Late Neogene counterclockwise rotation in the SW part of the Pannonian Basin

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Abstract: Earlier paleomagnetic studies suggested that counterclockwise rotating Adriatic microplate could have triggered the youngest rotations in the Hrvatsko Zagorje area (in the Slavonian Mts) and in the Mura-Zala Depression. Since the named areas are located quite far from the Eastern Adriatic coast, we decided to study the Krško and Karlovac Basins, which are situated in-between. From the collected 12 paleomagnetic localities (Badenian through Pontian sediments) ten yielded good paleomagnetic directions as a result of laboratory processing and statistical evaluation. They definitely point to the counterclockwise rotation of the area in post Early Pontian times. The angle of the rotation is about 20° (D=337°, I=50°, k=48, α_{95}=10°). Thus, we have found a missing tectonic link from the Hrvatsko Zagorje, Slavonian Mts and the Mura-Zala Basins to the Adriatic microplate and collected further paleomagnetic evidence for end of Miocene or even younger important tectonic movements in the South Pannonian Basin.

Key words: Neogene, South Pannonian Basin, paleomagnetism, rotation.

Introduction

At the southwestern rim of the Pannonian Basin in eastern Slovenia and northwestern Croatia, different pre-Neogene tectonic units are juxtaposed due to the complex tectonic evolution of this area (Fig. 1; Haas et al. 2000 and references therein). These units are mostly composed of Paleozoic and Mesozoic rocks of Dinaric, South Alpine and East Alpine affinity and comprise the basement overlain by Neogene sediments of the Mura Depression, Hrvatsko Zagorje, Sava Folds basins, including the Krško and Karlovac Basins. Paleomagnetic directions so far obtained for the Neogene sediments of the Mura Depression and the Hrvatsko Zagorje Basin show westerly declinations of remarkable consistency, which imply a definitely post Early Pontian, perhaps even a Lower Pliocene counterclockwise (CCW) rotation of these basins together with basins of similar age in the Slavonian Mts (Márton et al. 2002a,b). According to the interpretation of Márton et al. (2002b, 2003) this rotation is connected to the NNE motion and CCW rotation of the Adriatic microplate (Anderson & Jackson 1987; Calais et al. 2002; Devoti et al. 2002). This interpretation, however, is hampered by the fact that the Mura Depression, the Hrvatsko Zagorje Basin and the Slavonian Mts are located far away from the Eastern Adriatic coast, which belongs to the recently also moving and CCW rotating Adriatic microplate. By paleomagnetic measurements of Neogene sediments outcropping along the southwesternmost margin of the Pannonian Basin in Slovenia and Croatia, that is on the northern rims of the Krško and Karlovac Basins, respectively, we intended to "reduce the distance" and to fill up the data gap. Accordingly, we had to answer the question of whether the Badenian–Pontian sediments in this area provide a tectonic link towards Adria, or call for an interruption and alternative interpretation.

Geology and paleomagnetic sampling

The study area is located within the Sava Folds or the Sava transpressive wedge (e.g. Placer 1998), which belongs to the regional NE-SW striking Zagorje–Mid-Transdanubian Zone (Pamić & Tomljenović 1998). The zone is bounded by the Periadriatic-Balaton and Zagreb-Zemplén Lineaments to the north and south, respectively (Fig. 1; Csontos & Nagymarosy 1998; Fodor et al. 1998; Poljak et al. 2000; Haas et al. 2000 and references therein). Structurally, it is characterized by predominantly E- to ENE-striking kilometer scale folds and faults of Neogene–Quaternary age (Placer 1998; Prelogović et al. 1998; Tomljenović & Csontos 2001).

The Krško Basin is an asymmetrical syncline built up in its core by Ottnangian to Pontian sediments more than 2000 m thick (Poljak & Gosar 2001). Following a NE trend,

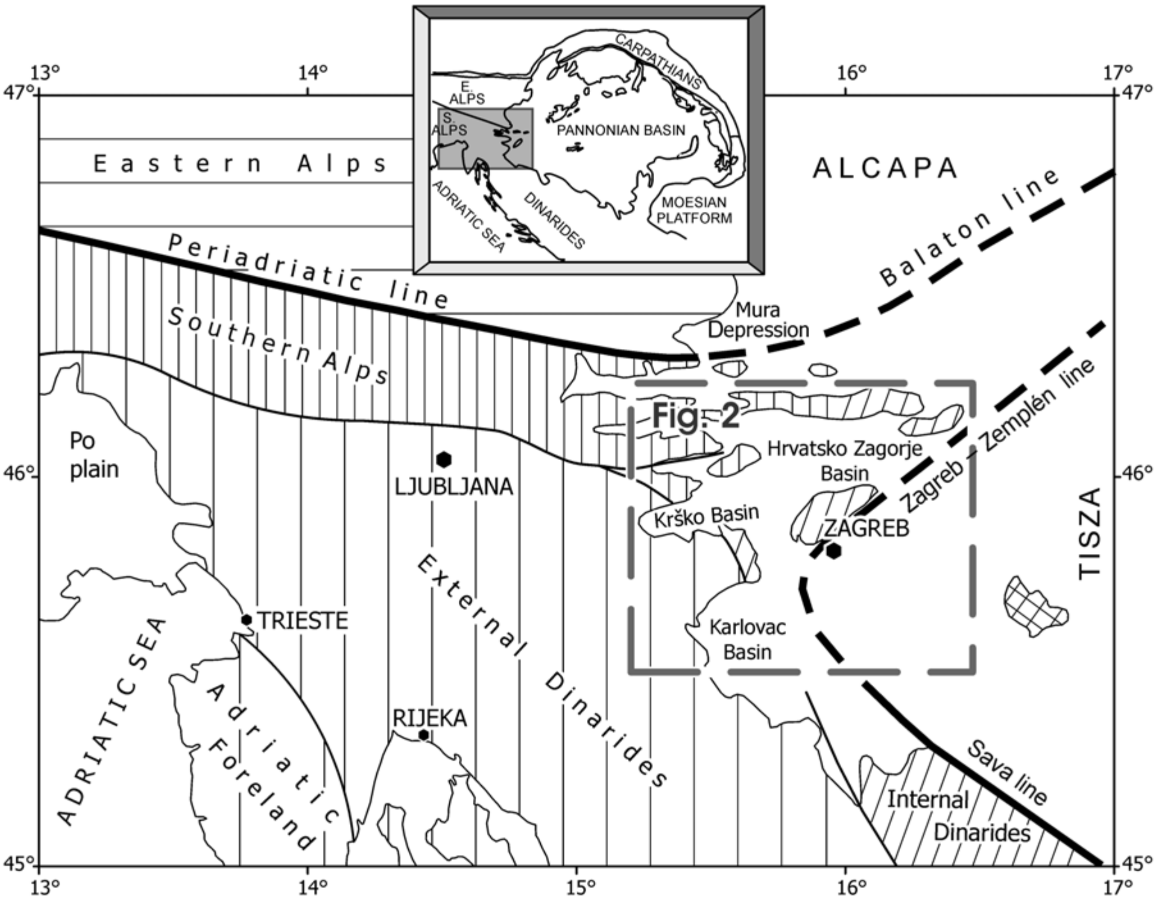

Fig. 1. Pre-Neogene basement at the junction of the Alps, Dinarides and the Pannonian Basin with major tectonic lines and Neogene sub-basins.

the syncline extends without a break into the Konjščina syncline (Hrvatsko Zagorje Basin, Šimunić et al. 1983, Tomljenović & Csontos 2001). The syncline transits into the Krško hills–Orlica anticline in the north, while it is bounded by the Žumberak/Gorjanci–Marija Gorica anticline or basement pop-up structure to the south. For the purpose of this study we collected samples from freshly excavated outcrops located along the northwestern limb of the Krško syncline (Fig. 2, localities 1–4) and from synclines north of it (Fig. 2, localities 8–10).

The Karlovac Basin is a NNW-trending graben located south of Žumberak/Gorjanci Mts, bounded by ENE-dipping listric and WSW-dipping antithetic normal faults (Tomljenović & Csontos 2001). During the Neogene, these faults accommodated several phases of predominantly ENE–WSW directed extension (most probably starting in the Ottnangian) followed by periods of shortening and inversion. The latest, Pontian to recent (ca. 6–0 Ma) shortening is particularly well observable along the northwestern basin margin, that is along the southeastern slopes of Žumberak/Gorjanci Mts where sediments of Badenian–Pontian age are exposed and were sampled for this study (Fig. 2, localities, 5–7).

Stratigraphy, depositional style and the history of Miocene deposits outcropping on the northwestern margins of the Krško and Karlovac Basins are similar (Fig. 3). The old-

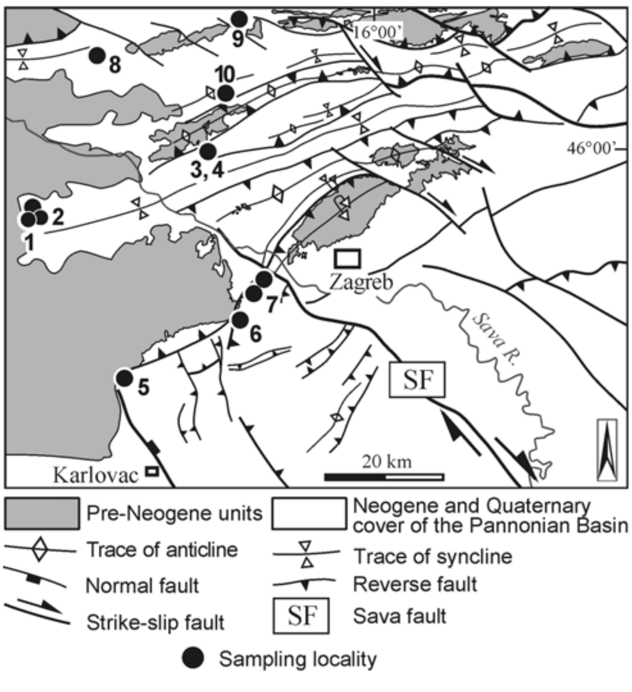

Fig. 2. Structural map of the study area with the successful paleomagnetic sampling localities numbered.

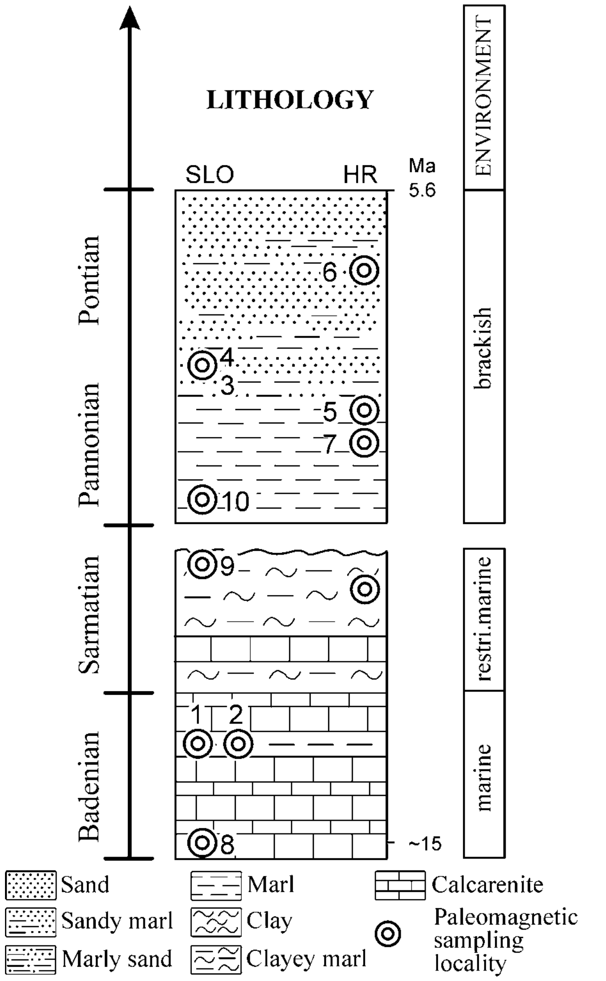

Fig. 3. Generalized lithological column of the sampling area also indicating environmental conditions.

est outcroping Neogene sediments are of Ottnangian–Karpatian age. Badenian is the time of marine transgression both in the Krško and Karlovac Basins. The sea became shallow at the end of Badenian. In the Sarmatian the salinity decreased and a basin of restricted salinity formed, reflecting reduced connection with the sea. Typical sediments are calcarenites and marls. The end of the Sarmatian is marked by a general shallowing trend, due to the onset of basin inversion (and of eustatic sea-level drop). A new sedimentary cycle started with the deposition of marls in the brackish Pannonian-Pontian lake. Upward in the succession, coarser clastic sediments appear, connected with sandy delta progradation. Miocene deposits are conformably or unconformably overlain by Pliocene and Pleistocene siliciclastic deposits, accumulated in small fresh water lakes, swamps and rivers (Verbič et al. 2000).

The collected paleomagnetic samples represent marl or clayey marl horizons of fresh artificial outcrops, such as building sites. Distribution of sampling localities with respect to their lithology, biostratigraphic ages and location within the two basins are shown in Figs. 2 and 3. The time represented by the studied rocks is about 9 million years, starting with 15 Ma (Badenian) and ending with 5.6 Ma (Pontian; Fig. 3). In spite of the young age, the sediments are considerably tectonized, mostly due to the latest shortening and basin inversion of Late Pontian to Quaternary age (Tomljenović & Csontos 2001).

Paleomagnetic measurements and results

The samples, which had been drilled and oriented in the field (the total number of collected localities is 12, successful localities are numbered in Fig. 2), were subjected to paleomagnetic measurements and analysis in the Paleo-

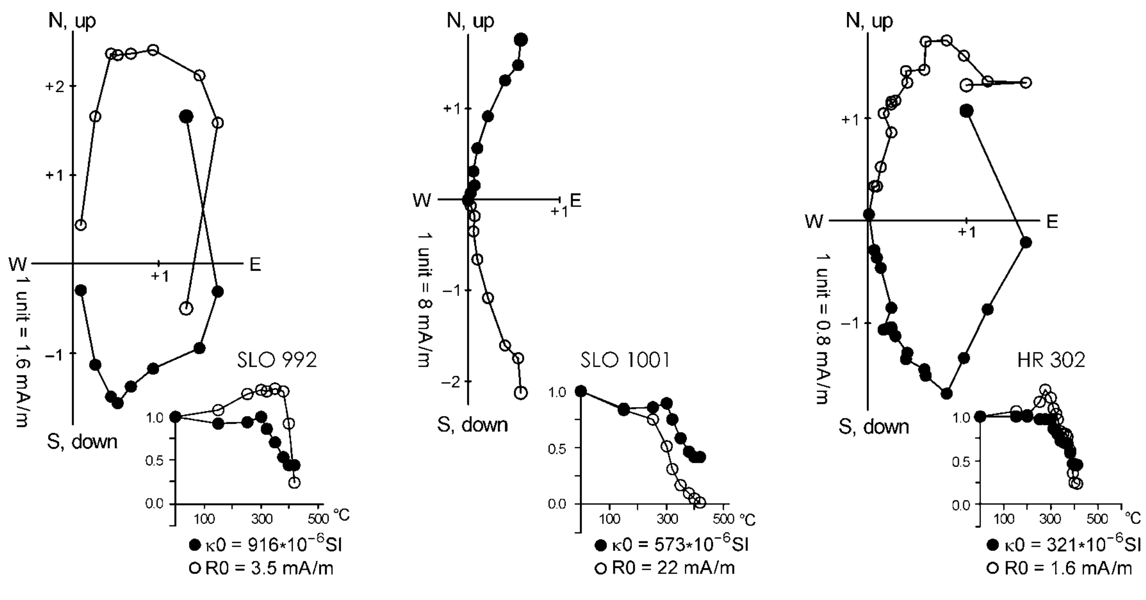

Fig. 4. Examples of the demagnetization behaviour of the natural remanent magnetization (NRM) and the magnetic susceptibility. In the Zijderveld diagrams, full/open circles: projection of the NRM in the horizontal/vertical plane; in the others susceptibility: dots, NRM intensity: circles. Note that the intensity of NRM decays parallel to the decay of the susceptibility, indicating that the NRM is basically residing in greigite.

magnetic Laboratory of the Eötvös Loránd Geophysical Institute of Hungary. The natural remanent magnetization and the magnetic susceptibility were first measured in the natural state, using JR4 and cryogenic magnetometers and KLY-2 kappabridge, respectively. The samples were subsequently demagnetized: most of them thermally, some of them by the alternating field method. The remanence was remeasured after each heating step and also the susceptibility, in the former case. The measurements were evaluated in the following way. Linear segments had been defined from the demagnetization curves (Fig. 4), and the corresponding directions subjected to statistical analysis. The exception is one of the Badenian localities (Table 1, locality 1), where the mean direction is based on the last demagnetization steps, before loosing (due to the weakness of the remanence) the magnetic signal.

The carrier of the natural remanence is either magnetite (Fig. 5) (accompanied by pyrite, as indicated by the dramatic increase of susceptibility on heating) or greigite (evidenced by a substantial decrease of the susceptibility from 300 °C, closely followed by an increase, the first indicating phase change of the iron sulphide, the second, conversion to magnetite, Fig. 4).

The two localities, one from the Krško Basin and one from the Karlovac Basin failed to yield paleomagnetic direction. The rest are statistically excellent (Pannonian–Pontian localities, Table 1) or acceptable (Badenian localities, Table 1).

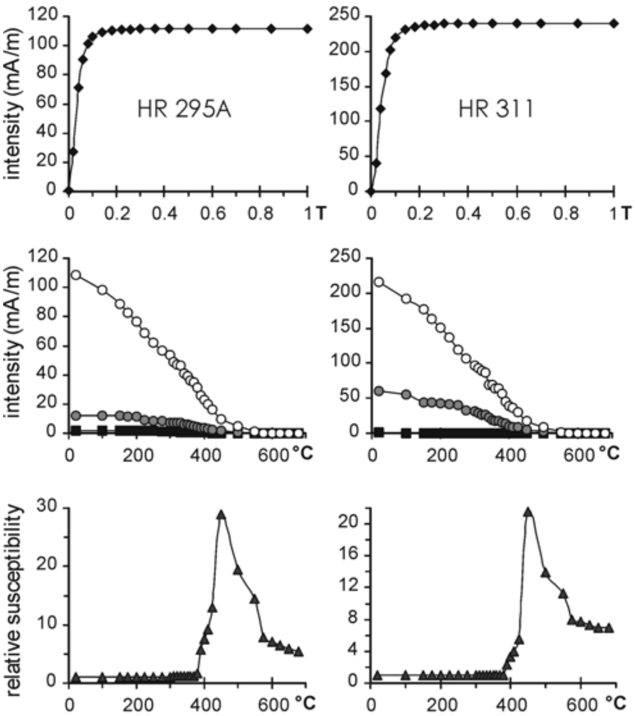

Fig. 5. Identification of the magnetic minerals. Typical isothermal remanent magnetization (IRM) acquisition curves (upper row), the behaviour of the three component IRM (Lowrie 1990) on thermal demagnetization (second row) and the change in susceptibility on heating (lowermost row). The hard (squares), the medium (dots) and soft (circles) components of the composite IRM were acquired in fields of 1.0, 0.36 and 0.12 T respectively.

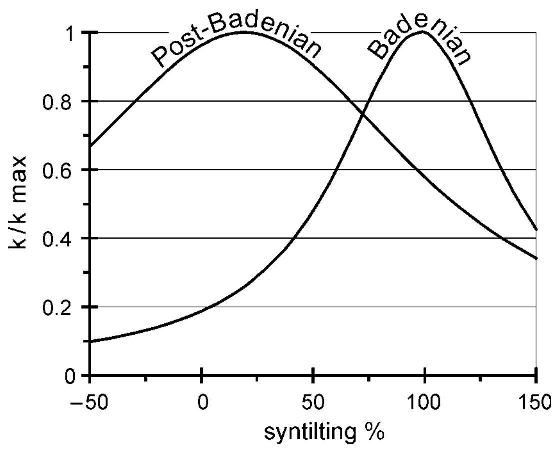

Fig. 6. Krško and Karlovac Basins, Neogene sediments. Regional tilt test for Badenian (positive response to untilting) and for younger (negative response) sediments.

Discussion and conclusion

The Badenian localities (Table 1, localities 1, 2 and 8) have westerly declinations, both before and after tilt corrections. Polarities are normal.

Among the younger localities, both normal and reversed polarities occur and their paleomagnetic directions are significantly different from that of the present Earth field, in the geographical co-ordinate system (before tilt correction).

Badenian localities 1, 2 and 8 (Table 1) give a positive response to a mechanically applied tilt test (Fig. 6). The overall mean direction in the tectonic system (after tilt corrections) is D = 309°, I = 60°, k = 35, α_{95} = 21°, N = 3). However, one cannot avoid noticing that two of the locality mean directions (localities 1 and 8) practically coincide, while the third one (locality 2) exhibits considerably larger CCW rotation than the first two (possible because of local tectonic disturbance).

While tilt test suggests that the paleomagnetic signal of the Badenian rocks was acquired before tilting, the same test is negative for the younger rocks. The overall mean direction calculated for the Pannonian–Pontian (and the Sarmatian, since the soft component is obviously not primary) localities is D = 337°, I = 50°, (statistical parameters k = 48, α_{95} = 10°, N = 6) before and D = 337°, I = 64° (k = 21, α_{95} = 13°, N = 6) after tilt corrections. Much better statistical parameters before tilt corrections suggest that the age of the remanence should be regarded as of post-tilting age, in spite of the mixed polarities. The lag between deposition and acquisition of the paleomagnetic signal does not hamper tectonic interpretation, since the age of the deposition is so young, that the time between deposition of the youngest rock (Pontian, around 7 Ma?) and deformation (starting around 6 Ma) is short, and the angle of the overall rotation is not influenced by tilt correction: it is the same (about 20°) in both the geographical and tectonic systems.

As the overall-mean paleomagnetic direction for the Badenian shows larger westerly deviation from the present

Table 1: Summary of the paleomagnetic directions. The mean paleomagnetic locality directions are based on the results of principal component analysis (Kirschvink 1980), except locality 1 (for explanation, see text). Key: **n/no** — number of used/collected samples; **D°, I° (Dc°, Ic°)** — declination, inclination before (after) tilt correction; k and α_{95}° — statistical parameters (Fisher 1953). Remark: locality 4 was excluded when calculating overall-mean paleomagnetic direction, due to suspected (on revisiting the locality) slumping.

Locality			n/no	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip
Krško Basin, Slovenia												
1	Šmarijeta SLO 955-960	*Badenian*	6/6	308	+66	28	13	327	+56	28	13	6/14
2	Dobruška Vas SLO 966-974	*Badenian*	6/8	287	+34	11	21	287*	+49*	26	13	110/45
8	Škarnice SLO 2127-132	*Badenian*	4/6	334	+16	65	12	318	+62	65	12	168/49
9	Nimno SLO 2145-150	*Sarmatian*	6/6	330**	+56**	186	5	344	+19	186	5	2/40
3	Pišece SLO 990-999	*Pannonian*	7/10	157	–51	68	7	162	–74	68	7	153/23
10	Hrastlje SLO 2160-170	*Pannonian*	8/11	336	+61	45	8	339	+62	45	8	92/2
4	Pišece SLO 1000-005	*Pontian*	6/6	20	+47	975	2	38	+59	975	2	160/18
Žumberak, Croatia												
5	Dol HR 289-299	*Pannonian*	6/11	142	–38	167	5	120	–49	167	5	196/25
6	Novoselci HR 300-307	*Pontian*	6/8	167	–42	91	7	181	–60	91	7	140/22
7	Molvice HR 308-313	*Pontian*	6/6	356	+51	320	4	12	+67	320	4	154/18

* — half of the samples without the other half after tilt correction, ** — soft component.

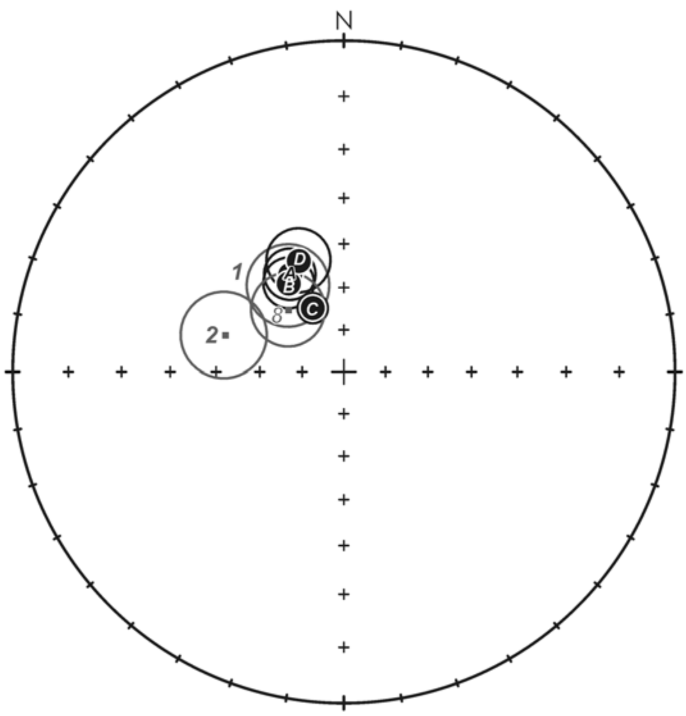

Fig. 7. Comparison between paleomagnetic overall-mean directions with confidence circles indicating the net post-Eocene rotation of the: **A** — Adriatic foreland (Márton 2006); **B** — net post-Pannonian rotation of the Mura–Zala Depression (Márton et al. 2002a); **C** — net post Early Pontian rotation of the Hrvatsko Zagorje plus Slavonian Mts (Márton et al. 2002b); **D** — and the net post Early Pontian rotation of the Krško–Karlovac Basins (present study). Badenian locality mean directions are numbered (numbers refer to Table 1). Stereographic projection.

north than that of the younger age group, one is tempted to interpret the difference as an earlier than the youngest counterclockwise rotation, taking place after the Badenian. However, the difference is due only to one locality (number 2, Table 1 and Fig. 7) and the paleomagnetic directions for the other two Badenian localities are very close to the overall-mean paleomagnetic direction for the younger age group (Fig. 7). Due to this situation we regard the larger westerly declination of the Badenian group as an indication to be followed up in the future, in contrast to the solid evidence of the present study for a post-Early Pontian 20° counterclockwise rotation.

Comparison between the results of the present study and earlier published paleomagnetic directions of corresponding age from the Hrvatsko Zagorje and the Mura-Zala Depression (Fig. 7) leads to the conclusion that the angles and the timings of the final CCW rotations are consistent in the whole south-western part of the basin. Since the area of the present study is closer to the Adriatic microplate than the previously investigated ones (Márton et al. 2002a,b) the idea of linking the rotation of the south-western Pannonian Basin to that of the Adriatic microplate became better supported than it was before the present study.

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