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New palaeomagnetic results from imbricated Adria: Ist island and related areas

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ABSTRACT

For the purpose of this work samples for palaeomagnetic analysis were taken from Upper Cenomanian and Lower Senonian shallow water limestones, as well as from Senonian pelagic limestones from both Ist and the surrounding islands. This area belongs to Imbricated Adria, which is characterized by gently folded and faulted strata with a Dinaridic (NW–SE) trend. An exception is Premuda island where the beds are strongly folded and are subvertical.
A total of 96 samples were drilled from 10 localities distributed between eight islands. The samples were then subjected to standard palaeomagnetic laboratory analysis and statistical evaluation. Eventually, six localities yielded statistically well-defined palaeomagnetic directions, which were shown pre date the folding in age.
The overall mean palaeomagnetic direction obtained for the study area, characterizing the Cenomanian–Early Senonian time period had a Declination of 334°, Inclination=+46°, with statistical parameters k=188, α_{95}=4.9°, defining a palaeomagnetic pole at λ(N)=63°, ϕ(E)=254°, δp=4.0°, δm=6.2°. This was compared with palaeomagnetic directions obtained for rocks of similar ages from stable Istria and the Kvarner islands. As the three palaeomagnetic directions are statistically identical, we conclude that there was no significant relative movement between the three areas after the Early Senonian.
The palaeomagnetic declination for the study area, which characterizes the post-Early Senonian rotation of the Adriatic microplate, is the same as the declination for the Pannonian–Pontian age group from the South Pannonian basin. As the palaeomagnetic signals in both cases are primary, the results of the present paper not only support the conclusion that the rotating Adriatic microplate triggered rotations in the South Pannonian basin, but also suggest that the Adriatic platform did not change its orientation between the late Cretaceous and the Early Pontian.

Keywords: imbricated Adria, palaeomagnetism, Late Cretaceous

1. INTRODUCTION

Tectonically oriented palaeomagnetic studies in Croatian territory started in the 1980s. The first results were published from Cretaceous rocks of stable Istria (area 1 in Fig.1, MÁRTON & VELJOVIĆ, 1983), followed by a number of papers concerning imbricated Istria and the Kvarner islands (MÁRTON & VELJOVIĆ, 1987, Fig. 1, areas 2–3), Kvarner islands (MÁRTON et al., 1990) and Dugi Otok (Fig 1., area 4) and Vis (Fig. 1, area 5) Islands (MÁRTON & MILICEVIĆ, 1994).

These results were obtained on platform carbonates which contain extremely small amounts of magnetic minerals, therefore, their bulk susceptibilities are invariably diamagnetic and their natural remanent magnetizations are of very low intensities. Consequently, platform carbonate samples sometimes fail to yield palaeomagnetic signals. Sometimes the palaeomagnetic directions have poor statistical parameters, as has been shown in pioneering work on the Adriatic platform carbonates. Nevertheless, there are quite a number of

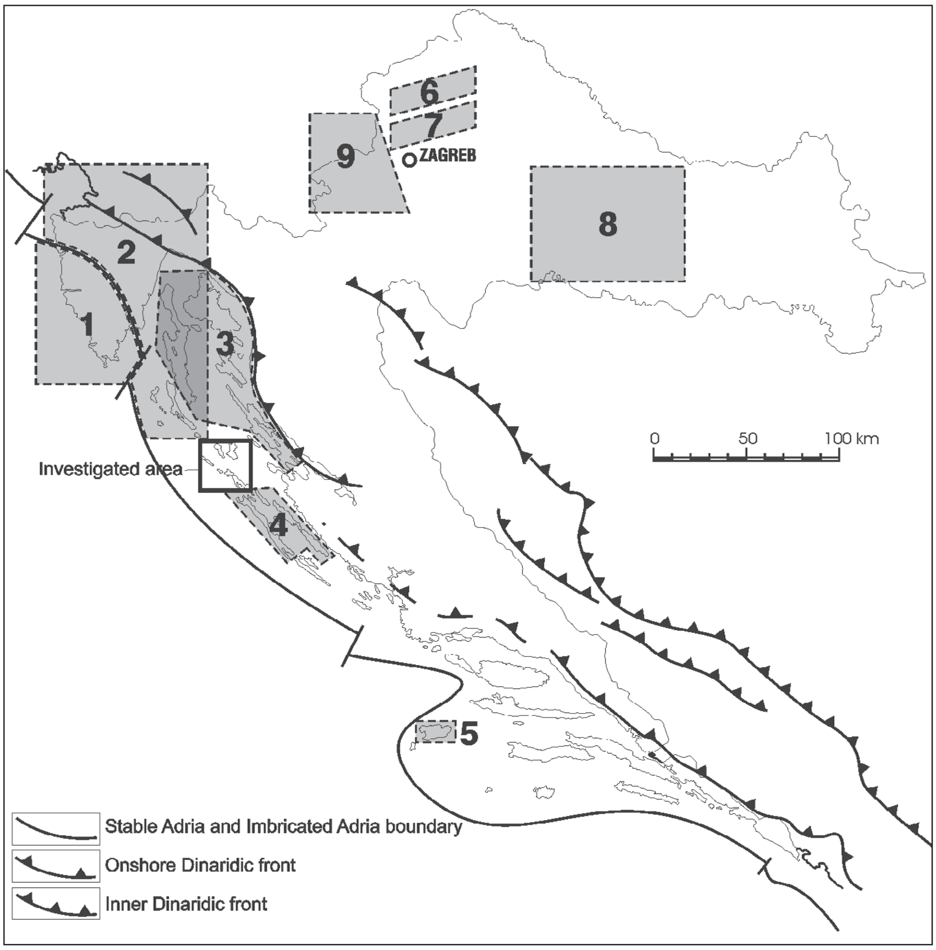

Figure 1: Sketch map of Croatia with main thrust fronts (after TARI, 2002 and MIKES et al., 2008). The areas of previous palaeomagnetic investigations are shaded. 1 – Stable Istria (MÁRTON & VELJOVIĆ, 1983, MÁRTON et al., 2003, 2008), 2 – Imbricated Istria and Kvarner islands (MÁRTON & VELJOVIĆ, 1987), 3 – Kvarner islands (MÁRTON et al., 1990), 4,5 – Dugi Otok and Vis (MÁRTON & MILICEVIĆ, 1994), 6,7,8 – Medvednica Mt., Ivancica Mt., Pozeska Mt, Krndija Mt. and Papuk Mt. (MÁRTON et al., 1999, 2002, 2005), 9 – Krsko and Karlovac basin (MÁRTON et al., 2006).

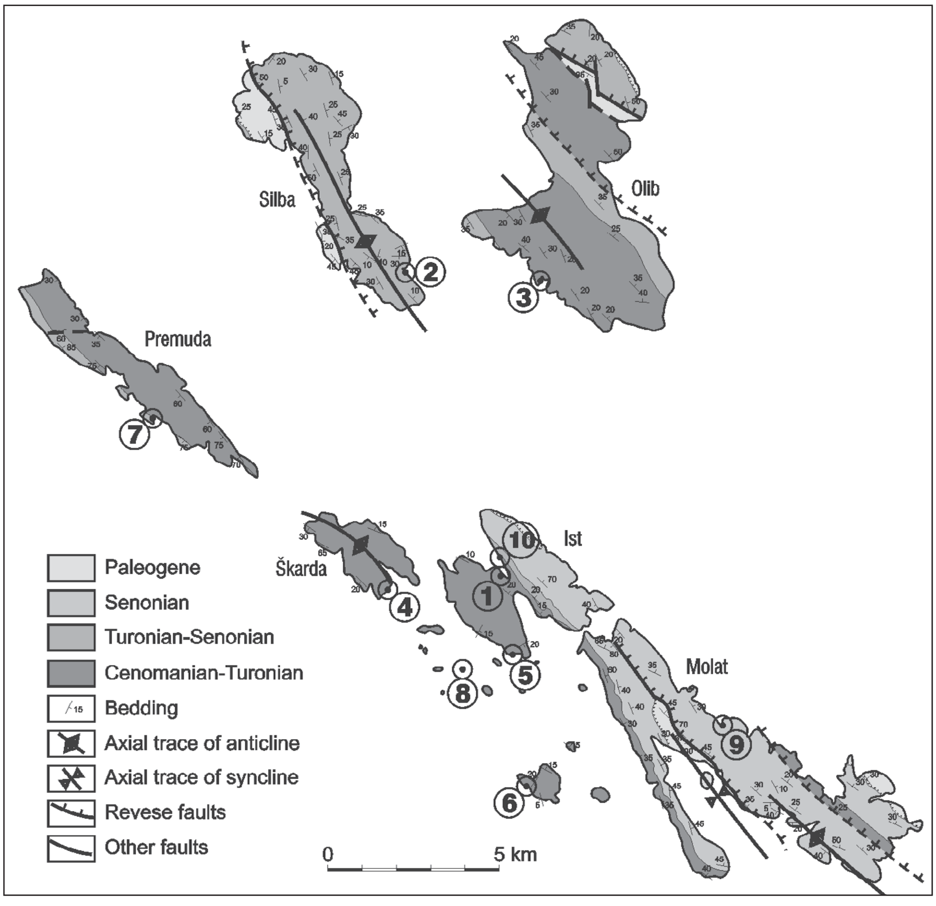

Figure 2: Simplified geological map (after MAMUZIĆ, 1970 and MAMUZIĆ et al. 1970), with the palaeomagnetic sampling localities 1–10.

previously published palaeomagnetic directions which have passed the present strict criteria developed to ensure good-quality data (see. MÁRTON et al., 2008)

Intensive and systematic palaeomagnetic investigation started in the early 1990s in two areas. The study of Adriatic platform carbonates (Fig. 1, area 1) resulted in the definition of an apparent polar wander path (APW) for the Tithonian through mid-late Eocene periods of time for stable Istria (MÁRTON et al., 2003, 2008). In the South Pannonian basin (Fig. 1, area 6–9), the targets were Tertiary rocks, which showed counter-clockwise (CCW) rotations of post-Early Pontian age. These rotations were interpreted as having been triggered by the CCW rotating Adriatic microplate (MÁRTON et al., 1999, 2002, 2005).

Palaeomagnetic observations in the area between the southern Pannonian basin and stable Istria are poorly distributed. As these observations are mostly from the 1980s, observations since 2006 have been concentrated on the tectonically more complicated External Dinarides. The present paper is an initial step in this vein, as it deals with the palaeomagnetism of an area belonging to the imbricated margin of stable Adria.

2. GEOLOGICAL BACKGROUND

Ist Island and its surrounding islands (Fig. 2), which are palaeogeographically part of Adriatic carbonate platform (VLAHOVIĆ et al., 2005), belong to a geotectonic unit, known variously as Adriaticum (HERAK, 1991), or Imbricated Adria (TARI, 2002) depending on the geotectonic interpretation. The region is characterized by gently folded and faulted Cretaceous and Palaeogene strata (which transgressively overlie the Cretaceous, MAMUŽIĆ & SOKAČ, 1967; MORO & JELASKA, 1994; ĆOSOVIĆ et al., 1994), with a Dinaridic (NW–SE) trend. An exception is Premuda island where the beds are strongly folded. Our study area is situated (Fig. 1) practically halfway between stable Adria and the Western thrust belt (TARI, 2002) or Dinaricum (HERAK, 1991).

In the study area, Upper Cretaceous, shallow water, peritidal limestones prevail (VLAHOVIĆ et al., 2005), which range in age from the Cenomanian–Lower Senonian (MAMUŽIĆ & SOKAČ, 1967; MORO & JELASKA, 1994). Early Turonian pelagic sediments deposited on a drowned platform are the exception (GUŠIĆ & JELASKA, 1990; MORO et al., 2002; VLAHOVIĆ et al., 2005). During the Mid Turonian, shallow-water sedimentation was re-established on Olib Island, while at Silba, Premuda and Ist islands pelagic sedimentation continued until the Senonian (KAPOVIĆ & BAUER, 1970; MORO, 1993). On most islands, strata are subhorizontal (Fig. 3) or SW and NE dipping with angles up 25° (Fig. 2). An exception is Premuda island with subvertical beds (Fig. 4).

Shallow water peritidal limestones are characterized by the vertical alteration of intertidal laminites and subtidal limestones. Subtidal limestones appear in two varieties: foraminiferal wackestone-packstones, rarely grainstones and rudist or chondrodonta floatstones. Depositional environments of these limestones were the shallow and protected parts of the carbonate platform. The pelagic limestones are characterized by the massive pelagic limestones with lenses of resedimented shallow water material, which could be in alteration with laminated pelagic limestones. The depositional environment could be deterrmined as a transition between the shallow platform and deeper basin (KAPOVIĆ & BAUER, 1970).

3. PALAEOMAGNETIC SAMPLING

For the purpose of this work, samples were taken from Upper Cenomanian and Lower Senonian shallow water limestones, as well as from Senonian pelagic limestones for palaeomagnetic studies. The strata sampled were invariably light grey or white in colour. Samples were drilled and oriented in the field with a magnetic compass. Beds with shallow dips were preferred, though at one locality (Premuda) subvertical strata were sampled (Fig. 4). Tilts of the sampled strata were recorded and used later, during the evaluation of the data as correction parameters for restoring the horizontal position of the beds.

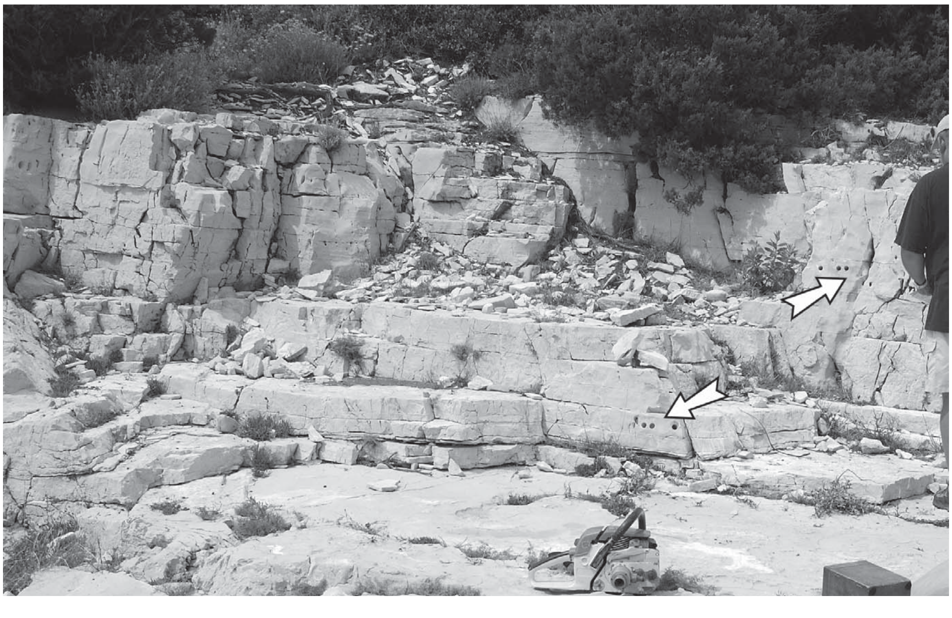

Figure 3: Subhorizontal beds at Ist island (locality 5) with palaeomagnetic boreholes (arrow).

Figure 4: Subvertical beds at Premuda island (locality 7) with palaeomagnetic boreholes (arrow).

The sampling localities are distributed over several islands, partly because of the character of the region, partly because several outcrops on the larger islands were heavily karstified (e.g. Olib, Silba). Among the sampling localities there are abandoned quarries (localities 5, 6 and 8 on Fig. 2) as well as natural coastal outcrops. Eventually, 96 samples were collected from 10 geographically distributed localities (Fig. 2 and Table 1).

4. LABORATORY PROCESSING AND RESULTS

The samples were cut into standard-size specimens and the natural remanent magnetization (NRM) as well as the magnetic susceptibility of each specimen was measured in the laboratory. The instruments used were JR4 and JR5A magnetometers and a KLY-2 Kappabridge. In case of magnetic intensities exceeding 12x10^{-5} A/m, one of the specimens (if the core was long enough to provide sister specimens) were demagnetized stepwise using the alternating field (AF) method, the other using the thermal method. At lower NRM intensities, both specimens were demagnetized with AF, (as years of experience with extremely weakly magnetic platform carbonates from Istria showed that the thermal method was not practicable in such cases, MÁRTON et al., 2003, 2008), and the better defined demagnetization curve of the sister specimens was used for evaluation. The first step of the evaluation was component analysis (KIRSCHVINK, 1980) of the

Table 1: Locality mean palaeomagnetic directions with statistical parameters for Ist island and related areas. Key: n/no: number used/collected samples (the samples are independently oriented cores), D, I, D_C, I_C: Declination, Inclination before and after tilt correction, k and α_{95}: Statistical parameters (FISHER, 1953).

	Locality	Lat.	Long.	N/N_o	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip
1	Ist, port HR 953-961	44°16′44.8″	14°45′25.5″	7/9	340	+52	21	13	329	+42	42	9	314/10 252/25
2	Silba, Nozdre bay HR 962-971	44°21′19.7″	14°43′24.3″	6/10	328	+40	55	9	334	+48	55	9	110/10
3	Olib, Sv. Nikola port Hr 972-80	44°21′19.9″	14°46′23.1″	0/9				*too weak*					
4	Škarda Hr 981-86	44°16′23.7″	14°42′58.6″	0/6				*too weak*					
5	Ist, abandoned quarry HR 987-995	44°15′22.9″	14°45′54.6″	9/9	336	+49	108	5	338	+48	108	5	42/2
6	Tramerka HR 996-904	44°13′21.9″	14°46′08.0″	6/9	337	+51	230	4	325	+45	230	4	271/12
7	Premuda, Široka bay HR 1137-154	44°19′05.3″	14°37′52.5″	5/18	3	−20	73	9	347	+45	73	9	219/82
8	Funestrala HR 1155-166	44°15′07.9″	14°44′39.0″	8/12	330	+44	98	6	332	+48	98	6	125/5
9	Molat, Vodomarka bay, HR 1167-172	44°14′17.1″	14°15′21.0″	6/6				*great circle distribution*					
10	Ist, Kosirača bay HR 1173-80	44°17′5.5″	14°45′21.5″	0/8				*too weak*					

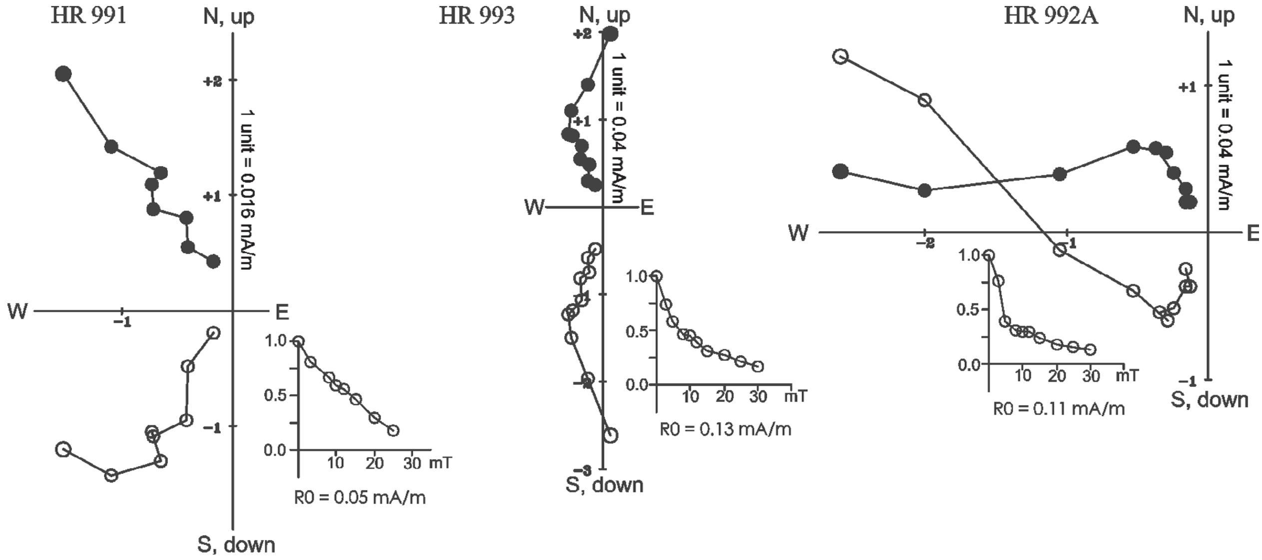

Figure 5: Typical demagnetization curves. AF demagnetized specimens from locality 5 showing the varied NRM intensities and the behaviour of the NRMs on demagnetization. Zijderveld diagrams plus normalized NRM intensity versus AF field. Key to the Zijderveld diagrams: filled circles are the projection of the palaeomagnetic vector onto the horizontal plane; open circles, projections onto the vertical plane.

demagnetization plots for linear segments. As Figs. 5 and 6 show, the demagnetization curves sometimes exhibit a single component, going practically to the origin (Fig. 5, specimen HR 991). However, the NRM is often composite, (despite the fact that the only magnetic mineral in the collected samples is magnetite, as Fig. 7 suggests), especially that of samples with stronger palaeomagnetic signals, (the demagnetization curves in Figs. 5 and 6, except HR 991). In all cases, the components ending at or close to the origin were chosen to represent the characteristic remanence (ChRM) of a sample, and the locality mean palaeomagnetic directions were calculated from one direction per independently oriented sample. As Table 1 documents, all locality mean palaeomagnetic directions have good statistical parameters and depart significantly from the present north. Thus, they can be considered as well-defined palaeomagnetic signals and as syn-

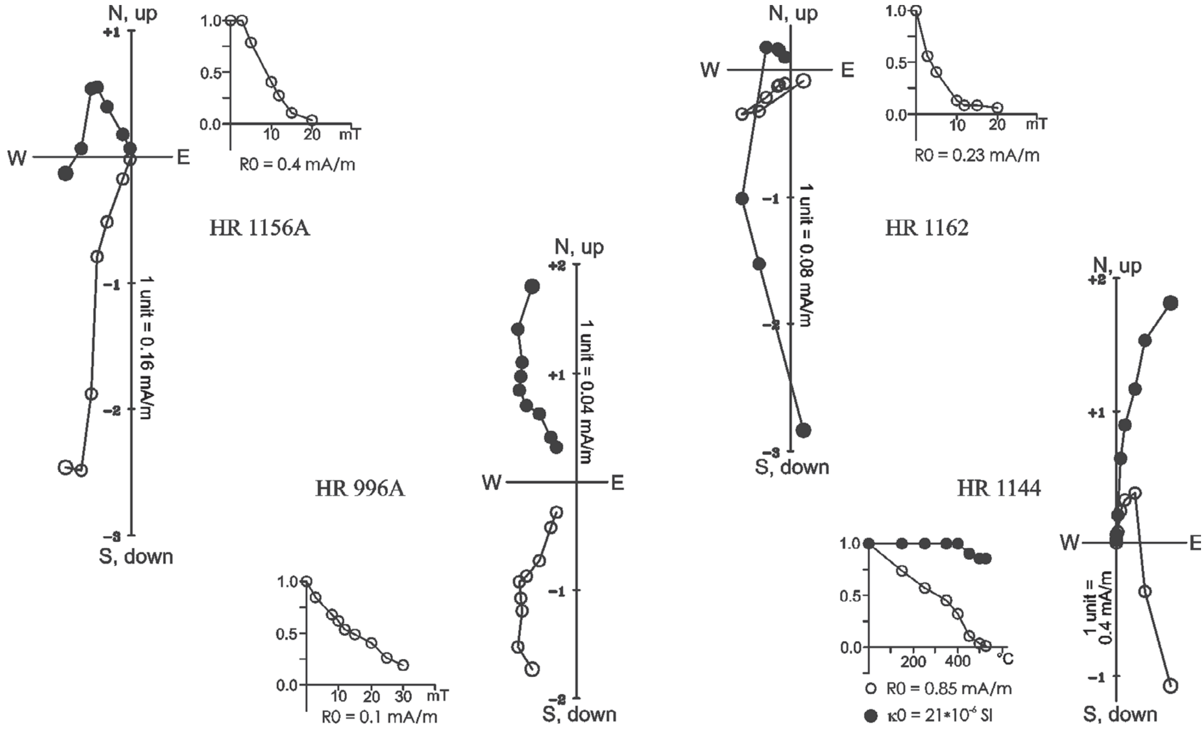

Figure 6: Typical demagnetization curves. AF demagnetized specimens from locality 8 (HR 1156 and HR 1162), documenting that after the removal of the overprint component, which is of different directions for the two specimens, the ChRMs are of similar directions. An AF demagnetized specimen from locality 6 (HR 996) and a thermally demagnetized one from locality 7 (HR 1144). Key is as for Fig.5, but for the last sample the smaller diagram is an intensity (circles) / susceptibility (dots) versus temperature diagram.

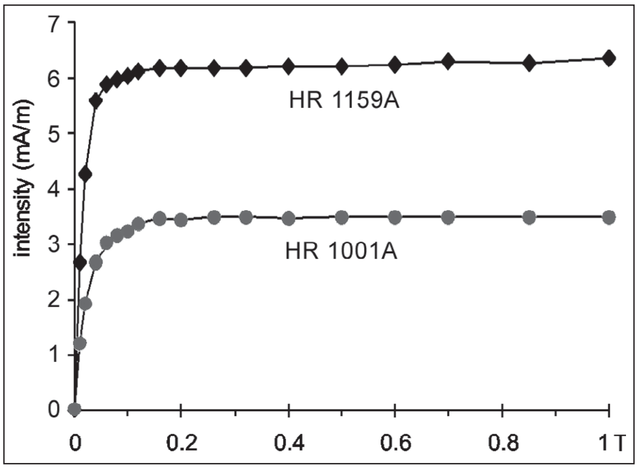

Figure 7: Magnetic mineralogy experiments. The acquisition behaviour of the isothermal remanent magnetization indicates magnetite as the only magnetic mineral in the samples.

folding Fisher analysis shows, they predate the age of folding (Table 2 and Fig. 8). The ChRMs of one locality (Vodomarka) were not suited for evaluation by the Fisher method since they exhibit a great circle distribution. This great circle (in the tectonic system) closely passes by the group of tilt-corrected palaeomagnetic directions of the other localities, suggesting that the component of the pre-folding age is similar to the ancient magnetic directions of other localities (Fig. 9). However, the statistical parameters for the overall palaeomagnetic direction are better without the locality of Vodomarka. Therefore the Cenomanian–Early Senonian of the study area is based on six geographically distributed localities (Table 2).

5. DISCUSSION AND CONCLUSIONS

The overall-mean palaeomagnetic direction predating the age of folding for the study area characterizes the Cenomanian–Lower Senonian time period. Palaeomagnetic direc-

Table 2: Oveall mean palaeomagnetic directions for Cenomanian–Early Senonian localities, before and after tilt corrections with statistical parameters and palaeomagnetic poles calculated from the tilt-corrected directions for Ist island and related areas, for stable Istria (the first version comprises the Cenomanian and Early Senonian localities, the second also Turonian localities) and for the Kvarner islands.

	N	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	λ(N)	ϕ(E)	δp	δm
Study area													
Cenomanian+lower Senonian	6	340	38	8	25.4	334	46	188	4.9	63	254	4.0	6.2
Stable Istria													
Cenomanian+Coniacian	8	323	45	44	8.5	334	51	65	7.5	66	259	6.9	10.1
Cenomanian–Coniacian	12	325	44	54	5.9	334	50	60	5.7	65	257	5.1	7.6
Kvarner islands													
Cenomanian–Turonian	6	309	45	33	11.9	327	47	27	13.1	59	263	10.9	16.9

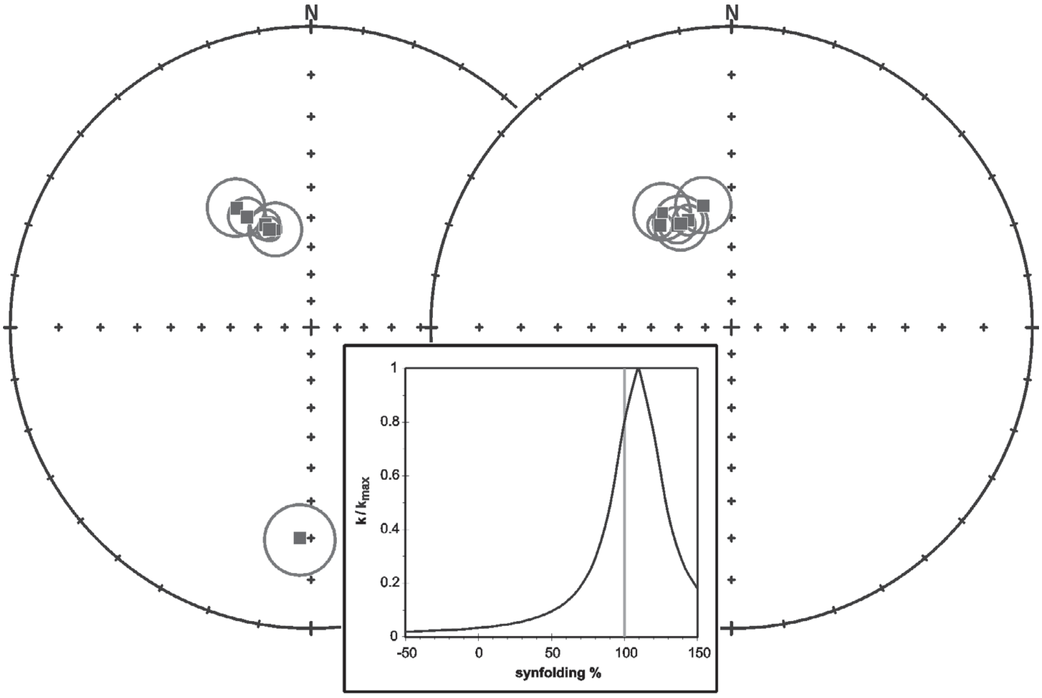

Figure 8: Locality mean palaeomagnetic directions with confidence circles before (left stereogram), and after (right stereogram), tilt corrections. The middle diagram shows the result of the syn-tilting Fisher analysis. The best grouping of the locality mean palaeomagnetic directions is achieved close to 100% unfolding and the peak is extremely high, meaning that the test is significant.

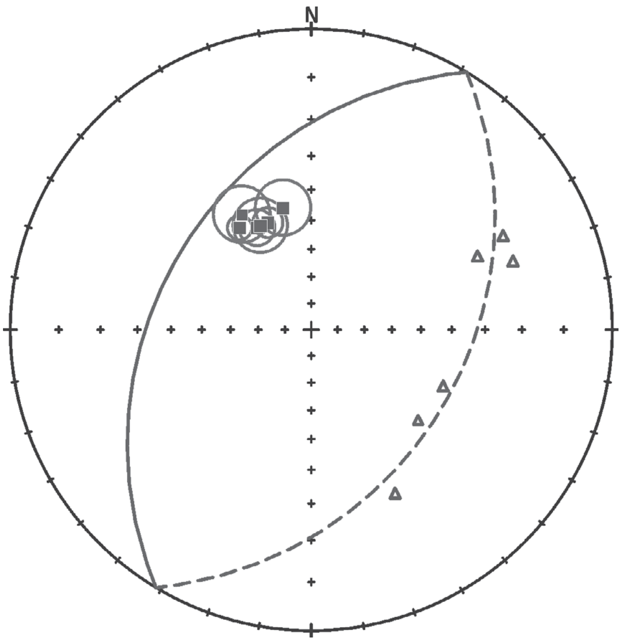

Figure 9: Overall mean palaeomagnetic directions for localities tabulated in Table 1 with confidence circles (all normal polarities), and the individual palaeomagnetic directions for locality 9 (all reversed polarities), exhibiting great circle distribution. Note that the great circle defined by the latter passes close to the cluster of the former. All directions are tilt corrected.

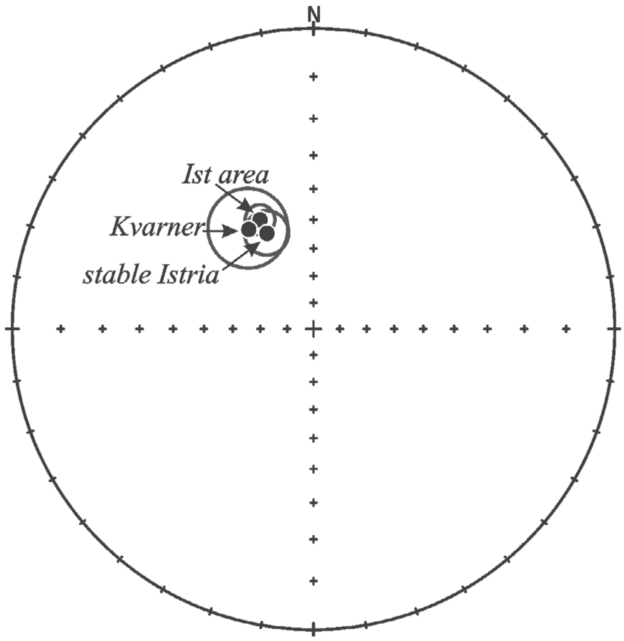

Figure 10: Overall mean palaeomagnetic directions with confidence circles for the Cenomanian–Early Senonian time period for the Ist area, stable Istria and the Kvarner islands. Stereographic projection, lower hemisphere.

tions published for rocks of similar ages are known from stable Istria and the Kvarner islands, the first representing the hard core of the Adriatic microplate (MÁRTON et al., 2003, 2008), the second the NW part of imbricated Adria. Before such a comparison it has to be emphasized that the results for the Cenomanian–Early Senonian time period of the present study are superior to those previously obtained from stable Istria and the Kvarner islands, in the sense that the age of the magnetization is better constrained. This is because the syn-tilting Fisher analysis yields the best statistics close to 100 % unfolding for the study area (Table 2) and the statistical improvement is significant (Fig. 8), while in the previously published cases the age of the magnetizations are not so tightly connected to the age of the sampled rocks. Nevertheless, the overall-mean palaeomagnetic directions for the Cenomanian–Early Senonian time period for the three above mentioned areas (Fig. 2) have statistically identical overall palaeomagnetic directions (Fig. 10). This situation has an important tectonic implication, which is the lack of large scale relative movement between the respective areas, after the Early Senonian. In other words, stable Istria and at least the NW part of its imbricated margin can be treated as a rigid block in the course of plate tectonic displacements from the late Cretaceous onwards.

The declination of the overall-mean palaeomagnetic direction obtained for the study area is 334°. Interestingly, the palaeomagnetic declination for a combined Pannonian–Pontian group of localities for the Southern Pannonian basin is also 334° (MÁRTON et al., 2002). As the palaeomagnetic signals in both cases are primary, the results of the present paper not only support the conclusion that the rotating Adriatic microplate triggered rotations in the South Pannonian basin (MÁRTON et al., 2002, MÁRTON, 2006), but also suggest that the Adriatic platform did not change its orientation between the late Cretaceous and the Early Pontian.

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