Int J Earth Sci (Geol Rundsch) (2009) 98:1097–1108
DOI 10.1007/s00531-008-0306-3

ORIGINAL PAPER

Ophiolitic detritus in Cretaceous clastic formations of the Dinarides (NW Croatia): evidence from Cr-spinel chemistry

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Received: 25 December 2007 / Accepted: 16 February 2008 / Published online: 7 March 2008

Abstract Cr-spinel is a common heavy mineral in the sandstones of Cretaceous synorogenic sedimentary formations of the NW Dinarides, Croatia. The rocks occur in isolated exposures in the uplifted basement units of Medvednica, Ivanšćica, Žumberak and Samobor Mountains near Zagreb. In this area, evidence of the early Alpine evolution of the Dinarides is obscured due to strong dismemberment of pre-Tertiary tectonostratigraphic units resulting from an intense tectonic history, as well as due to the widespread sedimentary cover of the Pannonian Basin. Electron microprobe analyses of detrital Cr-spinels from the Oštrc Formation reveal that in the Early Cretaceous the ophiolitic source area was predominantly composed of harzburgite peridotites and associated cumulate rocks, which developed in a supra-subduction zone setting. The supply of Cr-spinels with the same chemical signature remained dominant until the end of the Cretaceous, suggesting that exposed remnants of the same ophiolite belt persisted through the Cretaceous and/or that recycling was significant. Similarities with data reported from the Northern Calcareous Alps and the Transdanubian Central Range imply that a rather extensive harzburgitic ophiolite belt probably extended along the Adriatic margin during the Early Cretaceous. A slight trend of increasing variation in the Cr# is observed from the Early to the latest Cretaceous, suggesting that the source areas became more heterogeneous with the ongoing Cretaceous tectonic evolution. Differences in Cr-spinel compositions in two contemporaneous latest Cretaceous formations are well in line with existing data on heavy mineral proportions, which together identify contrasting hinterland geology for these formations and strongly suggest the coeval existence of two separate basins.

Keywords Cr-spinel chemistry · Provenance · Sandstones · Cretaceous · Dinarides · Croatia

Electronic supplementary material The online version of this article (doi:10.1007/s00531-008-0306-3) contains supplementary material, which is available to authorized users.

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Introduction

Cr-spinel is an important accessory mineral in mafic and ultramafic rocks, though its considerable chemical and mechanical stability make it a common accessory constituent of sedimentary rocks as well (Zimmerle 1984; Morton and Hallsworth 1999). Its potential to survive the sedimentary cycle, unlike other mafic and ultramafic rock components, often leaves Cr-spinel as the only remaining evidence of a once existing source of detritus, making it a promising target of investigation for provenance studies (Morton 1991). Detrital Cr-spinel chemistry has received considerable attention in studies of clastic sediments, particularly those associated with orogenic suture zones, where large masses of mafic and ultramafic rocks tend to be obducted onto the upper plate to form extensive ophiolite sequences (Pober and Faupl 1988; Árgyelán 1996; Cookenboo et al. 1997; Arai and Okada 1991; Hisada and Arai 1993; Lenaz et al. 2000, 2003; von Eynatten 2003; Zhu et al. 2004; Faupl et al. 2006).

During processes of partial melting of mantle rocks and fractional crystallization of magmas, the partitioning of elements between solid and melt has a profound effect on the composition of Cr-spinel (Irvine 1965, 1967; Kamenetsky et al. 2001). Studies of mafic and ultramafic rocks have identified the degree of partial melting of mantle peridotites, magma chemistry, temperature of crystallization, cooling rate, pressure and oxygen fugacity as influential factors (Dick and Bullen 1984; Sack and Ghiorso 1991; Arai 1992; Kamenetsky et al. 2001). The variable chemistry of Cr-spinel can provide useful information on the petrogenesis of ophiolite members exposed and eroded during the evolution of an orogen, allowing a better understanding of the tectonic history and nature of sediment dispersal.

This study presents single grain chemical data of detrital Cr-spinels from the sandstones of five Cretaceous clastic formations in the NW Dinarides, Croatia (Figs. 1, 2). The studied formations range in age from Early to latest Cretaceous, and consist of synorogenic deep-marine and shallow-marine sediments. They record important events in the early evolution of the northern Dinarides, including the Dinaride–Alpine transitional area. To date, a considerable amount of single grain Cr-spinel chemical data has been published from sedimentary formations of the Alpine–Carpathian region (e.g. Pober and Faupl 1988; Árgyelán 1996; Lenaz et al. 2000, 2003; Jablonský et al. 2001; von Eynatten 2003; Sciunnach and Tremolada 2004; Oszczypko and Salata 2005). However, hitherto, no data have been available from Cretaceous sediments of the NW Dinarides. Our new data allow comparison to be made with sedimentary formations and potential source ophiolites exposed today in neighboring areas. By means of Cr-spinel chemistry, our aim is to better constrain the composition and tectonic history of the obducted ophiolites supplying detritus into sedimentary basins of the NW Dinarides during the Cretaceous.

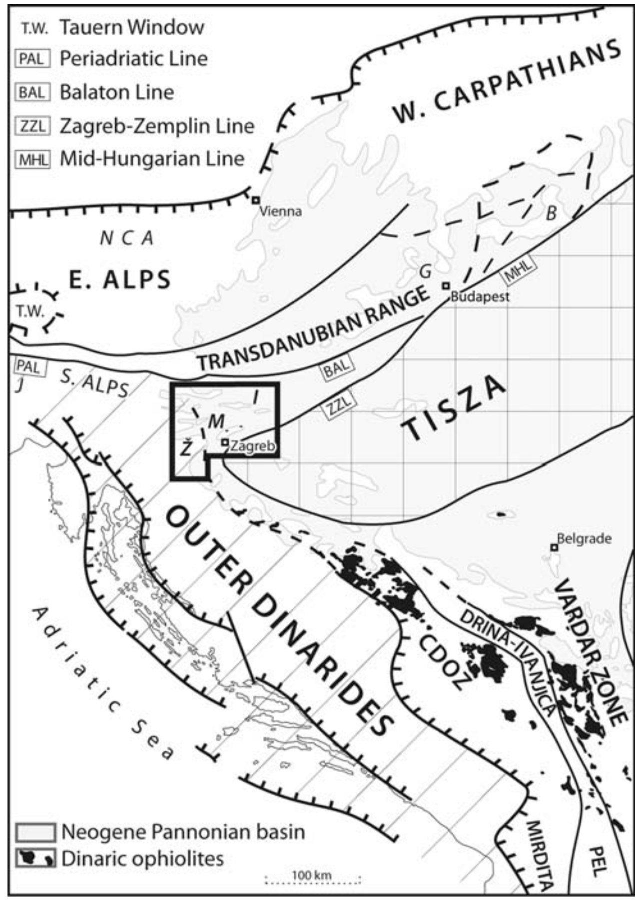

Fig. 1 Tectonic situation of the Alpine–Dinaric–Pannonian region with the main structural units outlined. Map compiled from different sources, mainly Haas et al. (2000), Haas and Kovács (2001), Aubouin et al. (1970) and geological map of Yugoslavia, 1:500,000 (1970). *B* Bükk Mts, *G* Gerecse Mts., *I* Ivanščica Mt, *J* Julian Basin, *M* Medvednica Mt, *Ž* Žumberak Mts., *CDOZ* Central Dinaride Ophiolite Zone, *NCA* Northern Calcareous Alps, *PEL* Pelagonian unit. *Framed area* is shown in Fig. 2

Geological setting

The Dinarides represent a major segment of the Alpine orogenic belt in SE Europe (Fig. 1). The Outer Dinarides are dominated by thick Mesozoic platform carbonates forming part of the Adriatic plate, while the Inner Dinarides are on the other hand represented by various lithologies, which occur in NW-SE trending tectonic zones (Aubouin et al. 1970; Pamić et al. 1998; Dimitrijević 1982, 2001; Tomljenović et al. 2008). Prominent features of the Dinaride nappe stack are extensive ophiolite units. These represent the remnants of the western Tethys Ocean, which existed between Eurasian and African continental elements during the Mesozoic, and may have consisted of several ocean branches or marginal basins (e.g. Dimitrijević and Dimitrijević 1973; Robertson and Karamata 1994; Channell and Kozur 1997). In the central and SE Dinarides, ophiolites occur in two zones: the Central Dinaride Ophiolite Zone (CDOZ) in the SW and the Vardar Zone in the NE. Separating them is the Drina-Ivanjica intermediate unit, which has been interpreted as a continental fragment (Aubouin et al. 1970; Dimitrijević and Dimitrijević 1973; Robertson and Karamata 1994) or as an out-of-sequence nappe derived from the northern Tethyan margin (Pamić et al. 1998). These major Dinaride tectonostratigraphic units extend southwards into the Hellenides. Towards the NW, at the Dinaride–Alpine junction in which the study area is located, the Dinaride structural pattern is obscured by Tertiary lateral displacements and considerable clockwise rotation (Haas et al. 2000; Tomljenović et al. 2008), as well as by the Neogene sedimentary cover. The evolution of the Inner Dinaride zones, as well as their northerly

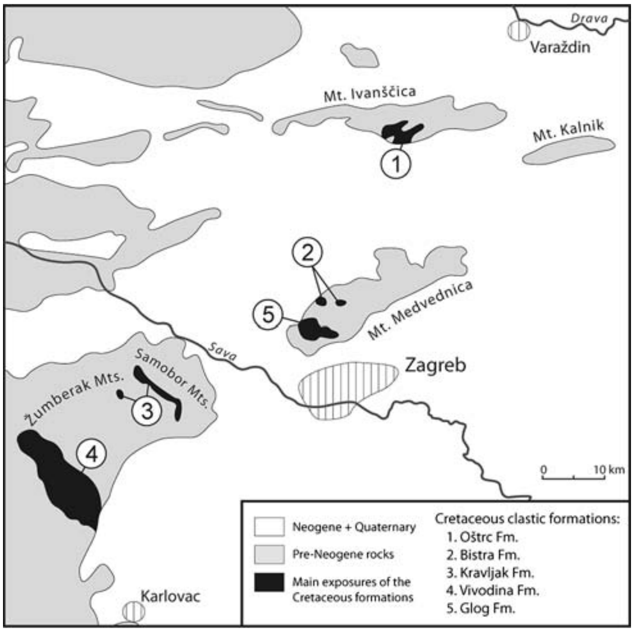

Fig. 2 Simplified geological map of the study area showing the distribution of the studied formations

continuation, is still a matter of debate. In the Alpine–Carpathian region, ophiolite occurrences of the western Tethys have been ascribed to the Meliata domain, while for others, such as those included in the Bükk Mts, a Dinaride affinity has long been recognized (Haas and Kovács 2001, and references therein). The connection of the Meliata domain itself with the southerly Dinaride ophiolite zones has been both advocated (e.g. Kovács 1982; Dal Piaz et al. 1995; Halamić and Goričan 1995; Gawlick et al. 1999) and contradicted (e.g. Kozur 1991; Channell and Kozur 1997). In the NW Dinarides, ophiolite fragments occur within a mélange complex collectively termed as Repno Complex (Babić and Zupanič 1978). Results obtained from dating both the matrix and the tectonized blocks of the mélange suggest a Triassic onset of ocean spreading, subduction beginning in the Middle Jurassic, and a Late Jurassic to Early Cretaceous closure of the oceanic basin (Halamić and Goričan 1995; Halamić et al. 1999; Babić et al. 2002).

The Cretaceous clastic formations considered in this paper are situated in a tectonically complex region between the Alps, Dinarides and Tisza (Fig. 1). The area bound by the Periadriatic-Balaton and Zagreb-Zemplén Lineaments, the Sava Composite Unit, comprises several juxtaposed structural units of different affinity. The intense dismemberment of this pre-Tertiary unit results from a severe and long-lasting Mesozoic to Cenozoic deformational history (Vörös 1993; Pamić et al. 1998, 2002; Haas et al. 2000; Tomljenović and Csontos 2001; Haas and Péró 2002; Babić et al. 2002; Csontos and Vörös 2004). The studied strata, together with other pre-Tertiary units, are exposed only in uplifted basement units, or "inselbergs," on the Ivanščica, Medvednica, Žumberak and Samobor Mountains (Fig. 2).

The Mesozoic sediments of Mt Ivanščica consist of deposits of the Adriatic platform and its NE margin, which occur in tectonic contact with a Jurassic ophiolitic mélange (Repno Complex, Babić et al. 2002). These are Late Triassic shallow marine carbonates, Jurassic pelagic limestones and cherts, and Tithonian-Valanginian "Aptychus Limestones," which are overlain by the *Oštrc Formation* (Fig. 2). The Oštrc Fm. is Barremian to Albian in age and dominated by siliciclastic turbidites (Fig. 3; Babić and Zupanič 1973; Babić 1975; Babić and Gušić 1978). Babić et al. (2002) suggested that these sediments were deposited on the subsided carbonate platform margin of the Adriatic plate. Facies and composition record a dramatic change in sedimentation due to the influx of high amounts of siliciclastic material. Heavy mineral spectra from sandstones of the Oštrc Fm. show a very high proportion of Cr-spinel (>90%), indicating, together with abundant mafic and ultramafic lithic fragments, a dominantly ophiolitic provenance with minor continental contribution (Zupanič et al. 1981).

Two Cretaceous clastic formations were investigated on Mt Medvednica (Fig. 2). The Aptian–Albian *Bistra Formation* consists of shallow-marine to coastal carbonates and clastic sediments (Gušić 1975; Crnjaković 1989). The shallow-marine environment probably developed on top of the exhumed Jurassic ophiolitic mélange complex, which also occurs in Mt Medvednica (Babić et al. 2002). The heavy mineral associations of the sandstones contain ultrastable minerals (zircon, tourmaline and rutile = ZTR), Cr-spinel and only minor proportions of other minerals (e.g. apatite, garnet, amphibole and epidote). The heavy minerals and framework composition reflect a mixed continental-ophiolitic provenance (Crnjaković 1989). The Maastrichtian *Glog Formation* consists of deep-water sandstone and marl deposits, which represent the youngest part of a Senonian alluvial to deep-water succession overlying low-grade metamorphic rocks, as well as the ophiolitic mélange (Babić et al. 1973; Crnjaković 1981, 1987). This sedimentary–metamorphic complex builds up the "core" of Mt Medvednica and underwent Early Cretaceous low-grade metamorphism (Belak et al. 1995; Belak 2005). Opinion is divided as to whether it is of Dinaride affinity (Haas et al. 2000), or does it rather derive from an easterly continental block (Tisza or Drina-Ivanjica Unit—Babić et al. 2002). The heavy mineral associations in the sandstones of the Glog Fm. are heavily dominated by ZTR, with only minor proportion of other heavy minerals (Crnjaković 1981). It is important to note that in the studied Glog samples, Cr-spinel occurs only in trace amounts, which is considerably less than in any of the other formations.

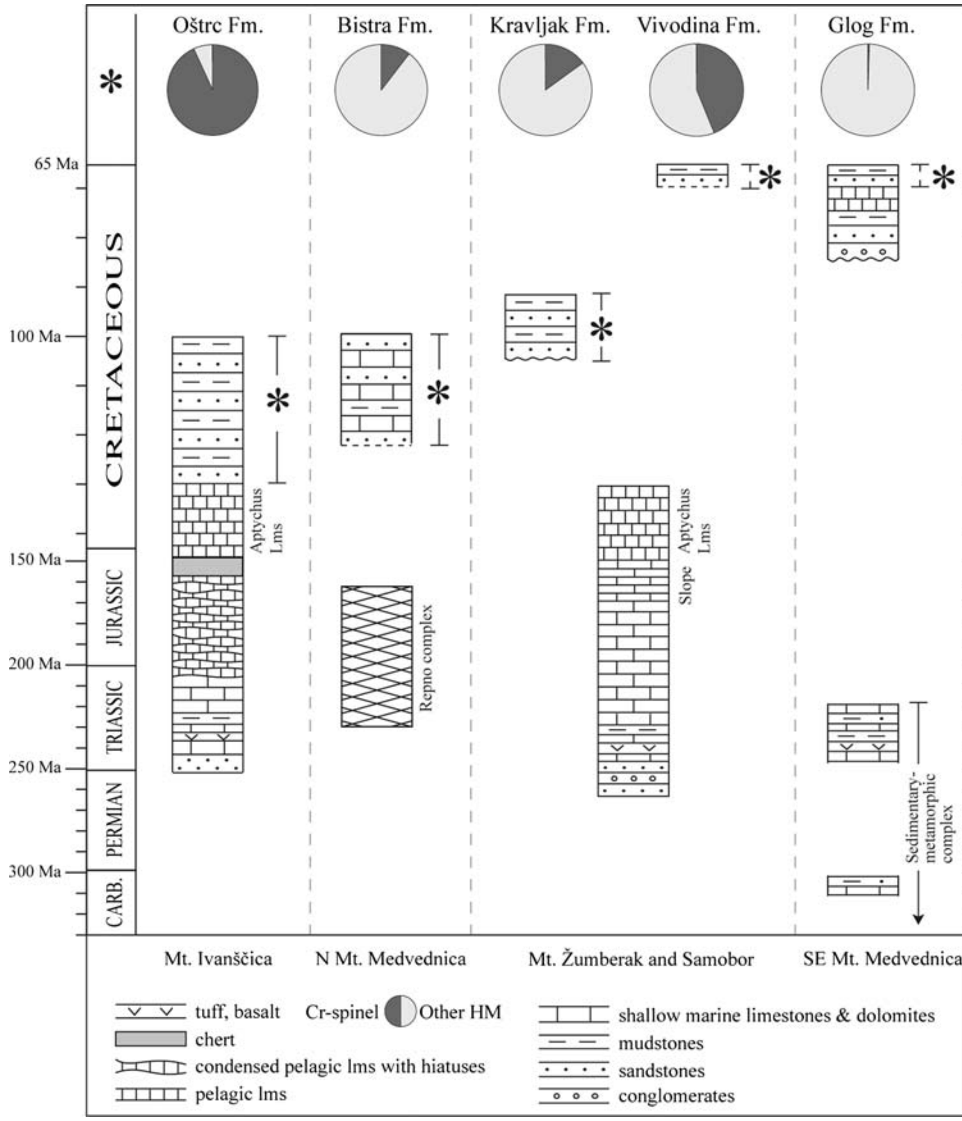

Fig. 3 Simplified chronostratigraphic logs of the studied formations and their basement. Average Cr-spinel abundances are presented at the *top* with *pie diagrams* (Crnjaković 1981, 1989; Crnjaković et al. 2000; Zupanič et al. 1981; Zupanič 1981). Note that the *vertical time scale* is not linear

The Albian–Cenomanian *Kravljak Formation* and the Maastrichtian *Vivodina Formation* are both deep-water turbiditic deposits and occur in the Žumberak and Samobor Mts. (Fig. 2), located in the SW edge of the Sava Composite Unit (Babić 1974; Zupanič 1981; Devidé-Nedéla et al. 1982). Probably, these formations record deposition on the distal Adriatic margin in the Late Cretaceous, and are laterally equivalent to the "Zone Prekarstique" (Babić 1974) described further to the SE in Bosnia-Herzegovina by Blanchet et al. (1970). The onset of clastic deposition in this area thus occurred earlier than elsewhere on the carbonate platform (Babić 1974; Ćosović et al. 2008; Mikes et al. 2008). Heavy mineral associations from the sandstones of these formations contain ZTR, Cr-spinel and garnet, as well as a minor proportion of other mineral species (e.g. epidote, amphibole, chloritoid), indicating derivation from both ophiolitic and continental sources (Zupanič 1981; Crnjaković et al. 2000).

Sampling and analytical procedures

Samples were taken from fine to medium grained sandstone beds, taking care to avoid sampling of weathered rock. Cr-spinel grains were obtained using standard heavy mineral separation procedures. Sandstone samples were crushed, dry-sieved down to <0.250 mm and the heavy fraction preconcentrated using a Wilfley-table. Carbonate was removed by 5% cold acetic acid treatment. Heavy minerals were separated by hot LST Fastfloat ($\rho = 2.85$ g cm^{-3}), embedded in epoxy and polished for microprobe analysis. Most sprinkled mounts contained sufficient amount of Cr-spinel grains, whereas Glog Formation spinels were separated by hand-picking due to their low abundance in the samples. Measured grains range in size from coarse silt to very fine sand.

In total, we have analyzed Cr-spinels from 17 sandstone samples taken from five different formations (Oštrc = 7, Bistra = 3, Kravljak = 2, Vivodina = 3, Glog = 2). Chemical data of 773 detrital Cr-spinel grains were obtained using a JEOL electron microprobe (JXA-8900RL) equipped with five wavelength dispersive spectrometers at the Geoscience Center Göttingen. Analyses were performed using an accelerating voltage of 20 kV, a beam current of 20 nA and a 3-μm beam diameter. Mg, Al, Cr, Fe, V, Si, Ti, Mn, Ni and Zn were analyzed. One spot analysis was performed in the center of each grain. Measured grains range in size from coarse silt to very fine sand. No zoning was evident, based on back-scattered electron images, neither were ferrian chromite rims encountered. Ferric iron content was calculated based on charge balance assuming stoichiometry, following the procedure of Barnes and Roeder (2001). All data are available in an Excel file in the electronic supplement.

Chemical characteristics of Cr-spinels in the studied Cretaceous formations

The chemical composition of Cr-spinel is commonly presented by values, which display considerable variation, such as Cr# (Cr/Cr+Al), Mg# (Mg/Mg+Fe^{2+}), TiO_2 and Fe^{3+}# (Fe^{3+}/Cr+Al+Fe^{3+}). During processes of partial melting in the mantle, Cr is strongly partitioned into the solid as compared to Al, which preferentially partitions into the melt. This makes the Cr# of Cr-spinel an excellent indicator of the degree of partial melting which its host peridotite underwent, since the degree of depletion is often suggestive of the tectonic setting (e.g. mid-oceanic ridge or supra-subduction zone). The causes for the variation of Mg# are more complex. The partitioning of Mg and Fe^{2+} is affected by the relative activities of Cr and Al in spinel, causing a shift towards lower Mg# with increasing Cr# (Dick and Bullen 1984). Furthermore, Mg# is dependent on temperature and cooling rate, as well as on magma chemistry during crystallization and re-equilibration processes. The TiO_2 content and Fe^{3+}# differ between Cr-spinels from residual mantle peridotites (“residual” or “mantle” spinels) and those formed by crystallization of the extracted melt (“magmatic” spinels). Residual spinels have low TiO_2 (<0.2 wt%), while those originating from cumulate and extrusive volcanic rocks tend to have higher TiO_2 (>0.2 wt%) (e.g. Kamenetsky et al. 2001).

Oštrc formation

In the Cr-spinels from the sandstones of the Oštrc Formation, Cr# values range from 0.39 up to 0.81, mostly (88%) between 0.50 and 0.70. Only 2% of the analyses fall below 0.45 (all of these coming from only one of the seven Oštrc samples). The Mg# displays a relatively wide range, from 0.37 to 0.76. Of the analyzed grains, 28% display TiO_2 concentrations above 0.2 wt%. It is interesting to note that a few of the grains display high TiO_2 concentrations, up to 2.17 wt%. When the residual spinels alone (<0.2 wt% TiO_2) are plotted on the Cr# versus Mg# diagram (Fig. 4), most of the data fall within the harzburgite field defined by Pober and Faupl (1988). Following the classification of Dick and Bullen (1984), they resemble Type II alpine-type peridotites, which are thought to evolve through a complex multistage melting history as may be encountered in a subduction zone. The high-Ti magmatic spinels (>0.2 wt% TiO_2) display a shift towards lower Mg#, as in the Fe–Ti trend of Barnes and Roeder (2001). Their similar range of Cr# values to the residual spinels (with a tendency towards higher Cr#), high Fe^{3+} and TiO_2, along with lower Mg#, suggest that these spinels could be the products of fractional crystallization and re-equilibration at lower temperatures due to slow cooling (Arai 1992; Kamenetsky et al. 2001), and thus probably derived from cumulate members containing disseminated Cr-spinel of the same ophiolite source (Dick and Bullen 1984; Pober and Faupl 1988; Barnes and Roeder 2001). On the Al_2O_3 versus TiO_2 discrimination diagram (Fig. 5) proposed by Kamenetsky et al. (2001), the residual spinels concentrate in the middle of the field of suprasubduction zone peridotites. Meanwhile, the magmatic spinels fall within fields defining volcanic rocks from different settings, but mostly group in the border region between MORB and arc basalts. The same can be observed on the TiO_2 versus Fe^{3+}# diagram when comparing the data with compositional fields proposed by Arai (1992). Several grains display compositions such as those found in ocean island basalts (i.e. intra-plate basalts).

Bistra formation

Generally, high-Cr# harzburgitic spinels predominate in the Early Cretaceous Bistra Fm. (Fig. 4), although the Cr# ranges differ noticeably between the three studied samples. Sample 05-H/B-201 contains spinels with Cr# above 0.50. A single outlier is a relatively high-Al spinel with a Cr# as low as 0.30. Similar to the spinels of the Oštrc Fm., the residual spinels of sample 05-H/B-201 fall predominantly within the harzburgite field, while the magmatic spinels display higher Cr# and shift towards lower Mg# values. Spinels from sample 05-H/B-216 have Cr# values above 0.40. Unlike in the two previous samples, in sample 05-H/B-207 Cr# values spread in a wider range, from 0.26 to 0.87. The proportion of magmatic spinels is also variable among the three studied samples (24, 13 and 19%). Overall, the variability between the samples suggests that the source area was rather heterogeneous and included small exposures of less depleted residual peridotites and magmatic rocks.

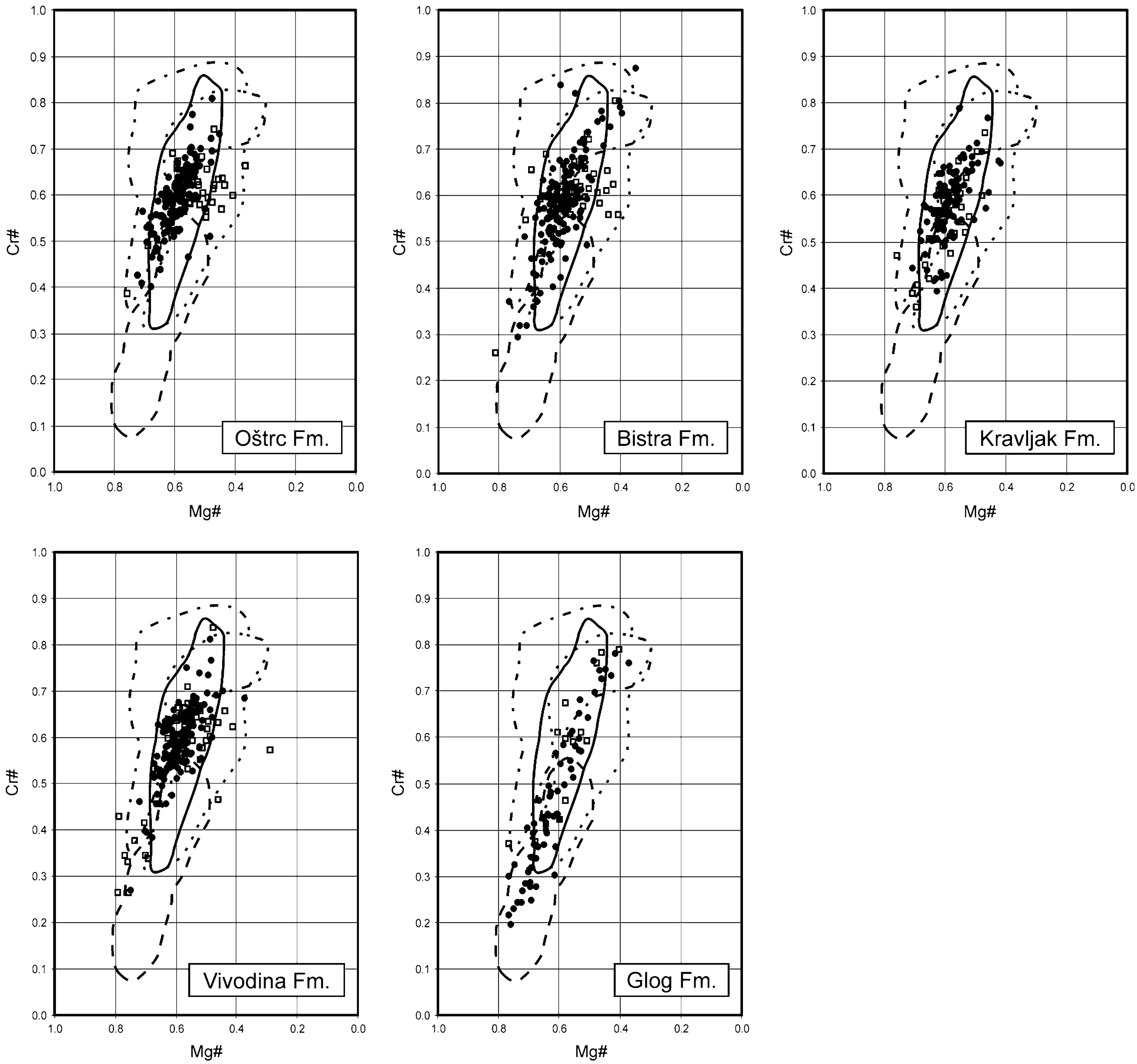

Fig. 4 Cr# versus Mg# diagrams of Cr-spinels from each formation. Fields after Pober and Faupl (1988). *full line* harzburgites, *dashed line* lherzolites, *dotted line* cumulates, *dash-dot* podiform chromites, *full circles* spinels with <0.2 wt% TiO_2, *open squares* spinels with >0.2 wt% TiO_2

Kravljak formation

The Cr-spinels from sandstones of the Albian–Cenomanian Kravljak formation display a range of Cr# values from 0.36 to 0.79, with only 2% of the data falling below 0.40. Most of the grains (83%) cluster within the 0.50–0.70 Cr# range, falling predominantly within the harzburgite field (Fig. 4). Twenty-four percent of the spinels can be classified as magmatic, the maximum recorded TiO_2 being 1 wt%. On the Al_2O_3 versus TiO_2 diagram, most of the spinels fall within the field of suprasubduction peridotites, while the magmatic grains fall predominantly in the MORB field (Fig. 5).

Vivodina formation

In the Maastrichtian Vivodina Formation, Cr-spinels display a wide range of Cr# and Mg# values (0.26–0.84 and 0.29–0.79, respectively), but concentrate (85%) within the 0.50–0.70 Cr# range like in the other formations. Twenty percent of the spinels classify as magmatic. These high-TiO_2 spinels concentrate in two groups on the Cr#–Mg# diagram (Fig. 4). The first group is characterized by high Cr# and low Mg#, very similar to those identified as cumulate spinels in the older formations (Ostrc, Bistra and Kravljak Fms.). The second group, however, displays low

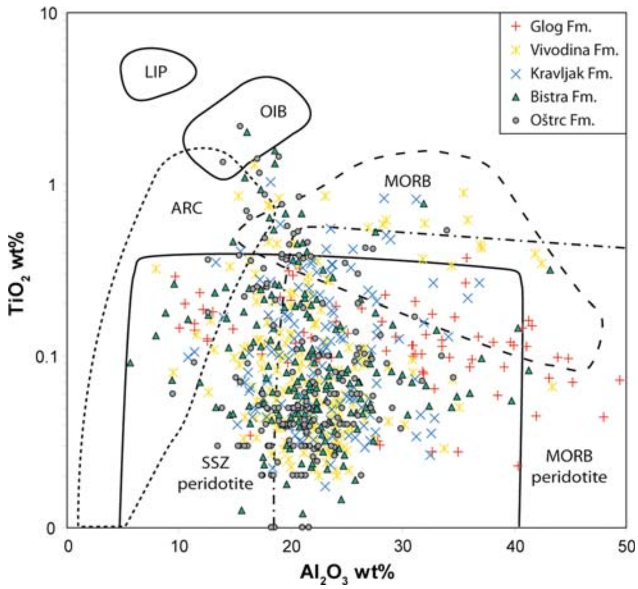

Fig. 5 TiO_2 versus Al_2O_3 diagram with Cr-spinel data from all five formations. Fields after Kamenetsky et al. (2001). *MORB* mid-ocean ridge basalt, *OIB* ocean-island basalt, *LIP* large igneous province, *ARC* island-arc magmas, *SSZ* supra-subduction zone

Cr# and higher Mg#, which is a characteristic of Cr-spinels identified in abyssal basalts (Dick and Bullen 1984). On the Al_2O_3 versus TiO_2 diagram, these tend to fall within the MORB field (Fig. 5). The residual spinels group in the middle of the suprasubduction zone field of the same diagram, as in the samples from the older three studied formations.

Glog formation

Of all the studied samples, the Cr-spinels from the Glog Fm. display the greatest range of Cr# values (0.20–0.79). The Cr# values spread continuously across the entire range (Fig. 4), lacking the predominance of high-Cr spinels identified in the other formations. The proportion of grains with TiO_2 content above 0.2 wt% is 16%. The highest recorded TiO_2 content is 0.36 wt%, much lower than that in the other formations.

Provenance and paleogeographic relations

Following the Tithonian–Hauterivian period, which was marked by widespread deposition of deep marine Aptychus limestones and marls, the closure of the western Tethys Ocean triggered a strong influx of siliciclastic material onto the passive margin of the Adriatic plate. This change in sedimentary regime is evident on Mt Ivanščica, where from the Barremian up to the Albian deep marine, clastic

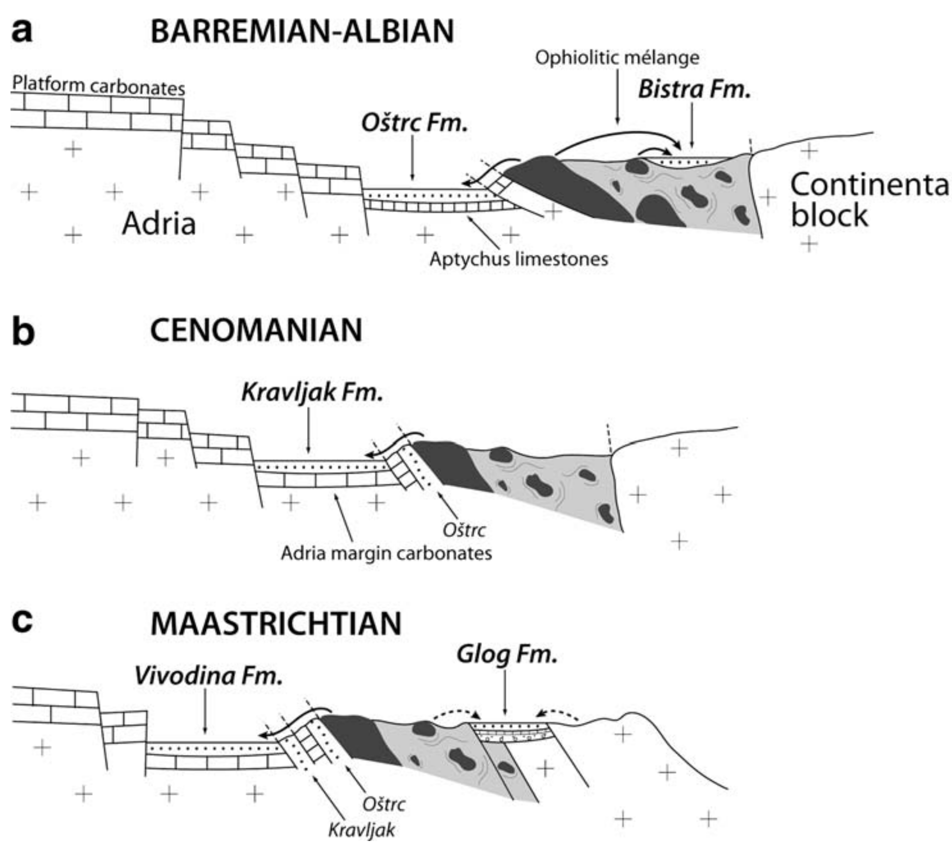

Fig. 6 Schematic cross-sections portraying the Cretaceous tectonic evolution of the study area and the major sources of Cr-spinels (*thick black arrows*) for the five studied formations. See text for details

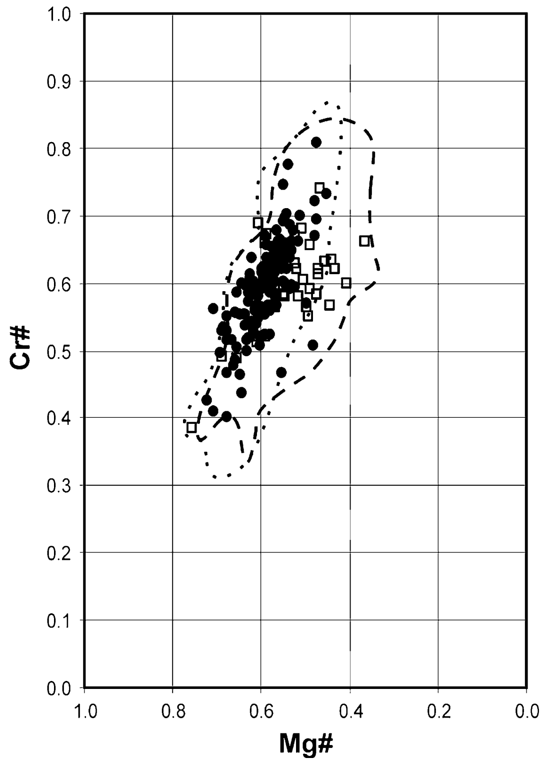

Fig. 7 A comparison of the data from the Oštrc Fm. with those published for the Rossfeld Fm., Northern Calcareous Alps (*dashed line*) and Gerecse Mts, Transdanubian Central Range (*dotted line*). *Full circles* spinels with <0.2 wt% TiO_2, *open squares* spinels with >0.2 wt% TiO_2

sediments rich in ophiolitic detritus (Oštrc Fm.) were deposited on top of pelagic limestones (Fig. 6a). Considering the ubiquity of ophiolitic lithoclasts and Cr-spinel, a source area consisting primarily of obducted ophiolites must have come into close proximity of the Oštrc Basin (Zupanič et al. 1981; Babić et al. 2002). The chemical compositions of the Cr-spinels (Fig. 4) indicate that these exposed ophiolites consisted mostly of harzburgitic peridotites and associated cumulate rocks, i.e. oceanic mantle and lower crustal rocks. The eroded mantle peridotites underwent a considerable degree of partial melting prior to their obduction, above the limit normally achieved at mid-oceanic ridges (Dick and Bullen 1984), and instead likely evolved in a supra-subduction zone setting. These characteristics of the source area apparently did not change significantly during continuous erosion and deposition of the Oštrc Fm., as no systematic change in Cr-spinel composition is detected among the seven studied samples.

In addition to Mt Ivanščica, Early Cretaceous formations containing abundant ophiolitic detritus are well known in the Northern Calcareous Alps (NCA; Rossfeld Fm.) and the Transdanubian Central Range (Gerecse Mts). Facies and petrologic similarities among these sedimentary successions have been recognized by previous authors

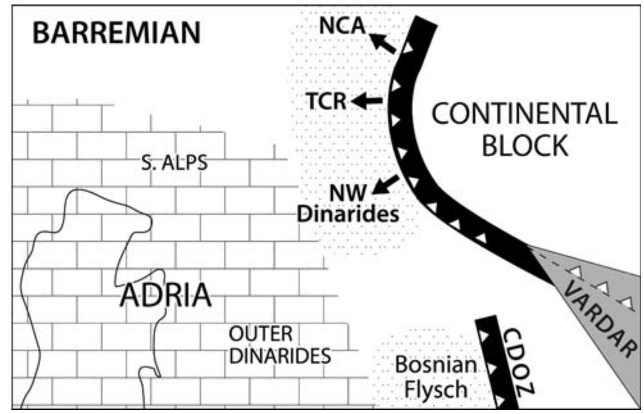

Fig. 8 Paleogeographic sketch map of the Dinaride–Alpine region during the Barremian. *NCA* Northern Calcareous Alps, *TCR* Transdanubian Central Range, *CDOZ* Central Dinaride Ophiolite Zone

(e.g., Decker et al. 1987; Faupl and Wagreich 1992; Császár and Árgyelán 1994), and a common provenance, the suture zone of the Tethys Ocean has been suggested (Pober and Faupl 1988; Árgyelán 1996; Babić et al. 2002). A comparison of Cr-spinel data from all three areas (Fig. 7) lends support for a common provenance of the ophiolitic material. Although they are today separated by hundreds of kilometers due to Cenozoic tectonic displacement, during the Mesozoic, the NCA and the Transdanubian Central Range sat adjacent to one another along the Tethyan passive margin (Kázmér and Kovács 1985; Schmidt et al. 1991; Vörös and Galácz 1998). During this time, Mt Ivanščica probably held a more southerly position and may represent an important link to the Inner Dinaride realms. A rather extensive ophiolite belt containing large harzburgite bodies, capable of providing large quantities of detritus over a regional scale, may have extended during the Early Cretaceous along the Adriatic margin, from the area of the NCA in the north to the Dinarides (Fig. 8). Today, in the surroundings of the northernmost Dinarides and in the East Alpine–Carpathian region, there are no major exposures of mantle rocks. They are restricted to smaller dismembered occurrences mostly within mélange complexes of the Sava Zone (Pamić 1997; Slovenec and Pamić 2002), the Alps and the Western Carpatians (Kozur 1991). Large ultramafic bodies are exposed in the CDOZ, in places occurring as several kilometers thick slices of oceanic lithosphere (e.g. Pamić et al. 2002). From the peridotites of the two major zones in the Inner Dinarides, Maksimović and Majer (1981) reported both high-Cr (common to the Vardar Zone) and low-Cr spinels (common to the CDOZ), but in fact there is likely to be a gradual transition in the degree of depletion of the mantle rocks within these zones (Pamić 1983). The northwesternmost peridotites of the CDOZ, such as those occurring in the Banija region, south of the study area, are lherzolitic with low-Cr# spinels

(Maksimović and Majer 1981), ruling them out as potential remnants of the obducted ophiolites, which supplied the Oštrc Fm. Although the ophiolites of the CDOZ were already obducted in the Early Cretaceous (Pamić et al. 2002; Robertson and Karamata 1994), detritus produced by their erosion was not transported into the Oštrc Basin. Rather, a connection to the Vardar Zone, where harzburgites predominate, is more conceivable (Fig. 8). The unusual spread in the Al content of the high-Ti spinels in some of the studied formations (Fig. 5) may be suggestive of a back-arc basin origin of the magmatic rocks from which some of these grains are derived from (Arai 1992; Kamenetsky et al. 2001).

The ophiolite source supplying most of the detritus of the Early Cretaceous Bistra Fm., exposed on Mt Medvednica, was mostly similar in composition to that supplying the Oštrc Fm. in that high-Cr# spinels dominate. Babić et al. (2002) suggested that the Bistra Fm. developed as a shallow basin on top of the ophiolitic mélange (Repno complex), whose remnants occur in the N part of Mt Medvednica. Serpentinized harzburgites as well as cumulate ultramafics with relatively high-Cr spinels are present as smaller tectonized blocks within this mélange (Šimunić and Pamić 1989; Slovenec and Lugović 2000) and may have presented a potential source (Fig. 6a). The variability encountered among the individual samples of the Bistra Fm. may reflect the smaller catchment area of the shallow marine environment and the heterogeneous nature of the mélange, which incorporated ophiolite fragments of slightly varying composition.

The supply of Cr-spinels from ophiolites with the same chemical signature as those supplying the Oštrc Fm. continued at least until the latest Cretaceous along the NE margin of the Outer Dinarides, as evident from the data obtained from the Kravljak and Vivodina Fms. Recycled Cr-spinels from older sedimentary formations being incorporated into propagating nappes (e.g. the Oštrc) may have represented an important source (Fig. 6b, c). However, the presence of ophiolite-derived lithoclasts and a relatively high proportion of Cr-spinels in the heavy mineral fraction of the Vivodina sandstones (up to 70%; Zupanič et al. 1981) suggest that exposed remnants of the above mentioned ophiolite belt persisted along the margin of the Adriatic plate at least until the end of the Cretaceous (Fig. 6b, c).

An additional source of Cr-spinels is recorded in the Maastrichtian. A number of grains in the Maastrichtian Vivodina sandstones (Figs. 4, 5) have compositions similar to those reported for abyssal/MORB basalts (Dick and Bullen 1984; Kamenetsky et al. 2001). Lenaz et al. (2000) obtained very similar results from Cr-spinels in the Maastrichtian to Middle Eocene sediments of the Julian Basin in the Southern Alps (Fig. 1), which imply a possible common provenance and a paleogeographic connection between the Julian and Vivodina basins.

The presence of many low-Cr# spinels in the Glog Fm. requires a separate source from that which supplied the other formations examined. The Glog Fm. belongs to a Senonian succession lying on a tectonized basement (Fig. 6c), presumably deposited in a piggy-back basin (Babić et al. 2002). The detritus in the Glog sandstones originated from an entirely continental hinterland probably composed of the sedimentary–metamorphic complex of Mt Medvednica (Crnjaković 1979). The dominant availability of felsic continental lithologies for erosion in the source area likely accounts for the small proportion of Cr-spinel in the HM spectra of Glog sandstones. The differences in Cr-spinel chemistry of the coeval Vivodina and Glog formations can be reconciled by the erosion of a heterogeneous ophiolite mélange source containing peridotite blocks of different degrees of depletion (Fig. 6c). Together with contrasting heavy mineral data and differences in the underlying lithology, these results suggest the coeval existence of two separate basins.

Although the supply of high-Cr# spinels prevailed in general, a slight trend of increasing variation in the Cr# (among both residual and magmatic spinels) is noticeable from the Early to the latest Cretaceous, suggesting that the source areas became more heterogeneous with the ongoing Cretaceous tectonic evolution of the Dinaride–Alpine region. Pober and Faupl (1988) and von Eynatten (1996) identified a trend of increasing lherzolitic component from Early to Late Cretaceous among sedimentary formations of the NCA and the Drauzug, which had a "southern provenance," i.e. sourced by the Tethys suture (Rossfeld Fm., Lavant Fm. and parts of the Gosau-type sediments).

Conclusions

1. Detrital Cr-spinel grains in the Early Cretaceous Oštrc Formation on Mt Ivanščica display relatively high Cr#. The ophiolite source consisted of harzburgitic mantle peridotites and associated cumulate rocks, which developed in a supra-subduction zone setting.
2. There is a similarity in detrital Cr-spinel compositions between the Oštrc Fm. and those reported from contemporaneous formation in the NCA and the Transdanubian Central Range. A rather extensive harzburgitic ophiolite belt, capable of providing large quantities of detritus over a regional scale, probably extended along the Adriatic margin during the Early Cretaceous, from the area of the NCA in the north to the northernmost Dinarides.
3. The supply of Cr-spinels with a high Cr# remained dominant throughout the Cretaceous. A likely source

was exposed remnants of the W Tethyan ophiolite belt, while recycling from Early Cretaceous sediments also played an important role.

4. The Cr-spinels from the Maastrichtian Glog Fm. on Mt Medvednica were derived from a source of different composition as compared to the contemporaneous Vivodina Fm. in the Žumberak Mts. Together with contrasting heavy mineral data and differences in the underlying lithologies, these results imply the coeval existence of two separate basins.
5. The source areas became more heterogeneous with the ongoing Cretaceous tectonic evolution, which is suggested by the increasing variation in the Cr# of Cr-spinels from the Early to the latest Cretaceous.

Acknowledgments This work was funded by the Deutsche Forschungsgemeinschaft project "Zircon fission-track chronology and heavy mineral chemistry of Cretaceous clastic formations of the Croatian Dinarides" and the Croatian Ministry of Science, Education and Sports project 119-1191155-1159 «Evolutionary Changes of the Dinarides from Subduction to Modern Adriatic Beaches». We would like to thank Prof. Peter Faupl and Prof. Wolfgang Frisch for their prompt reviews of the paper and their very useful suggestions. We thank Prof. Jožica Zupanič and Dr. Marta Crnjaković for sharing with us their knowledge on the studied sediments and field relationships in the study area.

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