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# Paleomagnetic and geochronologic constraints on the geodynamic evolution of the Central Dinarides

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ABSTRACT

The geodynamic evolution of the Dinaride Mountains of southeastern Europe is relatively poorly understood, especially in comparison with the neighboring Alps and Carpathians. Here, we construct a new chronostratigraphy for the post-orogenic intra-montane basins of the Central Dinarides based on paleomagnetic and $^{40}Ar/^{39}Ar$ age data. A first phase of basin formation occurred in the late Oligocene. A second phase of basin formation took place between 18 and 13 Ma, concurrent with profound extension in the neighboring Pannonian Basin. Our paleomagnetic results further indicate that the Dinarides have not experienced any significant tectonic rotation since the late Oligocene. This implies that the Dinarides were decoupled from the adjacent Adria and the Tisza–Dacia Mega-Units that both underwent major rotation during the Miocene. The Dinaride orogen must consequently have accommodated significant shortening. This is corroborated by our AMS data that indicate post-Middle Miocene shortening in the frontal zone, wrenching in the central part of the orogen, and compression in the hinterland. A review of paleomagnetic data from the Adria plate, which plays a major role in the evolution of the Dinarides as well as the Alps, constrains rotation since the Early Cretaceous to 48 ± 10° counterclockwise and indicates 20° of this rotation took place since the Miocene. It also shows that Adria behaved as an independent plate from the Late Jurassic to the Eocene. From the Eocene onwards, coupling between Adria and Africa was stronger than between Adria and Europe. Adria continued to behave as an independent plate. The amount of rotation within the Adria-Dinarides collision zone increases with age and proximity of the sampled sediments to undeformed Adria. These results significantly improve our insight in the post-orogenic evolution of the Dinarides and resolve an apparent controversy between structural geological and paleomagnetic rotation estimates for the Dinarides as well as Adria.


## 1. Introduction

The Dinarides mountain belt is located on the north-western part of the Balkan Peninsula, continues southwards into the Albanides, Hellenides and Taurides, and forms an integral part of the Alpine–Himalayan orogenic system. In comparison with the neighboring Alps and Carpathians, the Dinarides remain geologically under-explored, mainly due to the politically complicated situation in the 1990s. Although its Mesozoic and Paleogene pre- and syn-orogenic history has recently received increased attention (Korbar, 2009; Schmid et al., 2008; Ustaszewski et al., 2008a, 2008b) and efforts have been made to better understand its Miocene stratigraphy (de Leeuw et al., 2010; Jiménez-Moreno et al., 2008, 2009; Mandic et al., 2008, 2010), knowledge on its Neogene geodynamic evolution remains limited. After the main orogenic phase in the Eocene, a suite of intra-montane basins formed on top of the orogenic structure (Hrvatović, 2006; Pamić et al., 1998; Tari-Kovačić, 2002) and was occupied by a system of lakes. The exact timing and mechanism of basin formation as well as their paleogeographic history are still poorly understood. This clearly hampers our insight into the post-orogenic evolution of the mountain belt.

The most recent palinspastic reconstruction of south-eastern Europe (Ustaszewski et al., 2008a), based exclusively on structural geological data, attributes a 20° CCW post 20 Ma rotation to the Adriatic plate, whereas the Dinarides are thought not to have rotated at all. This stands in marked contrast with the simultaneous 30° CCW of Adria and the Dinarides inferred from post-middle Miocene paleomagnetic data by Márton et al. (2002). This apparent discrepancy between structural geological and paleomagnetic data has a large impact on the rates of shortening predicted for the south-western part of our study area (Ustaszewski et al., 2008a).

Recently, we have used integrated $^{40}Ar/^{39}Ar$ and magnetostratigraphic dating techniques to construct chronologic frameworks for

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the accumulated lacustrine sediments in various intra-montane basins of the Dinarides (de Leeuw et al., 2010, 2011a, 2011b; Jiménez-Moreno et al., 2009; Mandic et al., 2010, 2011). Here, we combine all individual results to present a complete overview of the timing of the main phases of intra-montane basin formation. In addition, we use the paleomagnetic data of these basins to determine the vertical axis rotations of the Dinarides, and we have measured anisotropy of magnetic susceptibility (AMS) to identify tectonic stress directions. These approaches provide improved insight into the post Early–Middle Miocene geodynamic evolution of the blocks constituting the Dinarides. A review of the collective Cretaceous to Paleogene paleomagnetic data that is available in the literature builds a framework for the new Neogene results and shows the pre- and synorogenic rotation of crustal fragments involved in the collision of Adria and Tisza–Dacia. The apparent conflict between paleomagnetic data in the literature and the most recent structural geologic palinspastic reconstruction (Ustaszewski et al., 2008a) is ultimately resolved.

## 2. The intra-montane basins of the Central Dinarides

The Dinarides are located on the convergent plate boundary separating the Adriatic and Tisza–Dacia micro-plates in the central part of the Mediterranean region (Fig. 1). The post-orogenic evolution of the Dinaride Mountains is characterized by the formation of a large number of intra-montane basins (Pamić et al., 1998). Oligocene strike-slip faulting in response to movement on the Peri-Adriatic fault initiated transtensional depressions (Hrvatović, 2006). In the resulting intra-montane depressions fluvial and lacustrine sediments accumulated.

In the middle Miocene, the north-eastern margin of the Dinarides was affected by profound extension in response to the rifting that initiated the Pannonian Basin (Tari-Kovačić, 2002). It largely subsided below the base-level of the adjacent Paratethys; a Mediterranean sized epi-continental sea that covered large parts of South-Eastern Europe at that time. In the more central and western parts of the Dinarides, this extensional phase reactivated Oligocene transpressive structures and consequently triggered the development of a series of lacustrine intra-montane basins.

According to Hrvatović (2006), the intra-montane basins continued to evolve as pull-apart structures. Ilić and Neubauer (2005), on the other hand, relate this phase of subsidence to pure extension partitioned in two phases; an early Miocene NE-SW directed phase and a middle Miocene NW–SE directed phase. Korbar (2009) resorts to yet another model of basin formation and invokes a wedge top position in order to explain the close coexistence of lacustrine and marine environments along the trust front. Formation of such a large suite of intra-montane basins represents a very marked phase in the post-orogenic evolution of the Dinarides. The sedimentary sequences between 200 and 2500 m thick sedimentary sequences that accumulated in the interior of the mountain chain can potentially provide a detailed record of this event. However, due to the strictly endemic nature of the lacustrine fauna, age inferences remained tentative. It was consequently hard to assess whether sedimentation took place syn- or diachronously, despite numerous lithostratigraphic correlations (Milojević, 1963; Muftić and Luburić, 1963; Pantić, 1961). Any correlation with the geodynamic evolution of Adria and the Pannonian domain was thus also problematic.

## 3. A chronostratigraphic framework for the Dinaride basins

Recently, high resolution magnetostratigraphic and $^{40}Ar/^{39}Ar$ studies were initiated in several of the intra-montane basins (de Leeuw et al., 2010, 2011a, 2011b; Jiménez-Moreno et al., 2009; Mandic et al., 2010, 2011). Here we integrate these and other data to arrive at a chronostratigraphic scheme for sedimentation in the intra-montane basins. An overview of the age and error calculation for the investigated volcanic ashes can be found in Supplementary Table 1.

### 3.1. Pag Island (Croatia)

The Island of Pag (Fig. 2) comprises a 120 m thick Miocene succession exposed along the Crnika Beach (Fig. 3) and represents the northwestern-most constituent of the Dinaride Lake System (Bulić and Jurišić-Polšak, 2009). Magnetostratigraphic data for the Crnika section revealed a long (113 m) reverse polarity interval, followed by a 7 m thick interval of normal polarity at the top (Jiménez-Moreno et al., 2009). Combined with biostratigraphic constraints based on mollusks and pollen, the magnetostratigraphic pattern of the Crnika section was correlated to chrons C5Cr and C5Cn.3n of the GPTS, between 17.1 and 16.7 Ma (Jiménez-Moreno et al., 2009) (Fig. 3).

### 3.2. Sinj basin (Croatia)

In the Sinj basin (Fig. 2), a 500 m thick limestone-dominated succession is well exposed along the Sutina stream near Lučane in the western part of the basin (Jiménez-Moreno et al., 2008; Mandic et al., 2008). Several volcanic ash layers intercalate with the lacustrine sediments and enabled absolute age dating (de Leeuw et al., 2010) (Table 1). A clear and reliable magnetostratigraphic pattern with 9 reversals was established (Fig. 3), firmly anchored to the timescale by $^{40}Ar/^{39}Ar$ dating of the intercalated volcanic ash layers (de Leeuw et al., 2010). The base of the section is constrained by the $^{40}Ar/^{39}Ar$ age for the Lučane 3 tuff layer of $17.91 \pm 0.18$ Ma (Fig. 3, Table 1). The age of the very top of the Lučane section is constrained by correlation of the uppermost normal interval to chron C5Bn.2n, yielding an age of 15.0 Ma.

### 3.3. Livno–Tomislavgrad Basin

Two successive lacustrine cycles are found in the Livno–Tomislavgrad Basin (Figs. 2, 3). Around 1700 m of predominantly marl and limestone constitute the first phase, and an additional 500 m of sediments constitute the second. The basal part of the sequence is exposed in the Tušnica section. The Tušnica volcanic ash is located within a 10 m thick coal seam bearing proboscidean remains. The overlying sediments (~1300 m thick) are exposed along the Ostrožac stream. Breccias, derived from the basin margins, first occur in the upper third and coarsen and thicken upwards in the section towards a mega breccia at the top. A second volcanic ash crops out along the shores of Lake Mandek. The reverse polarity interval of the Tušnica section is correlated to chron C5Cr, as constraint by an $^{40}Ar/^{39}Ar$ age of $17.00 \pm 0.17$ Ma for the Tušnica ash (de Leeuw et al., 2011b) (Fig. 3; Table 1). The Ostrožac section is correlated to the interval between C5Br and C5ABn, in agreement with the $^{40}Ar/^{39}Ar$ age of $14.68 \pm 0.16$ Ma for the Mandek ash (de Leeuw et al., 2011b). These correlations suggest an age of approximately 17 Ma for the base, and 12.6 Ma for the top of the Livno succession.

### 3.4. Gacko basin

The infill of the Gacko basin (Fig. 2) is ~360 m thick in the basin center (Mirković, 1980) and was sampled along a condensed 75 m section exposed in the Gračanica open pit coal mine. A 1.5 m thick prominent greenish volcanic ash layer is located in the top part of the section (Mandic et al., 2010). $^{40}Ar/^{39}Ar$ total fusion experiments for two samples of this ash provided a combined weighted mean age of $15.36 \pm 0.16$ Ma. However, due to a slight amount of excess argon, the $15.31 \pm 0.16$ Ma isochron age best reflects its crystallization age (Table 1). The reverse

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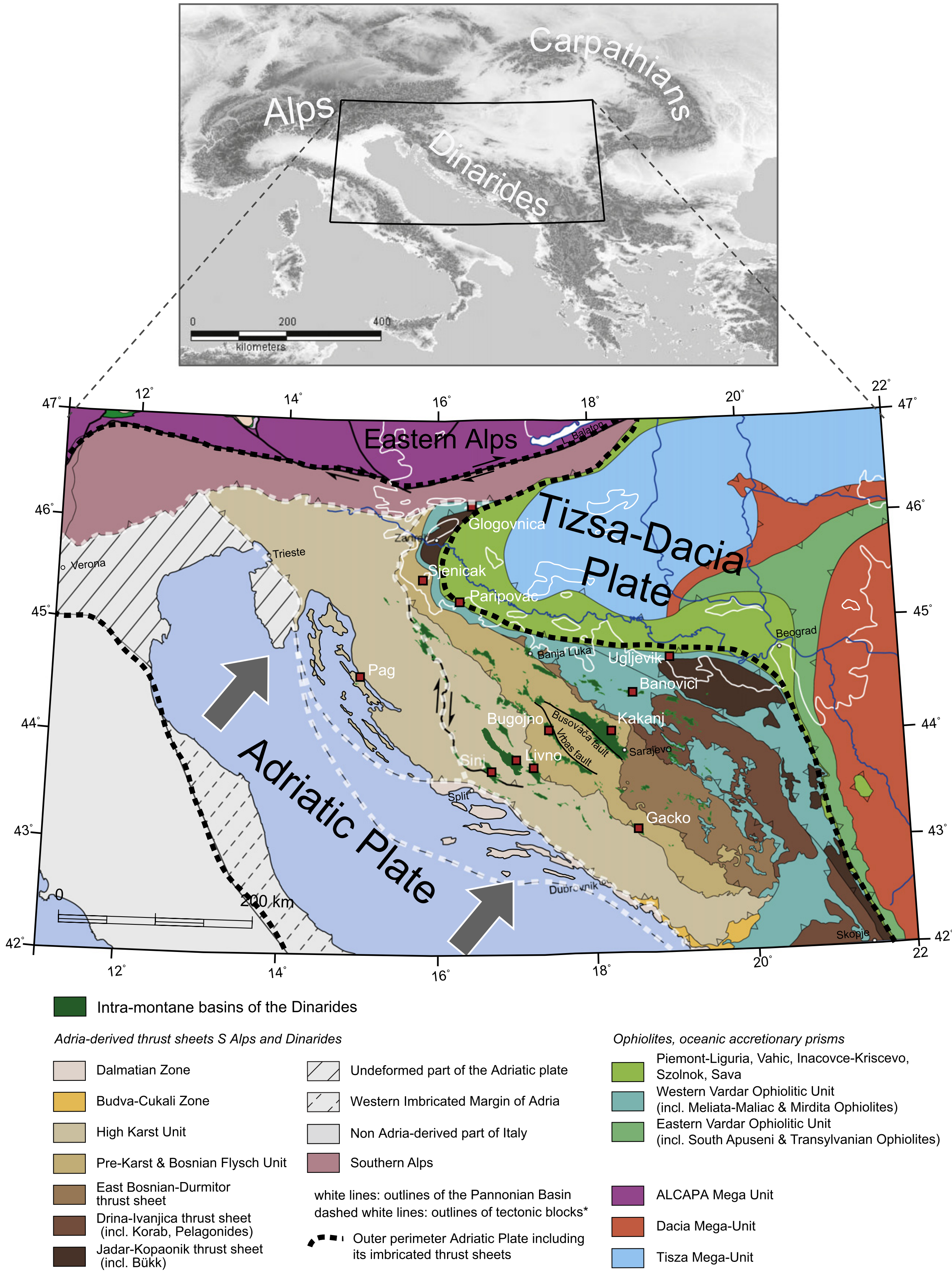


**Fig. 1.** Plate tectonic and geologic setting of the Dinarides and surrounding area, adapted from Schmid et al. (2008). The Neogene intra-montane basins as well as our sampling sites, main faults, major plate boundaries and the direction of movement of the Adriatic Plate are indicated.

polarity interval of the upper part of the Gacko section correlates to C5Br constrained by a $15.31 \pm 0.16$ Ma age of the Gacko tuff. The basal part of the succession has an estimated age of 15.85 Ma, assuming that the seven transgressive–regressive sequences correspond to ~100 kyr eccentricity cycles (Mandic et al., 2010). Extrapolation of sedimentation rates suggests that Lake Gacko disappeared around 15.0 Ma.

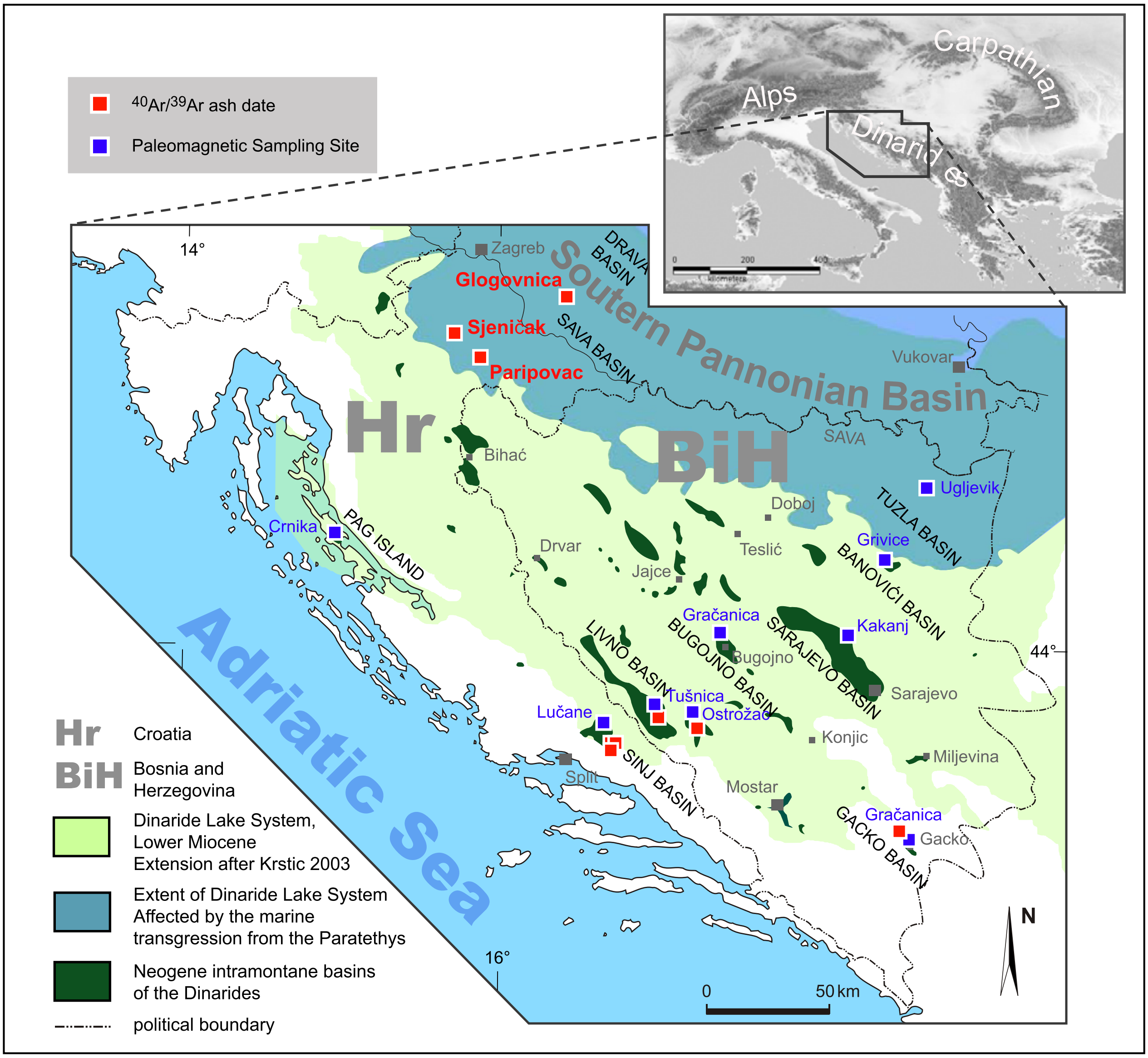


**Fig. 2.** Map with an overview of the sampling sites. The former extent of the Miocene Dinaride Lake System, the area affected by the Paratethys transgression, as well as the location of the intra-montane basins is indicated.

### 3.5. Bugojno and Sarajevo basins

The general quality of the paleomagnetic demagnetization diagrams (Supplementary material) was too low to arrive at a reliable magnetostratigraphy for the Bugojno and Sarajevo basins (Fig. 2). Both basins, however, bear elephantoid proboscidean remains (*Gomphotherium* and *Prodeinotherium bavaricum*) (Malez and Slišković, 1976; Milojević, 1964). The oldest occurrence of these proboscideans in Europe has been dated at 17.5 Ma by Pálfy et al. (2007) based on radio-isotopic ages for a tuff that overlies fossil footprint bearing sandstones and clays with *Gomphoterium* remains. The oldest dated occurrence of proboscideans in the Dinarides is at the Tušnica coal mine in the Livno–Tomislavgrad basin, here dated at 17.0 Ma. The occurrence of proboscideans thus indicates that the sections exposed in the Gračanica coal mine in the Bugojno basin and above the Kakanj coal seam of the Sarajevo basin are younger than 17.5 Ma. Additional age constraints in Bugojno come from a number of small mammal teeth, which pertain to *Democricetodon gracilis* and *Democricetodon mutilus*, associations that are correlated to the upper part of MN4 and MN5 (Wessels et al., 2008), i.e. between 17 and 13.8 Ma (Agustí et al., 2001).

### 3.6. Banovići basin

The infill of the late Oligocene–early Miocene Banovići Basin (Fig. 2) is approximately 500 m thick. The fauna of Turija mammal site, located just below the main coal layer of the basin, best compares with localities from the European MP30/MN1 mammal zones and Anatolian zone B (de Leeuw et al., 2011a). The magnetostratigraphic pattern of the 167 m long Grivice section reveals a long reversed interval interrupted by a short interval of normal polarity (Fig. 4), and correlates best to chrons C6Cr to C6Cn.2r of the GPTS. The MP30/MN1 Turija fauna would thus correlate with the base of C6Cr indicating an age of approximately 24 Ma.

### 3.7. Southern Pannonian Basin

In the area of the Southern Pannonian Basin (SPB, Fig. 2) back arc extension triggered the deposition of a series of continental, alluvial and lacustrine sediments up to 500 m thick (Pavelić et al., 2003) with fauna very similar to that of the Dinaride Lakes (Mandic et al., 2011). The series are generally overlain by transgressive marine deposits that indicate a wide-spread ingression of the Paratethys Sea into the SPB. Two volcanic

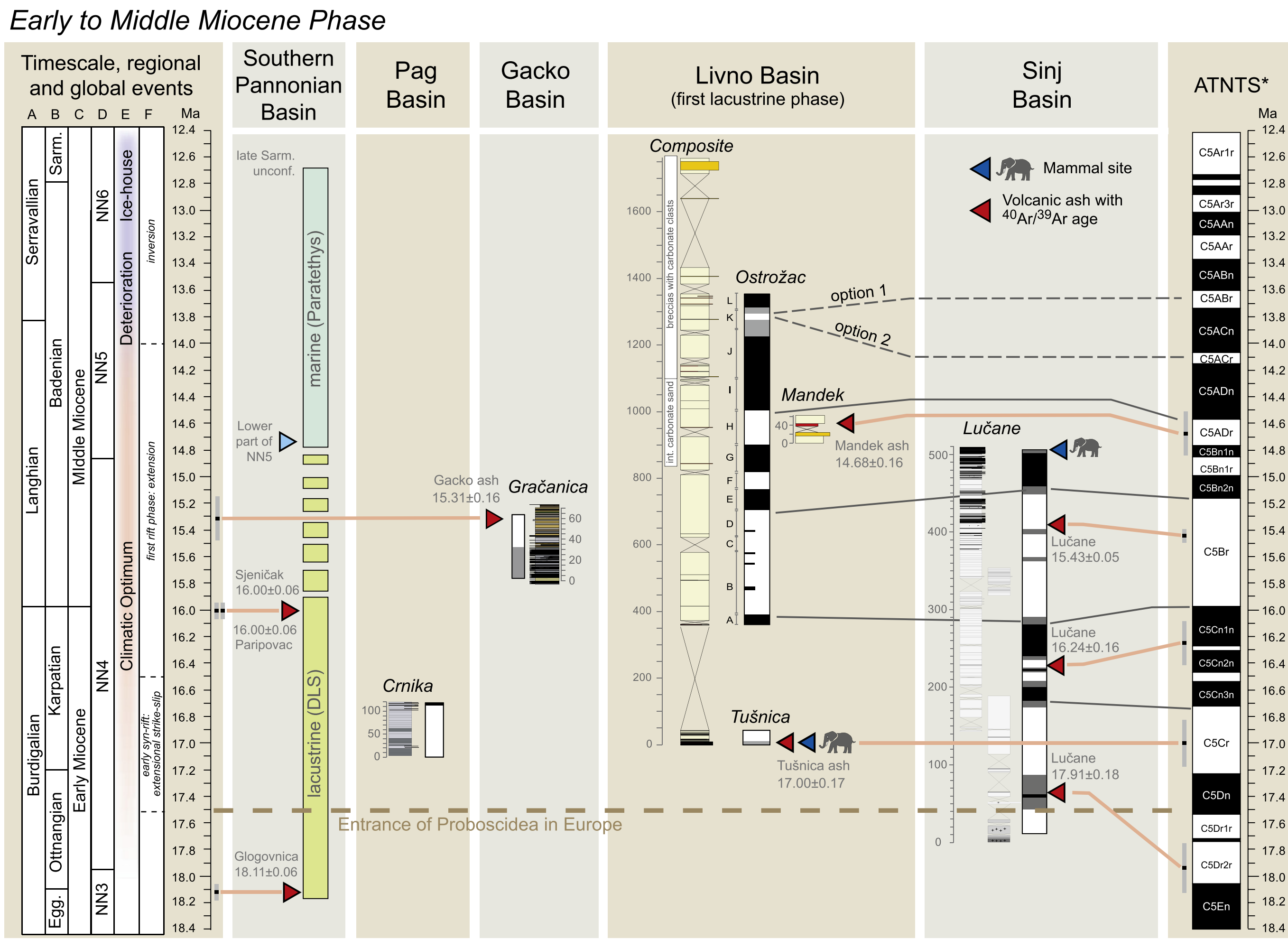


**Fig. 3.** Correlation of the DLS magnetostratigraphic records to the Astronomically Tuned Neogene Timescale (ATNTS) after Lourens et al. (2004). Red squares indicate intercalating tuffs with their corresponding $^{40}Ar/^{39}Ar$ ages. Global as well as regional Paratethys stages, calcareous nannoplankton zonation, global climatic developments and Pannonian basin tectonic events are indicated for the purpose of comparison. European Proboscidean Datum after Pálfy et al. (2007). Timing of the marine flooding of the southern Pannonian Basin after Ćorić et al. (2009). A) Mediterranean stages after Lourens et al. (2004) with changes according to Hilgen et al. (2009), B) Paratethys stages after Piller et al. (2007) with changes according to Grunert et al. (2010), C) Epochs and D) nannoplankton zones, both according to Lourens et al. (2004), E) Global climatic developments after Zachos et al. (2001), Abels et al. (2005), and Holbourn et al. (2007), F) Tectonic evolution of the Pannonian Basin after Huismans et al. (2002). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ash levels are located at the base and at the top of the continental series, respectively (Table 1). The weighted mean age for the lower (Glogovnica) ash is 18.11 ± 0.06 Ma. Weighted mean ages for the Sjeničak and Paripovac ashes are 16.00 ± 0.09 Ma and 16.00 ± 0.07 Ma respectively. These ages indicate that the SPB continental phase lasted at least 2 Myr (Mandic et al., 2011) and that it is largely coeval with the deposition of lacustrine sediments with similar fauna in the more interior parts of the Dinarides.

### 3.8. Ugljevik basin

The coal mine of the Ugljevik basin (Fig. 2), situated at the northern rim of the Dinarides, exposes around 100 m of late Oligocene lacustrine deposits succeeded by 70 m of marine Paratethys sediments (Vrabac et al., 1995). The small mammal assemblage recovered from the lacustrine sediments (Wessels et al., 2008) resembles the Late Oligocene ones from Thrace and Anatolia (Ünay et al., 2003). Its age is estimated to be late Oligocene but slightly older then Banovići (Wessels et al., 2008).

Our new chronostratigraphic results indicate an early to middle Miocene phase of basin formation and lacustrine deposition in the Central Dinarides (Fig. 3). At this time, the Dinaride Lake System stretched out from the Southern Pannonian Basin across the Dinarides as far out as the Pag Island in the north-west and the Gacko basin in the south-west. Pre-dating this Miocene phase, there is a late Oligocene phase from which deposits are present in the Ugljevik and Banovići basins. Chronostratigraphic constraints on this earlier phase remain rudimentary.

## 4. Late Oligocene to middle Miocene paleomagnetic rotation data

The paleomagnetic data also allow determination of the vertical axis rotation these basins experienced since deposition of their lacustrine infill. For the Pag, Sinj, Livno, Tomislavgrad, Gacko and Banovići basins demagnetization diagrams were of high quality and the established paleomagnetic directions are thus also suitable for constraining their rotation history.

For the Crnika section on Pag (Jiménez-Moreno et al., 2009), 121 directions are available. The vast majority is of reverse polarity and only 16 directions constitute the short normal polarity interval at the top of the section. The reversal test fails, because of a number of low inclination intermediate directions at the base of the short normal chron. The remaining normal directions are statistically too few in number. In order to overcome this problem, we have decided to rely on the 102 directions from the long and extensively sampled reversed chron. On these, the VanDamme cutoff (Vandamme, 1994)

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**Table 1**
Overview of $^{40}Ar/^{39}Ar$ ages for tuffs intercalated with DLS sediments. Ages printed in bold best represent the respective tuffs crystallization age. For tuffs dated with multiple total fusion experiments the peak probability density age is listed besides the weighted mean age. The uncertainty in all listed weighted mean ages and the isochron age of the Gacko tuff includes uncertainties in J, the age of the primary standard and decay constants, as reported in Kuiper et al. (2008) and Steiger and Jäger (1977). The other listed uncertainties are purely analytical. Uncertainties are reported at the 95% confidence level. MSWD is Mean Square Weighted Deviates, N is the total number of repetitions in the single fusion experiments and the total number of steps in the incremental heating experiments. n is the number of experiments used to calculate the weighted mean and isochron age.

| Sample | Location | Method | Weighted mean age (Ma) | n/N | MSWD | Peak probability distribution (Ma) | Mineral | Inverse isochron age | Inverse isochron intercept | Isochron MSWD | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Livno Basin* | | | | | | | | | | | |
| Mandek | N43 43 49.9 E017 01 21.6 | Multiple total fusion | 14.68 ± 0.16 | 10/10 | 2.09 | 14.7 | Feldspar | 14.90 ± 0.58 | 289 ± 18 | | This study |
| Tušnica | N43 44 25.8 E017 05 28.2 | Multiple total fusion | 17.00 ± 0.17 | 10/10 | 1.44 | 17.0 | Feldspar | 16.85 ± 0.09 | 318 ± 11 | | This study |
| *Sinj basin* | | | | | | | | | | | |
| Lučane 1 | N43 43 12.3 E016 35 30.1 | Multiple total fusion | **15.43 ± 0.05** | 7/10 | 0.81 | 15.43 | Sanidine | 15.39 ± 0.09 | 306 ± 19 | | De Leeuw et al. (2010) |
| Lučane 2 | N43 43 23.8 E016 35 43.1 | Multiple total fusion | **16.24 ± 0.16** | 6/10 | 0.05 | 16.23 | Sanidine | 16.24 ± 0.07 | 288 ± 43 | | De Leeuw et al. (2010) |
| Lučane 3 | N43 43 23.1 E016 36 37.7 | Incremental heating | **17.91 ± 0.18** | 18/36 | 2.09 | | Biotite | 17.88 ± 0.18 | 298 ± 2 | | De Leeuw et al. (2010) |
| *Gacko basin* | | | | | | | | | | | |
| Gacko | N43 10 38.2 E18 28 47.6 | Multiple total fusion | 15.36 ± 0.16 | 17/19 | 1.66 | | Feldspar | **15.31 ± 0.16** | 338 ± 12 | 0.92 | Mandic et al. (2010) |
| *Pannonian Basin System* | | | | | | | | | | | |
| Glogovnica | N46 08 20.3 E016 33 01.4 | Multiple total fusion | **18.11 ± 0.06** | 5 | 10 | 18.14 | Sanidine | 18.07 ± 0.08 | 368 ± 45 | | Mandic et al. (2010) |
| Sjeničak | N45 28 49.7 E015 50 17.4 | Multiple total fusion | **16.00 ± 0.06** | 8 | 10 | 15.92 | Plagioclase/ sanidine | 16.00 ± 0.09 | 295 ± 12 | | Mandic et al. (2010) |
| Paripovac | N45 16 16.4 E016 14 32.1 | Multiple total fusion | **16.00 ± 0.06** | 6 | 9 | 16.06 | Feldspar | 16.00 ± 0.07 | 297 ± 8 | | Mandic et al. (2010) |

was applied and eight outliers were discarded. The remaining 94 directions have an average declination of 182 ± 3.3°, and an average inclination of −56.5 ± 2.5° (Fig. 8). Bedding planes hardly vary along the Crnika section and this results in a non-significant Tauxe and Watson (1994) fold test.

The 221 paleomagnetic directions established for the magnetostratigraphy of the Lučane section in the Sinj basin (de Leeuw et al., 2010) were subjected to a fold test (Tauxe and Watson, 1994) in order to test their primary origin. Maximum clustering occurs close to 100% unfolding (Supplementary Fig. 2). This demonstrates that the directions are pre-folding and thus most likely primary. Since the dataset consists of both reversed and normal directions, a reversal test was applied. The reversed and normal directions do not share a common true mean direction. This is likely attributable to the incomplete removal of a present day overprint (Fig. 5) which displaces both the normal and reverse average in a westward direction. This effect is largely compensated for when the reversed directions are inverted to normal polarity and added to the set of normal directions. In order to discard outliers, the VanDamme cutoff is applied. The resulting average for the remaining 180 directions, has a declination of 355 ± 2.7° and an inclination of 56.4 ± 2.1.

Thermal demagnetization diagrams for the Ostrožac samples of the Livno–Tomislavgrad basin are of a higher quality than the AF demagnetization diagrams (de Leeuw et al., 2011b, Fig. 3). We therefore determine the rotation of the Ostrožac section exclusively based on the thermal results. These comprise both normal and reverse directions and for both sets outliers were discarded with the VanDamme cutoff. The reversal test (McFadden and McElhinny, 1990) succeeds with classification C and the two sets of opposite polarity were subsequently merged. This results in an average direction with a 13.8 ± 6.5° declination, and a 50.6 ± 6.1° inclination (Fig. 5). For the Tušnica section only AF demagnetization was carried out. These samples have a much higher NRM intensity than those from the Ostrožac section and the established directions are regarded as suitable for a rotation study. After removal of outliers with the VanDamme cutoff, the remaining reversed 12 samples provide an average direction with a 190.2 ± 15.9° declination and a −49.6 ± 15.4° inclination (Fig. 5). The Tušnica and Ostrožac sections share a common true mean direction and may thus be combined to arrive at an average 14.0 ± 5.8° declination and a mean 50.3 ± 5.5° inclination for the Livno–Tomislavgrad basin (Fig. 5). The combined set of Tušnica and Ostrožac directions was subjected to a fold test (Tauxe and Watson, 1994). Clustering is highest near 100% untilting (Supplementary Fig. 2), which suggests that these directions have a pre-tilt and therefore most likely primary origin.

The upper part of the Gračanica section in the Gacko basin is characterized by reversed directions, interpreted to be of primary origin (Mandic et al., 2010). The VanDamme cutoff was applied to the set of 18 directions and the surviving 16 directions yield an average declination of 180.7 ± 6.2° and an inclination of −51.0 ± 5.8° (Fig. 5).

The average direction for the Grivice section of the Banovići basin has a declination of 2.8 ± 2.8° and an inclination of 53.5 ± 2.4° (Fig. 5) based on 70 directions of both normal and reverse polarity (de Leeuw et al., 2011a). The reversal test is positive, but a fold test is not possible since all samples were taken along a section with a bedding plane of relatively constant orientation.

The demagnetization diagrams for samples from the Gračanica open pit coal mine in the Bugojno basin were of mixed quality. This is attributable to the high amount of organic content in the sediments. Several distinct levels provided a good paleomagnetic signal (Supplementary Fig. 2) and were considered suitable for rotational analysis. A total of 14 directions yield an average paleomagnetic direction for the Bugojno basin (Fig. 5) with a 359.1 ± 5.3° declination and a 50.0 ± 5.1° inclination.

The calculated directions and resulting averages and other statistical parameters for these 5 basins are displayed in Fig. 5 and in Supplementary Table 2. The expected magnetic field direction at the time of deposition was calculated for each location based on the 20 Ma pole

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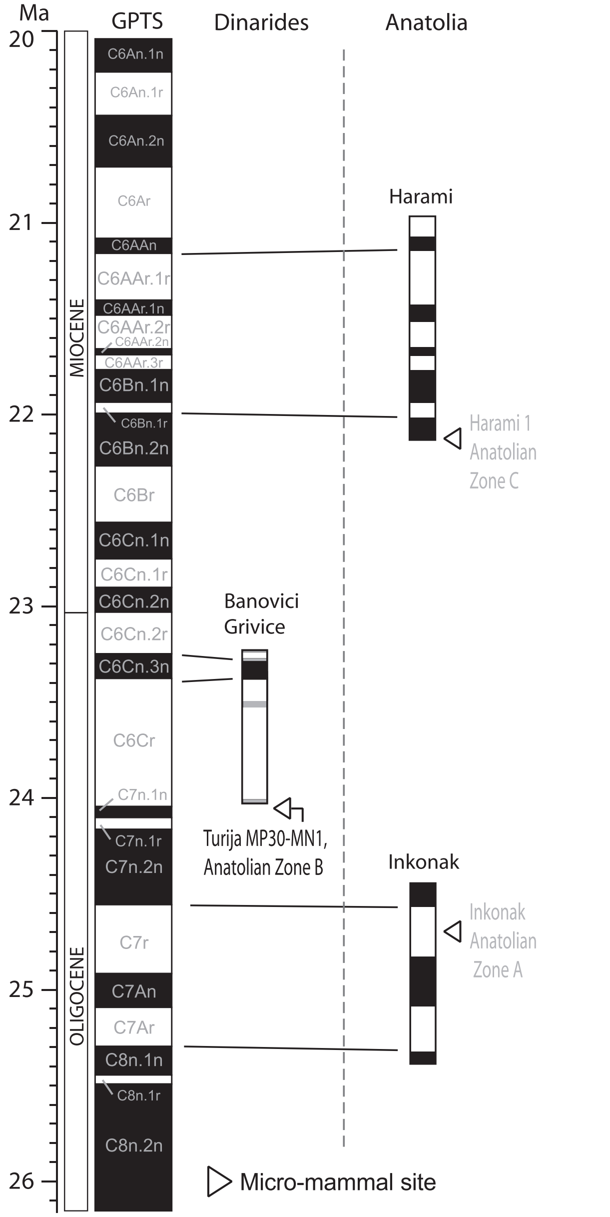


**Fig. 4.** Correlation magnetostratigraphic pattern of the Grivice section in the Banovići Basin to the GPTS 2004 and comparison with magnetostratigraphically calibrated mammal localities in Anatolia. Correlation of the Inkonak and Harami sites according to Krijgsman et al. (1996).

for Eurasia (Torsvik et al., 2008). Comparison of the expected and measured directions leads us to conclude that the intra-montane basins of the Central Dinarides have hardly rotated since their lacustrine sediments accumulated. The coherence of these results suggests that the Dinaride Block as a whole experienced no tectonic rotation since the Late Oligocene.

## 5. A compilation of Mesozoic and Cenozoic paleomagnetic data: the differential rotation of crustal fragments in the Dinarides

We have made a compilation of available literature data, ranging in age from early Cretaceous to Miocene to place our rotation results for the Central Dinarides in a comprehensive framework (Supplementary material). To facilitate comparison between the compiled paleomagnetic data and the palinspastic reconstruction of Ustaszewski et al. (2008a) we adhere to their tectonic subdivision and group the data accordingly. In the study area, four different tectonic blocks are distinguished (Fig. 6). The first of these blocks, progressing from the more internal to the more external parts of Adria, is its undeformed segment, exposed on a large part of the Istria peninsula. The second block, called SW imbricated Adria and Dalmatian Zone, consists of the southern part of the Croatian coast and islands attributed to the Dalmatian zone. The third block, called NW imbricated Adria and High Karst, consists of the northern Croatian islands and a large part of the imbricate structures of the High-Karst west of the Split–Karlovac fault. The fourth and last block, called the Dinaride Nappes and SW High Karst, consists of the Budva-Cukali zone, the High-Karst, Dalmatian and Pre-Karst units, the East-Bosnian Durmitor and Drina-Ivanjica nappes and obducted ophiolites, situated between the Split–Karlovac fault and Skadar–Peć (Shkodra/Scutari–Pejë/Peja) line.

All paleomagnetic data of the four investigated blocks come from sedimentary rocks (Supplementary data). After categorization according to location, the data were grouped according to age. For each site the net rotation was calculated based on a comparison of the observed declination with the directions of the magnetic field expected based on the location of the paleomagnetic pole of Eurasia with a corresponding age (Torsvik et al., 2008). For each age and location group, the mean declination was calculated using Fisher statistics, after the VanDamme cut-off was applied to exclude outliers (Supplementary data).

The amounts and timing of rotation for each of the four blocks that constitute the Dinarides with respect to Europe resulting from our compilation are summarized in Table 2 and Fig. 6. Undeformed Adria has rotated $48\pm10°$ counterclockwise (CCW) since the early Cretaceous of which $34\pm7°$ occur since the Middle Cretaceous. Its post Eocene rotation amounts to $28\pm13°$ but the post-20 Ma rotation is not constrained by paleomagnetic data. The small number of pre middle Cretaceous sites on the High Karst NW part of the imbricated carbonate platform, forces us to group all of them together and derive a $32\pm7°$ CCW rotation for this block. The Eocene rocks are rotated by a similar amount, although the error is very high. The post early Miocene rotation of the NW High Karst block is purely determined by data from the lacustrine Pag locality and amounts to only 3° CCW. The Dalmatian SW part of the imbricated carbonate platform has rotated $21\pm11°$ CCW since the Cretaceous, of which $15\pm7°$ CCW has occurred since the Eocene. The post 20 Ma rotation of this block is poorly constrained. The average rotation of sites in lacustrine sediments and positioned on the SW High Karst imbricated carbonate platform, pre-karst, Bosnian flysch, and Dinaric nappes amounts to only $3\pm6°$ CCW and thus indicates that this block did not experience any significant rotation since the late Oligocene.

The paleomagnetic data from the Sutorina Valley in Montenegro (Kissel et al., 1995), require an additional explanation. The sampled flysch sections in this valley are in principle located on the Dalmatian part of the carbonate platform according to the geological map (1:100.000). Paleomagnetic data indicate that these sites have hardly rotated since the Eocene. On the other hand, this does not accord with the 15° CCW rotation of the other sites located on this block. There are two possible explanations. First, the sampled "flysch" sections could be of Miocene rather than of Eocene age. Some authors in fact consider parts of the Eocene flysch deposits exposed along the Croatian Adriatic coast as Miocene, based on nannoplankton studies (Mikes et al., 2008, and references therein). This solution would imply the Dalmatian zone docked against the Central Dinarides just prior to the Miocene and has not rotated since. An alternative explanation would be that the Sutorina Valley flysch is actually located in the Budva-Cukali Zone, which then consequently would not have rotated since the Eocene.

We realize that we use pre-20 Ma data for undeformed Adria and the Dalmatian zone with post 20 Ma data for the Central Dinarides block. Absence of Miocene rocks on the former two blocks excludes a better paleomagnetic estimate of their post 20 Ma rotation. There

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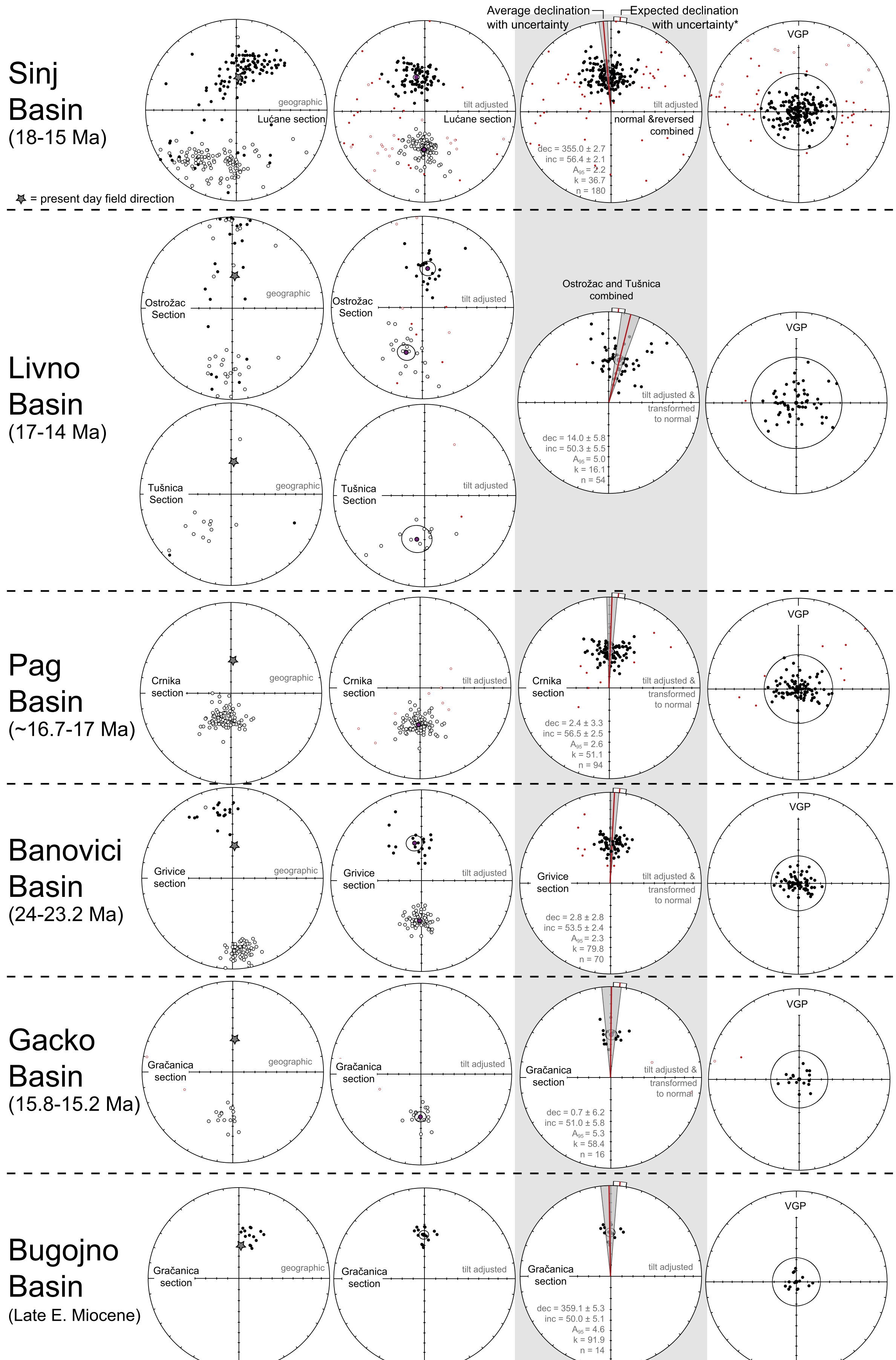


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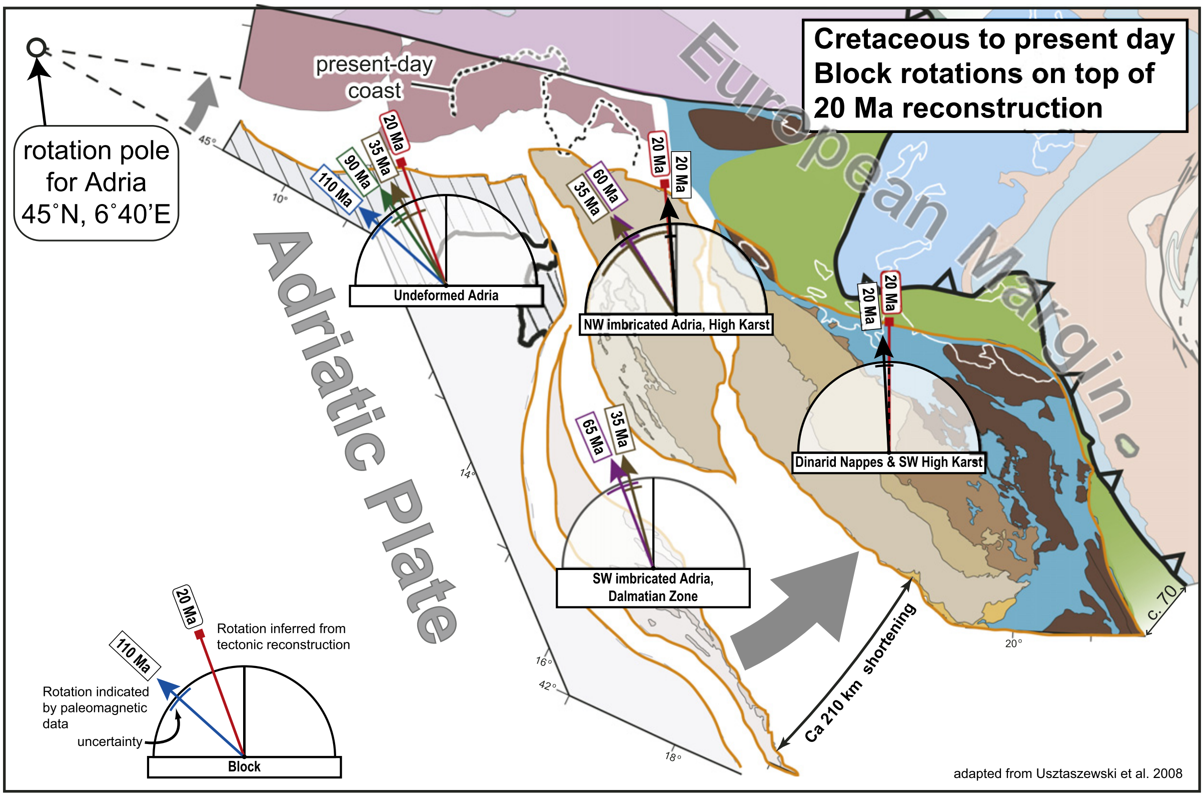


**Fig. 6.** Cretaceous to present day block rotations compiled from the available literature on top of the 20 Ma reconstruction of Ustaszewski et al. (2008a) of the different tectonic units that the Dinarides comprises. Arrows indicate the average rotation of rocks of the indicated age. The partial arc intersecting the arrows indicates the corresponding uncertainty. The rotation pole of Adria was drawn according to Ustaszewski et al. (2008a).

are currently no data older than the Late Oligocene available from the Central Dinarides.

The new paleomagnetic data from the Late Oligocene to Middle Miocene Dinaride Lakes clearly fit in the framework provided by the compiled Mesozoic and Cenozoic paleomagnetic data. Both magnitude and timing of the rotation are furthermore in good agreement with the rotations estimated by Ustaszewski et al. (2008a).

The apparent mismatch between paleomagnetic and structural geological data concerning the post-Eocene rotation of Adria originally arose from a postulated post-Pontian 30° rotation of sites in the Croatian part of the Pannonian basin (i.e. younger than 6.0–4.7 Ma, Krijgsman et al., 2010) attributed to push from the CCW rotation of Adria. This was assumed to have affected the whole Dinaride Block (Márton et al., 2003). However, paleomagnetic directions from Late Oligocene to Middle Miocene lacustrine sites located on the SW High Karst imbricated carbonate platform, pre-karst, Bosnian flysch, and External Dinaride nappes confirm that this block has not rotated since the late Oligocene. This is in agreement with the data of Kissel et al. (1995). The counterclockwise rotation of Adria cannot therefore, have driven the very young rotation of sites in the southwestern Pannonian basin. This rotation is most probably attributable to the last tectonic inversion event (latest Miocene to Pleistocene) in that part of the Pannonian Basin, which in places is characterized by NE–SW oriented strike slip faulting and temporally corresponds with the timing of the rotations (Márton et al., 2002). It is thus most likely that Adria has rotated only 20° since 20 Ma, as indicated by structural geological data (Ustaszewski et al., 2008a).

The lack of rotation of the Central Dinarides implies a decoupling of Dinarides from the Tisza–Dacia Mega-Unit. The latter block experienced a major clockwise rotation during the Miocene (van Hinsbergen et al., 2008). The differential movement between the two blocks could be accommodated along the sinistral strike-slip faults observed in the Southern Pannonian Basin (Pavelić, 2001; Tari-Kovačić, 2002). (Ustaszewski et al., 2008a) assumed that the Dinarides have remained attached to the Tisza–Dacia Mega-Unit but nevertheless had to make some geometrical adjustments along the Sava Zone thus acknowledging that a certain amount of decoupling has occurred.

## 6. Comparison of the compiled paleomagnetic data with the apparent polar wonder paths of Europe and Africa: can Adria be considered an independent micro-plate?

We have compared the compiled paleomagnetic data for the four blocks defined above with the apparent polar wonder path (APWP) of Europe (Torsvik et al., 2008) to determine their differential rotation with respect to Europe. We will now extend our analysis and compare the same dataset with the APWP of Africa (Torsvik et al., 2008) (Supplementary material) in order to assess if Adria was indeed an independent micro-plate in the time-span covered by the data. The rotation of the tectonic blocks in the study area with respect to Africa (Table 3) has been calculated in a similar way as their rotation with respect to Europe (Table 2). The results indicate that the blocks pertaining to Adria (undeformed Adria and the NW and SW parts of the imbricated carbonate platform) rotated around 60° CCW with respect to Africa and approximately 20° CCW with respect to Europe between the Late Jurassic and the Eocene and thus support an independent Adriatic Plate in this time period, in agreement with the

**Fig. 5.** Equal area diagram with ChRM directions for the sampled sections and sites in the different intra-montane basins. The red line indicates the average declination and the gray area the corresponding uncertainty (dDx). For a detailed explanation, we refer to the main text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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**Table 2**
Summary of the compiled rotation for each of the blocks the Dinarides comprise per time period with respect to Eurasia. For the purpose of comparison, the amount of rotation since 20 Ma as predicted by the tectonic reconstruction by Ustaszewski et al. (2008a) is listed. Counterclockwise rotations are denoted as negative, while clockwise rotations are positive.

| Block | Tectonic reconstruction | Paleomagnetic data | | | | |
|---|---|---|---|---|---|---|
| | <20 Ma | 14–24 Ma | 34–56 Ma | 66–71 Ma | 89–112 Ma | 112–151 Ma |
| Undeformed Adria | −20 | | −28 ± 13 | | −34 ± 7 | −48 ± 10 |
| NW part of the imbricated carbonate platform: high karst | −5 | −3 ± 4 | −34 ± 28 | | −32 ± 7 | |
| SW part of the imbricated carbonate platform: Dalmatian zone | −20–0 | | −15 ± 7 | −21 ± 11 | | |
| SW part of the imbricated carbonate platform: Dalmatian or Budva-Cukali zone | Not included | ? | −1 ± 5 | | | |
| SW imbricated carbonate platform (high karst), pre-karst, Bosnian flysch, and Dinaric nappes | 0 | −3 ± 6 | | | | |

reconstructions of Schmid et al. (2008). It should be noted that the rotation with respect to Africa is larger than that with respect to Eurasia until 66 Ma. This relation then reverses and from 56 Ma onwards the rotation of the Adria derived blocks with respect to Africa is smaller than with respect to Eurasia. This suggests that coupling of Adria with Africa became larger than its coupling with Eurasia during the Eocene, coincident with the onset of uplift in the Dinarides and the first accumulation of flysch deposits in the foreland (Ćorić et al., 2008). Because Adria experienced differential rotation with respect to both Europe and Africa from the Late Jurassic to the Eocene, and from the Eocene to present day, we consider it most likely that it behaved as an independent plate.

## 7. Neogene to recent deformation: AMS as an indicator of post-depositional strain

The anisotropy of the low field magnetic susceptibility (AMS) of sedimentary rocks provides a rapid and precise description of the average preferred mineral orientation, or fabric (Mattei et al., 1997). This fabric may in turn reflect the regional stress field (Tarling and Hrouda, 1993) and its recognition can shed light on the tectonic evolution of the area under consideration. In this study, we measured the AMS of 400 samples from 9 different sections according to the same methodology as applied by Vasiliev et al. (2009). The AMS tensors were calculated according to Jelínek (1977). Error ellipses of the susceptibility axes are calculated according to Jelínek and Kropáček (1978).

Fig. 7 provides an overview of the acquired AMS data for the Dinaride basins. The sediments of the Sinj, Gacko and Bugojno basins displayed only weak anisotropy, while a clear AMS pattern could be established from the other basins. Here, the minimum axis is generally oriented perpendicular to the bedding plane, which is characteristic of sedimentary fabrics. The maximum and intermediate axes are generally orthogonal and are interpreted to reflect post-depositional strain.

For the lacustrine sediments that accumulated on top of the Dinaride Carbonate Platform, i.e. the Pag and Livno–Tomislavgrad basin, the maximum axis of anisotropy (red arrows in Fig. 7) aligns with the average structural trend of the mountain range. This suggests that these basins were subject to compression orthogonal to the Dinaridic strike after deposition of the lake sediments, in marked contrast to results from the more internal parts of the orogen, i.e. the Sarajevo, and Banovići basin. Here, the maximum susceptibility axis is oriented perpendicular to the structural trend. This is interpreted to indicate post-depositional extension perpendicular to the mountain range. In Ugljevik, the maximum susceptibility axis is oriented nearly E–W and parallel to the average local strike in agreement with subsurface data (Horváth, 1995). In our view, this reflects a phase of N–S compression rather than E–W extension. Our results thus suggest that while NE–SW directed compression continued in the external Dinarides in post Middle Miocene times, the internal Dinarides underwent from NE–SW to N–S directed extension. The northeastern boundary of the orogen was affected by a post Langhian phase of N–S compression.

Our interpretation agrees well with the general post-orogenic tectonic framework for the Dinarides. In the Late Miocene and Pliocene, the collisional systems surrounding the Pannonian basin became locked and the region was subject to a compressional stress field (Huismans et al., 2002). The continuing NW motion of the Adriatic indenter led to N–S shortening across the Dinarides; this was associated with surface uplift and erosion and induced dextral wrenching along orogen parallel strike-slip faults (Ilić and Neubauer, 2005). Along the southern margin of the Pannonian basin, subsurface data demonstrate general inversion (Horváth, 1995). It is this phase of N–S compression that is also reflected in the AMS data for the Ugljevik basin. In the external and southern internal Dinarides, the direction of shortening was more NE–SW directed (Fodor et al., 1999; Ilić and Neubauer, 2005; Oldow et al., 2002), which is corroborated by the AMS results for the Pag and Livno–Tomislavgrad basins.

It is striking that late Oligocene sediments of the Banovići basin and Early Miocene sediments of the Sarajevo basins show maximum susceptibility axes with NE–SW directions. This signifies either orogen parallel compression or extension perpendicular to the orogen. The latter explanation seems to be more viable in this case since the second phase of intra-montane basin formation, in which extension penetrated deep into the Dinarides, largely postdates the sampled sediments. It is noteworthy however, that the late Miocene to recent inversion is not reflected in the AMS of these sediments.

**Table 3**
Summary of the compiled rotation for each of the blocks the Dinarides comprise per time period with respect to Africa. Counterclockwise rotations are denoted as negative, while clockwise rotations are positive.

| Block | Average amount of rotation sites within this age range have experienced with respect to Africa | | | | |
|---|---|---|---|---|---|
| | 14–24 Ma | 34–56 Ma | 66–71 Ma | 89–112 Ma | 112–151 Ma |
| Undeformed Adria | | −22 ± 13 | | −47 ± 7 | −87 ± 10 |
| NW part of the imbricated carbonate platform: high karst | −3 ± 4 | −27 ± 28 | | −45 ± 7 | |
| SW part of the imbricated carbonate platform: Dalmatian zone | | −8 ± 7 | −28 ± 11 | | |
| SW part of the imbricated carbonate platform: Dalmatian or Budva-Cukali zone | ? | 7 ± 5 | | | |
| SW imbricated carbonate platform (high karst), pre-karst, Bosnian flysch, and Dinaric nappes | 0 ± 6 | | | | |

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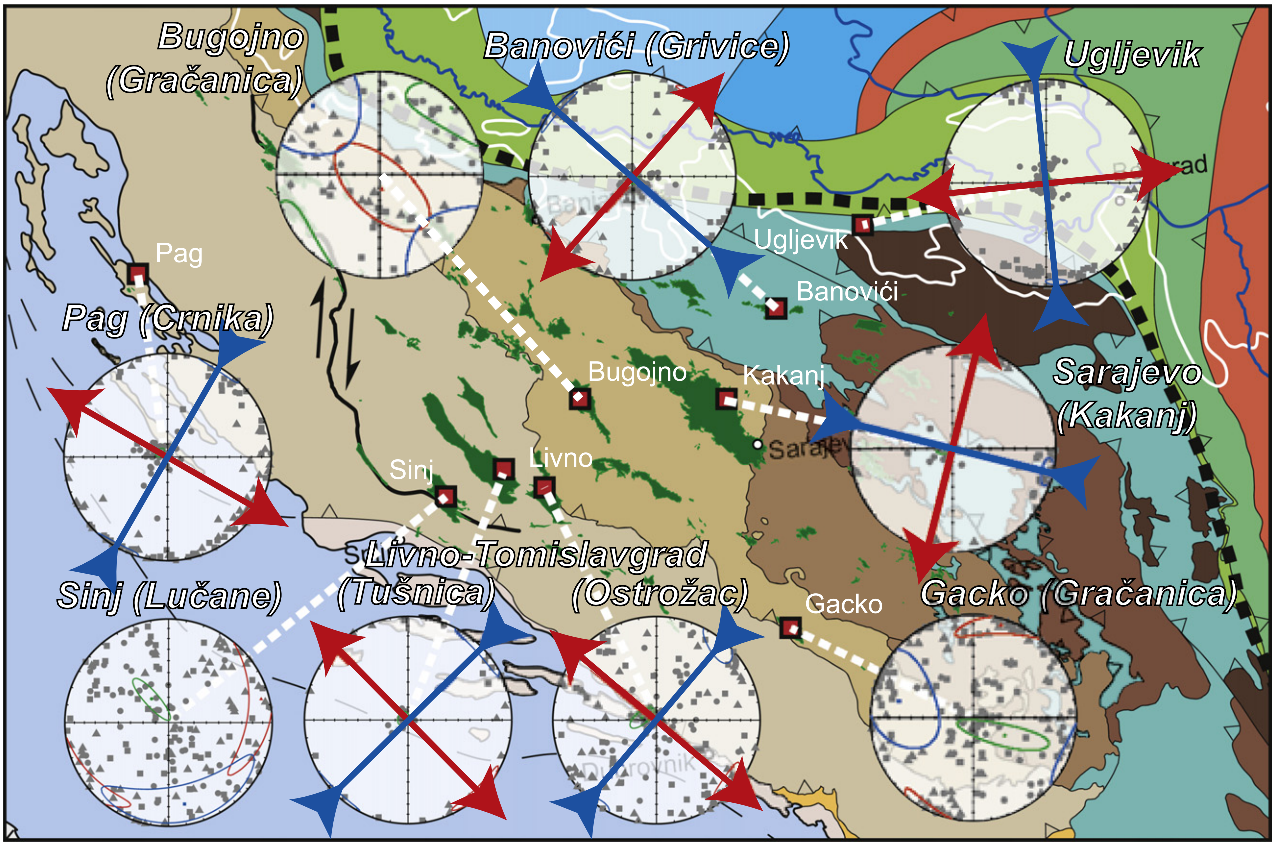


**Fig. 7.** Overview of AMS directions for the suite of sampled sections. In the equal area diagrams, circles indicate the minimum axes, squares the intermediate, and triangles the maximum axes of elongation. Anisotropy in the samples from the Sinj, Gacko and Bugojno basins was very low, which results in a large spread in directions. For the other locations the minimum axis is orthogonal to the bedding plane, as expected for a sedimentary fabric. The red arrows indicate the direction of potential extension, while the blue arrows indicate the direction of potential compression. Underlying map with tectonic units adapted from Ustaszewski et al. (2008a), for the legend, see Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 8. Consequences for the post-orogenic evolution of the Dinarides

Our results provide new insight into the post early Oligocene evolution of the Dinarides. The newly constructed chronology elucidates the timing of intra-montane basin formation. A first cycle of lacustrine sediments accumulated in basins induced by strike-slip faults penetrating deeply into the orogen (Hrvatović, 2006) in the latest Oligocene (Fig. 4). Optimum climatic conditions (Zachos et al., 2001) may have stimulated the formation of these lakes (de Leeuw et al., 2011a). Sedimentation apparently stalled in the Aquitanian and Early Burdigalian. A second and extensive phase of lacustrine deposition took place from 18 to ~13 Ma (Fig. 3). The Dinaride Lake System spread out over large parts of the orogen, when the Miocene Climatic Optimum (Zachos et al., 2001) induced favorable climatic conditions. The coincidence of this phase of intra-montane basin formation with the main phase of extension in the Pannonian Basin System suggests a causal link. Rifting-induced extension apparently penetrated into the Dinarides with an influence extending to its westernmost external reaches. This conclusion is corroborated by the data of Ilić and Neubauer (2005) who studied paleostress indicators near Prijepolje in the Central part of the Eastern Dinarides. They document a phase of NE–SW extension that resulted in opening of the intra-montane basins and occurred in conjunction with the main phase of extension in the Pannonian Basin. A phase of orogen parallel NW–SE directed extension followed and stimulated further growth of the basins.

Concurrent with the accumulation of DLS sediments in the intra-montane realm, lacustrine and alluvial sediments accumulated in the Sava and Drava depressions (Fig. 3). In the lower part of calcareous nannoplankton zone NN5 these basins subsided below the base-level of Paratethys and were flooded by marine incursion (Ćorić et al., 2009).Whereas some authors invoke a strike-slip mechanism to account for the subsidence of the Sava and Drava depressions (Hrvatović, 2006; Tari-Kovačić, 2002), others characterize them as half-grabens (Fodor et al., 1999; Pavelić, 2001).

Around 15 Ma, coal formation indicates shallowing of the Gacko basin, shortly after which sedimentation came to a halt. Simultaneously, coal formation in the Sinj basin intensified and breccias, originating from the margins, entered the lake. Carbonate sand layers entered the Livno–Tomislavgrad basin around the same time, and soon after, the first limestone breccias appeared in the Mandek section. An intensification of compressional tectonic activity is indicated by a coarsening and thickening of the breccias. Deposition continued until at least 13 Ma. While sedimentation in the intra-montane basins came to a halt, the central part of the study area was inverted (Tari-Kovačić, 2002). In the Sava and Drava depressions, deposition came to a halt as well, and a Late Sarmatian erosional unconformity developed (Saftić et al., 2003).

The Late Miocene to Pliocene evolution of the mountain chain was characterized by renewed shortening and dextral wrenching (Ilić and Neubauer, 2005; Picha, 2002; Pribicević et al., 2002; Tari-Kovačić, 2002). During this period most major faults accommodated a significant amount of strike-slip motion and this has significantly influenced the present day structural fabric of the study area. Interestingly, several authors (Hrvatović, 2006; Tari-Kovačić, 2002) have also invoked a strike-slip mechanism for the formation of the Miocene intra-montane basins. One of the main arguments for this is that the basins are often associated with major faults bear a strike-slip signature and generally have an en-echelon shape. The detailed stress analysis by Ilić and Neubauer (2005), on the other hand, reveals NE–SW

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extension during the Early to Middle Miocene. The extensional faults responsible for this have in most cases been reactivated and overprinted during late-stage wrenching. While a strike-slip component during the Miocene cannot be excluded, it is also possible that the intra-montane basins were formed by orogen-perpendicular extension and received their en-echelon shape later.

The current seismic activity and ongoing convergence between Adria and Europe (Bennett et al., 2008; Grenerczy et al., 2005; Oldow et al., 2002) indicate that deformation in the Dinarides is ongoing. A change in GPS velocities (Bennett et al., 2008; Grenerczy et al., 2005) between the central Dinarides, the Dalmatian coast and Adria, indicates that differential motions are taking place between these plates. This favors a model in which the larger part of the Adria push is accommodated by deformation within the Dinarides and only a small amount is transferred further east. Miocene, Pliocene and even Quaternary sediments are affected by faults (Dragičević et al., 1999; Pribicević et al., 2002) and the frontal thrusts are at present located in the Adriatic, just offshore the Croatian Islands (Korbar, 2009; Schmid et al., 2008; Tari-Kovačić, 2002).

## 9. Conclusions

An initial phase of basin formation struck the Dinarides in the latest Oligocene as evident from for example, the Banovići Basin. A second and more profound phase started around 18 Ma and continued until at least 13 Ma. It thus coincided with a phase of severe extension in the Pannonian Basin System, which suggests a causal link. At that time, the Dinaride Lake System extended from the Pag Island in the far west to the Gacko basin in the south and the Southern Pannonian Basin in the East. The prevailing optimum climatic conditions stimulated formation of the lakes. Our new paleomagnetic results and a reinterpretation of available data from the literature indicate that the Dinarides have not rotated since the deposition of the DLS sediments. This implies that the rotation of Adria was not transferred to the Croatian margin of the Pannonian Basin and that the shortening resulting from this rotation must have been mainly accommodated within the Dinarides, in accordance with the present-day GPS results. AMS results corroborate a post Middle Miocene shortening along the frontal zone of the Dinarides. In the more central parts of the Dinarides, the AMS pattern most likely reflects extension orthogonal to the average Dinaride strike. The absence of rotation in the Dinarides implies that the orogen remained largely decoupled from the Tisza–Dacia block since 24 Ma.

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