Swiss J Geosci
DOI 10.1007/s00015-012-0107-3

Provenance of Cretaceous synorogenic sediments from the NW Dinarides (Croatia)

Borna Lužar-Oberiter · Tamás Mikes · István Dunkl · Ljubomir Babić · Hilmar von Eynatten

Received: 30 January 2012 / Accepted: 6 July 2012

Abstract Scarce basin remnants of Cretaceous synorogenic sediments exposed in the Medvednica, Ivanščica, Žumberak Mts. and Samobor Hills of northern Croatia record the early orogenic history of the NW Dinarides. The provenance of sandstones from five clastic formations (Oštrc, Bistra, Kravljak, Vivodina and Glog) which cover a time span from Early to late Late Cretaceous was studied by combining petrography, whole-rock geochemistry, heavy mineral chemistry and detrital zircon fission track dating. These sediments record at least two major regional thermotectonic events which correlate well with those affecting both the Alps and the Tisza-Dacia unit to the north and east, and the central Dinaride region to the south. Short zircon fission track lag times in Barremian to Albian sediments indicate that continental fragments of the distal Adria plate margin underwent relatively fast, synsedimentary exhumation in the Early Cretaceous. Moreover, a clear dominance of Campanian zircon cooling ages (80–73 Ma) in Maastrichtian sandstones indicates detritus deriving from the erosion of newly and rapidly exhumed basement units which had undergone Late Cretaceous metamorphism in the Eastern Alps and/or the Tisza-Dacia region. Probably, the rapid Maastrichtian erosion generating metamorphic detritus occurred to a great extent on neighbouring Austroalpine basement units, and/or on the upper plate Tisza-Dacia unit during the subduction stage or the initial stages of the continent–continent collision with Adria. Development of the accretionary wedge probably resulted in a renewed availability of ophiolites for erosion within small and/or dynamically changing catchments, which can be deduced from the notable differences in reconstructed source lithologies for the coeval Glog and Vivodina formations. Combined evidence from sedimentary provenance indicators precludes the Dinaride (Adriatic) basement as a significant source for the Maastrichtian sediments.

Keywords Dinarides · Croatia · Cretaceous · Sandstone provenance · Geochemistry · Heavy mineral chemistry · Fission track thermochronology

Editorial Handling: W. Winkler and A. G. Milnes.

Electronic supplementary material The online version of this article (doi:10.1007/s00015-012-0107-3) contains supplementary material, which is available to authorized users.

B. Lužar-Oberiter (✉) · Lj. Babić
Department of Geology, Faculty of Science,
University of Zagreb, Horvatovac 102a,
10000 Zagreb, Croatia
e-mail: bluzar@geol.pmf.hr

T. Mikes · I. Dunkl · H. von Eynatten
Abteilung Sedimentologie/Umweltgeologie,
Geowissenschaftliches Zentrum der Universität Göttingen,
Goldschmidtstrasse 3, 37077 Göttingen, Germany

Present Address:
T. Mikes
Institut für Geowissenschaften, Goethe-Universität Frankfurt,
Altenhöferallee 1, 60438 Frankfurt am Main, Germany

T. Mikes
Biodiversität und Klima Forschungszentrum (BiK-F),
Senckenberganlage 25, 60325 Frankfurt am Main, Germany

1 Introduction

Provenance studies which integrate results from multiple analytical approaches offer an in-depth view into the history of clastic material and the characteristics of its source areas (e.g. Weltje and von Eynatten 2004). Apart from the

Published online: 29 August 2012

benefits for reconstructing the general lithological makeup of source areas, the ability to derive information related to source rock petrogenesis and thermal history by means of heavy mineral chemistry and single grain dating techniques is of particular value in geodynamically active regions (e.g. von Eynatten et al. 1996; Ruiz et al. 2004; Mange and Morton 2007). Thus, in orogenic settings where evidence of past events is often obscured by strong tectonothermal overprint, dismemberment and erosion, clastic material provides indispensable information relating to the tectonic history of such regions if suitable analytical approaches are employed.

The Dinarides are a major segment of the Alpine orogenic belt and represent an important element in the tectonic history of the Mediterranean region. The NW Dinarides are of particular interest due to their proximity to major neighbouring tectonic units, the Alps in the north and the Tisza-Dacia unit to the east (Fig. 1). This Dinaride–Alpine–Tisza transitional area is characterized by considerable geological complexity (Haas et al. 2000). Its long-lasting deformational history included Triassic rifting and ocean spreading, two phases of ophiolite obduction and nappe stacking (Late Jurassic to Early Cretaceous, as well as Late Cretaceous), and severe lateral and rotational displacements in the Cenozoic (Vörös 1993; Tomljenović and Csontos 2001; Babić et al. 2002; Csontos and Vörös 2004; Haas and Péró 2004; Schmid et al. 2008; Tomljenović et al. 2008; Ustaszewski et al. 2009, 2010). In the Cretaceous, synorogenic basins formed, and were filled with clastic material composed of variable proportions of ophiolitic, continental and carbonate detritus. The remnants of these basins, exposed in northern Croatia, document the early evolution of the Dinaride orogen which has been heavily masked by Cenozoic deformation. Based on detailed petrography, litho- and biostratigraphy, previous work has already assessed the general paleogeography and sedimentary provenance of these basins, suggesting that they represent different paleogeographic settings (Babić et al. 1973, 2002; Babić 1974; Crnjaković 1979, 1981, 1989; Zupanič 1981; Zupanič et al. 1981; Lužar-Oberiter 2009). More recently, detrital Cr-spinel chemistry revealed additional details with respect to the ophiolites obducted onto the margin of the Adria plate (Lužar-Oberiter et al. 2009). These authors also provided regional correlations with coeval clastic formations in the Eastern Alps and the Transdanubian Central Range (Hungary).

In this paper we present a provenance study of sandstones from the NW Dinarides (Croatia) ranging in age from Early to late Late Cretaceous. We focus on the siliciclastic components and combine an assortment of provenance sensitive indicators, including petrography, whole-rock geochemistry, tourmaline and garnet chemistry, and zircon fission track thermochronology. The main goal of our study was to constrain the composition and dynamics of continental source terrains being exhumed and eroded during the Cretaceous orogeny of the Dinarides, as well as to shed new light on the paleogeographic relationships between the NW Dinarides and neighbouring Alpine, Tisza-Dacia, and southerly Dinaride units.

2 Geological outline of the Dinarides

The general structure of the Dinarides consists of two main tectonic domains, the External and the Internal Dinarides. The External Dinarides are dominated by thick Mesozoic platform carbonates which formed on the Adria plate and were incorporated into SW-verging structures during Cenozoic deformation (e.g. Aubouin et al. 1970; Blašković 1998; Vlahović et al. 2005; Ustaszewski et al. 2008; Korbar 2009). The tectonostratigraphic elements of the Internal Dinarides, by contrast, consist of a wide range of lithologies, and are arranged in dominantly NW–SE trending Mesozoic to Cenozoic tectonic structures (Fig. 1). Further to the southeast, these zones extend into the Hellenides. In the NW Dinarides however, in the vicinity of the Dinaride–Alpine–Tisza junction, where the study area is situated, this structural pattern is considerably complicated by Cenozoic lateral displacements and block rotations (Haas et al. 2000; Tomljenović et al. 2008), as well as obscured by the Neogene sedimentary cover of the Pannonian Basin. A large number of schemes have been established for the tectonostratigraphy of the Dinarides (e.g. Aubouin et al. 1970; Pamić et al. 1998; Dimitrijević 2001; Schmid et al. 2008). In this paper we follow the concept of Schmid et al. (2008). Accordingly, from the southwest towards the northeast, the Internal Dinarides consist of: (1) the Pre-Karst and Bosnian Flysch Unit, (2) the West Vardar Ophiolitic Unit, (3) thrusted sheets composed of partly metamorphosed post-Variscan basement units of the distal margin of Adria, and (4) the Sava Zone (Fig. 1).

The Pre-Karst is a transitional zone between the Mesozoic shallow-marine carbonate platform units of the External Dinarides (i.e. the Adriatic carbonate platform), and the more internal, basinal environments of the distal margin of Adria. It comprises Upper Triassic to Upper Cretaceous shallow marine, slope and deep-marine carbonates which are unconformably overlain by Upper Cretaceous clastics (Blanchet et al. 1970; Babić 1973, 1974; Dragičević and Velić 2002). Here, siliciclastic deposition was initiated earlier than in the External Dinarides further SW (Blanchet et al. 1970; Babić 1974). In the Central Dinarides these clastics have been designated as the Ugar Formation, which is dominated by clastic carbonate, typically consisting of thin-bedded marls, calcarenites and sandstones, as well as thick carbonate

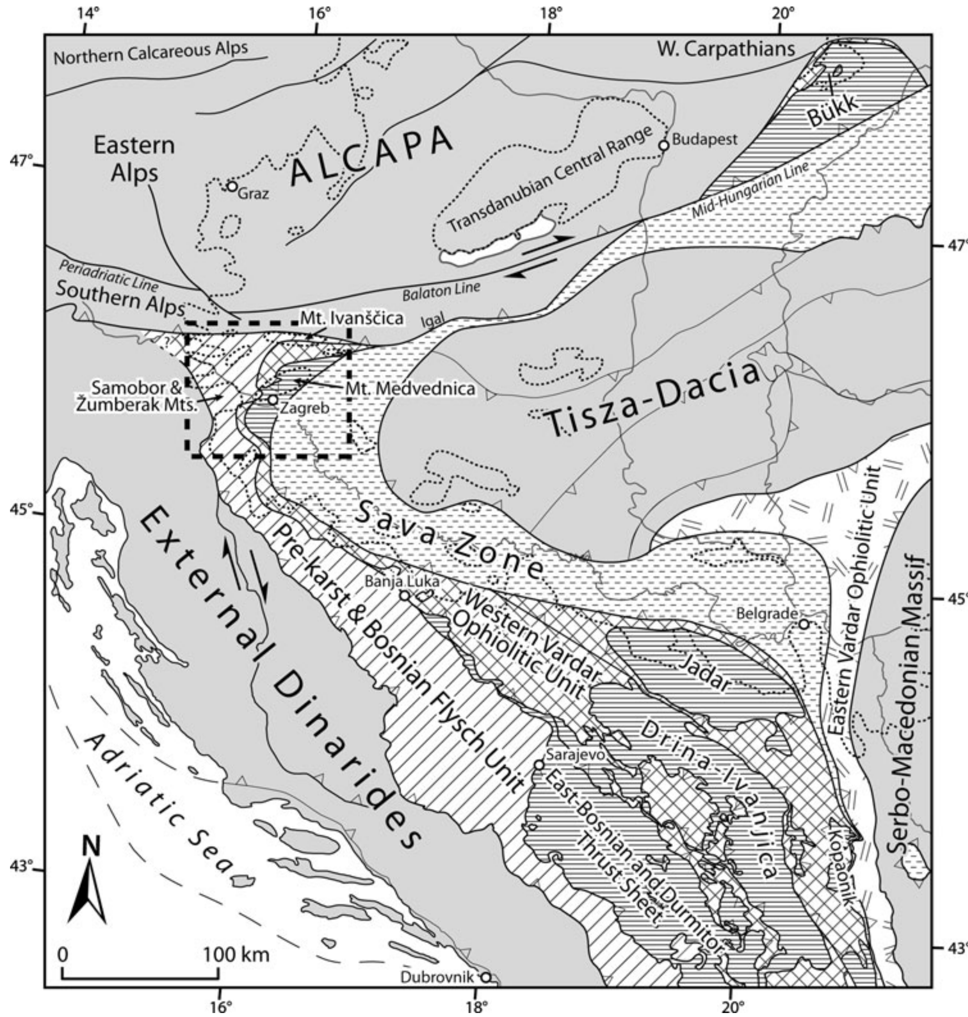
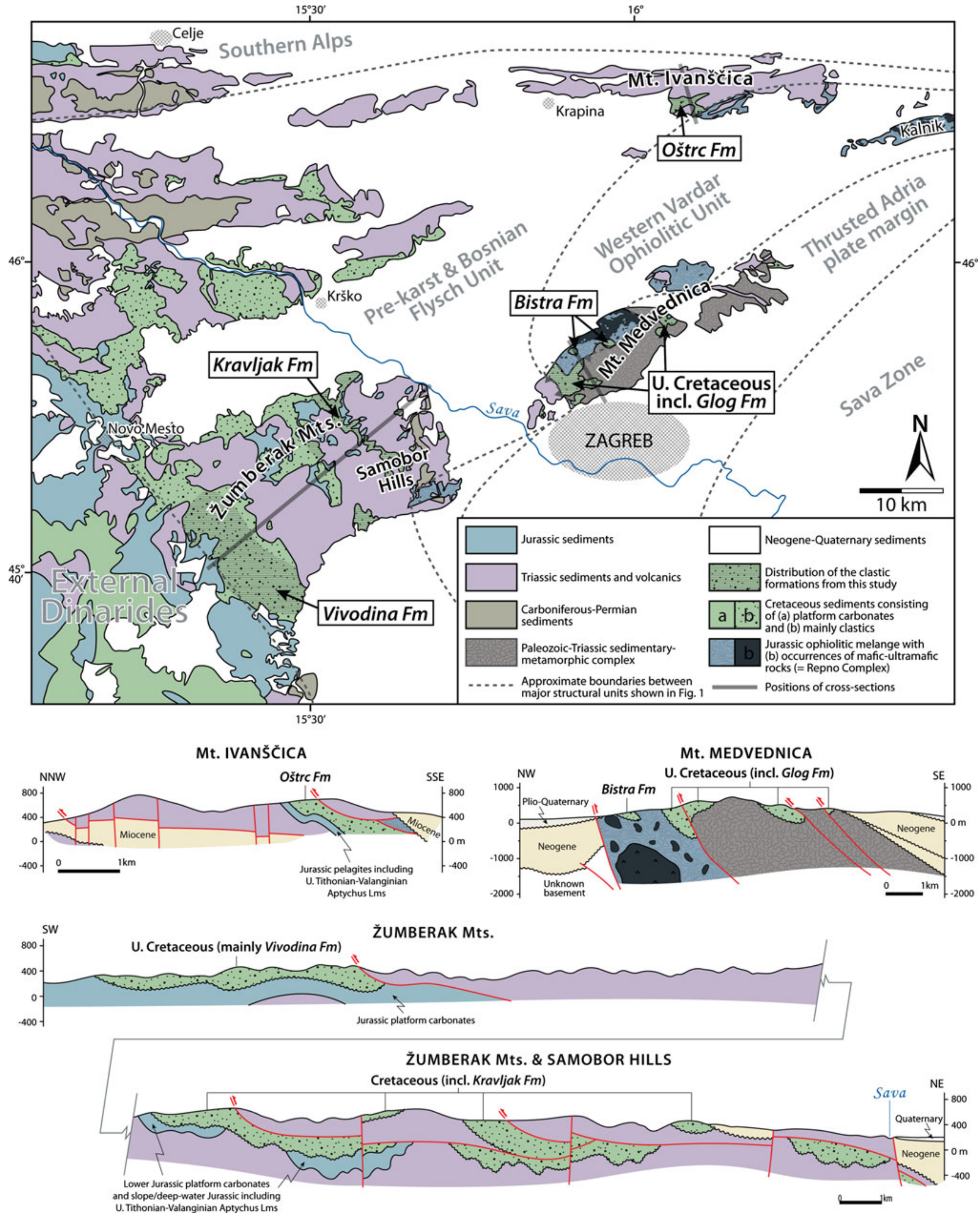


Fig. 1 Map of the Dinaride–Alpine–Pannonian region showing the major structural units of the Dinarides (after Schmid et al. 2008, with modifications in the area of the NW Dinarides after Aubouin et al. 1970; Haas et al. 2000; Tomljenović et al. 2008). ALCAPA: tectonic mega-unit which includes the Austroalpine nappes and the Central and Inner West Carpathians. Position of the study area is marked by the *rectangle*

mass flow deposits. Based on the observation that at places it is separated by an angular unconformity from older deposits, it has been proposed to represent a Gosau-type basin formed in response to a pre-Turonian orogenic event (Schmid et al. 2008). However, such an analogy awaits further evidence since a Late Cretaceous extensional regime comparable to that leading to the opening and subsidence of the Gosau basins in the Northern Calcareous Alps (Neubauer et al. 1995; Wagreich and Decker 2001) has hitherto not been documented in the External Dinarides. The Pre-Karst unit extends into the NW Dinarides and includes the area of the Žumberak Mts. and Samobor Hills where the Albian–Cenomanian Kravljak and the Maastrichtian Vivodina formations crop out (Figs. 1, 2; Babić 1974; Zupanič 1981; Devidé-Nedéla et al. 1982).

More internally, to the east of the Pre-Karst zone, the central part of the Dinarides includes a belt of older, Upper Jurassic to Lower Cretaceous flysch containing abundant ophiolitic detritus and representing a clastic wedge developed in front of the West Vardar ophiolite thrust sheets obducted onto the Adria plate margin (Bosnian Flysch; Blanchet et al. 1969; Hrvatović 2000; Mikes et al. 2008). In the NW Dinarides, a clastic formation with similar characteristics, the Oštrc Formation, crops out on Mt. Ivanščica (Zupanič et al. 1981; Lužar-Oberiter et al. 2009).

Prominent features of the Inner Dinaride nappe stack are extensive ophiolite bodies, either incorporated into ophiolitic mélange or representing large thrust sheets of obducted oceanic lithosphere (Pamić et al. 2002). Interpretations vary on how these Dinaric ophiolites formed. They collectively belong to the Western Vardar Ophiolitic Unit which has been interpreted to represent a single ophiolite thrust sheet formed by late Jurassic obduction of the Neotethys onto the passive margin of Adria (Bernoulli and Laubscher 1972; Schmid et al. 2008, and references therein). However, contrasting interpretations have advocated the closure of multiple ocean branches or marginal basins (e.g. Dimitrijević and Dimitrijević 1973; Robertson and Karamata 1994; Channell and Kozur 1997). The northwesternmost exposure of the Western Vardar Ophiolitic Unit is located in northwestern Croatia (Mt. Medvednica, Mt. Ivanščica and Mt. Kalnik) and is referred to as the Repno Complex (Figs. 1, 2; Babić et al.



15°30′
16°
46°
45°40′
Celje
Southern Alps
Mt. Ivanšćica
Krapina
Kalnik
Oštrc Fm
Western Vardar Ophiolitic Unit
Thrusted Adria plate margin
Pre-karst & Bosnian Flysch Unit
Krško
Bistra Fm
Mt. Medvednica
Kravljak Fm
U. Cretaceous incl. Glog Fm
Sava
Sava Zone
Novo Mesto
Žumberak Mts.
Samobor Hills
ZAGREB
N
10 km
External Dinarides
Vivodina Fm
Jurassic sediments
Triassic sediments and volcanics
Carboniferous-Permian sediments
Paleozoic-Triassic sedimentary-metamorphic complex
Approximate boundaries between major structural units shown in Fig. 1
Neogene-Quaternary sediments
Distribution of the clastic formations from this study
Cretaceous sediments consisting of (a) platform carbonates and (b) mainly clastics
Jurassic ophiolitic melange with (b) occurrences of mafic-ultramafic rocks (= Repno Complex)
Positions of cross-sections
Mt. IVANŠĆICA
NNW
Oštrc Fm
SSE
Miocene
Jurassic pelagites including U. Tithonian-Valanginian Aptychus Lms
1km
Mt. MEDVEDNICA
NW
U. Cretaceous (incl. Glog Fm)
SE
Bistra Fm
Plio-Quaternary
Neogene
Unknown basement
ŽUMBERAK Mts.
SW
U. Cretaceous (mainly Vivodina Fm)
Jurassic platform carbonates
ŽUMBERAK Mts. & SAMOBOR HILLS
Cretaceous (incl. Kravljak Fm)
Sava
NE
Quaternary
Neogene
Lower Jurassic platform carbonates and slope/deep-water Jurassic including U. Tithonian-Valanginian Aptychus Lms

◀ **Fig. 2** Simplified geological map of the study area (marked in Fig. 1) showing the distribution of the studied sediments (after Basic geological map of Yugoslavia, 1:100,000; Babić et al. 2002). Below are simplified cross-sections of Mt. Ivanščica (northern and central parts modified after Šimunić et al. 1982), Mt. Medvednica (modified after Šikić et al. 1977; Tomljenović et al. 2008) and Žumberak Mts.–Samobor Hills (modified after Šikić et al. 1977; Prtoljan 2001). *Color patterns* in the cross-sections are analogous to those in the map key, while additional information regarding specific lithologies is noted where appropriate. Faults and thrusts are marked in *red*

2002). Radiolarian biostratigraphy on the blocks and palynomorph studies on the matrix of the mélange suggest that, in this area, oceanic subduction started in the Middle Jurassic and ended around the Late Jurassic/Early Cretaceous (Halamić and Goričan 1995; Halamić et al. 1999; Babić et al. 2002). These age data are in good agreement with independent data from several Dinaride localities on high-temperature geochronology of metamorphic soles (189–161 Ma) and on biostratigraphic dating of shallow-marine carbonates onlapping the obducted ophiolites (see Mikes et al. 2009 for a review). The mélange and large ophiolite thrust sheets are transgressively overlain by Jurassic and Lower Cretaceous shallow-marine limestones (Bortolotti et al. 1971; Charvet and Termier 1971; Charvet 1978) and shallow-marine to alluvial siliciclastic deposits. Siliciclastic-dominated units known in some detail include the studied Bistra Formation (see description below; Fig. 2) and, in the Central Dinarides, the Pogari Formation (Jovanović 1961; Hrvatović 2006).

Geochemical and biostratigraphic data from Upper Cretaceous ophiolites with bimodal volcanic suites in the northern Dinarides are regarded to indicate that a remnant oceanic basin persisted until the Late Cretaceous, probably in a back-arc setting (Karamata et al. 2000; Pamić et al. 2000, 2002; Ustaszewski et al. 2009). These ophiolites are rooted in the Sava Zone (Fig. 1) where a suture zone formed by the final collision of the Internal Dinarides with the Tisza-Dacia unit in the Paleogene (Pamić 2002; Schmid et al. 2008; Ustaszewski et al. 2009, 2010).

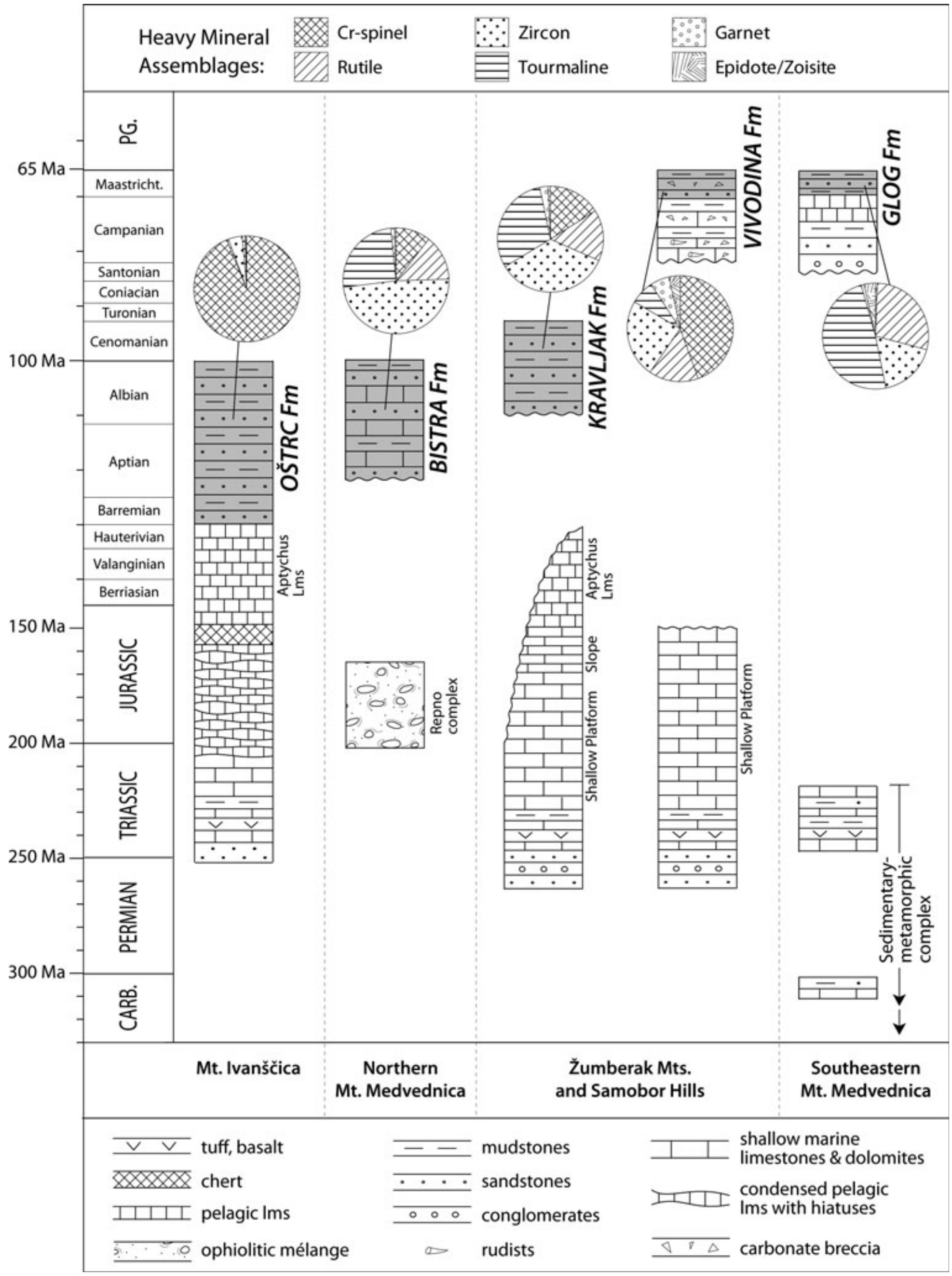
Occurring in tectonic contact with elements of the Western Vardar Ophiolite Unit are large thrust sheets of continental crust consisting of metamorphic and non-metamorphic Palaeozoic and Mesozoic formations, representing fragments of the Adria distal margin which have been incorporated into the nappe stack together with the ophiolites (Fig. 1). In the SE and Central Dinarides these include the Drina–Ivanjica, Jadar–Kopaonik and parts of the East Bosnian–Durmitor thrust sheets. In the NW Dinarides in Croatia this includes the sedimentary-metamorphic complex of Mt. Medvednica, and further to the NE, the continental unit of the Bükk Mts. in Hungary, which was displaced in the Cenozoic by a dextral strike-slip fault system of the Mid-Hungarian Line (Fig. 1). The studied Maastrichtian Glog Formation is part of a sedimentary succession which transgressively overlies the metamorphosed Adriatic basement complex of Mt. Medvednica (Fig. 2; Crnjaković 1979). The studied Lower Cretaceous Oštrc Formation overlies the non-metamorphic Upper Triassic to Lower Cretaceous shallow to deep marine sedimentary succession exposed in Mt. Ivanščica (Fig. 2; Zupanič et al. 1981), which likewise represents a fragment of the Adria distal margin (Babić et al. 2002). Today, Mt. Medvednica and Mt. Ivanščica both show a structural trend which is oblique to the main NW–SE trend of the Central Dinarides. Tomljenović et al. (2008) showed that this is due to their Late Paleogene 130° clockwise rotation and eastward tectonic escape, and hence their original orientation used to be parallel to the main orogenic strike of the Dinarides.

3 Stratigraphy, sedimentology and composition of the Cretaceous clastic formations

Mesozoic sediments of Mt. Ivanščica consist of passive margin marine deposits of Adria overthrust by Jurassic ophiolitic mélange of the Repno Complex described in the previous chapter (Fig. 2). The entire sedimentary succession consists of Permian clastics, Triassic clastics and carbonates overlain by Upper Triassic platform carbonates, Jurassic pelagic limestones and cherts, and Tithonian–Valanginian "Aptychus Limestones", which are in turn overlain by the clastic Barremian–Albian *Oštrc Formation* (Fig. 3; Babić and Zupanič 1973, 1978; Babić 1975; Babić and Gušić 1978; Babić et al. 2002). Facies and composition of the Oštrc Formation record a dramatic change in sedimentation style due to an abrupt influx of high amounts of siliciclastic material (Zupanič et al. 1981). It consists mostly of turbiditic arenites (occasionally rudites) alternating with shales, siltstones, marls and marly limestones. The arenites are mostly of mixed carbonate-siliciclastic composition, ranging from calcarenites with typically 70–90 % carbonate component to sandstones with >50 % siliciclastic component. Their heavy mineral associations contain a very high proportion of chrome spinel (>90 % among transparent heavy minerals), which indicates, together with abundant mafic and ultramafic lithic fragments, a dominantly ophiolitic provenance with minor continental contribution (Zupanič et al. 1981; Lužar-Oberiter et al. 2009).

Two Cretaceous clastic formations were investigated at Mt. Medvednica. The Aptian–Albian *Bistra Formation* consists of shallow-marine to coastal carbonates and clastic sediments which crop out in the northern part of Mt. Medvednica (Fig. 2; Gušić 1975; Crnjaković 1989). It developed on top of the exhumed Jurassic ophiolitic

Fig. 3 Chronostratigraphic and lithostratigraphic logs of the studied clastic formations and their basement (Babić et al. 2002; Lužar-Oberiter et al. 2009, and references therein). Note scale change at 150 Ma. *Pie charts* illustrate the average compositions of heavy mineral assemblages in the sandstones of each investigated formation (Crnjaković 1981, 1987, 1989; Zupanič 1981; Zupanič et al. 1981)



mélange complex (Fig. 3; Babić et al. 2002). The Bistra Formation consists of sandstones, calcarenites, shales, marls, conglomerates, oyster biostromes, as well as occasional coal lenses and seams. The heavy mineral associations of the sandstones consist of ultrastable minerals (zircon, tourmaline and rutile, ZTR), Cr-spinel, and only minor proportions of other minerals (e.g. garnet, apatite), which reflect a mixed continental-ophiolitic provenance (Crnjaković 1989).

The Maastrichtian *Glog Formation* consists of alternating turbiditic sandstones and marls exposed in the S part of Mt. Medvednica (Fig. 2). It represents the youngest part of a transgressive Upper Cretaceous alluvial to deep-water succession overlying rocks of the imbricated Palaeozoic–Triassic Adriatic basement wedge which underwent Cretaceous low-grade metamorphism (Fig. 3; Crnjaković 1981, 1987; Belak et al. 1995; Belak 2005; Judik et al. 2006). Crnjaković (1981) reported a strong dominance of ZTR within the heavy mineral associations of the sandstones, with only minor proportion of other heavy minerals (e.g. epidote, garnet). In spite of scant exposures, the age and facies heterogeneity of the Upper Cretaceous succession containing the Glog Formation allows it to be tentatively correlated with the sedimentary fill of the Gosau basins in the Northern Calcareous Alps (Wagreich and Faupl 1994).

The *Kravljak* and *Vivodina formations* both consist of deep-water turbiditic deposits situated in the Žumberak Mts. and Samobor Hills, located in the SW part of the study area (Fig. 2; Babić 1974; Zupanič 1981). Babić (1974) reported an Albian–Cenomanian age for the Kravljak Formation deposits, which overlie various Upper Triassic to Lower Cretaceous carbonates (Fig. 3). The Kravljak Formation is composed of marls intercalated with turbiditic arenite (rarely rudite) layers of mixed carbonate–siliciclastic composition. Heavy mineral associations in the sandstones are dominated by ZTR, but also contain significant Cr-spinel and minor amounts of garnet and apatite (Crnjaković 1987; Crnjaković et al. 2000). The Vivodina Formation is younger, dated as Maastrichtian by planktic foraminifera (Devidé-Nedéla et al. 1982). It probably represents a continuous deep-water sedimentation following a Campanian transgression that is marked by carbonate breccias and rudist limestones, although a direct transition is difficult to observe in the field (Moro et al. 2010). The succession consists of marls, sandstones, calcarenites and calcirudites. Two types of turbiditic beds can be clearly differentiated based on their composition, grain-size, and thickness. The first turbidite type comprises thick (often >1 m) carbonate beds consisting of coarse rudite carbonate lithoclasts at their bottom which grade upward into finer-grained, mostly skeletal detritus. Zupanič (1981) reported that the upper fine-grained parts of these thick beds may contain admixtures of siliciclastic material (up to 30 %). The second type of turbidites are much thinner (predominantly 10–20 cm) sandstone beds of mixed carbonate–siliciclastic composition. For the purpose of this study, samples were only taken from this latter type of beds. Heavy mineral associations in these sandstones contain ZTR, considerable amounts of Cr-spinel as well as minor garnet and epidote/zoisite, indicating derivation from both ophiolitic and continental sources (Zupanič 1981).

4 Methods

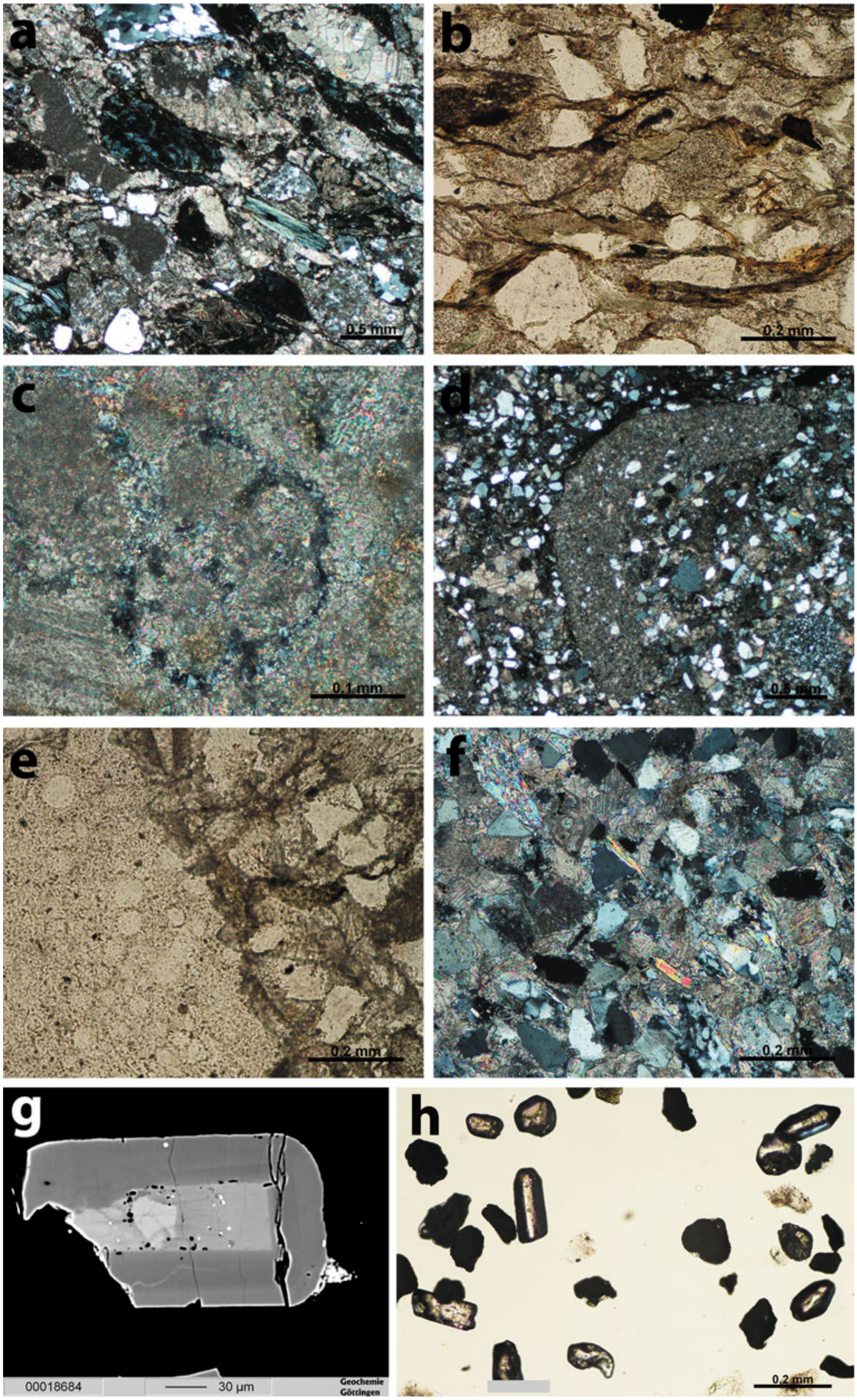
Sampling was performed in outcrops with reliable lithostratigraphic control only, from fine- to medium-grained sandstones. Weathered outcrops and samples were avoided. The geographic locations of all sampling points are given in the Online Resource 1.

For whole-rock geochemical analysis, fresh pieces of each sample devoid of calcite veins were crushed and pulverized in an agate ball-mill. Loss on ignition (LOI) was determined gravimetrically on 1 g of sample by heating overnight at 1,050 °C. For the XRF analysis powdered samples were fused with Merck Spectromelt A12 to borate glass discs. Major and trace element concentrations (for Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Zr, Nb, Ba, Pb, Y) were determined on a PANalytical AXIOS X-ray spectrometer at the University of Göttingen (Department of Geochemistry, Geoscience Center). Trace element concentrations have 1–2 % relative precision. All Fe is reported as Fe_2O_3.

For zircon fission track (ZFT) analysis and heavy mineral chemistry a sufficient number of heavy mineral grains needed to be extracted from the sandstone samples. Approximately 4–5 kg of sample was crushed with a jaw crusher, dry sieved and the <250 μm fraction was run on a Wilfley shaking table. The pre-concentrated samples were then treated with 5 % acetic acid to remove any carbonate, and the heavy fraction was separated from the undissolved residue using warm LST Fastfloat (Polytungstates Europe) heavy liquid. Zircon concentrates for preparing fission track mounts were obtained by electromagnetic separation. Heavy mineral grains remaining in the magnetic fraction were used for microprobe analyses.

For microprobe analysis tourmaline and garnet grains were mounted in epoxy, prepared by sprinkling the magnetic heavy mineral fraction or by handpicking of individual grains where low abundance was encountered. The mounts were ground and polished in consecutive steps to reduce relief at the grain–resin contacts, and then carbon coated. All microprobe analyses were performed using a JEOL electron microprobe (JXA-8900RL) equipped with five wavelength dispersive spectrometers at the University of Göttingen (Department of Geochemistry, Geoscience Center). One spot analysis was performed in the center of each grain for all garnets and a part of the tourmalines. Tourmaline grains which showed zoning on the back-scattered electron image were analyzed in more than one spot. Analytical conditions used for each mineral phase are given in the Online Resource 2.

For ZFT analysis randomly selected aliquots of zircon grains were embedded in PFA Teflon. To reveal spontaneous tracks the previously polished grains were etched with KOH–NaOH melt at 228 °C for 22–43 h. From each sample, two mounts were prepared and etched for different times. The external detector method was used. Irradiations were performed in nuclear reactors at Garching, Germany and Oregon State University, USA (neutron fluence 1.5×10^{15} n/cm^2). After irradiation the attached low-U mica detectors were etched with 40 % HF at 24 °C for 25 min to expose induced tracks. Track counting was performed using a Zeiss Axioskop microscope at 1,000× magnification equipped with a computer controlled FT Stage System of T. Dumitru. At least 60 zircon grains were measured from each sample, except for sample 05-H/M-60 in which only 50 countable grains were encountered. ZFT ages were determined by the zeta method (Hurford and


a
0.5 mm
b
0.2 mm
c
0.1 mm
d
0.5 mm
e
0.2 mm
f
0.2 mm
g
00018684
30 μm
Geochemie Göttingen
h
0.2 mm

◀ **Fig. 4** **a–f** Microphotographs of sandstones from the studied formations: **a** Calcareous litharenite dominated by ophiolitic rock fragments including serpentine fragments, chlorite flakes and altered mafic clasts with intersertal texture. A large metamorphic rock fragment can be seen in the upper part of the image; Oštrc Formation, sample 05-H/O-313/1. **b** Lithic wacke in which chlorite flakes have been "squeezed" between framework grains to form a pseudomatrix; Oštrc Formation, sample 05-H/O-309. **c** A silicified test of a foraminifera; Oštrc Formation, sample 05-H/O-318. **d** An orbitolinid foraminifera composed of agglutinated quartz grains within a litharenite; Bistra Formation, sample 05-H/B-207. **e** Radiolarite rock fragment with visible outlines of radiolarian; Bistra Formation, sample 05-H/B-207. **f** Litharenite dominated by metamorphic rock fragments; Glog Formation, sample 05-H/G-102. **g** Back-scattered electron image of a zoned tourmaline with a detrital core and multiple growth rims; Oštrc Formation, sample 05-H/O-318. **h** Heavy mineral separate dominated by zircons, many of which are at least slightly rounded; Glog Formation, sample 05-H/G-102

Green 1983), calculated using a personal ζ-factor of 124.7 ± 2.3. Visualization of the data was performed using Trackkey (Dunkl 2002).

5 Results

5.1 Petrography

With rare exceptions, all analyzed sandstones are classified as litharenites to sublitharenites with a predominantly carbonate matrix.

In the Oštrc Formation most sandstones are calcareous litharenites (Fig. 4a), but lithic wackes with a dominantly chlorite pseudomatrix also occur (e.g. sample 05-H/O-309, Fig. 4b). Intense replacement by carbonate strongly obscures the primary texture, which may hamper identification of framework grains. Carbonate grains include carbonate lithoclasts and skeletal fragments of echinoderms and planktic foraminifera, which are often silicified (Fig. 4c). Among the major framework components ophiolitic lithoclasts are the most abundant (Fig. 4a). These are common fragments consisting of serpentine and chlorite, mafic volcanic clasts with subophitic to intersertal texture, as well as fragments of devitrified glass. Sedimentary lithic fragments of shale, siltstone and sandstones are frequent. Metamorphic grains include quartzite, foliated quartz–sericite, quartz–chlorite, slate and phyllite fragments. Quartz occurs both as monocrystalline and polycrystalline grains. Chert is common and in some cases contains visible radiolaria. Feldspars occur sporadically, mostly as twinned plagioclase, but K-feldspars are also present. Cr-spinel and opaque grains can be readily identified in thin sections.

In the sandstones from the Bistra Formation quartz is slightly more abundant than lithic fragments (Fig. 4d). It is usually subangular to angular, and occurs as monocrystalline or polycrystalline grains. Lithic fragments include various sedimentary, metamorphic and igneous lithologies. Sedimentary lithoclasts are mostly shale fragments, while siltstone and sandstone fragments occur more rarely. Chert clasts are very common and often contain visible radiolaria (Fig. 4e). Metamorphic clasts include quartzite, quartz–sericite, quartz–chlorite and phyllite fragments. Mafic clasts with ophitic texture occur relatively rarely. Marl intraclasts occur in some samples. Observed carbonate grains are mostly skeletal fragments of *Orbitolina* (Fig. 4d), which can be very abundant, and echinoderms.

All examined sandstones from the Kravljak Formation are fine-grained. Carbonate replacement of siliciclastic particles and recrystallization of carbonate particles is intensive. Quartz usually predominates over lithic fragments, is subangular to angular, and most commonly monocrystalline. Metamorphic grains are common, and include quartzite, quartz–sericite, quartz–chlorite and phyllite fragments. Sedimentary lithoclasts are mostly shale fragments. For some grains, constituted of oriented or unoriented minute transparent flakes with or without small quartz grains in between, it is difficult to differentiate whether they are of volcanic origin or represent shale fragments. Chert is commonly encountered. Feldspars were rarely observed, and are largely altered. Mafic clasts with ophitic texture and serpentine clasts are rare.

In the Vivodina Formation sandstones, lithic fragments slightly predominate over quartz. Grains of ophiolitic origin are abundant. These are most commonly mafic clasts with ophitic texture or chlorite grains. Quartz occurs mostly as angular to subangular monocrystalline grains. Polycrystalline grains are less common. As in the Kravljak Formation, grains of uncertain volcanic and/or shale origin are common. Metamorphic lithic fragments include foliated quartzite and quartz–mica aggregates, as well as fine grained phyllitic fragments. Individual muscovite flakes and feldspar grains occur sporadically.

Sandstones of the Glog Formation contain similar amounts of quartz and lithic fragments, while feldspars are less common. Quartz grains are angular to subangular, mostly with undulatory extinction. Metamorphic grains strongly dominate among the lithic fragments (Fig. 4f). These include a variety of weakly to strongly foliated quartzite, quartz–muscovite and quartz–chlorite aggregates. Muscovite flakes are very common. Biotite flakes occur rarely. Among feldspars, both plagioclase and K-feldspars are present. They are in most cases weakly to heavily altered with numerous minute sericite flakes. Carbonate components include fragments of planktic foraminifera and echinoids, indistinguishable recrystallized grains and carbonate cement.

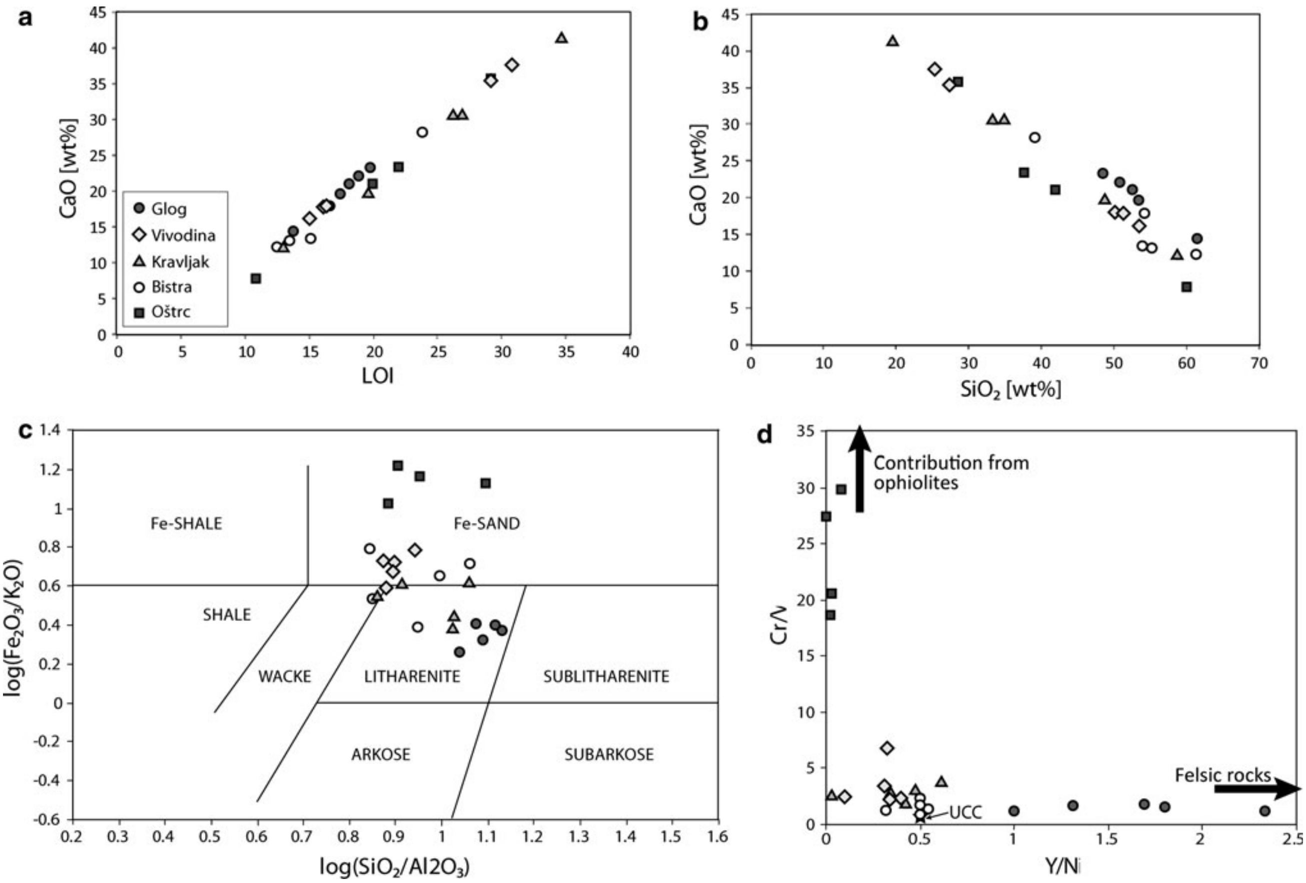


Fig. 5 Major and trace element geochemistry of the Cretaceous sandstones. **a** CaO–LOI and **b** CaO–SiO_2 plots display strong correlations, suggesting that CaO is almost entirely associated with the carbonate content. **c** Classification of the analyzed sandstone samples from each formation based on the scheme of Herron (1988). **d** Cr/V versus Y/Ni plot (McLennan et al. 1993). Increased Cr/Ni values (and low Y/Ni), which are particularly pronounced in the samples from the Oštrc Formation, indicate a larger contribution of material from ophiolitic sources. UCC, average upper continental crust (McLennan 2001)

5.2 Whole-rock geochemistry

Major and trace element concentrations for 24 analyzed sandstone samples are given in Online Resource 3, and some results are summarized in Fig. 5. In the analyzed Cretaceous sandstones CaO concentrations range from 7.9 to 41.4 wt%. Positive correlation exists between CaO and loss on ignition (LOI), as well as a strong negative correlation between CaO and SiO_2 (Fig. 5a–b), indicating that CaO is almost entirely associated with detrital and secondary carbonate phases.

In Fig. 5c, compositions are plotted on the diagram of Herron (1988) which uses logarithmic ratios of SiO_2/Al_2O_3 versus Fe_2O_3/K_2O to distinguish between different types of sediment lithologies. SiO_2/Al_2O_3 reflects the ratio of quartz to clay minerals, which is affected partly by the grain size and maturity of the sediment. Fe_2O_3/K_2O reflects the amount of lithic fragments relative to feldspar. Most of our samples plot in the litharenite and Fe-sand fields. This classification agrees with the observed petrographic composition of these sandstone samples, all of which are characterized by an abundance of lithic rock fragments and quartz relative to feldspars. Some differences are evident though, most notably between the Oštrc and Glog formations. Samples from the Oštrc Formation have the highest Fe_2O_3/K_2O ratios and all plot within the field of Fe-sand. The Glog Formation samples on the other hand all have lower Fe_2O_3/K_2O, and all plot as litharenites. Samples from the Bistra, Kravljak and Vivodina formations plot close to the Fe-sand/litharenite boundary, though the Vivodina Formation samples tend to have higher Fe_2O_3/K_2O values than those of the Kravljak Formation. These differences in Fe_2O_3/K_2O ratios between different formations reflect the variable amount of contribution from mafic and ultramafic minerals, which agrees with the observed abundance of ophiolitic lithoclasts in the Oštrc Formation, their presence in the Bistra, Kravljak and Vivodina formations, and lack thereof in the Glog Formation.

The Cr/V versus Y/Ni diagram in Fig. 5d (McLennan et al. 1993) illustrates the degree of contribution from ophiolite sources. The ratio Cr/V is a measure of Cr enrichment relative to the general concentration of "ferromagnesian" trace elements, i.e. those preferentially occurring in mafic/ultramafic lithologies. Cr is concentrated in Cr-spinel, while Y is a proxy for mid to heavy rare-earth elements (REE), preferentially fractionated into garnet and other accessory minerals such as zircon and xenotime. Ultramafic and mafic source rocks are characterized by high Cr/V and low Y/Ni ratios, while felsic rocks have the opposite, low Cr/V and high Y/Ni. Oštrc Formation samples have Cr/V values in the range of 20-30, well above the other samples, as well as very low Y/Ni. Samples from the Bistra, Kravljak and Vivodina formations have Cr/V and Y/Ni values much closer to those of average upper continental crust (Cr/V = 0.8 and Y/Ni = 0.5; McLennan 2001) suggestive of some contribution from ophiolites, however, much more limited than is the case for the Oštrc Formation. On the other hand, the conspicuously high Y/Ni values (and low Cr/V) in the Glog Formation samples, well above those of the average upper continental crust, are shifted towards average values of felsic rocks (Y/N ~6; Condie 1993), suggesting a purely continental source, well in line with the observed petrographic composition.

5.3 Tourmaline chemistry

Microprobe analyses of the detrital tourmalines are given in Online Resource 4 and summarized in Fig. 6. The concentrations of Al, Fe and Mg in tourmalines have been plotted on ternary diagrams (Fig. 6a) and compared to the fields defined by Henry and Guidotti (1985). Generally, in all of the studied samples most grains carry chemical signatures characteristic of metapelitic source rocks (Fig. 6b, fields 4 and 5 = 70–79 %). The primarily metamorphic origin, as opposed to granitoid sources, is supported by their dominantly high Ti and low Zn contents (Fig. 6c; Viator 2003). Back-scattered electron imaging reveals prominent discontinuous zoning in many of the tourmaline grains, often suggesting several phases of growth. Crystals with cores (in some cases rounded) and metamorphic overgrowths (Fig. 4g) are present in each of the studied formations, likely indicating a previous phase of recycling and derivation from metasedimentary rocks. Only minor differences in the proportion of tourmaline types can be observed between Lower and Upper Cretaceous sandstones. Tourmalines which originated from granitoid sources are slightly more common in the Early Cretaceous and Cenomanian (9–15 %) than in uppermost Cretaceous sandstones (3–4 %). Most of the tourmaline analyses from the Lower Cretaceous (Oštrc and Bistra formations) fall within the field of metapelites coexisting with an Al-saturating phase, while those from the Cenomanian and uppermost Cretaceous (Kravljak, Vivodina and Glog formations) are more commonly from metapelites not coexisting with an Al-saturating phase. Furthermore, measurements falling into the field of Fe^{3+}-rich Qtz–Tur rocks/skarns/metapelites are somewhat more common in the uppermost Cretaceous.

5.4 Garnet chemistry

Microprobe analyses of the detrital garnets are given in Online Resource 5. Garnet major element compositions are plotted on (Fe + Mn)–Mg–Ca diagrams in Fig. 7, with outlines of fields as proposed by Morton et al. (2004). Most of the analyzed garnets from the Cretaceous sandstones are characterized as low-Mg and variable-Ca (Type B) grains, indicating that their dominant source were probably greenschist to amphibolite facies metasediments. However, distinctly low-Mg and low-Ca garnets, which have high Mn concentrations, are conspicuous in samples of the Bistra and Glog formations (also present in the Vivodina Formation) and may point to intermediate-acidic igneous sources (Mange and Morton 2007). High-grade granulite facies metasediments may have supplied a lesser amount of the garnets with high Mg and low Ca content (Type A). The subordinate amounts of high-Mg and high-Ca garnets (Type C) point to exposures of medium to high-grade metabasic rocks in the source area, however, these played only a local role in the supply of garnets to the Cretaceous basins, as indicated by a well-separated population in one of the Glog Formation samples (Fig. 7; Online Resource 5).

5.5 Zircon fission track analysis

Single grain detrital zircon fission track ages were obtained from a total of seven sandstone samples (Table 1; Fig. 8). The age populations within the bulk single grain age distributions were identified by the Popshare software (Dunkl and Székely 2002) using a Simplex algorithm and assuming Gaussian distribution for the populations (Fig. 9). The scatter assigned to the mean values refers to 1 σ of the populations. In two samples from the Oštrc Formation most of the ZFT ages range from the Carboniferous to the Cretaceous. The youngest ZFT age populations in the two Oštrc Formation samples have been identified at 134 ± 14 Ma (sample 05-H/O-311) and 145 ± 36 Ma (sample 05-H/O-309). The older single-grain ZFT ages make up more diffuse populations with means at 193 ± 65 and 219 ± 64 Ma, respectively. In the Bistra Formation sandstones the ZFT ages are equally distributed among three populations with means at 122 ± 45, 172 ± 17 and 281 ± 53. In the Kravljak Formation, the youngest population has been identified at 159 ± 30 Ma, while an older more diffuse population lies at 275 ± 51 Ma.

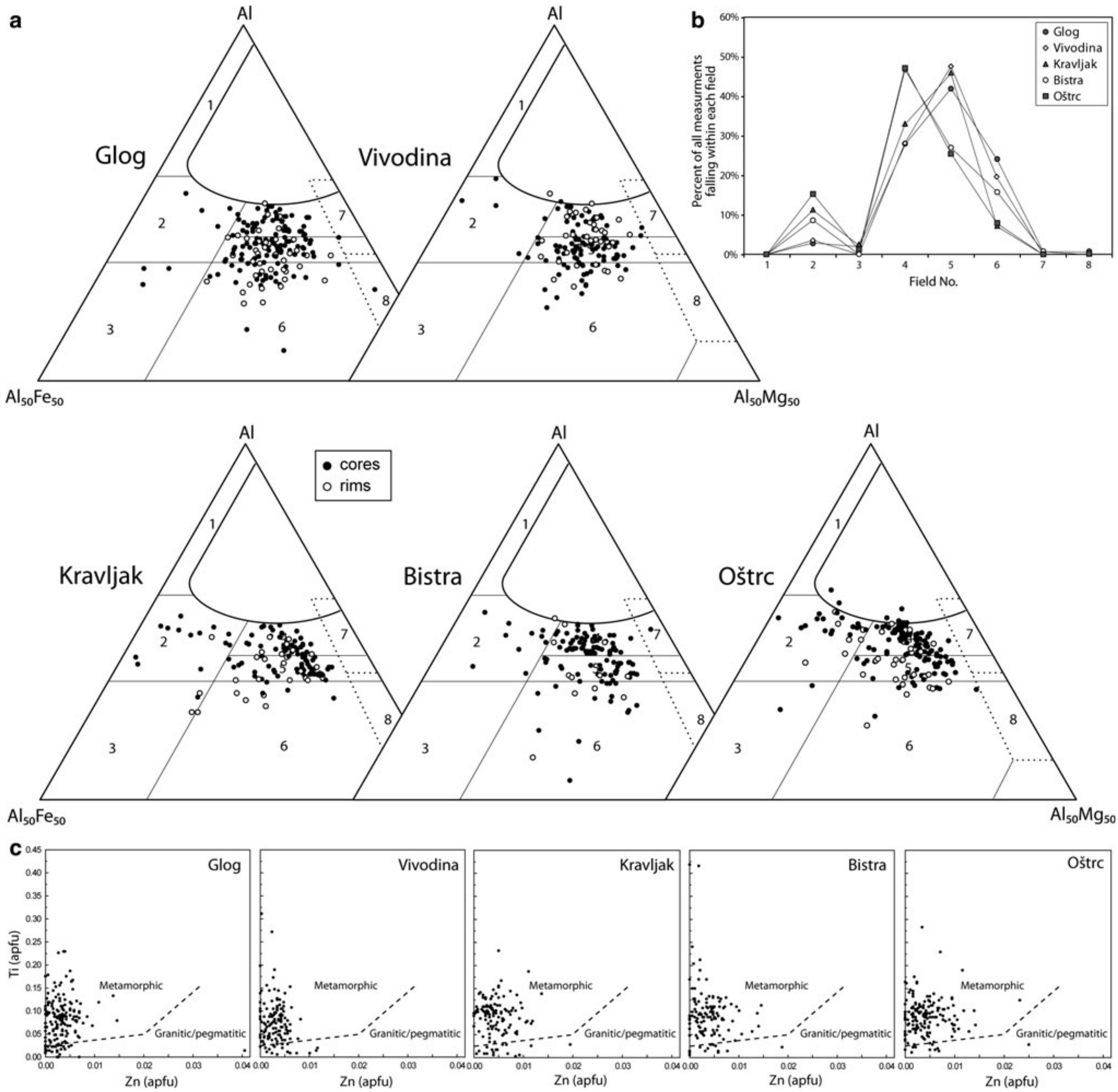


Fig. 6 Detrital tourmaline compositions from Cretaceous sandstones. **a** Chemistry of detrital tourmalines from each of the studied formations plotted onto Al–Fe–Mg diagrams. Discrimination fields are after Henry and Guidotti (1985): (*1*) Li-rich granitoids, (*2*) Li-poor granitoids, (*3*) Fe^{3+}-rich Qtz-Tur rocks (hydrothermally altered granites), (*4*) Metapelites coexisting with an Al-saturating phase, (*5*) Metapelites not coexisting with an Al-saturating phase, (*6*) Fe^{3+}-rich Qtz–Tur rocks/skarns/metapelites, (*7*) Low-Ca metaultramafics and Cr and V-rich metasediments, (*8*) Metacarbonates and metapyroxenites. **b** Plot showing the proportions of tourmaline measurements falling into the fields of the Al–Fe–Mg diagrams. **c** Plots of Ti versus Zn in tourmalines which show a dominance of tourmalines with metamorphic affinity. Discrimination criteria is after Viator (2003)

A clear-cut difference in ZFT age distributions exists between the Maastrichtian and all older samples (Table 1; Fig. 9). In the Maastrichtian, a young, Late Cretaceous ZFT age population clearly dominates the age distributions. In the sample from the Vivodina Formation the youngest ZFT age population is clearly identified at 76 ± 13 Ma, and incorporates most of the measured crystals. All remaining single-grain ages spread very diffusely throughout the Late Palaeozoic and Mesozoic (149 ± 58 Ma), which very probably indicates that one or more additional sources were involved by the catchment system. In the Glog Formation the predominance of younger ages is the most distinct; in both analyzed sandstone samples all zircon grains belong to a single age

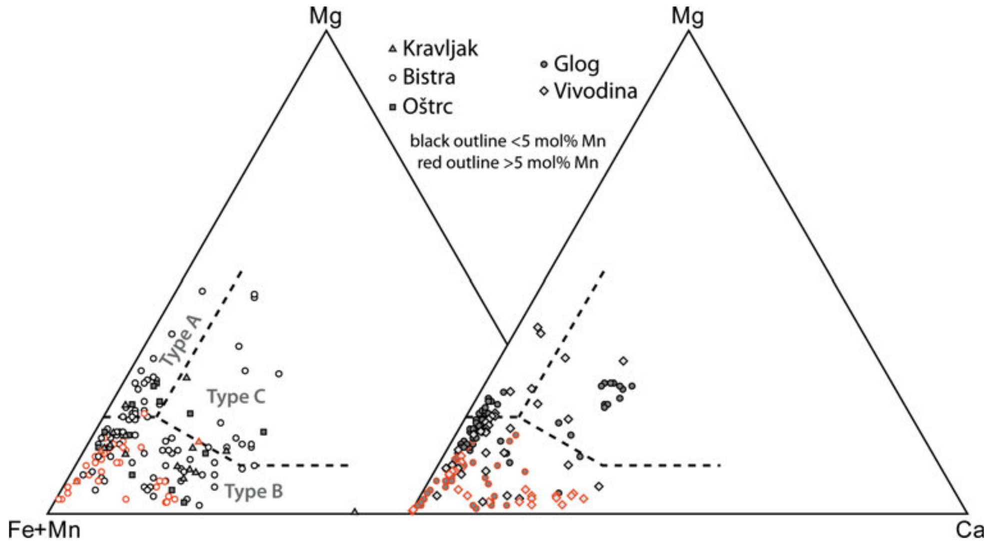


Fig. 7 Detrital garnet compositions from Cretaceous sandstones. Classification fields are outlined after Morton et al. (2004): Field A represents high Mg, low Ca garnets which typically derive from granulite facies metasediments; Field B represents variable Ca, low Mg garnets characteristic of greenschist to amphibolite facies metasediments, but may also derive from intermediate-acidic igneous rocks; Field C represents high Ca, high Mg garnets which typically derive from medium to high-grade metabasic rocks

population at 80 ± 18 Ma (sample 05-H/G-109) and 73 ± 23 Ma (sample 05-H/G-105/1).

6 Provenance and implications for Cretaceous evolution of the Adriatic margin

6.1 Early Cretaceous to Cenomanian

The Cretaceous clastic formations of the NW Dinarides record the evolution of an area which was—throughout most of the Mesozoic—situated at the northern periphery of the Adria plate, close to the western termination of the Neotethys (Fig. 10). Based on the current stratigraphic framework for the studied formations and the new sandstone provenance data presented herein, we propose a paleotectonic reconstruction of the NW Dinaride area for the Late Mesozoic (Fig. 11). Intraoceanic subduction within the Neotethys started in the late Early Jurassic, as evidenced by published geochronological ages from metamorphic soles of Dinaride ophiolites (see Mikes et al. 2009 for a compilation). This was eventually followed by one of the principal large scale events in the evolution of the Dinarides, the Late Jurassic-Early Cretaceous obduction of ophiolites onto the margin of Adria (e.g. Aubouin et al. 1970; Bortolotti et al. 1971; Charvet 1978; Zupanič et al. 1981; Babić et al. 2002). This orogen-wide event was accompanied by nappe stacking and the development of pro-wedge flexural basins, both in the NW Dinarides (Oštrc Formation; Zupanič et al. 1981; Babić et al. 2002) and the Central Dinarides (Vranduk Formation; Mikes et al. 2008, and references therein), as well as further to the north in the Austroalpine domain (Gerecse Hills and Rossfeld Formation; Tari 1995; Árgyelán 1996; Faupl and Tollmann 1979; Faupl and Wagreich 2000). Tomljenović et al. (2008) showed that in the NW Dinarides compressional deformation during the Early Cretaceous was accommodated by northward, orogen-parallel propagation of nappes which resulted in a weak regional metamorphic overprint, as well as orogen-perpendicular shortening in the Albian. Early Cretaceous cooling ages have been reported from the low-grade metamorphic rocks of Medvednica Mt. (Belak et al. 1995; Judik et al. 2006), the Bükk Mts. in NE Hungary (Árkai et al. 1995) and the Drina-Ivanjica Unit (Milovanović 1984). Compressional tectonics in the Late Jurassic and Early Cretaceous were also recorded in various other parts of the Adria plate, such as e.g. the Apulian and Adriatic carbonate platforms, as well as the Austroalpine domain and the Transdanubian Central Range (Mindszenty et al. 1995; Matičec et al. 1996; Frisch and Gawlick 2003; Csontos et al. 2005; Vlahović et al. 2005).

This early tectonic phase had a profound impact on sedimentation by introducing siliciclastic detritus onto the Adria plate margin, which from the Late Triassic to the end of the Jurassic experienced shallow carbonate platform to deep marine pelagic deposition in a passive margin setting (Fig. 3). Although large ophiolite bodies, such as those of the West Vardar Ophiolitic Unit in the Central Dinarides, are today not exposed to such an extent in the East Alpine–Carpathian and NW Dinaride areas, the dominant mafic–ultramafic signature among framework components, in heavy mineral assemblages, and in the geochemical composition of Oštrc Formation sandstones (Figs. 4a, 5d) testifies that during the earliest Cretaceous the nappes of the NW Dinarides included significant parts composed of obducted oceanic lithosphere. Similarities in chemical composition of detrital Cr-spinels suggest that these ophiolite massifs, which were dominantly of harzburgitic composition, represented an important source of detritus on a larger regional scale (Pober and Faupl 1988;

Table 1 Results of single grain fission track analyses of detrital zircons from Cretaceous sandstones of the NW Dinarides

Formation	Sample	No. crystals	RhoS	[Ns]	RhoI	[Ni]	RhoD	[Nd]	Chi-sq. P (%)	Dispersion	Central Age ± SD	Population I			Population II			Population III		
												Mean	SD	Pop. weight	Mean	SD	Pop. weight	Mean	SD	Pop. weight
Glog	05-H/G-109	60	69.50	[4,311]	46.29	[2,871]	8.50	[6,236]	2	0.13	79.4 ± 2.9	**80**	18	100						
Glog	05-H/G-105/1	61	71.69	[3,115]	37.79	[1,642]	5.96	[3,996]	7	0.13	70.5 ± 3	**73**	23	100						
Vivodina	05-H/M-6	60	72.35	[3,442]	41.72	[1,985]	8.50	[6,236]	0	0.30	89.9 ± 4.8	**76**	13	71	**149**	58	29			
Kravljak	05-H/M-60	50	114.76	[3,531]	22.62	[696]	6.02	[3,996]	30	0.12	187.6 ± 9.6	**159**	30	64	**275**	51	36			
Bistra	05-H/B-201	60	108.59	[5,177]	23.22	[1,107]	6.14	[3,996]	0	0.37	173.8 ± 11.2	**122**	45	32	**172**	17	33	**281**	53	35
Oštrc	05-H/O-311	60	103.25	[3,938]	23.41	[893]	5.89	[3996]	2	0.21	160.7 ± 8.5	**134**	14	31	**193**	65	69			
Oštrc	05-H/O-309	64	127.79	[5,527]	27.72	[1,199]	6.09	[3,996]	0	0.26	170.5 ± 8.9	**145**	36	50	**219**	64	50			

SD standard deviation

Track densities (Rho) are as measured ($\times 10^5$ tracks/cm^2); number of tracks counted (N) shown in brackets. Chi-sq. P (%), probability obtaining Chi-square value for n degree of freedom (where n = no. crystals-1); Disp., Dispersion, according to Galbraith and Laslett (1993). Central ages calculated using dosimeter glass: CN2 with $\zeta_{CN2} = 124.7 \pm 2.2$ for zircon. Modeled detrital zircon fission track age populations were identified within the bulk single grain age distributions by the PopShare computer software (Dunkl and Székely 2002) using a Simplex algorithm and assuming Gaussian distribution for the populations

Árgyelán 1996; von Eynatten and Gaupp 1999; Jablonský et al. 2001; Lužar-Oberiter et al. 2009).

Along with the obducted ophiolites, the exhumed source units supplying siliciclastic material to the Early Cretaceous basins of the NW Dinarides also incorporated variable but significant amounts of continental lithologies (Zupanič et al. 1981; Crnjaković et al. 2000). The sandstones of the Barremian-Albian Oštrc Formation regularly contain zircon, as well as sedimentary and metamorphic lithoclasts in addition to the predominant ophiolitic material (Figs. 3, 4a; Zupanič et al. 1981). The youngest detrital ZFT age populations of 145–134 Ma in the Lower Cretaceous Oštrc Formation reveal a rather short lag time and thus reflect relatively fast exhumation of basement units, which cooled not before the earliest Cretaceous. These units are interpreted to have been thermally overprinted Palaeozoic–Mesozoic sequences of the distal Adria plate (Fig. 11a) that were incorporated into the thrust complex together with the obducted ophiolitic units (Fig. 11b). Various lithoclasts of Triassic, Jurassic and Lower Cretaceous carbonate rocks within the Barremian to Cenomanian calcarenites and calcirudites of the NW Dinarides (Oštrc and Kravljak formations) prove that the Mesozoic cover of the imbricated Adriatic basement was actively eroded during pro-wedge deposition (Babić 1974; Zupanič et al. 1981). This compares well to evidence from other parts of the Eastern Alps–Dinarides (Csontos et al. 2005; see also Charvet 1978, 1980; Császár and Árgyelán 1994; Gardin et al. 1996; Mikes et al. 2008; Schlagintweit et al. 2008; Marroni et al. 2009). The contribution of detritus from continental lithologies increased over time (Fig. 5d). Importantly, the 122 ± 45 Ma detrital ZFT population identified in the Aptian–Albian Bistra Formation (Table 1; Fig. 9) strongly suggests that cooling and exhumation of Adriatic basement units was not confined to a relatively short time interval in the earliest Cretaceous at all places, but locally continued at least to the Aptian.

At the beginning of the Late Cretaceous there is a decline in the supply of Early Cretaceous ZFT ages (Fig. 9; Kravljak Formation) even though the Adriatic basement remained the major source of continental detritus. This possibly resulted from a waning exhumation of particular segments of the Adriatic basement, which had undergone Late Jurassic to Early Cretaceous thermal overprint. Furthermore, this pattern might also suggest that the relatively widely documented Early Cretaceous cooling ages (ZFT as well as K/Ar) relate to only a spatially restricted, thin zone of the Adriatic basement that was rapidly removed by hanging wall erosion in the Early to early Late Cretaceous after its incorporation into the thrust wedge. The Jurassic ZFT ages which predominate in the Kravljak Formation (Fig. 9), and are also present in the Bistra and Oštrc formations, may reflect cooling after the Jurassic thermal

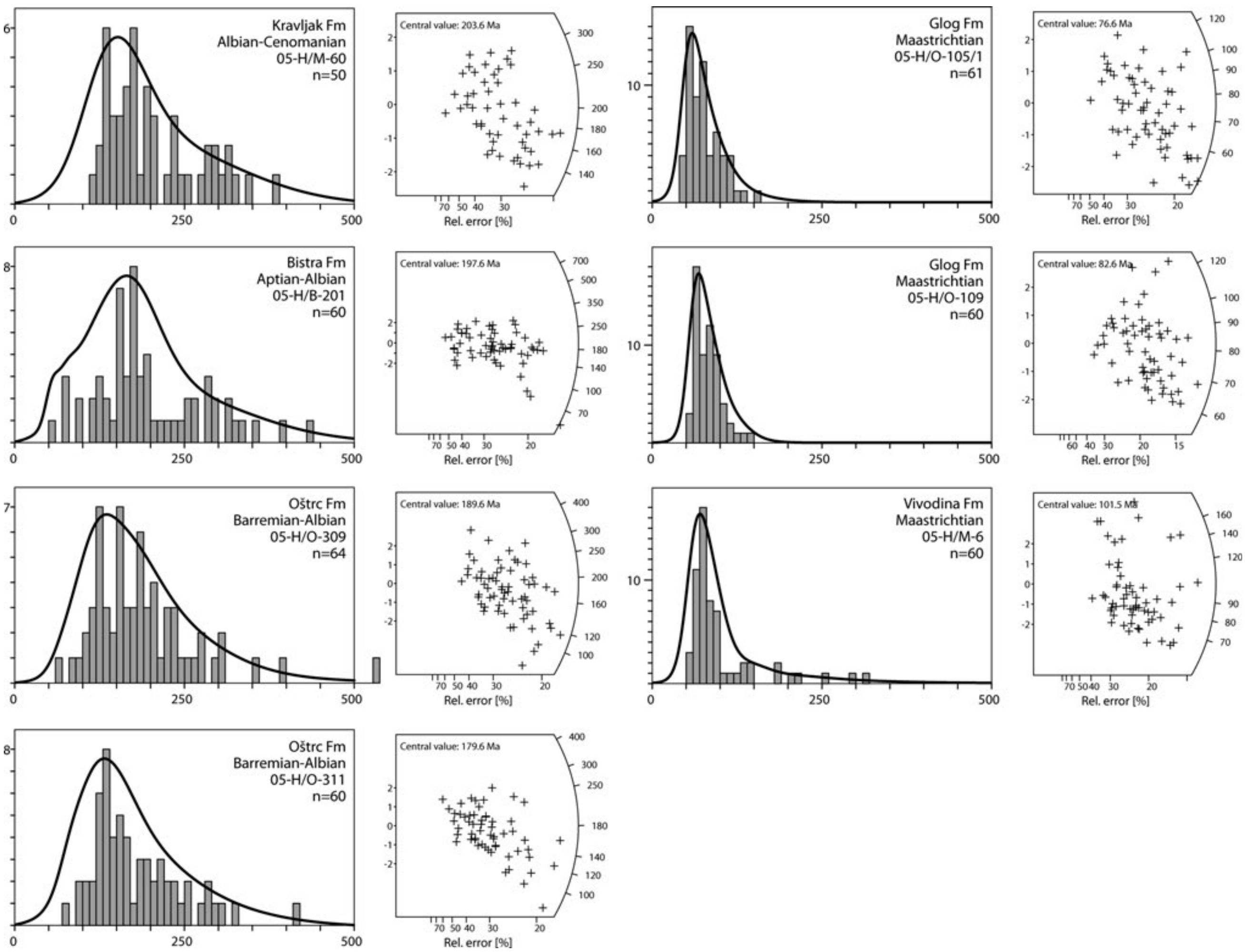


Fig. 8 Single grain fission track age distributions of detrital zircons from the Cretaceous sandstones. The *black lines* within the histograms represent age spectra (probability density plots) computed according to Hurford et al. (1984). *Radial plots* are according to Galbraith (1990)

overprint in the distal Adria plate margin. Such ages are well documented from the Pelagonian Unit, the Eastern Alps, and the Szarvaskő–Mónosbél Nappe of the Bükk Mts. (Árkai et al. 1995; Most et al. 2001; Frank and Schlager 2006).

The older and more diffuse ZFT age populations in Lower Cretaceous to Cenomanian sandstones consist of Triassic to Late Carboniferous single grain ages, which indicate that a significant part of the exhumed Adriatic continental units were not affected by Neotethyan tectonothermal events. We suggest that these age components derive from parts of the Adriatic basement which had not experienced obduction-related thermal overprint.

Preliminary U–Pb dating of detrital zircon from the Bistra Formation (own unpublished data) has shown that many of the zircon grains which carry Jurassic FT ages have in fact Permo-Triassic crystallization ages. Permo-Triassic crystallization and cooling ages both primarily reflect the low-P high-T regional metamorphic event in the Adria plate due to rifting of the Neotethys, associated igneous activity, and subsequent cooling of the continental crust (Schuster and Stuwe 2008). Evidence of such Permo-Triassic magmatism and metamorphism is well known in the region, from both the NW and Central Dinarides (Bébien et al. 1978; Pamić 1983; Jurković and Palinkaš 2002; Pamić et al. 2004; Goričan et al. 2005), as well as the SE part of the Eastern Alps (Thöni 1999). It cannot be ruled out that the 9–15 % of granitic tourmalines (Fig. 6) detected in the Lower Cretaceous and Cenomanian sandstones, as well as the occurrence of garnets with intermediate to acidic igneous affinities (Fig. 7), in fact reflect the erosion of magmatic Permo-Triassic sources, although a derivation from pre-Variscan to Variscan basement or reworking from Permo-Triassic sediments is also possible.

It can be summarized that during the Early Cretaceous, clastic sedimentation in the NW Dinarides occurred within a flexural basin (Oštrc Formation) in front of an

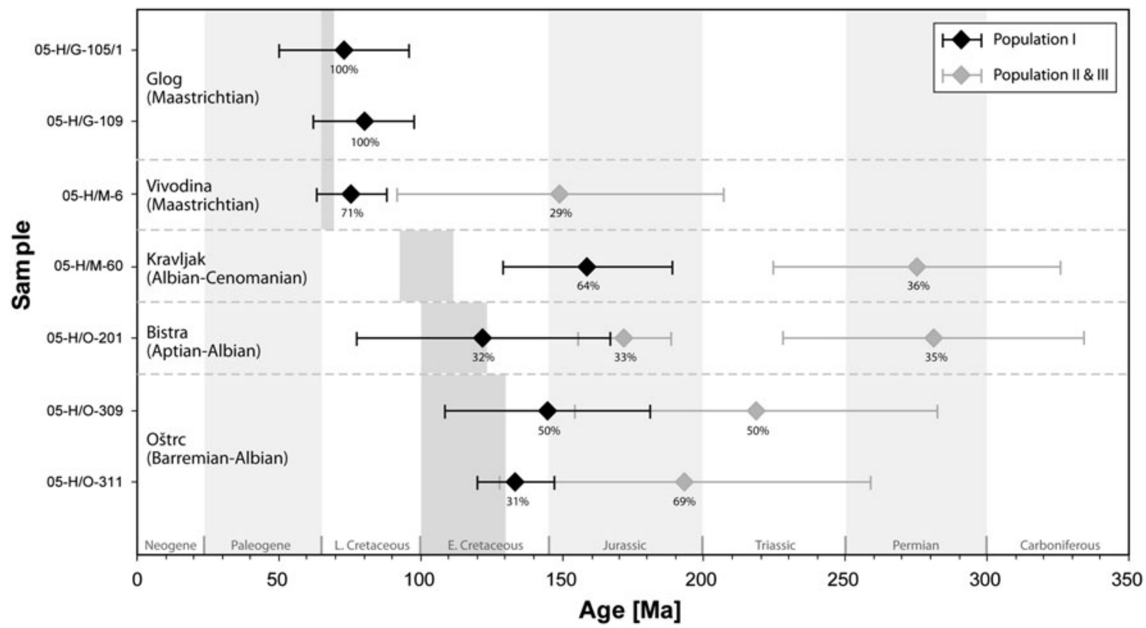


Fig. 9 Modeled detrital zircon fission track age populations identified within the bulk single grain age distributions by the PopShare computer software (Dunkl and Székely 2002) using a Simplex algorithm and assuming Gaussian distribution for the populations. *Diamonds* correspond to population means while the extents of the *whiskers* represent the first standard deviations. *Dark gray bars* indicate the depositional ages of the studied clastic formations

ophiolite-continental thrust complex as well as in shallow marine environments (Bistra Formation) which formed on top of this rapidly exhuming wedge (Fig. 11b; Babić et al. 2002; Lužar-Oberiter et al. 2009). A similar situation is recorded in the Central Dinarides, where sandstones of the Pogari and Vranduk formations display detrital ZFT age populations largely similar to those in the Oštrc and Bistra formations (Neubauer et al. 2003; Mikes et al. 2008). Nappe propagation caused siliciclastic sedimentation to migrate towards more external parts of the Adria plate (Kravljak Formation), reaching the margin of the Adriatic Carbonate Platform in the Albian-Cenomanian (Fig. 11b; Babić 1974; Lužar-Oberiter, 2009). It is possible that parts of the Early Cretaceous clastic basins (Oštrc and Bistra formations) were incorporated into the propagating nappes, although in light of the heavy mineral and ZFT data, Late Cretaceous recycling of Lower Cretaceous clastics was not significant.

A coeval erosion of continental (metamorphic and mature sedimentary) source rocks along with a predominantly ophiolitic input has also been documented in the Lower Cretaceous successions of the Austroalpine domain (Eastern Alps and Gerecse Hills—Faupl and Tollmann 1979; Pober and Faupl 1988; Császár and Árgyelán 1994; von Eynatten and Gaupp 1999). Available detrital thermochronological data indicate short lag times and hence relatively rapid exhumation in these areas as well (von Eynatten et al. 1997).

6.2 Maastrichtian

In the latest Cretaceous, the area of the NW Dinarides probably consisted of more or less coeval basins, evolved in at least two different settings (Fig. 11c). In the Maastrichtian these basins received either mixed ophiolitic-continental (Vivodina Formation) or purely continental (Glog Formation) siliciclastic detritus, and are proposed here to have formed in a pro-wedge and wedge-top setting, respectively. The overwhelming dominance of Campanian ZFT ages (80–73 Ma) in the sandstones of both the Vivodina and Glog formations clearly distinguishes them from all of the older formations studied. Older ZFT ages are either entirely insignificant (Glog Formation), or constitute only a minor proportion of the zircon grains interpreted to have been derived from a minor source component of the imbricated Adriatic basement (Vivodina Formation). The abundance of metamorphic lithoclasts, particularly in the Glog Formation (Fig. 4f), the fact that most of the analyzed zircons are rounded (Fig. 4h), as well as the dominantly metamorphic chemical signatures of tourmalines and garnets (Figs. 6, 7), altogether suggest that in the Maastrichtian the sediments were derived primarily from metamorphic sources which had undergone rapid exhumation with almost synsedimentary cooling. The lack of euhedral zircon grains indicates that the products of Late Cretaceous igneous activity known from the Sava Zone (Pamić et al. 2000; Ustaszewski et al. 2009; Starijaš et al. 2010)

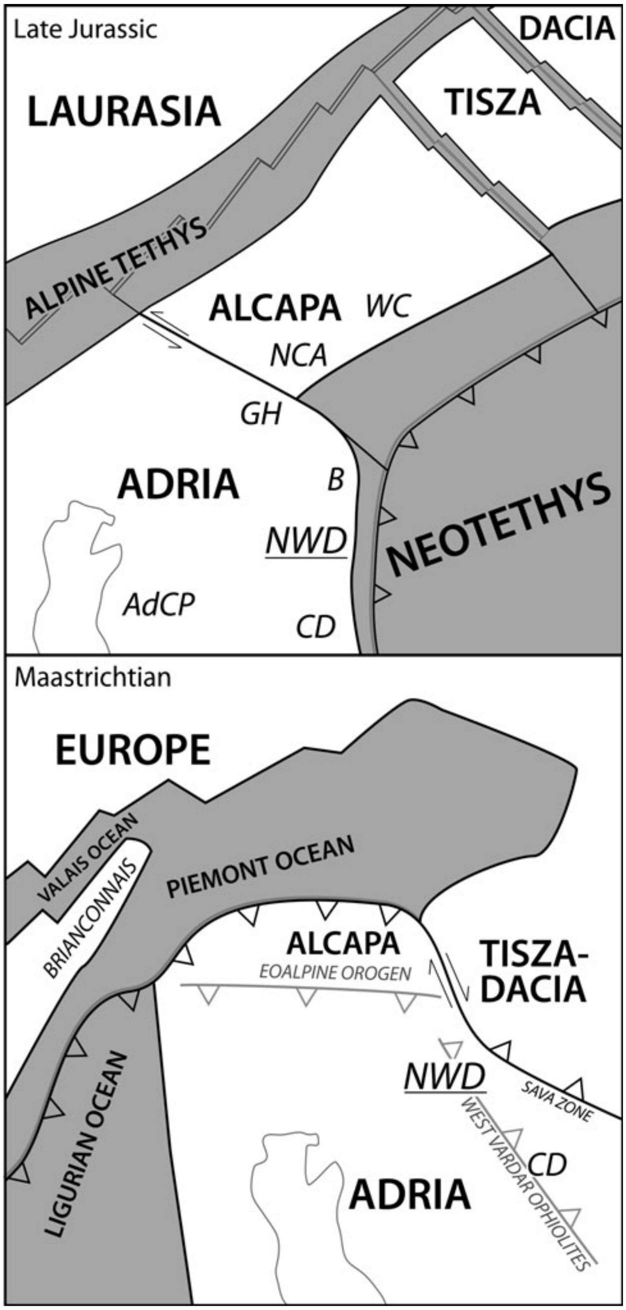


Fig. 10 Paleotectonic models of the Adria plate margin and neighbouring units during the Late Jurassic and Maastrichtian, with approximate position of the northwestern Dinarides (NWD). *White areas* continental lithosphere, *grey areas* oceanic lithosphere. *AdCP* Adriatic Carbonate Platform, *B* Bükk, *CD* Central Dinarides, *GH* Gerecse Hills, *NCA* Northern Calcareous Alps, *WC* Western Carpathians (compiled after Csontos and Vörös 2004; Haas and Péró 2004; Handy et al. 2009; Missoni and Gawlick 2011; Schmid et al. 2008)

were not available for erosion. Meanwhile, the renewed increase in the proportion of Cr-spinel and that in whole-rock Cr/V values in the Maastrichtian Vivodina Formation (Figs. 3, 5d) are most consistent with the erosion of a West Vardar ophiolitic thrust sheet. Sava Zone ophiolites obducted onto the northern Adria margin in the Late Cretaceous (Ustaszewski et al. 2009), might also have contributed ophiolitic detritus.

Taking into account its dominantly metamorphic signature, the source of the newly exhumed material is apparently puzzling, as significant exposures of metamorphic units with Campanian cooling ages are scarce in the NW and Central Dinarides. However, Judik et al. (2006) detected relatively young, Late Cretaceous illite K–Ar ages (80 ± 13 Ma) in meta-igneous and metavolcanoclastic rocks of Mt. Medvednica. Árkai et al. (1995) reported a well-isolated but subordinate 79 ± 3 Ma K/Ar age component from a comprehensive dataset on metasedimentary and metavolcanic units of the Bükk Mts.; ZFT ages from the same units group around 90 Ma. In the Prekarst Zone (Fig. 1) of the Central Dinarides, Mikes et al. (2008) identified only a very small population of detrital ZFT ages of around 80 Ma in the Upper Cretaceous Ugar Formation. Combined evidence from sedimentary provenance indicators thus seems to preclude the Dinaride (Adriatic) basement as a significant source component for the Maastrichtian sediments.

Hence, if the material did not derive from local or more southerly Central Dinaride sources, a derivation of sediment from northerly and/or easterly sources, such as the Eastern Alps and the Tisza-Dacia unit, must clearly be taken into account, where similar zircon FT and argon ages have been widely reported (see Stüwe 1998; Tari et al. 1999; Schuster and Frank 2000; Benedek et al. 2001—their Figs 11 and 12; Dunkl et al. 2003; Wölfler et al. 2008). Detrital white mica with Late Cretaceous cooling ages occur in the Upper Gosau Subgroup of the Northern Calcareous Alps from the Campanian onwards (Fig. 1; Faupl and Wagreich 2000). They are well documented in the Austroalpine basement units of the Eastern Alps (Neubauer et al. 1995; Fügenschuh et al. 1997; Thöni 1999; Dunkl et al. 2003; Balogh and Dunkl 2005) and Western Carpathians (e.g. Koroknai et al. 2001). Also, Late Cretaceous cooling ages have been reported from the Tisza-Dacia unit (Balogh et al. 1990; Árkai et al. 2000; Lelkes-Felvári et al. 2003; Biševac et al. 2010) and the Igal Unit (Árkai et al. 1991). The continent–continent collision of the distal Adria margin with the Tisza-Dacia unit (Fig. 10), and the related suture formation that commenced along with the closure of the Late Cretaceous Sava remnant ocean, did not start until the latest Cretaceous (Ustaszewski et al. 2010).

We suggest that the marked changeover in the detrital signatures recorded by the Vivodina and Glog formations witnesses that paleo-catchments feeding the Late Cretaceous basins of the NW Dinarides already tapped the exhuming parts of the adjacent tectonic units, such as the Eastern Alps and/or—with respect to the Dinarides-Tisza collision—the upper plate Tisza-Dacia unit (Fig. 11c).

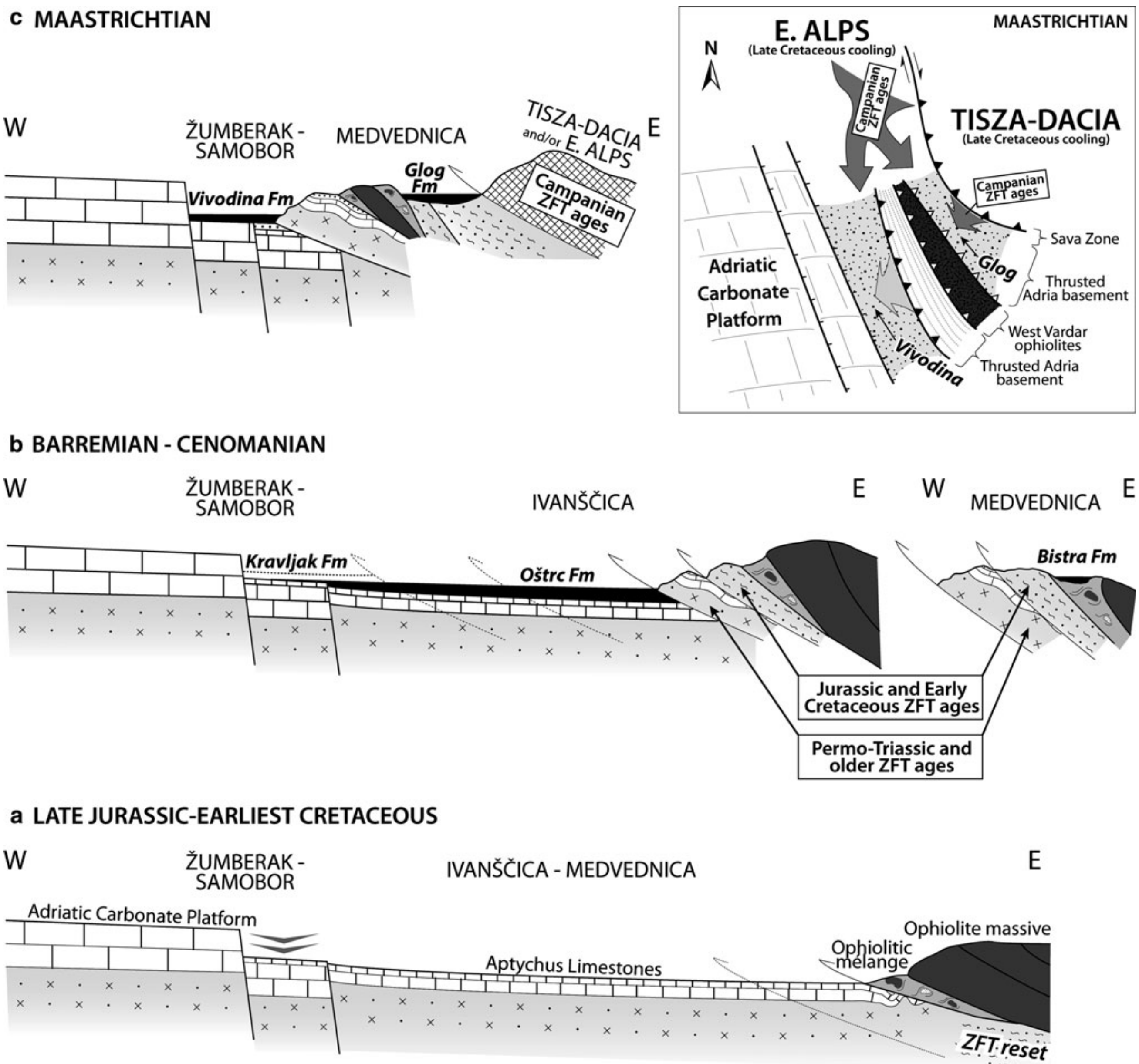


Fig. 11 Schematic cross-sections and paleogeographic sketch illustrating the tectonic evolution of the NW Dinarides and development of the Cretaceous synorogenic sedimentary formations **a** During the Late Jurassic–earliest Cretaceous Neotethys ophiolites are obducted onto the Adria plate margin. Exhumation of overprinted Adriatic basement is initiated. **b** During the Barremian–Cenomanian period there is an ongoing nappe stacking and exhumation of Adriatic basement. Flysch basins (Oštrc Formation) form in front of propagating ophiolite-continental nappes, while shallow marine to coastal environments (Bistra Formation) developed along their emerged parts. In the Albian–Cenomanian nappe advancement and associated clastic sedimentation (*dashed lines* Kravljak Formation) approaches the flanks of the Adriatic Carbonate Platform. **c** The continent–continent collision of the distal Adria margin with the Tisza-Dacia unit and/or local exhumationin the Austroalpine realm in the Maastrichtian causes the erosion of newly, rapidly exhumed basement units which supply multiple, more or less coeval basins formed both on top of and in front of the Internal Dinaride imbricate wedge. *Inset map* depicts a possible scenario that accounts for the sediment dispersal into the basins

With a comparable pattern, from the Campanian onwards, heavy mineral spectra of the Upper Gosau Subgroup in the Northern Calcareous Alps record a dominant switchover from an ophiolite-dominated source area to that composed chiefly of high-grade metamorphic rocks (Woletz 1967; Wagreich and Faupl 1994). Furthermore, a part of the Upper Austroalpine Unit acted as a major extension–extrusion corridor already during the Late Cretaceous (Neubauer et al. 1995; Froitzheim et al. 1997; Krenn et al. 2008), accompanied by the exhumation of structurally deeper Austroalpine units (e.g. Gleinalm Dome) and the coeval opening of the adjacent Central Alpine Gosau basins (such as the Santonian to Maastrichtian Kainach Basin—Ratschbacher et al. 1989; Neubauer et al. 1995). The relatively well-documented Late Cretaceous cooling and exhumation history of the southeastern part of the Eastern Alps allows us to propose that it formed part of the sediment source area supplying the NW Dinaride basins.

Basement thermochronological data from the Tisza-Dacia unit as summarized above demonstrate that rapid Maastrichtian exhumation generating metamorphic detritus with a short lag time could also occur on the approaching upper plate Tisza-Dacia unit, either already during the subduction stage or during the initial stages of the continent–continent collision.

7 Conclusions

1. Nappe stacking in the NW Dinarides, initiated prior to the Barremian, resulted in the exhumation and erosion of segments of the Adriatic basement tectonically overlain by obducted oceanic lithosphere. Such nappes were composed of low to medium-grade metamorphic rocks which supplied zircons with Early Cretaceous FT cooling ages to basinal (Oštrc Formation) and shallow-marine (Bistra Formation) depositional environments. Cooling and exhumation of basement units continued until the late Early Cretaceous.

2. Supply of detritus from ophiolites and continental rocks with Early Cretaceous ZFT cooling ages decreased by the Albian-Cenomanian (Kravljak Formation), and gave way to that characterized by Jurassic ZFT ages. This changeover in the source area is most probably due to an increased availability of Adriatic basement units that cooled subsequent to the widespread Middle–Late Jurassic thermal event in the Dinarides and which have not been later thermally overprinted due to obduction.
3. In the Early Cretaceous to Cenomanian, additional significant amounts of detrital material were derived from unreset Permo-Triassic sequences and continental units of the Adria plate affected by Permo-Triassic igneous activity and low-P high-T regional metamorphism due to rifting of the Neotethys.
4. In the latest Cretaceous, the NW Dinarides probably consisted of more or less coeval pro-wedge and wedge-top basins. An abrupt switchover to an overwhelming dominance of Campanian ZFT ages (80–73 Ma) in both the Vivodina and Glog formations points to widespread rapid exhumation and cooling of metamorphic basement units in the source areas. Exhumation of the southeastern Austroalpine basement and/or the Tisza-Dacia unit most probably accounts for the observed detrital ZFT age distribution in the Maastrichtian.
5. The Late Cretaceous continent–continent collision probably caused a major rearrangement of the catchment systems, which resulted in a renewed availability of ophiolitic source areas to erosion. Differences in reconstructed source lithologies for the coeval Glog and Vivodina formations suggest small and/or dynamically changing catchments developing on the accretionary wedge.

Acknowledgments This work was funded by the Deutsche Forschungsgemeinschaft grant 436 KRO 17/1/05 ("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 are grateful to Jožica Zupanič and Marta Crnjaković for sharing with us their knowledge on the Cretaceous sediments and field relationships in the study area. Andreas Kronz kindly provided his expertise during microprobe analyses. We thank Oregon State University and Technical University of Munich (Garching) for the neutron irradiations. Robert Košćal helped in the preparation of some of the figures. We are thankful to the reviewers; Michael Wagreich and Michele Marroni, for their constructive suggestions which helped to improve the manuscript.

References

Árgyelán, G. B. (1996). Geochemical investigations of detrital chrome spinels as a tool to detect an ophiolitic source area (Gerecse Mountains, Hungary). *Acta Geologica Hungarica, 39*, 341–368.

Árkai, P., Balogh, K., & Dunkl, I. (1995). Timing of low-temperature metamorphism and cooling of the Paleozoic and Mesozoic formations of the Bükkium, innermost Western Carpathians, Hungary. *Geologische Rundschau, 84*, 334–344.

Árkai, P., Bérczi-Makk, A., & Balogh, K. (2000). Alpine low-T prograde metamorphism in the post-Variscan basement of the Great Plain, Tisza Unit (Pannonian Basin, Hungary). *Acta Geologica Hungarica, 43*, 43–63.

Árkai, P., Lantai, C., Fórizs, I., & Lelkes-Felvári, G. (1991). Diagenesis and low-temperature metamorphism in a tectonic link between the Dinarides and the Western Carpathians: the basement of the Igal (Central Hungarian) Unit. *Acta Geologica Hungarica, 34*, 81–100.

Aubouin, J., Blanchet, R., Cadet, J.-P., Celet, P., Charvet, J., Chorowicz, J., Cousin, M., Rampnoux, J.-P. (1970). Essai sur la géologie des Dinarides. *Bulletin de la Société Géologique de France*, *12*(7), 1060–1095.

Babić, L. (1973). Upper Tithonian to Valanginian basinal sediments west of Bregana [In Croatian with English summary]. *Geološki vjesnik Zagreb, 26*, 11–27.

Babić, L. (1974). Hauterivian to Cenomanian time in the region of Žumberak, Northwestern Croatia: stratigraphy, sediments, paleogeographic and paleotectonic evolution [In Croatian with English summary]. *Geološki vjesnik Zagreb, 27*, 11–33.

Babić, L. (1975). Condensed Liassic sedimentation on Mt. Medvednica and Mt. Ivanščica (Northern Croatia) and its significance for the interpretation of the paleogeographic evolution of the Inner Dinaric Belt [In Croatian with English summary]. *Geološki vjesnik Zagreb, 28*, 11–28.

Babić, L., & Gušić, I. (1978). Review of fossils from the "clastic complex with ophiolites" of Mt. Ivanščica and their stratigraphic importance [In Croatian with English summary]. *Geološki vjesnik Zagreb, 30*, 1–19.

Babić, L., Gušić, I., & Devidé-Nedéla, D. (1973). Senonian breccias and overlying deposits on Mt. Medvednica (northern Croatia) [In Croatian with English summary]. *Geološki vjesnik Zagreb, 25*, 11–27.

Babić, L., Hochuli, P. A., & Zupanič, J. (2002). The Jurassic ophiolitic mélange in the NE Dinarides: dating, internal structure and geotectonic implications. *Eclogae Geologicae Helvetiae, 95*, 263–275.

Babić, L., & Zupanič, J. (1973). Uppermost Jurassic and Early Cretaceous on Mt. Ivanščica (Northern Croatia) [In Croatian with English summary]. *Geološki vjesnik Zagreb, 26*, 267–271.

Balogh, K., & Dunkl, I. (2005). Argon and fission track dating of Alpine metamorphism and basement exhumation in the Sopron Mts. (Eastern Alps, Hungary): thermochronology or mineral growth? *Mineral Petrol, 83*, 191–218.

Balogh, K., Kovács, Á., Pécskay, Z., Svingor, É., & Árkai, P. (1990). Very low- and low-grade metamorphic rocks in the pre-Tertiary basement of the Drava Basin, SW-Hungary, II: K-Ar and Rb-Sr isotope geochronologic data. *Acta Geologica Hungarica, 33*, 69–78.

Bébien, J., Blanchet, R., Cadet, J. P., Charvet, J., Chorowicz, J., Lappiere, H., et al. (1978). Le volcanisme Triasique des Dinarides en Yougoslavie: sa place dans l'évolution géotectonique périméditerranéenne. *Tectonophysics, 4*, 159–176.

Belak, M. (2005). *Metamorphic rocks of the blueschist and greenschist facies on the Medvednica Mt*. Ph.D. dissertation, University of Zagreb, Zagreb, Croatia.

Belak, M., Pamić, J., Kolar-Jurkovšek, T., Pécskay, Z., Karan, D. (1995). The Alpine regional metamorphic complex of Medvednica (northwestern Croatia) [In Croatian]. In *Proceedings*, *1st Croatian Geological Congress* (pp. 67–70). Opatija: Croatian Geological Society.

Benedek, K., Nagy, Zs, Dunkl, I., Szabó, C., & Józsa, S. (2001). Petrographical, geochemical and geochronological constraints on igneous clasts and sediments hosted in the Oligo-Miocene Bakony Molasse, Hungary: evidence for Paleo-Drava River system. *Int J Earth Sci, 90*, 519–533.

Bernoulli, D., & Laubscher, H. (1972). The palinspastic problem of the Hellenides. *Eclogae Geologicae Helvetiae, 65*, 107–118.

Biševac, V., Balogh, K., Balen, D., & Tibljaš, D. (2010). Eoalpine (Cretaceous) very low- to low-grade metamorphism recorded on the illite-muscovite-rich fraction of metasediments from South Tisia (eastern Mt Papuk, Croatia). *Geologica Carpathica, 61*, 469–481.

Blanchet, R., Cadet, J.-P., Charvet, J. (1970). Sur l'existance d'unités intermédiaires entre la zone du Haut-Karst et l'unité du Flysch Bosniaque, en Yugoslavie: la sous-zone Prékarstique. *Bulletin de la Société Géologique de France, 12*(7), 227–236.

Blanchet, R., Cadet, J.-P., Charvet, J., Rampnoux, J.-P. (1969). Sur l'existence d'un important domaine de flysch tithonique-crétacé inférieur en Yougoslavie: l'unité du flysch bosniaque. *Bulletin de la Société Géologique de France, 11*(7), 871–880.

Blašković, I. (1998). The two stages of structural formation of the coastal belt of the External Dinarides. *Geologia Croatica, 51*, 75–89.

Bortolotti, V., Ficcarelli, G., Manetti, P., Passerini, P., Pirini Radrizzani, C., & Torre, D. (1971). A Jurassic sequence on top of the Zlatibor ultramafic massif (Jugoslavia). *Bollettino della Società Geologica Italiana, 90*, 415–428.

Channell, J. E. T., & Kozur, H. W. (1997). How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine paleogeography. *Geology, 25*, 183–186.

Charvet, J. (1978). Essai sur un orogène alpin: Géologie des Dinarides au niveau de la transversale de Sarajevo (Yougoslavie). *Publications de la Société Géologique du Nord, 2*, 1–554.

Charvet, J. (1980). Développement de l'orogène dinarique d'après l'étude du secteur transversal de Sarajevo (Yougoslavie). *Revue de Géologie Dynamique et de Géographie Physique, 22*, 29–50.

Charvet, J. & Termier, G. (1971) Les Nérinéacés de la limite Jurassique-Crétacé de Bjeliš (Nord de Sarajévo, Yougoslavie). *Annales—Société Géologique du Nord, 91*, 187–191.

Condie, K. C. (1993). Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. *Chem Geol, 104*, 1–37.

Crnjaković, M. (1979). Sedimentation of transgressive Senonian in Southern Mt. Medvednica [In Croatian with English summary]. *Geološki vjesnik Zagreb, 32*, 81–95.

Crnjaković, M. (1981). Maastrichtian flysch sediments in the south–west part of Mt. Medvednica [In Croatian with English summary]. *Geološki vjesnik Zagreb, 34*, 47–61.

Crnjaković, M. (1987). *Sedimentology of Cretaceous and Paleogene clastics of Mt. Medvednica, Ivanščica, and Žumberak*. Ph.D. dissertation, University of Zagreb, Zagreb, Croatia.

Crnjaković, M. (1989). Lower Cretaceous shallow marine deposits in Mt. Medvednica [In Croatian with English summary]. *Acta Geologica Zagreb, 19*, 61–93.

Crnjaković, M., Babić, L., & Zupanič, J. (2000). Albian-Cenomanian arenites overlying Dinaric platform carbonates contain detritus derived from continental and ophiolitic rocks. In B. Tomljenović, D. Balen, & B. Saftić (Eds.), *Special Issue PANCARDI 2000 Vijesti Hrvatskog geološkog društva, 37*. Croatian Geological Society: Dubrovnik.

Császár, G., & Árgyelán, G. B. (1994). Stratigraphic and micromineralogical investigations on Cretaceous formations of the Gerecse Mountains, Hungary and their palaeogeographic implications. *Cretaceous Res, 15*, 417–434.

Csontos, L., Sztanó, O., Pocsai, T., Bárány, M., Palotai, M., & Wettstein, E. (2005). Late Jurassic–Early Cretaceous Alpine deformation events in the light of redeposited sediments. *Geolines, 19*, 29–31.

Csontos, L., & Vörös, A. (2004). Mesozoic plate tectonic reconstruction of the Carpathian region. *Palaeogeogr Palaeoclimatol Palaeoecol, 210*, 1–56.

Devidé-Nedéla, D., Babić, L., & Zupanič, J. (1982). Maastrichtian age of the Vivodina flysch in Žumberak and the surroundings of Ozalj (Western Croatia) based on planktonic foraminifera [In Croatian with French summary]. *Acta Geologica Zagreb, 35*, 21–36.

Dimitrijević, M. D. (2001). Dinarides and the Vardar Zone: a short review of the geology. *Acta Vulcanologica, 13*, 1–8.

Dimitrijević, M. D., & Dimitrijević, M. N. (1973). Olistostrome mélange in the Yugoslavian Dinarides and Late Mesozoic plate tectonics. *J Geol, 81*, 328–340.

Dragičević, I., & Velić, I. (2002). The northeastern margin of the Adriatic Carbonate Platform. *Geologia Croatica, 55*, 185–232.

Dunkl, I. (2002). Trackkey: a Windows program for calculation and graphical presentation of fission track data. *Computers and Geosciences, 28*, 3–12. Available online at: http://www.sediment.uni-goettingen.de/staff/dunkl/software/.

Dunkl, I., Frisch, W., & Grundmann, G. (2003). Zircon fission track thermochronology of the southeastern part of the Tauern Window and the adjacent Austroalpine margin, Eastern Alps. *Eclogae Geologicae Helvetiae, 96*, 209–217.

Dunkl, I., & Székely, B. (2002). Component analysis with visualization of fitting; PopShare, a Windows program for data analysis (abstract). *Geochimica et Cosmochimica Acta, 66*, 201.

Faupl, P., & Tollmann, A. (1979). Die Roßfeldschichten: Ein Beispiel für Sedimentation im Bereich einer tektonisch aktiven Tiefseerinne aus der kalkalpinen Unterkreide. *Geologische Rundschau, 68*, 93–120.

Faupl, P., & Wagreich, M. (2000). Late Jurassic to Eocene Palaeogeography and Geodynamic Evolution of the Eastern Alps. *Mitteilungen der Österreichischen Geologischen Gesellschaft, 92*, 79–94.

Frank, W., & Schlager, W. (2006). Jurassic strike slip versus subduction in the Eastern Alps. *Int J Earth Sci, 95*, 431–450.

Frisch, W., & Gawlick, H.-J. (2003). The nappe structure of the central Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion—a contribution to understanding the orogenic evolution of the Eastern Alps. *Int J Earth Sci, 92*, 712–727.

Froitzheim, N., Conti, P., & van Daalen, M. (1997). Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and its significance for the tectonics of the Eastern Alps. *Tectonophysics, 280*, 267–293.

Fügenschuh, B., Seward, D., & Mancktelow, N. (1997). Exhumation in a convergent orogen: the western Tauern window: the western Tauern window. *Terra Nova, 9*, 213–217.

Galbraith, R. F. (1990). The radial plot: graphical assessment of spread in ages. *Nucl Tracks Radiat Meas, 17*, 207–214.

Galbraith, R. F., & Laslett, G. M. (1993). Statistical models for mixed fission track ages. *Nucl Tracks Radiat Meas, 21*, 459–470.

Gardin, S., Kici, V., Marroni, M., Pandolfi, L., Pirdeni, A., & Xhomo, A. (1996). Litho- and biostratigraphy of the Firza flysch, ophiolite Mirdita nappe, Albania. *Ofioliti, 21*, 47–54.

Goričan, Š., Halamić, J., Grgasović, T., & Kolar-Jurkovšek, T. (2005). Stratigraphic evolution of Triassic arc-backarc system in northwestern Croatia. *Bulletin de la Société Géologique de France, 176*, 3–22.

Gušić, I. (1975). Lower Cretaceous imperforate Foraminiferida of Mt. Medvednica, Northern Croatia (Families: Litoulidae, Ataxophragmidiidae, Orbitolinidae). *Paleontologica Jugoslavica, 14*, 7–48.

Haas, J., Mioč, P., Pamić, J., Tomljenović, B., Árkai, P., Bérczi-Makk, A., et al. (2000). Complex structural pattern of the Alpine–Dinaridic–Pannonian triple junction. *Int J Earth Sci, 89*, 377–389.

Haas, J., & Péró, Cs. (2004). Mesozoic evolution of the Tisza Mega-unit. *Int J Earth Sci, 93*, 297–313.

Halamić, J., & Goričan, Š. (1995). Triassic radiolarites from Mts. Kalnik and Medvednica (Northwestern Croatia). *Geologica Croatica, 48*, 129–146.

Halamić, J., Goričan, Š., Slovenec, D., & Kolar-Jurkovšek, T. (1999). A Middle Jurassic radiolarite-clastic succession from the Medvednica Mt. (NW Croatia). *Geologica Croatica, 52*, 29–57.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., & Bernoulli, D. (2009). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth Sci Rev, 102*, 121–158.

Henry, D. J., & Guidotti, C. V. (1985). Tourmaline as a petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine. *Am Mineral, 70*, 1–15.

Herron, M. M. (1988). Geochemical classification of terrigenous sands and shales from core or log data. *J Sediment Petrol, 58*, 820–829.

Hrvatović, H. (2000). Passive continental margin formations (Bosnia Flysch). In J. Pamić & B. Tomljenović (Eds.), *PANCARDI 2000 Fieldtrip Guidebook, Vijesti Hrvatskog geološkog društva, 37* (pp. 71–72). Dubrovnik: Croatian Geological Society.

Hrvatović, H. (2006). *Geological guidebook through Bosnia and Herzegovina* (172 pp.). Sarajevo: Geological Survey of Federation Bosnia and Herzegovina.

Hurford, A. J., Fitch, F. J., & Clarke, A. (1984). Resolution of the age structure of the detrital zircon populations of two Lower Cretaceous sandstones from the Weald of England by fission track dating. *Geol Mag, 121*, 269–277.

Hurford, A. J., & Green, P. F. (1983). The zeta age calibration of fission-track dating. *Isotope Geoscience, 41*, 285–317.

Jablonský, J., Sýkora, M., & Aubrecht, R. (2001). Detritic Cr-spinels in Mesozoic sedimentary rocks of the Western Carpathians (overview of the latest knowledge) [in Slovak with English abstract]. *Mineralia Slovaca, 33*, 487–498.

Jovanović, R. (1961). *Prilog poznavanju prostranstva i facija mezozioka "unutrašnje zone Dinarida" u NRBiH [in Serbian with German summary]* (pp. 38–63). Budva: III Kongres geologa Jugoslavije.

Judik, K., Balogh, K., Tibljaš, D., & Árkai, P. (2006). New age data on the lowtemperature regional metamorphism of Mt. Medvednica (Croatia). *Acta Geologica Hungarica, 49*, 207–221.

Jurković, I., & Palinkaš, L. (2002). Discrimination criteria for assigning ore deposits located in the Dinaridic Paleozoic-Triassic formations to Variscan or Alpidic metallogeny. In D. J. Blundell, F. Neubauer, & A. von Quadt (Eds.), *The Timing and Location of Major Ore Deposits in an Evolving Orogen, Geological Society Special Publication, 204* (pp. 229–245). London: Geological Society of London.

Karamata, S., Olujić, J., Protić, L., Milovanović, D., Vujnović, L., Popević, A., et al. (2000). The western belt of the Vardar Zone—the remnant of a marginal sea. In S. Karamata & S. Jankovic (Eds.), *International Symposium Geology and metallogeny of the Dinarides and the Vardar zone* (pp. 131–135). Banja Luka: Academy of Sciences and Arts Republika Srpska.

Korbar, T. (2009). Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates. *Earth Sci Rev, 96*, 296–312.

Koroknai, B., Horváth, P., Balogh, K., & Dunkl, I. (2001). Alpine metamorphic evolution and cooling history of the Veporic basement in northern Hungary: new petrological and geochronological constraints. *Int J Earth Sci, 90*, 740–751.

Krenn, K., Fritz, H., Mogessie, A., & Schlaflechner, J. (2008). Late Cretaceous exhumation history of an extensional extruding wedge (Graz Paleozoic Nappe Complex, Austria). *Int J Earth Sci, 97*, 1331–1352.

Lelkes-Felvári, G., Frank, W., & Schuster, R. (2003). Geochronological constraints of the Variscan, Permian-Triassic and Eo-alpine (Cretaceous) evolution of the Great Hungarian Plain basement. *Geologica Carpathica, 54*, 299–315.

Lužar-Oberiter, B. (2009). *Provenance of Cretaceous clastic sediments from the Western Dinarides of Croatia*. Ph.D. dissertation, University of Zagreb, Zagreb, Croatia.

Lužar-Oberiter, B., Mikes, T., von Eynatten, H., & Babić, L. (2009). Ophiolitic detritus in Cretaceous clastic formations of the Dinarides (NW Croatia): evidence from Cr-spinel chemistry. *Int J Earth Sci, 98*, 1097–1108.

Mange, M. A., & Morton, A. C. (2007). Geochemistry of heavy minerals. In M. A. Mange & D. T. Wright (Eds.), *Heavy minerals in use, developments in sedimentology, 58* (pp. 345–392). Amsterdam: Elsevier.

Marroni, M., Pandolfi, L., Onuzi, K., Palandri, S., & Xhomo, A. (2009). Ophiolite-bearing Vermoshi flysch (Albanian Alps, northern Albania): elements for its correlation in the frame of Dinaric-Hellenic Belt. *Ofioliti, 34*, 95–108.

Matičec, D., Vlahović, I., Velić, I., & Tišljar, J. (1996). Eocene limestones overlying Lower Cretaceous deposits of western

Istria (Croatia): Did some parts of present Istria form land during the Cretaceous? *Geologia Croatica, 49*, 117–127.

McLennan, S.M. (2001). Relationships between the trace element composition of sedimentary rocks and upper continental crust. *Geochem Geophys Geosyst, 2*. doi:10.1029/2000GC000109.

McLennan, S.M., Hemming, S., McDaniel, D.K., Hanson, G.N. (1993). Geochemical approaches to sedimentation, provenance and tectonics. In M. J. Johnsson, & A. Basu (Eds.), *Processes controlling the composition of clastic sediments. GSA special paper*, *284* (pp. 21–40). Boulder: Geological Society of America.

Mikes, T., Baresel, B., Kronz, A., Frei, D., Dunkl, I., Tolosana-Delgado, R., et al. (2009). Jurassic granitoid magmatism in the Dinaride Neotethys: geochronological constraints from detrital minerals. *Terra Nova, 21*, 495–506.

Mikes, T., Christ, D., Petri, R., Dunkl, I., Frei, D., Báldi-Beke, M., et al. (2008). Provenance of the Bosnian Flysch. *Swiss J Geosci, 101*(Suppl 1), 31–54.

Milovanović, D. (1984). Petrology of low-grade metamorphic rocks of the middle part of the Drina-Ivanjica Palaeozoic [in Serbian with English summary]. *Glasnik Prirodnjačkog Muzeja u Beogradu (Ser. A), 39*, 13–139.

Mindszenty, A., D'Argenio, B., & Aiello, G. (1995). Lithospheric bulges recorded by regional unconformities. The case of Mesozoic-Tertiary Apulia. *Tectonophysics, 252*, 137–161.

Missoni, S., & Gawlick, H.-J. (2011). Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden; Austroalpine, Germany). *Int J Earth Sci, 100*, 1605–1631.

Moro, A., Ćosović, V., Benić, J., & Dokmanović, J. (2010). Taxonomy of rudists from the Campanian transgressive sediments of Brašljevica, Donje Orešje and Sv. Martin, northern Croatia. *Turkish J Earth Sci, 19*, 613–633.

Morton, A. C., Hallsworth, C., & Chalton, B. (2004). Garnet compositions in Scottish and Norwegian basement terrains: a framework for interpretation of North Sea sandstone provenance. *Mar Petrol Geol, 21*, 393–410.

Most, T., Frisch, W., Dunkl, I., Balogh, K., Boev, B., Avgerinas, A., et al. (2001). Geochronological and structural investigations of the northern Pelagonian crystalline zone—constraints from K/Ar and zircon and apatite fission track dating. *Bull Geol Soc Greece, 34*, 91–95.

Neubauer, F., Dallmeyer, R. D., Dunkl, I., & Schirnik, D. (1995). Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps—kinematics, cooling history and sedimentary response in a sinistral wrench corridor. *Tectonophysics, 242*, 79–98.

Neubauer, F., Pamić, J., Dunkl, I., Handler, R., & Majer, V. (2003). Exotic granites in the Cretaceous Pogari Formation overstepping the Dinaric Ophiolite Zone mélange in Bosnia. *Annales Universitatis Scientiarum Budapestiensis, Sectio Geologica, 35*, 133–134.

Pamić, J. (1983). Permo-Triassic rift faulting and magmatism of the Dinarides. *Annales de la Société Géologique du Nord, 103*, 133–141.

Pamić, J. (2002). The Sava-Vardar Zone of the Dinarides and Hellenides versus the Vardar Ocean. *Eclogae Geologicae Helvetiae, 95*, 99–113.

Pamić, J., Balogh, K., Hrvatović, H., Balen, D., Jurković, I., & Palinkaš, L. (2004). K–Ar and Ar–Ar dating of the Palaeozoic metamorphic complex from the Mid-Bosnian Schist Mts., Central Dinarides. Bosnia and Herzegovina. *Mineral Petrol, 82*, 65–79.

Pamić, J., Belak, M., Bullen, T. D., Lanphere, M. A., & McKee, E. H. (2000). Geochemistry and geodynamics of a Late Cretaceous bimodal volcanic association from the southern part of the Pannonian Basin in Slavonija (Northern Croatia). *Mineral Petrol, 68*, 271–296.

Pamić, J., Gušić, I., & Jelaska, V. (1998). Geodynamic evolution of the Central Dinarides. *Tectonophysics, 297*, 251–268.

Pamić, J., Tomljenović, B., & Balen, D. (2002). Geodynamic and petrogenetic evolution of Alpine ophiolites from the central and NW Dinarides: an overview. *Lithos, 65*, 113–142.

Pober, E., & Faupl, P. (1988). The chemistry of detrital chromian spinels and its implications for the geodynamic evolution of the Eastern Alps. *Geologische Rundschau, 77*, 641–670.

Prtoljan, B. (2001). Relationships of thrust-fold and horizontal mechanisms of the Mt. Žumberak part of the Sava nappe in the northwestern Dinarides, West Croatia. *Acta Geologica Hungarica, 44*, 67–80.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S. M., & Neugebauer, J. (1989). Extension in compressional orogenic belts: the eastern Alps. *Geology, 17*, 404–407.

Robertson, A. H. F., & Karamata, S. (1994). The role of subduction-accretion processes in the tectonic evolution of the Mesozoic Tethys in Serbia. *Tectonophysics, 234*, 73–94.

Ruiz, G. M. H., Seward, D., & Winkler, W. (2004). Detrital thermochronology—a new perspective on hinterland tectonics, an example from the Andean Amazon Basin, Ecuador. *Basin Res, 16*, 413–430.

Schlagintweit, F., Gawlick, H. J., Missoni, S., Hoxha, L., Lein, R., & Frisch, W. (2008). The eroded Late Jurassic Kurbnesh carbonate platform in the Mirdita Ophiolite Zone of Albania and its bearing on the Jurassic orogeny of the Neotethys realm. *Swiss J Geosci, 101*, 125–138.

Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., et al. (2008). The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss J Geosci, 101*, 139–183.

Schuster, R., & Frank, W. (2000). Metamorphic evolution of the Austroalpine units east of the Tauern Window: indications for Jurassic strike slip tectonics. *Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 42*, 37–58.

Schuster, R., & Stuwe, K. (2008). Permian metamorphic event in the Alps. *Geology, 36*, 603–606.

Šikić, K., Basch, O., Šimunić, A. (1977). Basic geological map of Yugoslavia M 1:100000, sheet Zagreb. Croatian Geological Survey, Zagreb, Federal Geological Institute Belgrade.

Šimunić, A., Pikija, M., Hećimović, I. (1982). Basic geological map of Yugoslavia M 1:100000, sheet Varaždin. Croatian Geological Survey, Zagreb, Federal Geological Institute Belgrade.

Starijaš, B., Gerdes, A., Balen, D., Tibljaš, D., & Finger, F. (2010). The Moslavačka Gora crystalline massif in Croatia: a Cretaceous heat dome within remnant Ordovician granitoid crust. *Swiss J Geosci, 103*, 61–82.

Stüwe, K. (1998). Heat sources of Cretaceous metamorphism in the Eastern Alps—a discussion. *Tectonophysics, 287*, 251–269.

Tari, G. (1995). Eoalpine (Cretaceous) tectonics in the Alpine/Pannonian transition zone. In Horváth, F., Tari, G., & Bokor, Cs. (Eds.) Extensional collapse of the Alpine orogene and Hydrocarbon prospects in the Basement and Basin Fill of the Western Pannonian Basin. AAPG International Conference and Exhibition, *Guidebook to fieldtrip No. 6. Hungary* (pp. 133–155). Nice, France.

Tari, G., Dövényi, P., Dunkl, I., Horváth, F., Lenkey, L., Stefanescu, M., Szafián, P., Tóth, T. (1999). Lithospheric structure of the Pannonian basin derived from seismic, gravity and geothermal data. In B. Durand, L. Jolivet, F. Horváth, M. Séranne (Eds.) *The Mediterranean basins: Tertiary extension within the Alpine orogen. Geological Society Special Publication*, *156*, (pp. 215–250). London: Geological Society of London.

Thöni, M. (1999). A review of geochronological data from the Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilung, 79*, 209–230.

Tomljenović, B., & Csontos, L. (2001). Neogene–Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko zagorje and Karlovac Basins, Croatia). *Int J Earth Sci, 90*, 560–578.

Tomljenović, B., Csontos, L., Márton, E., Márton, P. (2008). Tectonic evolution of the northwestern Internal Dinarides as constrained by structures and rotation of Medvednica Mts., North Croatia. In S. Siegesmund, B. Fügenschuh, N. Froitzheim (Eds.), *Tectonic Aspects of the Alpine–Carpathian-Dinaride System*, *Geological Society Special Publication*, *298*, (pp. 145–167). London: Geological Society of London.

Ustaszewski, K., Kounov, A., Schmid, S.M., Schaltegger, U., Krenn, E., Frank, W., Fügenschuh, B. (2010). Evolution of the Adria-Europe plate boundary in the northern Dinarides: From continent–continent collision to back-arc extension. *Tectonics, 29*, TC6017.

Ustaszewski, K., Schmid, S. M., Fügenschuh, B., Tischler, M., Kissling, E., Spakman, W. (2008). A map-view restoration of the Alpine–Carpathian–Dinaridic system for the Early Miocene. *Swiss J Geosci, 101*(Supplementary Issue 1), 273–294.

Ustaszewski, K., Schmid, S. M., Lugović, B., Schuster, R., Schaltegger, U., Bernoulli, D., et al. (2009). Late Cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): implications for the collision of the Adriatic and European plates. *Lithos, 108*, 106–125.

Viator, D.B. (2003). *Detrital tourmaline as an indicator of provenance: chemical and sedimentological study of modern sands from the Black Hills, South Dakota*. M.Sc. thesis, Louisiana State University, Baton Rouge, Louisiana, USA.

Vlahović, I., Tišljar, J., Velić, I., & Matičec, D. (2005). Evolution of the Adriatic Carbonate Platform: palaeogeography, main events and depositional dynamics. *Palaeogeogr Palaeoclimatol Palaeoecol, 220*, 333–360.

von Eynatten, H., & Gaupp, R. (1999). Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: constraints from framework petrography, heavy mineral analysis and mineral chemistry. *Sediment Geol, 124*, 81–111.

von Eynatten, H., Gaupp, R., & Wijbrans, J. R. (1996). $^{40}Ar/^{39}Ar$ laserprobe dating of detrital white micas from Cretaceous sediments of the Eastern Alps: evidence for Variscan high-pressure metamorphism and implications for Alpine orogeny. *Geology, 24*, 691–694.

von Eynatten, H., Gaupp, R., Wijbrans, J.R., Brix, M., (1997). Provenance of Cretaceous synorogenic sediments in the Eastern Alps: an integrated approach using mineralogical, geochemical, and geochronological methods. *Terra Nova, 9*, Abstract Supplement No. 1, IX. EUG, p. 593.

Vörös, A. (1993). Jurassic microplate movements and brachiopod migrations in the western part of the Tethys. *Palaeogeogr Palaeoclimatol Palaeoecol, 100*, 125–145.

Wagreich, M., & Decker, K. (2001). Sedimentary tectonics and subsidence modeling of the type Upper Cretaceous Gosau basin (Northern Calcareous Alps, Austria). *Int J Earth Sci, 90*, 714–726.

Wagreich, M., & Faupl, P. (1994). Palaeogeography and geodynamic evolution of the Gosau Group of the Northern Calcareous Alps (Late Cretaceous, Eastern Alps, Austria). *Palaeogeogr Palaeoclimatol Palaeoecol, 110*, 235–254.

Weltje, G. J., & von Eynatten, H. (2004). Quantitative provenance analysis of sediments: review and outlook. *Sediment Geol, 171*, 1–11.

Woletz, G. (1967). Schwermineralvergesellschaftungen aus ostalpinen Sedimentationsbecken der Kreidezeit. *Geologische Rundschau, 56*, 308–320.

Wölfler, A., Dekant, Ch., Danišík, M., Kurz, W., Dunkl, I., Putiš, M., et al. (2008). Late stage differential exhumation of crustal blocks in the central Eastern Alps: evidence from fission track and (UTh)/He thermochronology. *Terra Nova, 20*, 378–384.

Babić, L., & Zupanič, J. (1978). Late Mesozoic of Ivanščica [In Croatian]. In L. Babić, & V. Jelaska (Eds.), *Vodič ekskurzije 3. Skupa sedimentologa Jugoslavije* (pp. 11–23). Zagreb: Croatian Geological Society.

Zupanič, J. (1981). Non-carbonate detritus from arenite sediments of Maastrichtian Vivodina Flysch (Žumberak, Western Dinarides) [In Croatian with English summary]. *Geološki vjesnik Zagreb, 34*, 109–120.

Zupanič, J., Babić, L., & Crnjaković, M. (1981). Lower Cretaceous basinal clastics (Oštrc Formation) in the Mt. Ivanščica (Northwestern Croatia) [In Croatian with English summary]. *Acta Geologica Zagreb, 11*, 1–44.