Arsenic (mg/l)	0.035	0.001–0.005	–	0.076
Chlorides (mg/l)	6.0–6.9	6.0–10.1	5.7	18.6

Based on the analysis of a large number of groundwater samples taken from wells and piezometers in the period from the year 2004 to the year 2010, a mixed water type could be with certainty confirmed, but without the possibility of the analysis of some water-bearing layers (MILOSAVLJEVIĆ & POLOMČIĆ 2010).

According to the Alekin classification, the groundwater belongs to the hydrocarbonate class and the sodium–magnesium–calcium group. The chemical composition of the groundwater according to the classification of Kurlov can be expressed by the following formula:

$$M_{0,44-0,53}\frac{HCO^{3}{}_{95}}{(Na+K)_{39}Mg_{37}Ca_{24}}T_{16,9}$$

Concerning the groundwater of the town source in Bečej, the general evaluation from the point of view of the quality of the potable water is that the water is of a good quality after specific treatment in the water-processing factory. The, to some extent, increased content of ammonia is common for deeper water-bearing horizons. The increased iron content, recorded only in some samples, does not affect health but can affect the color and taste of the water. An increased arsenic content was recorded in only some samples; thus, there is no general increased presence of arsenic. Additionally, it has not been determined whether the arsenic occurrence in the water is organic or inorganic.

The head in the water-bearing layers I, II, and III, indicating to a hydraulic connection of these three water-bearing layers, was realized outside of the study area. In order to confirm this hypothesis, an analysis was performed and the physico-chemical characteristics of the water from some water-bearing horizons were determined. Comparing the content of some components of the chemical composition of the groundwater, it was confirmed that the contents of specific components from the water-bearing layers I, II and III are very similar and that, undoubtedly, one aquifer formed in the three water-bearing horizons with almost identical hydrodynamic and hydrochemical indicators (MILOSAVLJEVIĆ & POLOMČIĆ 2010) (Table 2).

The physico-chemical characteristics of the deeper water-bearing layer IV, tapped by the piezometer P-7/1, are essentially different from the nearest layer III. The difference can be seen in all parameters, which indicates that there is no, or very little, hydraulic connection between them.

Hydrodynamic characteristics of the Vodokanal–Bečej Source

In the past 30 years, from the year 1980 to the year 2010, about 25 wells were drilled in the Bečej Town Source, of which 15 are active, two out of use and eight are destroyed. Several layers were most frequently tapped simultaneously by wells: two layers were tapped simultaneously by 12 wells, all three layers were tapped by 10 wells simultaneously, and only one layer was tapped by three wells.

The filtration characteristics of the porous media in the Bečej Town Source were determined based on test pumping data, being partly the result of parameter identification from a hydrodynamic model of the source (CHENG & MOROHUNFOLA 1993). The tapped water-bearing layers with the values of their hydraulic conductivity are presented in Table 3.

In the period from the year 1980 to the year 2010, groundwater monitoring was realized at the source. The states of the head from the year 1980 to the year 2010 are presented in Figure 6. The groundwater table measured in the year 1980 was at almost at same depth in all three layers. To some extent, the higher differences in the head measured in the year 2010 are the consequence of the small distance from the wells

Table 3. Survey of water-bearing layers being tapped at Vodokanal–Bečej Source and surrounding sources with survey of hydraulic conductivity values.

Mark of well	Tapped water-bearing layer	Hydraulic conductivity (m/s)
VODOKANAL Source		
B0-1	II, III	1.90×10^{-4}
B0-2	I, II, III	1.21×10^{-4}
BI-2/1	II, III	1.46×10^{-4}
BI-3	I, II	5.00×10^{-4}
BI-3/1	I, II, III	1.21×10^{-4}
BI-4	I, II	5.50×10^{-4}
BIII-1	I, II, III	1.75×10^{-4}
BIII-1/a	I, II, III	1.42×10^{-4}
BIII-2	I, II, III	2.93×10^{-4}
BIII-3	I, II, III	3.19×10^{-4}
BIII-4	III	8.50×10^{-4}
BIII-4/1	I, II, III	1.90×10^{-4}
BIII-5	III	9.70×10^{-4}
BIII-6	II, III	1.90×10^{-4}
BS-5	I, II, III	3.98×10^{-4}
BS-6	I, II, III	3.33×10^{-4}
SOJA PROTEIN Source		
B-1	III	2.30×10^{-4}
B-4	II, III	2.04×10^{-4}
LINDE GAS Source		
B-1	I	6.18×10^{-4}

and the varied pumping intensity. The highest head losses were observed at the piezometers located in the central part of the source (P-1, P-4, P-6 and P-7/2), where pumping is the most intensive, while the lowest head losses were observed at the piezometers located at peripheral part of the source (P-2, P-3 and P-5). The recorded values of the groundwater table at the piezometers confirmed that these three water-bearing layers represent a unique hydrodynamic whole.

Based on the cross-section of the head states covering the span of 30 years (1980–2010) (MILOSAVLJEVIĆ & POLOMČIĆ 2010) (Fig. 4), it can be seen that the head loss was below all expectations and previously given prognoses.

A head loss of 3.04 m was recorded at the piezometer P-7/1, the filter of which is located in the water-bearing level IV, in the period of 1980 to 2010 years. As this water-bearing layer is not tapped by any wells in the vicinity, the only explanation is that the groundwater "pours off" into the nearest water-bearing layer III.

In order to determine the yield of the water-bearing layers, rheometric measurements were realized at 10 wells (Fig. 5) and the following results were obtained (MILOSAVLJEVIĆ & POLOMČIĆ 2010):

– at the wells where layers I and II are tapped (BO-2 and BI-3/1), layer I works with 86.5–90 % and layer II with only 10–13.5% of the total capacity,
– at wells where layers II and III are tapped (7 wells), the layers mainly gave unequal amounts of water and
– in case of water tapping from all three layers, measurements were performed at only one well (BIII-1), where the layers were also unequally active.

By having access to the well capacity, it can be seen that initial capacity of the wells was relatively high (17–37 l/s), and that it decreased rapidly with exploitation owing to fast ageing of the wells. Working age of wells according to past experience at the Bečej Town Source is, on average, 8 to 9 years (Fig. 6). Revitalizations were frequently performed; on average, one or two per well. After revitalization, the age of the wells was extended by two to five years.

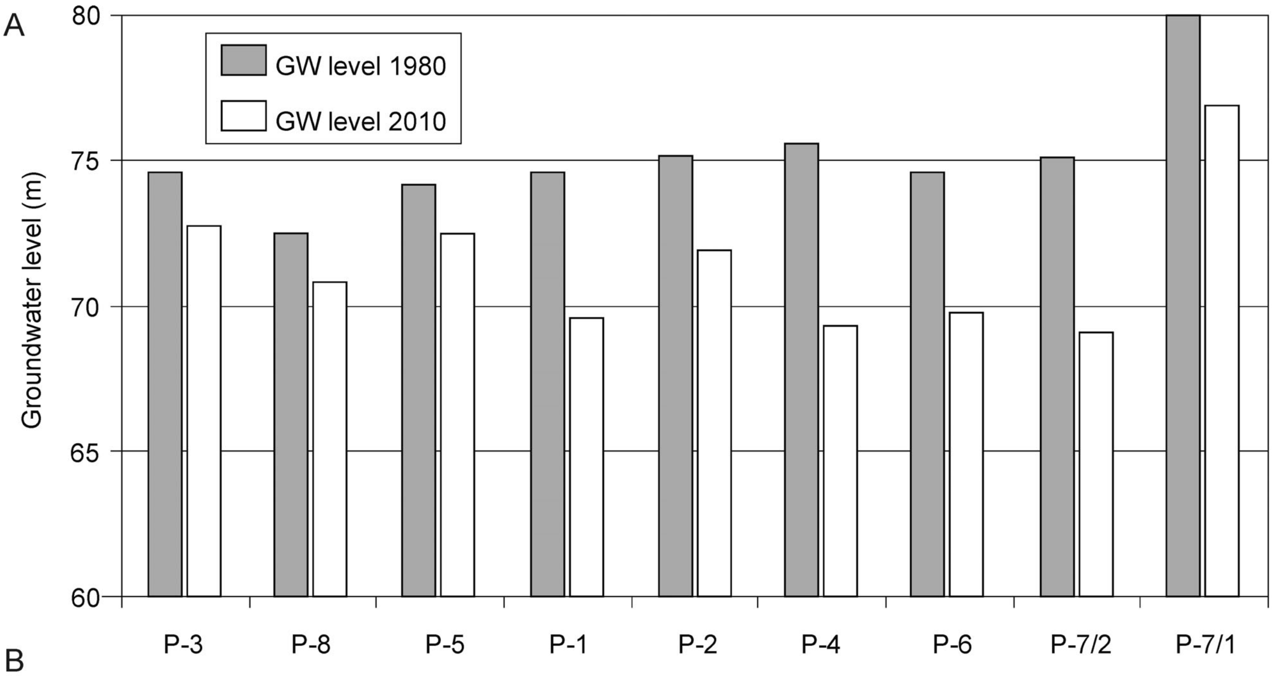
Hydrodynamic model of wider area of the Vodokanal–Bečej Source

A hydrodynamic model was developed in order to simulate the current groundwater exploitation at the Vodokanal–Bečej Source and to determine the groundwater balance. The code selected to develop the numerical model was MODFLOW-2000; a modular, three-dimensional finite difference groundwater flow model developed by the US Geological Survey (HARBAUGH *et al.* 2000). The program Groundwater Vistas 5.33b (Environmental Simulations International, Ltd.) was used in the present study. The development concept of the groundwater source hydrodynamic model for the Bečej water supply is based on the simulation of three-dimensional finite difference groundwater flow. The development of this model included the steps from the basic interpretation of input data, the schematization of porous environment, flow field and flow conditions to the formation and calibration of the model. Natural factors, such as the type and characteristics of distributed geological members, the distribution of water-bearing layers and aquafuges, filtration characteristics of the porous environment, conditions, mechanism and the groundwater flow regime, as well as a the desired goal within the set assignment had decisive impacts on the selection of the basic characteristics of the mathematical model of the Vodokanal–Bečej Source (POLOMČIĆ 2001).

Flow field geometry and discretization of the wider area of the Vodokanal–Bečej Source

The developed hydrodynamic model includes the wider area of the Vodokanal–Bečej Source. Locations

A



B

Piezometer	P-3	P-8	P-5	P-1	P-2	P-4	P-6	P-7/2	P-7/1
Tapped water-bearing layer	I		II	III		II, III			IV
The average annual decline in the level (m)	0.06	0.06	0.06	0.17	0.11	0.21	0.16	0.20	0.10

Fig. 4. State of the head at Bečej Town Source measured between 1980 and 2010. **A,** Diagram of groundwater level in the piezometers; **B,** Table with average annual decline in the groundwater level observed in the pieozometers.

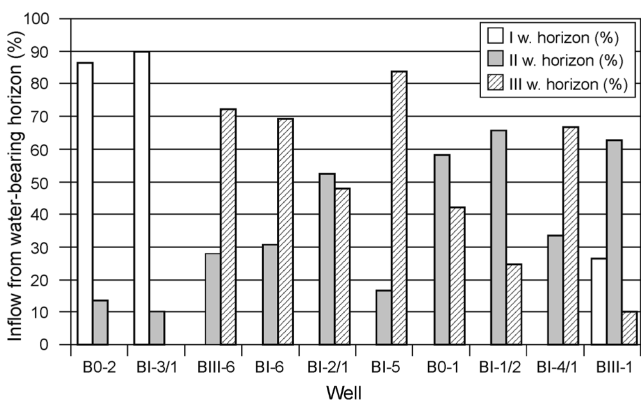


Fig. 5. Results of rheometric examinations at the Bečej Town Source.

of facilities in the area included in the model used for defining of spatial characteristics of isolated schematized lithological members are given in Fig. 1. The performed schematization of the hydrogeological environment is based on the existence of water impermeable overlying and underlying sediments, and the three water-bearing layers being separated by clayey sediments and clayey interlayers of limited distribution within each water-bearing layer (POLOMČIĆ 2002). To summarize, observed from the surface of the terrain, the corresponding model layers and terrain are presented in Table 4.

Although in total five water-bearing layers were recorded in the study area, only the tapped layers are included in the model. The shallowest water-bearing-layer, being neither in direct hydraulic connection with the lower layers nor used for water supply, is also in the first model layer. The water-bearing layer IV (not being used for water supply) is not included in the model.

The three-dimensional hydrogeological model in two cross-sections within the wider area of the Vodokanal–Bečej Source is shown in Figs. 7 and 8. The tapped water-bearing layers, in which filter constructions of the exploitation wells are placed, are marked in dark grey color. As stated before, the overlying layer, the underlying layer, and interlayer deposits are composed of poorly permeable and water impermeable sediments.

The distribution of all layers can be seen in the presented three-dimensional profiles, thereby the existence of clay interlayers in the water-bearing layers at particular localities and the merge of the first and second water-bearing layers (at the locality of the Linde Gas Source) are evident.

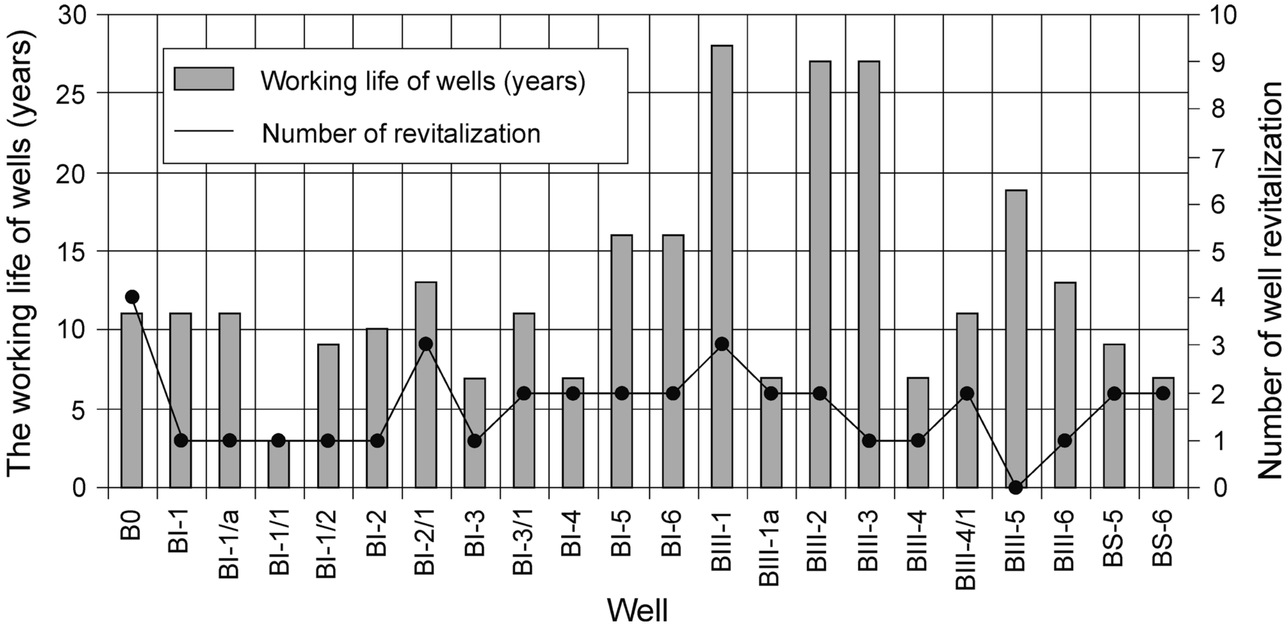


Fig. 6. Survey of working age and number of revitalizations of the wells of the Vodokanal Bečej Source.

Table 4. Lithological members and model layers of wider area of groundwater source Vodokanal–Bečej.

Complex of clayey and sandy overlying sediments	1	clayey and sandy sediments
I water-bearing layer with clay interlayer	2	overlying part of I water bearing layer
	3	clay interlayer grading laterally into sands of I water bearing layer
	4	underlying part of I water bearing layer
clayey sediments	5	clayey and sandy sediments
II water-bearing layer with clay interlayer	6	overlying part of II water bearing layer
	7	clay interlayer grading laterally into sands of II water bearing layer
	8	underlying part of II water bearing layer
clayey sediments	9	clayey sediments
III water-bearing layer with clay interlayer	10	overlying part of III water bearing layer
	11	clay interlayer grading laterally into sands of III water bearing layer
	12	underlying part of III water bearing layer
floor clayey sediments	13	clayey sediments

Basic dimensions of the matrix included in the study area are 12800 m × 13200 m, covering an area of 168.96 km^2. The discretization of the flow field in the plan was performed with a basic cell value of 400 m × 400 m, which is condensed in the source zone by a square net with dimensions of 25 m × 25 m (POLOMČIĆ 2004). The terrain included in the model is divided by a net of squares and rectangles with the dimensions of 322 rows × 197 columns and is comprised of 824 642 active model cells (POLOMČIĆ *et al.* 2011).

Boundary conditions

The following boundary conditions were applied in the hydrodynamic model of the Vodokanal–Bečej Source:

- "vertical balance", result (effective) infiltration, as a result of infiltration differences of precipitation and evapo-transpiration
- general head boundary
- boundary condition with a set flow – a discretization net cell ("inner contour").

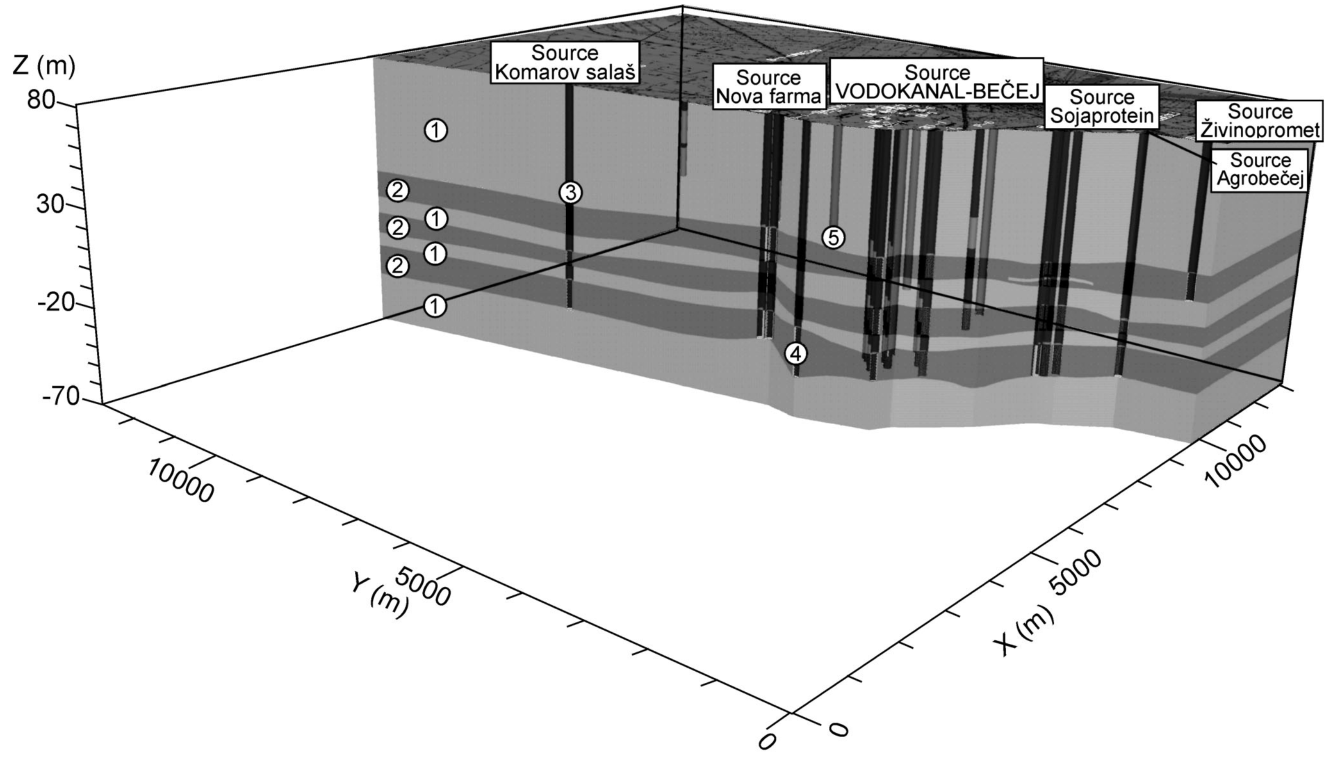


Fig. 7. 3D hydrogeological profile of the model of the town source: cross-section north–south. Legend: **1,** poorly permeable layer; **2,** water-bearing layer; **3,** well structure; **4,** well screen; **5,** piezometer.

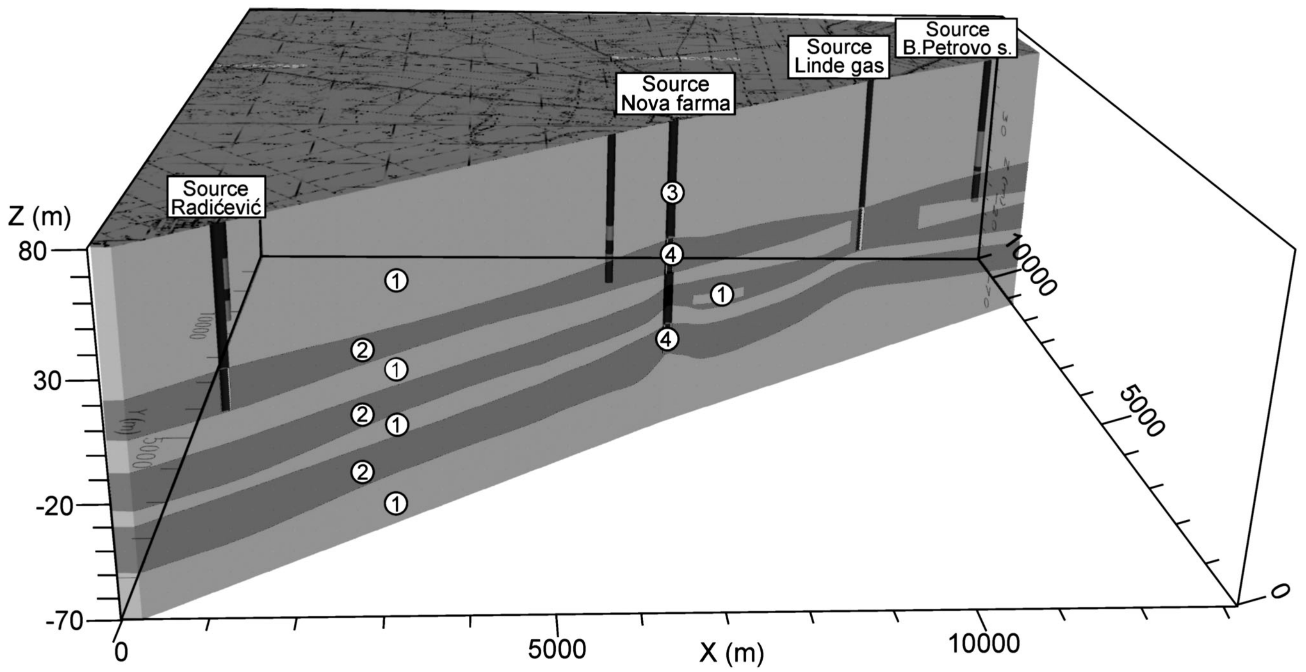


Fig. 8. 3D hydrogeological profile of the model of the town source: cross-section SW–NE. Legend: **1,** poorly permeable layer; **2,** water-bearing layer; **3,** well structure; **4,** well screen.

In the overall groundwater balance, the so-called "vertical balance" of the study area affects the tapped water-bearing layers to some extent. Here, the vertical balance implies the effective resultant infiltration (POLOMČIĆ 2008). This value is comprised of the sum of infiltration by precipitation, evaporation from groundwater and evapo-transpiration. Additionally, the depth to groundwater table, the state of humidity, as well as the lithological composition of the soil in the zone above the aquifer are highly significant. A precipitation value of 10 % was taken as the initial value of effective infiltration and this boundary condition was set only in the first layer of the model. Average monthly values of precipitations at the Bečej Meteo-

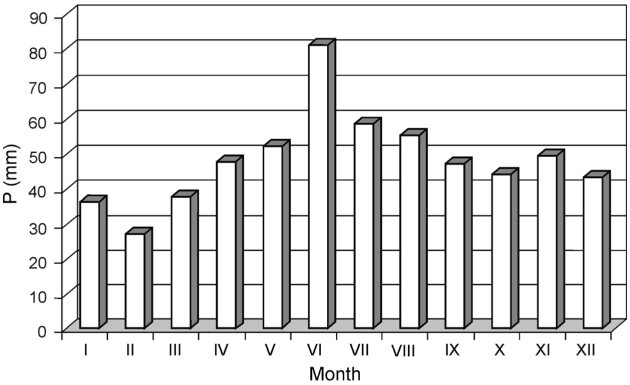


Fig. 9. Average monthly values of precipitations for period from 1978 to 2010 (M.S. Bečej).

rological Station for the period from 1978 to 2008 are shown in Fig. 9.

As stated before, there are several water-bearing layers at the wider area of the Vodokanal–Bečej Source, three of which are tapped for water supply. With regard to conditions of sedimentation and the development of these water-bearing layers, their sources of recharge are situated far from the study area. The impact of these distant recharge sources on the hydrodynamic model of the Vodokanal–Bečej Source was set *via* the boundary condition of the general head for each of the water-bearing layers.

A hydrodynamic analysis of the groundwater regime according to the recorded groundwater table was conducted in order to determine the value of the head to be set by this boundary condition for each water-bearing layer. Groundwater hydrographs at the piezometers of the Vodokanal–Bečej Source for the period from 1st August 2007 to 28th May 2010 are presented in Fig. 10.

The general conclusion from Fig. 10 is that identical fluctuation trends of the head were recorded at all piezometers, characterized by lower levels during the summer and early autumn months as a consequence of higher tapping of groundwater. In addition, from an analysis of the values of the hydraulic head registered at each piezometer separately, it can be concluded that all three water-bearing layers are in the hydraulic connection. In the exploratory area, the connection of the first and second water-bearing layers was registered in the area of the source "Linde Gas" (Fig. 8). The head oscillations in the piezometers indicate that the hydra-

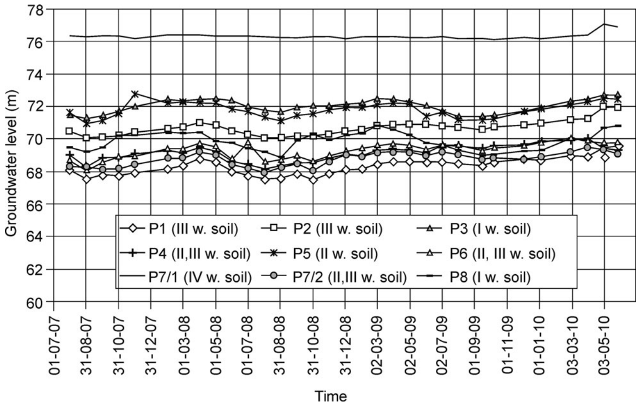


Fig. 10. Hydrographs of the head at the monitoring facilities of Vodokanal–Bečej Source in the period from 1st August 2007 to 28th May 2010.

ulic connection of the three water layers was realized outside the investigation area. The exception is the P-7/1 piezometer, the filter of which is located in the fourth water-bearing layer, which is not tapped by wells in the study area and is not included in the model.

The impact of the exploitation wells at the sources was simulated *via* the set flow boundary condition. The locations of wells in the area included in the model are shown in Figure 1. The values of well yield of and groundwater table in the wells at the Vodokanal–Bečej Source were recorded for the period from 1st August 2007 to 28th May 2010 (Fig. 11).

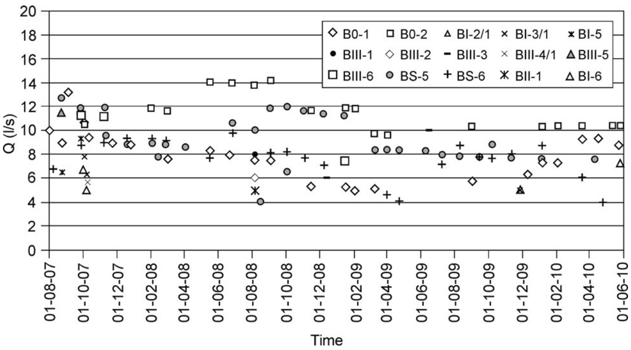


Fig. 11. Diagram of the recorded single well flows at the Vodokanal–Bečej Source in period from 1st August 2007 to 28th May 2010.

The capacity values of the remaining wells located at the other sources on the area included in the model were set at values recorded during exploitation of several years and range from 1.0–13.3 l/s (MILOSAVLJEVIĆ & POLOMČIĆ 2010). Well screens at the Vodokanal–Bečej Source and the remaining sources were set according to their real mounting position as multi-segmented ones in one, two or three water-bearing layers.

Results of the model calibration

The calibration of the model is realized under transient flow conditions with a time of one day for the analyzed period of time (1st August 2007 to 28th May 2010), being at the lowest level of the iterations divided into 10 parts of unequal duration (factor 1.2) (POLOMČIĆ 2004). The groundwater flow model was calculated and simulated as real flow under pressure or with a free table in each discretization cell individually, whereby the flow model conditions were changed with time in accordance with the real conditions.

The model calibration was completed when, according to the evaluation of the model author, satisfactory concordance between the recorded groundwater tables and those obtained in the calculations (Figs. 12, 13 and 14). The head layout in the tapped water-bearing layers at the end of the period for which the model was calibrated is shown in Figures 15–17 (28th May 2010).

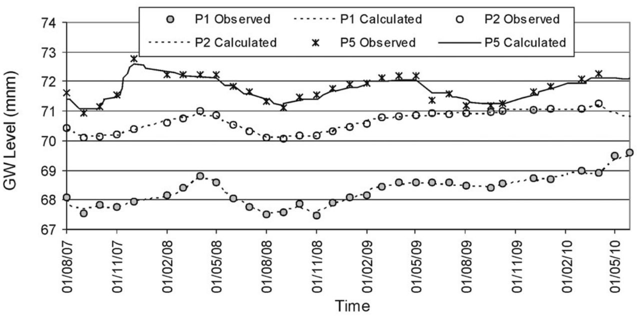


Fig. 12. Diagram of the observed and calculated heads in the piezometers which screened only in the second (P5), and in the third water-bearing layer (P1 and P2) for the whole model calibration period.

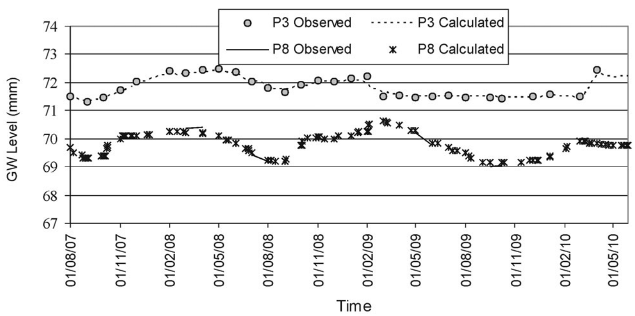


Fig. 13. Diagram of the observed and calculated heads in the piezometers which screened only the first water-bearing layer for the whole model calibration period.

The groundwater balance was analyzed for the Vodokanal–Bečej Source for each well. Respecting the results of the rheometric investigations (Fig. 5) and the performed simulation of the town source work, the average well capacities and inflows from the water-bearing layers for each the wells were obtained (Table 5).

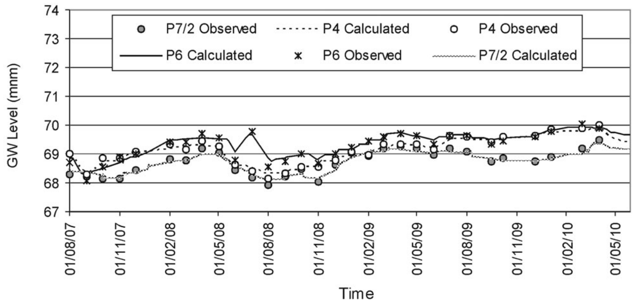


Fig. 14. Diagram of the observed and calculated heads in the piezometers which screened the second and third water-bearing layers for the whole model calibration period.

The largest amount of water flow up comes from water-bearing layer III (43.93 %) as a consequence of the largest number of wells tapping water from this layer. Then follows the inflow from layer II (33.4 %) and the least from water-bearing layer I (22.57 %).

Table 5. Groundwater balance at Vodokanal–Bečej Source.

Well	Well capacity (l/s)	Inflow from I water horizon (l/s)	Inflow from II water horizon (l/s)	Inflow from III water horizon (l/s)
B0-1	8.1	0.00	4.72	3.38
B0-2	11.5	9.95	1.55	0.00
BI-2/1	5.9	0.00	3.06	2.84
BI-3/1	6.4	5.76	0.64	0.00
BI-5	7.9	0.00	1.30	6.60
BI-6	5.3	0.00	1.63	3.67
BII-1	5.0	1.75	1.25	2.00
BIII-1	8.0	2.10	5.05	0.85
BIII-2	6.0	1.48	3.48	1.04
BIII-3	8.0	1.36	4.96	1.68
BIII-4/1	5.7	0.00	0.00	5.70
BIII-5	11.7	1.76	2.46	7.49
BIII-6	9.9	0.00	2.75	7.15
BS-5	9.5	1.14	3.52	4.85
BS-6	7.5	0.98	2.63	3.90
Total	116.4	26.3	39.0	51.1

Conclusions

Groundwater from three water-bearing layers comprising a unique hydrodynamic whole is used for domestic and industrial water supply to the wider area of Bečej. The stated layers are located at depths from 60 to 130 m. There are clayey interlayers within water-

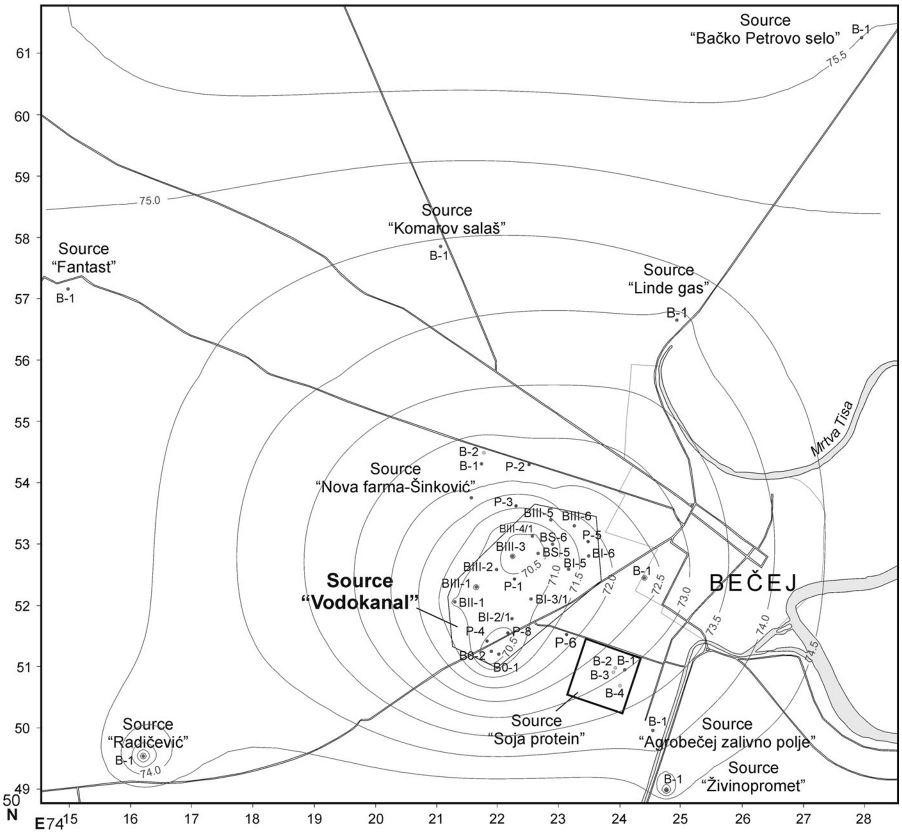


Fig. 15. Map of the head layout in water-bearing layer I in the wider surroundings of the Vodokanal–Bečej Source at the end of the model calibration period.

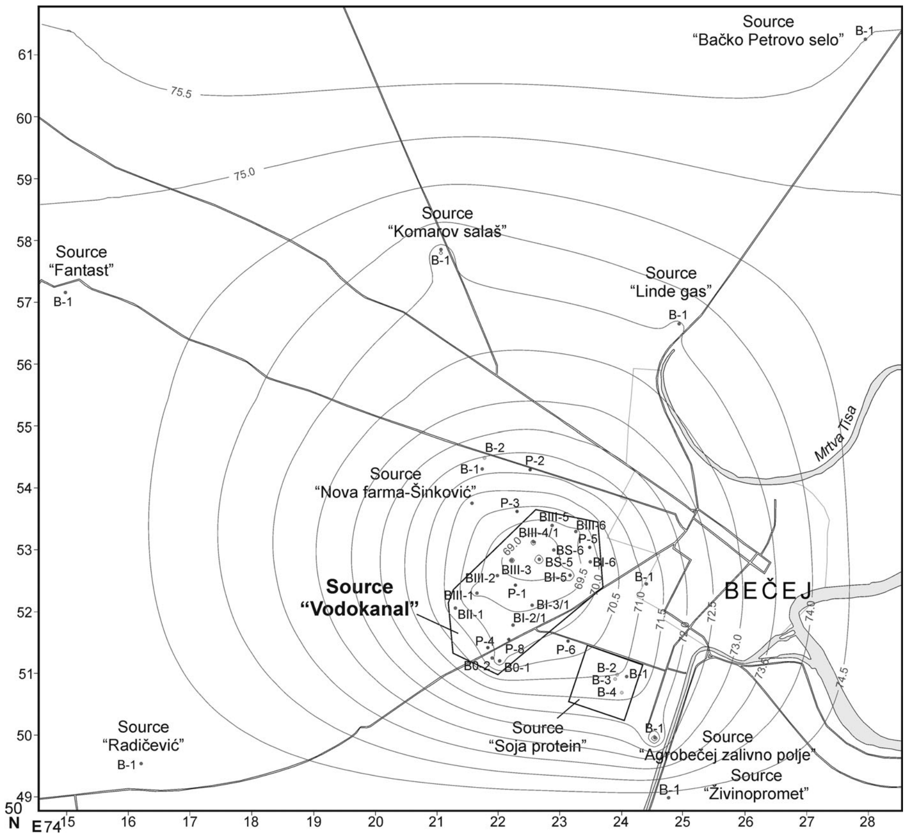


Fig. 16. Map of head layout in water-bearing layer II in the wider surroundings of Vodokanal–Bečej Source at the end of the model calibration period.

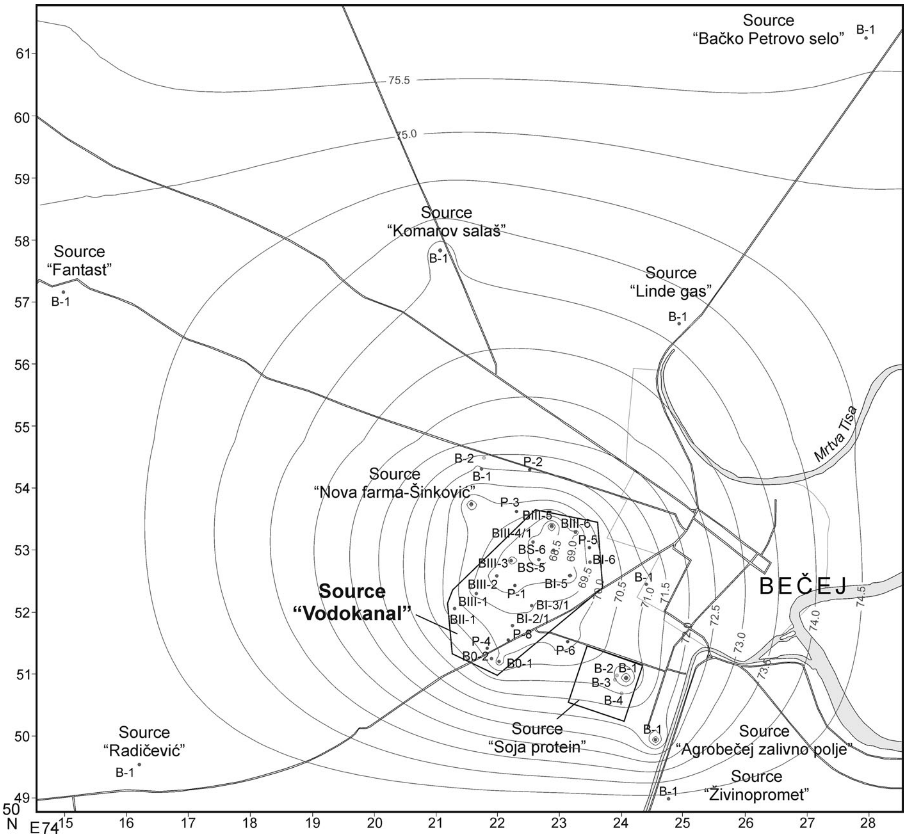


Fig. 17. Map of the head layout in water-bearing layer III in the wider surroundings of the Vodokanal–Bečej Source at the end of the model calibration period.

bearing layers at the Vodokanal–Bečej Source that serve for water supply to the population and industry of Bečej. The Source is comprised of 15 drilled wells the filter structures of which tap one or more water-bearing layers. The quality of the groundwater is burdened with an increased content of ammonia. Increased contents of arsenic and iron were recorded in some water samples. The water must be treated in the water treatment plant before usage. According to the Alekin classification, the groundwater belongs to the hydrocarbonate class, sodium–magnesium–calcium group.

Fast ageing of the wells is present at the Source. The average working life of wells at the town source is 8–9 years.

During past 30 years, groundwater table has been monitored. Recorded values of groundwater table at piezometers confirmed that the three tapped water-bearing layers represent a unique hydrodynamic whole. The results of hydrochemical examination additionally confirmed this statement.

A multilayer hydrodynamic model with overall 13 layers was developed for the determination of the groundwater balance at the Vodokanal–Bečej Source. The relatively large area included in the model and the numerous layers conditioned the existence of 824 642 active model cells. The model included the town and 11 surrounding groundwater sources. The simulation of the working of the sources was performed under non-stationary conditions for a period of over two and a half years.

The conducted hydrodynamic analysis of the groundwater regime at the Vodokanal–Bečej Source showed that the highest amount of water flow is from the water-bearing layer III (43.93 %), then from layer II (33.4 %), and the least from the water-bearing layer I (22.57 %).

The result of the performed investigations states indicate that it is possible to tap considerably higher amounts of groundwater than those being tapped presently.

Acknowledgements

The authors wish to thank the reviewers Romeo Eftimi (Tirana, Albania) and Aleksey Benderev (Sofia, Bulgaria), for useful discussions and comments that significantly improved the paper. The research was supported by the Public Corporation VODOKANAL BEČEJ – Waterworks and Sewerage, Bečej). Thanks also go to our dear colleagues, Milan Đekić, Stanislav Milosavljević, Zorica Popović & Miroslav Milaković (Tehnoproing-Company for technology, production and engineering, Novi Sad) for their research support on the terrain, and to Gallusz Zsolt &

SVETLANA KARABAŠ for all the technical support and providing the results of the monitoring of the Town source.

References

CHENG, A.H.-D. & MOROHUNFOLA, O.K. 1993. Multilayered leaky aquifer systems, I, Pumping well solutions. Water Resources Research, 29: 2787–2800.

HARBAUGH, A.W., BANTA, E.R., HILL, M.C. & MCDONALD, M.G. 2000. MODFLOW-2000: The U.S. Geological Survey Modular Ground-Water Model. User Guide to Modularization Concepts and the Ground-Water Flow Process. U.S. Geological Survey Open-File Report 00-92, Reston, VA, USA, pp. 121.

MILOSAVLJEVIĆ, S. & POLOMČIĆ, D. 2010. Study on the possibilities of expanding the capacity of the source "Vodokanal Bečej and evaluating the impact of the source "Soja Protein". 165 pp. Tehnoproing (Tehnical Documentation), Serbia. (in Serbian).

POLOMČIĆ, D. 2001. Hydrodynamic research, opening and managing the groundwater sources in intergranular porous media. 273 pp. Monograph, Faculty of Mining and Geology, Serbia (In Serbian).

POLOMČIĆ, D. 2002. Types of schematization of hydrogeological systems for the needs of hydrodynamic models. XIII Yugoslav Symposium of Hydrogeology and Engineering Geology, 389–396. Herceg Novi, Yugoslavia (in Serbian).

POLOMČIĆ, D. 2004. The influence of size of space and time discretization on the accuracy of the conception results of hydrodynamic models. *Radovi Geoinstituta*, 197–209 (in Serbian).

POLOMČIĆ, D. 2008. Hydrodynamical model of the open pit "Polje C" (Kolubara Coal Basin, Serbia). IV International Conference "Coal 2008", Belgrade, 407–419.

POLOMČIĆ, D., ĐEKIĆ, M., MILOSAVLJEVIĆ, S., POPOVIĆ, Z., MILAKOVIĆ, M., RISTIĆ-VAKANJAC, V. & KRUNIĆ, O. 2011. Sustainable use of groundwater resources in terms of increasing the capacity of two interconnected groundwater sources: a case study Bečej (Serbia). 11th International Multidisciplinary Scientific Geo-Conference & EXPO SGEM 2011 – Modern Management of Mine Producing, Geology and Environmental Protection, 599–606. Sofia, Bulgaria.

Резиме

Хидрогеолошке и хидродинамичке карактеристике изворишта подземних вода за јавно водоснабдевање Бечеја (северна Србија)

За потребе снабдевања водом становништва и индустрије на ширем подручју Бечеја, захватају се подземне воде из три водоносна слоја која се налазе на дубинама од 60 до 130 m. Градско извориште Бечеја („Водоканал–Бечеј“) састоји се од 15 експлоатациоинх бунара који каптирају наведена три водоносна слоја. Извориште карактерише релативно брзо старење бунара, и релативно мало опадање пијезометарског нивоа. Бунарима је најчешће каптирано више водоносних слојева: на 12 бунара каптирана су истовремено два слоја, на 10 су каптирана сва три, а на 3 бунара је каптиран један слој.

На изучаваном терену у вертикалном профилу до дубине око 170 m развијено је пет водоносних слојева. Најплићи водоносни слој залеже до дубине око 30 m и има велико хоризонтално распрострањење. Изграђен је од лесоидних седимената у горњем и ситнозрних, местимично заглињених пескова у доњем делу. У овим хетерогеним седиментима формирана је издан са слободним нивоом чије се воде не користе за јавно водоснабдевање или за потребе индустрије.

Три дубља водоносна слоја, која леже на дубини од 60–130 m, изграђена су од ситнозрних до средњезрних пескова и користе се за водоснабдевање становништва и индустрије. Сва три слоја имају регионално распрострањење и представљају један хидрогеолошки комплекс стваран у сличним седиментолошким речно-језерским и речно-барским условима у току доњег и средњег плеистоцена. Каптирани водоносни слојеви (I, II и III) међусобно су раздвојени пакетима глине и песковите глине дебљине 5–20 m. Ова изолација није потпуна и омогућава делимичну хидрауличку повезаност. У регионалној размери, изграђују једну издан са нивоом под притиском. Поред тога, према североистоку у домену изворишта „Линде гас“, I и II водоносни хоризонти се спајају у један. Све ово указује да се ради о једној сложеној хидродинамичкој целини.

Анализом каротажних дијаграма уочено је да се унутар појединих водоносних слојева јављају прослојци и сочива глиновитог материјала дебљине 2–6 m.

У подини каптираног III водоносног слоја на дубини од око 149–155 m и од око 161–167 m регистрован је IV водоносни слој под притиском који је захваћен једино пијезометром П7/1 и због неповољног квалитета подземних вода не користи се за водоснабдевање.

Пијезометарски нивои у каптираним водоносним слојевима I, II и III потврдили су да се ради о хидрауличкој повезаности ова три водоносна слоја која се остварује и ван изучаваног простора. Као додатна потврда повезаности ова три водоносна слоја су физичко-хемијске карактеристике вода из појединих водоносних хоризоната. Упоређењем садржаја појединих компоненти хемијског састава подземних вода утврђено је да су садржаји одређених компоненти из I, II и III водоносног слоја веома слични и да се неспорно ради о једној издани

формираној у три водоносна хоризонта са скоро истоветним хидродинамичким и хидрохемијским показатељима. Према класификацији Алекина подземне воде припадају хидрокарбонатној класи, натријумско-магнезијумско-калцијумској групи.

На основу пресека стања пијезометарских нивоа у распону од тридесет година (1980–2010) утврђено је да је пад пијезометарског нивоа испод свих очекивања и раније постављених прогноза, и да износи 6–21 cm годишње.

У циљу утврђивања издашности одређених водоносних слојева, вршена су реометријска мерења на 10 бунара. На основу ових мерења је утврђено је да су каптирани слојеви углавном давали неједнаке количине воде.

За потребе извођења симулације постојеће експлоатације подземних вода на изворишту „Водоканал–Бечеј“ и утврђивања биланса подземних вода формиран је хидродиамички модел. Концепција израде хидродинамичког модела заснива се на симулацији тродимензионалног струјања подземних вода применом методе коначних разлика. Терен обухваћен моделом је издељен мрежом квадрата и правоугаоника димензија 322 реда × 197 колоне и састоји се од 824.642 активних моделских ћелија, у 13 моделских слојева. Еталонирање модела је спроведено у нестационарним условима струјања, са временским кораком од једног дана за анализирани временски период (01. 08. 2007. – 28. 05. 2010. год.), који је на нижем нивоу итерација подељен на 10 делова, неједнаког трајања (фактор 1,2). Постигнуто је веома добро слагање регистрованих и прорачунатих вредности пијезометарских нивоа. Као резултат процеса калибрације модела, добијене су карте распореда пијезометарског нивоа за сваки водоносни слој и за сваки временски пресек (преко 1000 пресека). Такође, одређени су елементи биланса водоносних слојева на градском изворишту Бечеја. Највеће количине вода дотичу из III водоносног слоја (43,93 %) као последица највећег броја бунара који захватају воде из овог слоја. Потом следи дотицај из II (33,4 %), и на крају из I водоносног слоја (22,57 %).

Како резултат спроведених истраживања стоји да је могуће захватати и знатно веће количине подземних вода него што се данас захватају.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	72	159	Београд, децембар 2011 Belgrade, December 2011

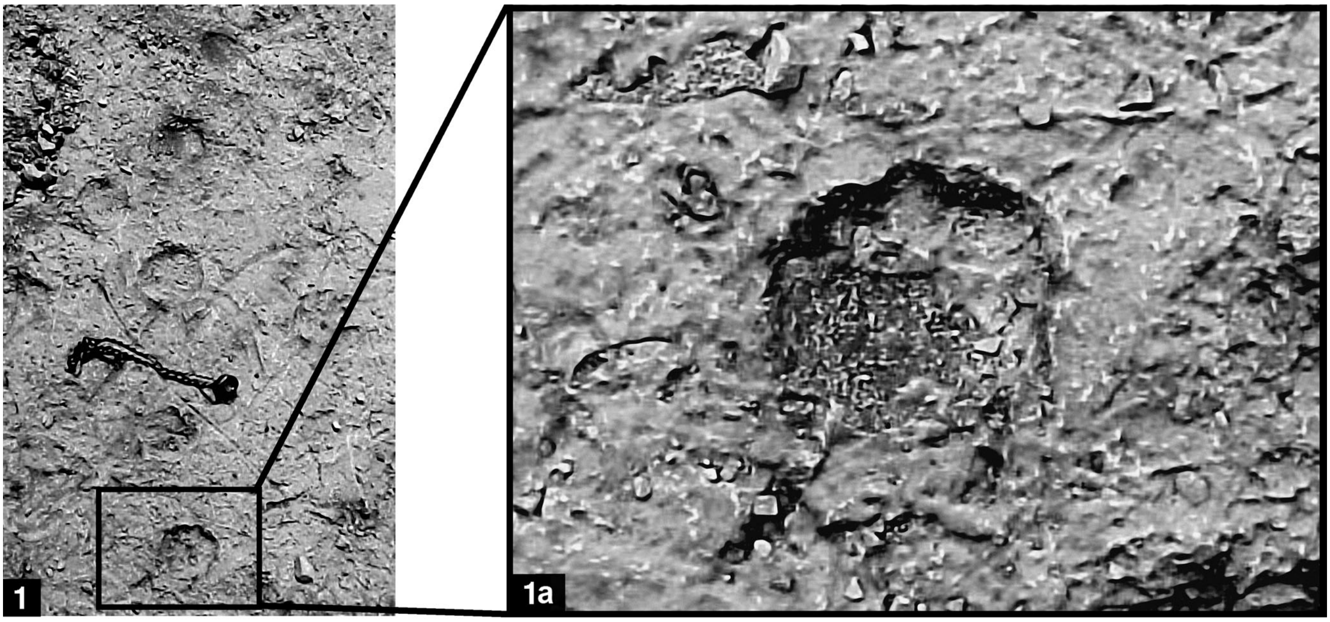
DOI: 10.2298/GABP1172159C

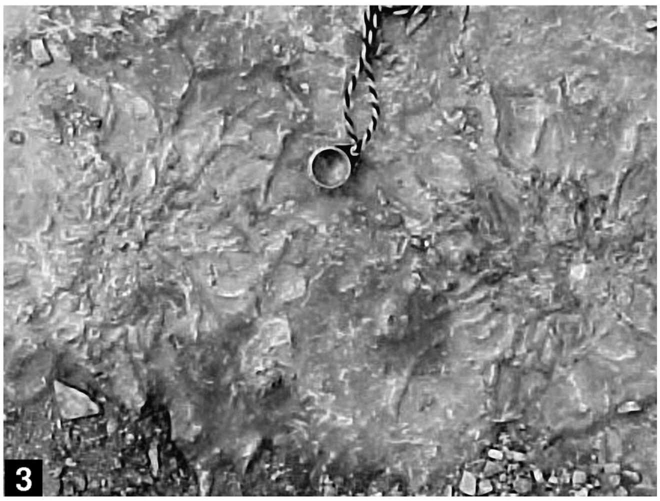
Brief report

Dinosaur tracks in the Struganik Quarry (western Serbia)

Antonella Cammarosano[1]

On the way by the village Struganik, Paola de Capoa[1] and Rajka Radoičić[2] stopped for a closer look at some Senonian limestones in the Struganik Quarry. Eye-catching in the largest surface of a layer with various trace fossils were some tracks taken to be of a dinosaur. Mrs de Capoa lent me the photographs taken of the tracks for identification, which could be Sauripod tracks (Figs. 1–2). Trace fossils on the same surface (Fig. 3).





[1] Dipartmento Scienze della Terra, Università di Napoli “Federico II”. Largo San Marcellino, 10, 80142 Napoli, Italy.
[2] Kralja Petra I, 38, 11000 Belgrade.

Instructions for authors

Geološki anali Balkanskoga poluostrva is issued annally and publishes original scientific contributions over a wide range of topics in any field of the geological sciences. The journal accepts papers in English of moderate length, not exceeding 50 double spaced manuscript pages, including illustrations.

Submit three copies of a double-spaced manuscript and illustrations (good photocopies), plus an electronic version of the manuscript. Leave adequate margins of 3 cm, on all sides, and the right margin unjustified with no automatic hyphenation. Typewritten manuscripts will not be accepted. Do not send large files (e.g. photographic illustrations) as e-mail attachments, but submit them on a CD-ROM sent by air-mail.

Material being described must be registered as part of a formal collection housed in some recognised Institution so that it is accessible and available for study by other workers.

Paper should be arranged as follows: title, name and surname (in full) of author or authors, abstract, key words, adresses (foot note on the 1st page) with a mention of the parent organisation and e-mail address, text, acknowledgements, references, summary, figures, tables, and plate captions.

The title of the paper should be short, but expressing the principal aim of the paper.

The abstract must be concise, not more than 200–250 words, and should be informative, stating the results presented in the article rather than describing its contents. Inclusion of references in the abstract is not recommended.

After the abstract, list 5–8 **keywords** which describe the subject matter of the work. They should be arranged from general to more specific ones.

The text should be written as clear and understandable as possible. Use up to threee levels of headings. Their hierarchy should be indicated in the left-hand margin of the text. Italics are used only for the name of genera and species, or if a word is italicized in the original title. References should be cited in the text as follows: DAMBORANEA (2002) or (DANBORANEA 2002) for a single author; FÜRSICH & HEINZE (1998) or (FÜRSICH & HEINZE 1998), for two authors; RICCARDI *et al*. (1991) or (RICCARDI *et al*. 1991) for multiple-author works.

References should be classified alphabetically according to the author's names. Include only published papers mentioned in the text, unpublished reports will be accepted only in exeptional cases. Do not abbreviate the titles of journals and give the names of symposium volumes and edited books. For books it is necessary to give the publisher's name and place of publication. References in Cyrillic alphabet must be transliterated to the Latin alphabet. The titles of the paper in a non-Latin alphabet should be translated into English with an indication of the original language in parenthases, while the name of the journal must be transliterated into Latin alphabet. Examples are as follows:

AGER, D.V. 1963. *Principles of Paleoecology*. 318 pp. McGraw-Hill, New York.

OWEN, E.F. 1962. The brachiopod genus Cyclothyris. *Bulletin of the British Museum (Natural History)*, *Geology*, 7 (2): 2–63.

RABRENOVIĆ, D. & JANKIČEVIĆ, J. 1984. Contribution to the study of Albian near Topola. *Geološki anali Balkanskoga poluostrva*, 48: 69–74 (in Serbian, English summary).

SMIRNOVA, T.N. 1960. About a new subfamily of the Lower Cretaceous dallinoid. *Paleontologičeskii Žurnal*, 2: 116–120 (in Russian).

SULSER, H. 1996. Notes on the taxonomy of Mesozoic Rhynchonellida. *In*: COOPER, P. & JIN, J. (eds.), *Brachiopods*, 265–268. Balkema Press, Rotterdam.

Acknowledgments should be as short and concise as possible.

A **summary** (up to 15% of the paper) is published in Serbian and should contain the essence of all new data and the conclusions.

Illustrations can be submitted as conventional hard-copies or in electronic form. The preferred formats for graphics is CDR (600 dpi) and for photographs and plates TIFF (600 dpi). All original drawings and photographs should be in the form of glossy prints of profesional quality. The illustrations should have a width of 8.4, 12 or 17.5 cm, the final limit is the size of type area (17.5 × 24.5). Lines and letters must be suitable for reduction. It is also recommended to send copies reduced to the size for publication; after reduction, the smallest lettering should be not less then 1 mm and not greater than 4 mm in height (in the Arial font). The aproxiamte position of figures and tables should be indicated in the manuscript margin. Do not incorporate illustrations in the text of the paper. Figure, table and plate captions should be listed on separate sheets. The author's name and figure number should be indicated at the foot of the illustration. The figure numbers can be writen by hand on a paper copy of the plate or on a transparent overlay, not on the plate itself. The cost of printing colour figures must be paid in full by the author.

Authors will receive one and if necessary two **proofs**. These must be returned within the time limit indicated. If this does not happen, the publication of the paper will be postponed automatically to a later date.

50 **reprints** per article will be provided free of charge for the author (in the case of multi-authored papers, the senior author will receive the reprints).

All **correspondence**, enquires and manuscript submissions should be directed to the Editor-in-Chief of *Geološki anali Balkanskoga poluostrva*.

Prof. Dr. Vladan Radulović
Department of Palaeontology
Faculty of Mining and Geology
University of Belgrade
Kamenička 6, 11000 Belgrade
Serbia
E-mail: vrad@eunet.rs

ГЕОЛОШКИ АНАЛИ БАЛКАНСКОГА ПОЛУОСТРВА
ANNALES GÉOLOGIQUES DE LA PÉNINSULE BALKANIQUE

Vol. 72 **December, 2011**

Contents

Brief report