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Reappraisal of the paleomagnetism of the Miocene intramontane Pag and Drniš-Sinj basins, External Dinarides (Croatia)

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Abstract

This paper presents paleomagnetic results from the Miocene offshore Pag and the twin onshore (Drniš-Sinj) basins. Earlier magnetostratigrapic results were published from both basins, which documented that the lake sediments were good targets for paleomagnetism. From the Pag basin, we sampled the oldest and youngest segments of the 1200m long Crnika section and obtained statistically different paleomagnetic directions from the two parts. During a repeated visit to the section it was revealed that modern gravity–driven creeping can account for this, i.e. the results from the Pag basin should be rejected from regional tectonic interpretation.

The overall-mean paleomagnetic direction for the Drniš-Sinj basin has excellent statistical parameters, its high quality is further supported by positive regional fold/tilt and reversal tests, based on seven geographically distributed localities. The results suggests 13-20° CCW rotation with respect to Africa and 21-27° with respect to stable Europe, during the last 15 million years. As the External Dinarides are the loci of a complicated network of Miocene and even younger tectonic zones, we can not export the observed rotation for the whole unit, but consider our results as one step in obtaining robust kinematic constraints for the post-Oligocene tectonic history of the External Dinarides.

Keywords:

External Dinarides; Miocene intramontane basins; paleomagentism

Introduction

The External Dinarides are a fold and thrust belt situated NE of the gently deformed Adriatic foreland (Adriatic "autochthon"). The External Dinarides have a complex geotectonic structure which was the subject of a large number of studies over a long time (e.g. Auboin, 1973, Dimitrijević, 1982, Herak, 1986, Pamić et al., 1998, Tari, 2002, Ustaszewski et al., 2008, Korbar, 2009). Pioneering paleomagnetic investigations were carried out both in the Adriatic autochthon and in the External Dinarides on Cretaceous platform carbonates (Márton and Veljović, 1983, 1987, Márton et al., 1990, Márton and Miličević, 1994) and on the Eocene flysch and some outcrops of Miocene and Mio-Pliocene lake sediments of the External Dinarides (Speranza, 1995, Kissel et al., 1995). Paleomagnetic investigations were resumed in the area in the second part of the 1990s and extended to the foreland of the Southern Alps (Márton et al., 2003, 2008, 2010a, 2010b, 2011, 2014). These provided reliable kinematic constraints for subdividing the External Dinarides, into a mainland part (imbricated Adriatic plate margin units in Fig. 1a), and an offshore belt (imbricated Adriatic plate in Fig. 1a). The large scale relative movement between them is evidenced on one hand by the remanences of pre-folding age measured on Jurassic platform carbonates from the Velebit Mts and the Gorski Kotar region (Márton et al., 2011) and of post-folding age measured on Permian rocks (Werner et al., 2015), and, on the other hand, by remanences of pre-folding age measured on Cretaceous platform carbonates from the Northern Adriatic islands. The timing of the relative movement(s?), however, is a matter of speculation. One possibility is that the post-Eocene CCW rotation of Adria (Márton, 2006, Márton et al., 2002, 2014, Ustaszewski et al., 2008) did not involve the whole External Dinarides, but only the imbricated Adriatic plate. In this case, Miocene paleomagnetic declinations from the imbricated Adriatic plate margin must be different from those inferred or measured for the gently deformed and imbricated Adriatic plate of Fig. 1a.

During the Miocene, sedimentation in the External Dinarides took place in intramontane lake basins. The majority of the intramontane basins are located on the mainland (Fig. 1a) while in the offshore part they are only locally preserved, as in the Pag island, at the foot of the Velebit Mts (Fig. 1a). Periods of lacustrine sedimentation include the latest Oligocene and post-Early Burdigalian times. Selected sections from some of the above basins were studied for magnetostratigraphy (Mandić et al., 2008, Jiménez-Moreno et al., 2009, de Leeuw et al., 2010) pointing out to the existence of good paleomagnetic signals, but paleomagnetic directions were not published. In order to obtain reliable results for tectonic interpretation, we sampled in 2011 several outcrops from Pag island and from the Drniš-Sinj basin. Subsequently, paleomagentic locality mean directions were published by de Leeuw et al., (2012) for several Miocene magnetostratigraphy sections (one result from each basin), with the conclusion that no rotation had affected the External Dinarides during or after the Miocene. The aim of the present paper is to show, how the tectonic interpretation calls for modification when the paleomagnetic directions for the two mentioned basins represent geographically distributed localities.

Geological setting – Stratigraphy and tectonics of the study area

The studied deposits belong to long-lived freshwater basins that formed on the pre-Miocene basement. These basins were restricted to the northern part of the Dinarian-Anatolian Island which acted as geographic barrier between the Paratethys and the proto-Mediterranean, and are named the Dinaride Lake System (Krstić et al., 2003), while the deposits are named Illyric, which is an unformal lithostraticraphic unit (Bulić and Jurišić-Polšak, 2009). The general characteristics of the lacustrine units are low sedimentation rate of predominantly carbonate sediments, tephra occurences and post-depositional tectonic deformation that is not uniform in space and time. The basement of the lacustrine deposits is a complex assemblage of rocks incorporated into the Dinarides fold-thrust belt, generally subdivided into two tectonic domains: the External Dinarides extending along the eastern margin of the Adriatic Sea, and the Internal Dinarides located more to the NE (Fig. 1a). The External Dinarides are composed of mostly shallow-marine Mesozoic platform carbonates, with subordinate Palaeozoic and Cenozoic carbonate and siliciclastic deposits (e.g. Vlahović et al., 2005; Sremac, 2012) derived exclusively from the eastern part of the Adriatic plate (e.g. Schmid et al., 2008). In contrast, the Internal Dinarides are built up of very variable rocks, from siliciclastic and carbonate sediments, ophiolites associated with radiolarites, greywackes and shales, blueschists, tectonized ophiolites, metamorphic rocks, and granitoids (see Pamić et al., 1998, Schmid et al., 2008, and references therein).

The Sinj Basin is located in the marginal part of the Frontal thrust of the imbricated Adriatic plate margin (Tari, 2002; Schmid et al., 2008; Fig. 1a or High Karst of Dinaric SW Unit *sensu* Korbar 2009). It is 38 km long and 9 km wide, and oriented NW–SE (Fig. 1, b3). The rim of the basin comprises Triassic to Eocene platform carbonate rocks. Clastic rocks like the Eocene-Oligocene Promina Formation and the Lower Triassic Muć Formation (Marinčić et al., 1976; Papeš et al., 1982) occur only in the western margin. The basin itself is affected in its central part by the doming of Permo-Triassic evaporites (Raić et al., 1984). The Miocene lacustrine succession is about 510 m thick and consists of limestones with coal intercalations and a few tephra beds (Mandic et al., 2008; de Leeuw et al., 2010). The sedimentary environment was lacustrine littoral that, due to water-level changes, turned into a swamp. Based on magnetostratigraphic, ^{40}Ar/Ar^{39} and fossil large mammals studies, deposition took place between 18 and 15 Ma (Jiménez-Moreno et al., 2008; de Leeuw et al., 2010). Post-depositional tectonics caused irregular deformation of the lacustrine deposits. In the central part of the basin, the dip system reflects structural domes due to diapiric uplift of the Permo-Triassic evaporates. Elsewhere the bedding dip directions and angles show many different local variations. The deformation was strongest in the western part of the basin indicated by a syncline in the Sutina creek at the Lučane locality, and subvertical beds in the westernmost part of the basin.

The Drniš basin is about 30 km WNW from the Sinj Basin (Fig. 1, b2). The 15 km long Miocene basin fill has a triangular shape, and is surrounded by Jurassic and Cretaceous platform carbonates and clastic and carbonate rocks of the Eocene-Oligocene Promina Formation. The Miocene lacustrine limestones crop out along the margins of the basin while a few scattered outcrops of the Permian evaporites, Triassic clastics and igneous rocks occur within the basin. The lacustrine deposits of the Drniš basin have not yet been dated by modern stratigraphic methods, but are strongly correlative with the Sinj Basin limestones suggesting a similar age and probably being parts of a same large lacustrine depositional system. Later, these deposits were affected by post-depositional tectonics that caused partitioning into two basins separated by uplifted blocks.

Due to the lack of younger undeformed deposits, dating the deformation of the lake sediments of the Sinj and Drniš basins is problematic. For that reason, additional data from the neighbouring Livno basin have to be considered. This basin is located in Bosnia and Herzegovina, about 15 km north of the Sinj basin, where the youngest Miocene deposits (approximately 12.6 Ma, de Leeuw et al., 2011) are tectonically more deformed (Raić et al., 1984) than the unconformably overlying marls, sands, clays and coal beds. The latter, considered to belong to the Pliocene, also experienced deformation as indicated by inclined beds up to 24° (Raić et al., 1984). A palaeobiogeographical study also suggests a tectonic event in the region, which generated barriers for a freshwater fish species that split between 12.4 and 9.2 Ma (Perea et al., 2010).

On the island of Pag the studied Miocene lacustrine deposits occur in a small elongated NW-SE striking basin which presently comprises only 0.16 km^2 surface area (Fig. 1, b1), unconformably overlying the Eocene carbonate-clastic complex (Mamužić et al., 1970; Jurišić-Polšak and Bulić, 2007). A succession of outcrops of weakly lithified lake sediments form a steep wall along the Crnika beach. The more than 190m thick Crnika section consists of dominantly silty or clayly oncoide limestones with coal intercalations and sparse thin bentonite strata in the oldest parts. Magnetostratigraphic data combined with biostratigraphic constraints (based on molluscs and pollen) yielded deposition age between 17.1 and 16.7 Ma (Jiménez-Moreno et al., 2009). The deposits were affected by post-depositional tectonics as indicated by NNW inclined beds. Additional deformation is being produced by modern gravity-driven creeping of some parts of the succession, more likely in the older than the younger part of the section.

Paleomagnetic sampling

From the Sinj basin Early Miocene lacustrine limestones were drilled at geographically distributed localities (Fig. 1, b3). In addition, a massive vitriclastic volcanic ash layer was also sampled from Poljaci. The ash consists dominantly of glass shards, phenocrysts of plagioclase, quartz and mica. Locality Lučane (SD5, Fig. 1, b3) has a particular interest, as it represents one flank of a plunging syncline, while locality Sutina (SD4), the other limb. The „Lučane flank" was studied earlier for magnetostratigraphy (de Leeuw et al., 2011) and the direction was published without correction for plunge (de Leeuw et al., 2012). We were able to determine the plunge of the syncline, so could apply a full tectonic correction. In addition to the Miocene lacustrine deposits, we also drilled the single Cretaceous outcrop accessible for sampling within the basin, with the aim of obtaining some control on the position of the basement with respect to stable Adria. The collected Cretaceous samples are dominantly mud-supported limestones, fossil content *Accordiella conica* Farinacci, *Rotorbinella scarsella* Torre, *Murgella lata* (Luperto-Sinni), *Montcharmontia appeninica* De Castro, includes *Thaumatoporella parvovesiculifera* (Raineri), *Scardonea* sp. pointing to late Santonian age.

In the Drniš basin, samples were drilled from lacustrine limestone at Ojdanići (Fig. 1, b2). The age of the limestone here is assigned, by analogy to the Sinj basin, as Early Miocene. The bedding dip was somewhat variable in the outcrop, thus several measurements were recorded and the tectonic tilt was calculated as their average.

From the Crnika section on Pag island we drilled samples from the SE and NW ends of the outcrop, from grey weakly lithified limestones (Fig. 1, b1). The bedding dip at the eastern end was variable and not very well defined, while at the western end it was very clearly visible and precisely measurable.

At each locality, the paleomagnetic cores were magnetically oriented in situ, wrapped tightly in aluminium and plastic foils and kept refrigerated till they were processed in the laboratory.

Laboratory processing of the oriented samples

The cores drilled and oriented in the field were cut into standard-size specimens. The remanent magnetization (NRM) of most specimens was measured in the natural state, followed by magnetic susceptibility anisotropy (AMS) measurements. From each locality, one or more samples were selected for experimental demagnetization. One specimen per sample was demagnetized stepwise by alternating field (AF), the other thermally, till the NRM signal was lost. After each demagnetization step, the NRM was re-measured, and in case of thermal demagnetization, the magnetic susceptibility was monitored. As the thermal method nearly always yielded better defined demagnetization curves for the lake sediments than the AF, the majority of the samples were thermally demagnetized in several steps. The Cretaceous samples, on the other hand, were successfully demagentized by AF method. The demagnetization curves were then analyzed for linear segments and the component heading towards the origin was considered as the characteristic remanence.

For measuring the NRM and IRM JR-4 and JR-5A magnetometers, for susceptibility and AMS measurements KLY-2 Kappabridge was used. The thermal demagnetization was made in a TSD-1 non-magnetic oven, the AF demagnetization with LDA-3A and DEMAG-0179 equipments. For the IRM acquisition experiments a Molspin pulse magnetizer was used.

Results

Crnika section

The samples from the older part of the Crnika section were dark, while those from the younger part were lighter grey. Despite of the colour difference, probably connected to environmental changes in the lake, the NRM intensities before demagnetization are in a narrow range, around $5x10^{-4}$A/m, the initial susceptibilities in the 10^{-5}SI range. On AF demagnetization, an artifact remanence seems to build up from 30 mT (Fig. 2a) and that is why the preferred method was the thermal one. On thermal demagnetization, susceptibility increases monotonously from 200°C in the older part of the section (Fig. 2b), while in the younger part, susceptibility starts to increase from room temperature, first very gently, then moderately from 200°C, and speeds up above 275°C (Fig. 2c). It seems that the unusually early increase of the susceptibility (below 275°C) is due to the decomposition of non-ferrimagnetic constituents of the sediments, but the newly formed magnetic mineral did not prevent fairly well defined demagnetization curves being obtained up to 350-400°C. The characteristic magnetization is of reversed polarity in the older, and of normal polarity in the younger part of the section. In the first case, the characteristic remanent magnetization is isolated above 275°C on, while in the second case, above 150°C. Jiménez-Moreno et al. (2009) suggested that, in the first 60m of the section to which the older samples of our collection belong, the principal ferrimagentic mineral was greigite, while in the interval of 101-120m, where the younger samples were collected, it was multidomain magnetite. The NRM intensity versus susceptibility curves of our study, however, suggest that the actual carrier of the NRM must be magnetic iron sulphide at the oldest as well as the youngest part of the section for the NRM practically decays by 400°C, while the susceptibility dramatically increases from 275°C on, which must be the manifestation of the conversion of an iron sulphide (possibly greigite) to magnetite. Additional indications for greigite as the principal magnetnic mineral are the slow increase of the IRM intensity before 0.02 T (in the youngest part of the section only), the relatively high proportion and early decay of the IRM component acquired between 0.2 and 0.36T the loss of the major proportion of the softest and medium hard components of the IRM by 400°C (Fig. 3).

The AMS measurements (Table 1) reveal a typical sedimentary fabric for the older part of the section, with weak anisotropy but well clustered minimum directions before demagnetization (Fig. 4a) which became even tighter grouped above 380°C (Fig. 4b). The minima are somewhat displaced from the vertical before and also after applying 260/20° (Fig. 4c) as the most reliably looking tilt correction. For the upper part of the section, AMS measurement after heating the specimens to 380°C (Fig. 4e) provided also a better defined sedimentary fabric than before demagnetization (Fig. 4d) and the bedding dip measured in the field was efficient in perfectly restoring the magnetic foliation plane to the horizontal (Fig. 4f).

Drniš and Sinj basins

The lake sediments of the Drniš and Sinj basins have typically stronger NRM values in the natural state (mostly in the 10^{-3}A/m range) than those of the Crnika section. The magnetic susceptibility is very variable between localities, the highest positive values characterize the Poljaci marls (Table 1), while the other outcrops yielded even lower positive or even negative values. The Santonian mudstone also have negative susceptibility, similarly to that of the Cretaceous platform carbonates of the Adriatic region (Márton et al., 2008). Weak susceptibilities suggest that the magnetic minerals are present in very low concentration, both in the Santonian and in the Miocene sediments.

Demagnetization of the NRM of the lake sediments was more successful with thermal than with AF method (Fig. 5, specimens 1448B, thermal, 1448A, AF demagnetization). Stepwise thermal demagnetization (all diagrams in Fig. 5, except specimen 1448A) yielded excellent or fairly well defined curves, up to 400°C with a complete decay of the NRM between 400 and 450°C. The susceptibility versus temperature curves typically exhibit a moderate decrease before starting to increase. The decay of the NRM and the behaviour of the susceptibility together point to greigite as the carrier of the NRM. The Santonian samples had weak NRM, responded well to AF demagnetization, and eventually yielded well-defined demagnetization curves (Fig. 5, HR 1919).

The NRM of the tephra from Poljaci poorly responded to thermal, but was fairly stable on AF demagnetization up to 40-60 mT. Thus, the determination of the characteristic remanent magnetization was possible for all the collected samples (Table 2). The AMS fabric is foliated, the bedding dip estimated in the field brings the minima somewhat closer to the vertical on tilt correction (Table 1).

Discussion

Crnika section

The paleomagnetic directions computed separately for the 10-15m (reversed polarity) and 113-120m (normal polarity) segments are far apart before tilt corrections. For the tilt correction to be applied for the first group there were options (Fig. 6). One of them 230/30° brought very close the result of the present study to the one published by de Leeuw et al. (2012) for the reversed polarity segment. The paleomagentic direction for the 113-120m part of the section, applying the very well -defined tilt correction, approaches that of the reversed polarity segment, but remains significantly different (Fig. 6). A field inspection a year after the sampling revealed that gravity driven creep has been affecting the section, which was much more intensive in the older than in the younger part of the section. Owing to the is situation, the Crnika section must be excluded from all regional tectonic interpretations, despite the success in obtaining statistically well defined paleomagnetic directions for both segments of the section.

Drniš - Sinj basin

The Miocene lake sediments yielded good paleomagnetic results, except for locality SD6 (Table 2). Before tilt or full tectonic corrections (the latter applies to localities SD4 and SD5), the locality mean paleomagnetic directions are highly scattered. The scatter is dramatically reduced by applying tectonic corrections and the fold/tilt test is positive (Table 3). The paleomagnetic direction for locality SD4, where the strata are steeply inclined, somewhat departs from the tight cluster (Table 2 and Fig. 7), that is why the apparent rotation with respect to Africa and stable Europe was calculated with and without locality SD4. In the first case, the overall mean declination suggests about 20°, in the second, about 13-14° CCW rotation with respect to Africa and naturally somewhat larger angles with respect to stable Europe (about 27° and 21°, respectively), during the last 20-10 Ma (Table 3). The situation is similar, when the result for the tephra (locality SD3) is included, which obviously has post-folding/tilting magnetization (Fig. 7) due to the secondary origin of the magnetite during the crystallization of the volcanic glass.

In a previous study de Leeuw et al. (2012) published a locality mean direction, based on 198 samples from a single section from the Sinj basin (Table 2, SD5a). It is documented in Table 2 that our results from the same section (locality SD5b), from which we sampled some beds where the drill holes of the previous study were observable, has practically identical declination after simple tilt correction. This again shows the high reliability of the laboratory processing and evaluation in independent paleomagnetic laboratories. However, the declination of this paleomagnetic direction is somewhat biased, due to the fact that the Lučane section belongs to a syncline plunging towards 167/17°, i.e. the calculation of the correct paleomagnetic declination of pre-folding age requires a full tectonic correction. When full tectonic correction is applied to locality SD5b and to SD4 (the latter was sampled from a steeper dipping part of the syncline, in the Sutina creek; Table 2) the locality mean declinations deviate about 10° more from the present north in the CCW sense than they do on the simple tilt corrections.

The result from a single locality of Santonian age (SD10) from the northern margin of the basin also indicates CCW rotation.

As the present study documents, a paleomagnetic direction from a single locality is insufficient to constrain the horizontal displacement of a whole basin. From paleomagnetic point of view, we have now a tight control on the Drniš-Sinj basin, in the form of a reliable kinematic constraint for the post-middle Miocene tectonic history of a limited area of the imbricated Adriatic plate margin units (Fig. 1a). As they are the loci of the complicated network of young tectonic zones, like the Split-Karlovac dextral fault zone (Fig. 1a), which generated a number of reverse faults that are more or less perpendicular to the main line (Hrvatski geološki institut - HGI, 2009), we can not exclude the possibility that the Miocene intramontane basins and their basements behaved in a non-uniform manner.

Conclusions

The results presented here were obtained on fully oriented cores, drilled and oriented in the field, from several geographically distributed localities in the Pag and the Drniš-Sinj Miocene basins of the External Dinarides. The Crnika section in Pag island and the Lučane section from the Sinj basin was earlier studied, primarily for magnetostratigraphy, and only later interpreted from tectonic point of view by de Leeuw et al. (2012). We revisited both sections for sampling and included the results in the final tectonic interpretation. We also studied one Santonian locality at the northern margin of the Sinj basin. We obtained good quality and statistically well–defined mean directions for all localities, except one in the Sinj basin.

Some results of the present study lend themselves for direct comparison with those by de Leeuw et al. (2012), since they represent the same segments of the two above mentioned sections. Comparison demonstrates that independent sampling, laboratory processing and statistical evaluation in different paleomagnetic laboratories defined practically the same paleomagnetic mean directions for the same segments, when simple tilt corrections were applied.

Despite of the good quality paleomagnetic results we obtained for both, the reversed and normal polarity parts (de Leeuw et al., 2012 published results only for the first) of the Crnika section, this must be disregarded from any regional tectonic interpretation as the mean paleomagnetic directions for the reversed and normal polarity segments are statistically different. This conclusion was reinforced by an inspection of the section a year after our sampling, when gravity driven creep was detected, which more seriously affected the reversed polarity zone than the normal polarity part. The creep probably occurs intermittently, and must have been inactive for some years, since the paleomagnetic directions of the present study and that of the previous by de Leeuw et al. (2012) for the reversed polarity segment are practically the same.

For the Drniš-Sinj basin we obtained reliable kinematic constraint for post-middle Miocene tectonic movement, based on geographically distributed sedimentary localities, with paleomagnetic directions tightly grouping after simple tilt or full tectonic corrections (positive fold test). The overall-mean paleomagnetic direction suggests moderate CCW rotation of the basin (20°in average, if SD4 is included and 13° without SD4, Table 3 and Fig. 7) in post-middle Miocene times. A tephra intercalation with post-tectonic magnetization is in line with this conclusion and a Santonian locality from the northern margin of the basin indicates that the basement was involved. The results of the present study and that of de Leeuw et al (2012) for the Lučane section are very close after simple tilt correction. Nevertheless, as the section belongs to a plunging syncline, it needs a full tectonic correction. When this is applied the paleomagnetic direction for this section fits the picture of general CCW rotation.

Although this result of the present study satisfies all the main criteria for reliability in tectonic interpretation, yet it is a matter of speculation if the rotation is due to tectonic activity connected e.g. to the Split-Karlovac strike slip zone and related reverse faults or the consequence of the general displacement of the High Karst subunit (Fig. 1a) of the External Dinarides. It is quite possible that on closer inspection, similar areas to the Drniš-Sinj basin, the other Neogene sediments of other intramontane basins could provide evidence for rotation, as the imbricated Adriatic plate margin units were intensively tectonized after the formation of these Neogene intramontane basins.

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	Locality	n	κ 10^{-6} SI	max D°	max I°	max conf	inter D°	inter I°	inter conf	min D°	min I°	min conf	L(%)	F(%)	P(%)
Pag basin															
C1a	Crnika NRM 10-15m HR 1387-396	5	55	320 318	11 1	22.7/4.4	230 48	1 16	22.7/9.3	134 224	78 74	9.5/4.7	0.2	0.9	1.1
	Crnika TH380 10-15m	6	601	0 358	5 8	17.2/1.9	269 89	11 8	17.8/6.2	114 224	78 78	7.8/1.9	0.2	1.7	1.9
C2	Crnika NRM 113-120m HR 1397-407	5	32	4 184	6 4	31.5/17.5	273 274	8 5	38.1/8.1	130 58	80 84	27.9/17.8	0.3	0.3	0.5
	Crnika TH380 113-120m	5	662	338 339	14 4	53.6/1.2	70 69	4 3	53.6/3.1	177 201	76 85	3.2/1.8	0.1	1.4	1.5
Drnis basin															
SD1	Ojdanići, lake sediment, HR 1408-417	6	18	355 260	6 3	28.3/19.9	94 90	54 4	25.7/12.7	261 261	34 85	24.4/14.5	0.2	0.3	0.5
Sinj basin															
SD2	Poljaci, marl, HR 1418-427	6	181	6 186	12 15	59.2/5.9	272 278	18 6	59.3/16.3	128 30	68 73	19.9/5.1	0.1	0.1	0.2
SD3	Poljaci, tefra, HR 1428-433	6	52	14 9	35 12	51.7/3.9	274 278	14 5	53.3/7.5	166 168	52 77	25.5/4.3	0.5	1.1	1.7

Table 1. Summary of locality mean Anisotropy of Magnetic Susceptibility directions. Localities are numbered according to Fig. 1.

Key: n: number of samples (the samples are independently oriented cores); K: mean susceptibility; D, I, conf: declination, inclination and the related confidence ellipse of the maximum, intermediate and minimum directions (upper row before, lower row after tilt correction); P, L, F: degree of anisotropy, lineation, foliation.

Locality	Lat.N,	Lon.E	n/no	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip	Lat°	Lon°	δm°	δp°
Pag, Crnika section																
C 1a Previous study de Leeuw et al., 2012	44.45°	15.03°	94/95	?	?	?	?	182.4	-56.5	51.1	2.1	?				
C 1b 10-15 m, HR 1384-396	44°30'26"	14°58'16"	13/13	205.6	-32.6	35.7	7.0	188.5	-58.2	35.7	7.0	230/30*				
C 2 113-120 m, HR 1397-407	44°30'35"	14°57'56"	11/11	334.9	+74.0	59.8	6.0	**338.7**	**+64.1**	59.8	6.0	345/10				
Drniš-Sinj basins																
SD 1 Ojdanići, HR 1408-417	43°47'25"	16°18'43"	10/10	111.1	-34.5	153.8	3.9	**170.8**	**-67.9**	153.8	3.9	84/51	80.4	338.6	6.5	5.5
SD 2 Poljaci, marl, HR 1418-427	43°42'59"	16°39'38"	8/10	181.3	-84.7	268.4	3.4	**165.1**	**-54.9**	268.4	3.4	342/30	75.9	255.8	4.8	3.4
SD 3 Poljaci, tefra, HR 1428-433	43°42'59"	16°39'38"	6/6	**342.4**	**+58.5**	49.9	9.6	343.4	+33.5	49.9	9.6	345/25	76.1	273.8	14.2	10.6
SD 4 Sutina creek, HR 1434-444	43°43'11"	16°35'27"	10/11	207.0	-25.7	58.4	6.4	141.5	-51.9	58.4	6.4	248/70				
								128.8	**-51.6**	58.4	6.4	+plunge 163/17	48.9	288.6	8.8	6.0
SD5a Lučane, Previous study de Leeuw 2012	43.70°	16.62°	180/221	?	?	?	?	175.0	-56.4	36.7	1.8	?				
SD5b Lučane, HR 1445-453	43°43'17"	16°35'35"	9/9	217.5	-33.3	227.4	3.4	173.9	-63.8	227.4	3.4	248/45				
								163.3	**-63.8**	227	3	+plunge 163/17	78.0	300.7	5.4	4.3
SD 6 Strmendolac, HR 1454-463	43°36'24"	16°45'03"				Large scatter						216/16				
SD 7 Otok, HR 1464-473	43°41'18"	16°43'58"	7/10	188.8	-62.4	67.9	7.4	**173.6**	**-57.5**	67.9	7.4	300/10	82.6	239.9	10.8	7.9
SD 8 Jelinčići, HR 1474-481	43°42'23"	16°40'58"	6/8	336.0	+42.0	26.4	13.3	**341.8**	**+67.7**	26.4	13.3	150/26	75.9	322.4	22.2	18.6
SD 9 Bajagić, HR 1921-933	43°46'12"	16°39'15"	9/13	184.5	-52.6	44.8	7.8	**170.9**	**-55.6**	49.6	7.4	245/7,234/11,269/11	79.7	242.1	10.6	7.6
Santonian																
SD 10 Rumin, HR 1909-920	43°47'32"	16°37'48"	10/12	329.0	+15.3	40.4	7.7	**328.7**	**+44.3**	40.4	7.7	150/29	59.1	261.9	9.7	6.1

Table 2. Summary of locality mean paleomagnetic directions for the Crnika section (Pag), Drniš and Sinj basins based on the results of principal component analysis (Kirschvink, 1980). Localities are numbered according to Fig. 2. Key: Lat.N, Lon.E: Geographic coordinates (WGS84) measured by GPS (Garmin GPSmap 60CSx), n/no: number of used/collected samples (the samples are independently oriented cores); D, I (Dc, Ic): declination, inclination before (after) tilt correction; k and α_{95}: statistical parameters (Fisher, 1953); Lat and Lon: coordinates of the paleomagnetic pole; δm and δp: half cones of the error ellipse of the paleomagnetic pole.

Drniš and Sinj basins	N	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	Reversal test		Fold test		Pole				with respect to Africa				Age	with respect to Europe			
																		Rotation		Poleward displace.			Rotation		Poleward displace.	
										class	observ. γ (critical γ)	class	%	Lat°	Lon°	K	A95	°	±	°	±	Ma	°	±	°	±
Sedimentary localities																										
SD 1, 2, 4, 5b, 7, 8, 9	7	359.5	+53.7	6.5	25.7	341.2	+60.7	59.5	7.9	Rbi	8.1 (24.3)	pos.	81.9 ±19.2	76.6	286.7	33.2	10.6	-19.3	10.8	2.1	8.0	10Ma	-26.2	11.6	4.3	8.6
																		-19.5	11.3	3.6	8.4	20Ma	-28.1	12.5	7.2	9.1
SD 1, 2, 5b, 7, 8, 9	6	351.0	+57.6	7.0	27.3	347.9	+61.3	160.7	5.3	Rbi	8.3 (14.1)	pos.	92.5 ±12.2	81.0	285.4	104.4	6.6	-13.4	7.1	2.6	5.2	10Ma	-20.2	8.2	4.8	6.1
																		-13.6	7.7	4.1	5.8	20Ma	-22.2	9.5	7.7	6.7
Sedimentary localities + tephra																										
SD 1, 2, 3*,4, 5b, 7, 8, 9	8	357.3	+54.5	7.4	21.7	341.4	+60.5	68.9	6.7	Ra	3.5 (17.6)	ind.	82.0 ±16.0	76.5	285.0	38.5	9.0	-19.3	9.2	1.6	6.9	10Ma	-26.2	10.1	3.9	7.5
																		-19.5	9.7	3.1	7.4	20Ma	-28.1	11.2	6.7	8.1
SD 1, 2, 3*, 5b, 7, 8, 9	7	349.7	+57.8	8.3	22.2	347.0	+60.9	181.2	4.5	Ra	4.4 (15.0)	pos.	92.7 ±10.2	80.4	283.0	116.0	5.6	-14.1	6.1	2.1	4.6	10Ma	-20.9	7.4	4.3	5.5
																		-14.3	6.9	3.6	5.2	20Ma	-22.9	8.8	7.2	6.2

Table 3. Drniš and Sinj basins. Overall mean paleomagnetic direction before (D°, I°) and after (D_C°, I_C°) tilt correction, reversal and fold tests, virtual geomagnetic pole and apparent rotation with respect to the coeval African and Stable European virtual geomagnetic pole for 10 and 20 Ma (Torsvik at al., 2012, 20Ma running mean, inclination corrected for flattening f=0.6).

Key: α_{95}°, k and A_{95}°, K statistical parameters (Fisher, 1953) for paleomagnetic direction and virtual geomagnetic pole, respectively. Reversal test according McFadden and McElhinney (1990) and direction-correction tilt test according Enkin (2003).

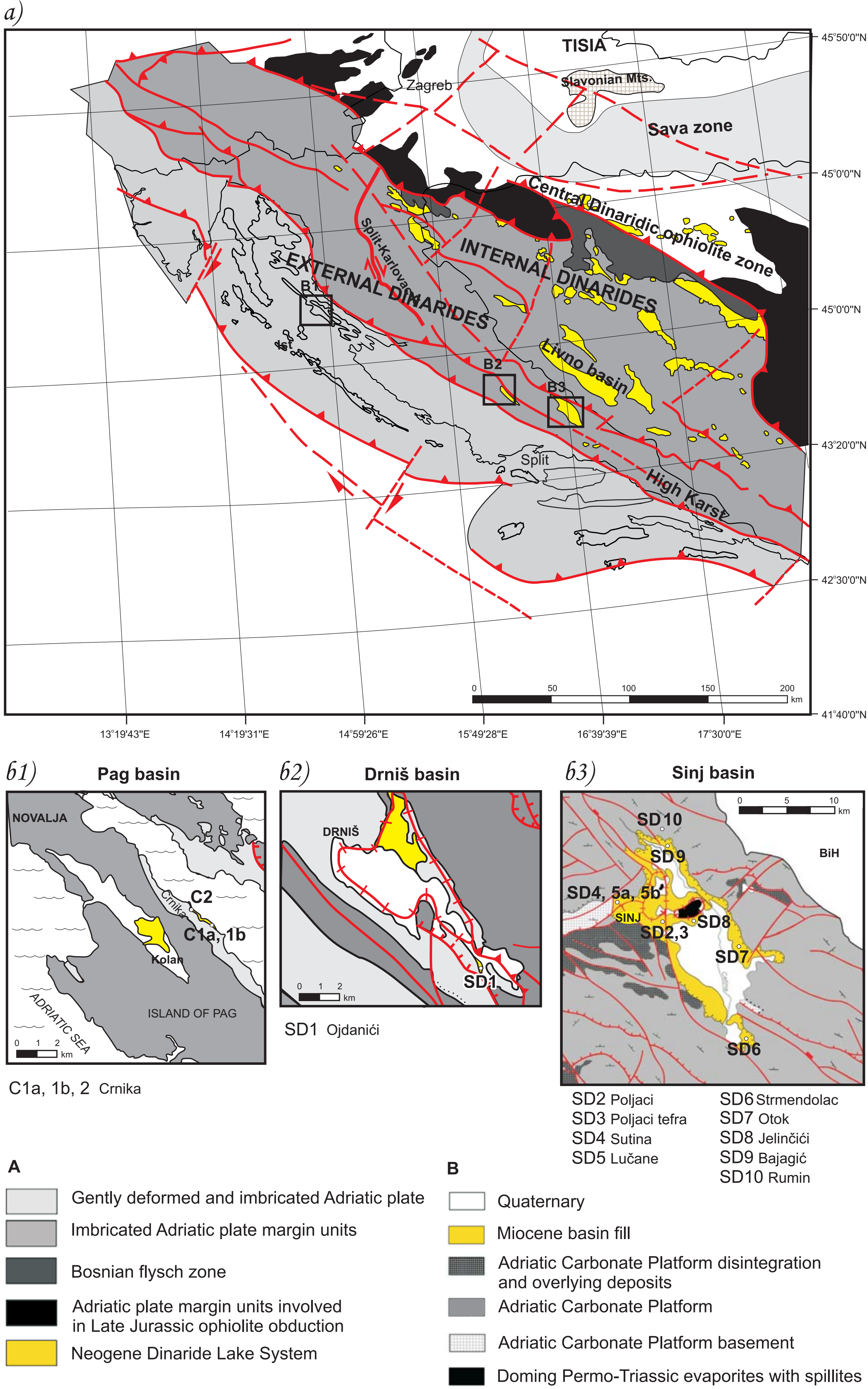

Fig. 1 Tectonic map of the Dinarides and southern Pannonian basin (a) compiled and modified after Tari, (2002), Schmid et al., (2008), Tomljenović et al., (2008), and Ustaszewski et al., (2008). Geologic map of the Pag basin (b1), Drniš basin (b2) and Sinj basin (b3) simplified after Geologic map of Republic of Croatia, 1: 300 000, Hrvatski Geološki Institut - HGI, (2009).

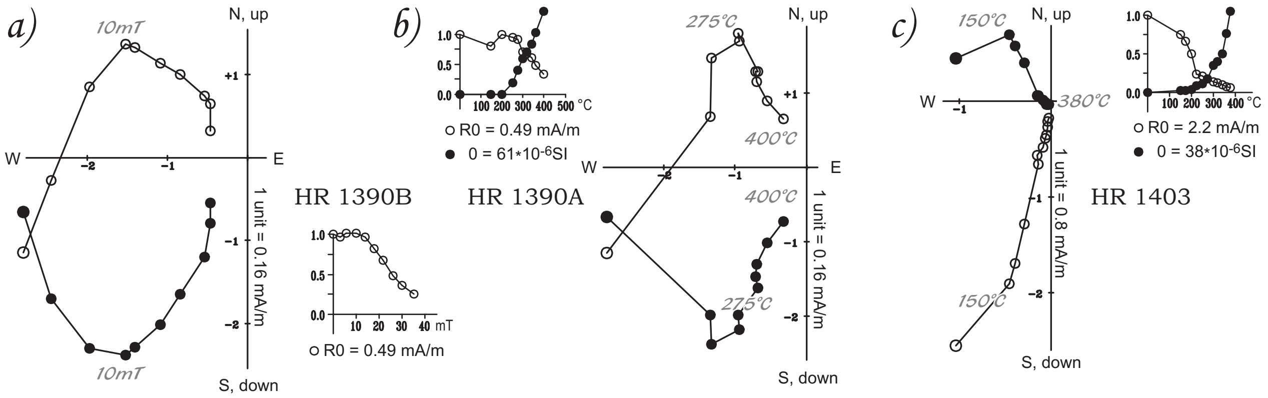

Fig. 2 Crnika section, Pag island. Typical demagnetization diagrams. Each orthogonal projection (Zijderveld diagram) is accompanied by normalized NRM or NRM/susceptibility versus demagnetization field or demagnetization temperature diagram. The scale for the susceptibility is logarithmic. Diagrams 2a and 2b documents the behaviour of the NRM of sister specimens on AF (2a) and thermal (2b) demagnetization, respectively from the oldest, and 2c a typical thermal demagnetization curve for the youngest part of the section. The last demagentization step, 450°C in 2b is not shown, because of the extreme instability of the NRM (interpreted as a signal postdating the final decay of the NRM and the 80% increase of the susceptibility compared to the one measured after 400°C.

Key: Orthogonal plots: dots are projection of the vector onto the horizontal, circles onto the vertical plane. Normalized intensity or intensity /susceptibility diagrams: intensity - circles, susceptibility - dots.

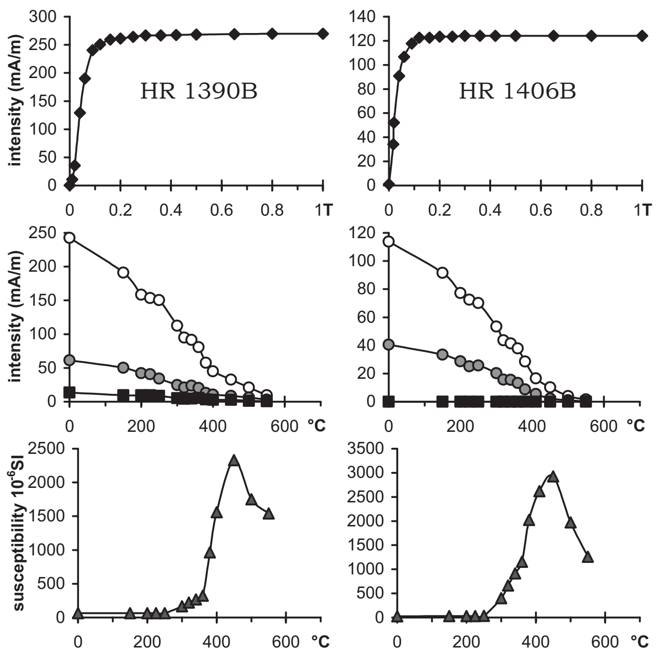

Fig. 3 Examples of the acquisition of the isothermal remanent magnetization (IRM) and the thermal demagnetization of the 3-component IRM (Lowrie, 1986) accompanied by the susceptibility measured after each heating step. The components of the IRM were acquired in fields of 1T (squares), 0.36T (dots) and 0.12T (circles), respectively.

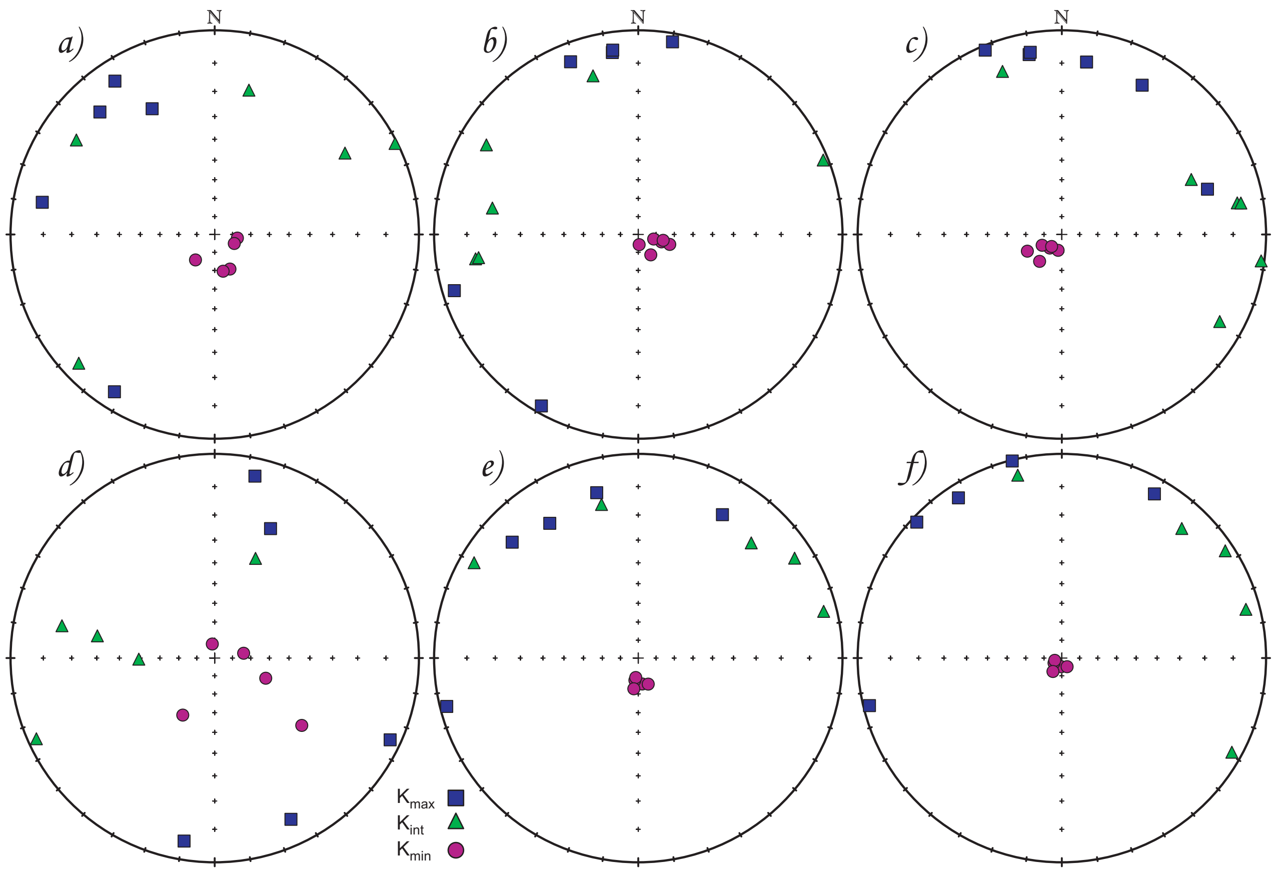

Fig. 4 Pag island, Crnika section. Magnetic fabrics observed for 10-15m (a-c) and 113-120m (d-f) of the section. On the left side the results of measurements before demagnetization and in the geographic system are plotted, the central and right side stereoplots show the fabrics after the 380°C demagnetization step, in the geographic and tectonic systems, respectively.

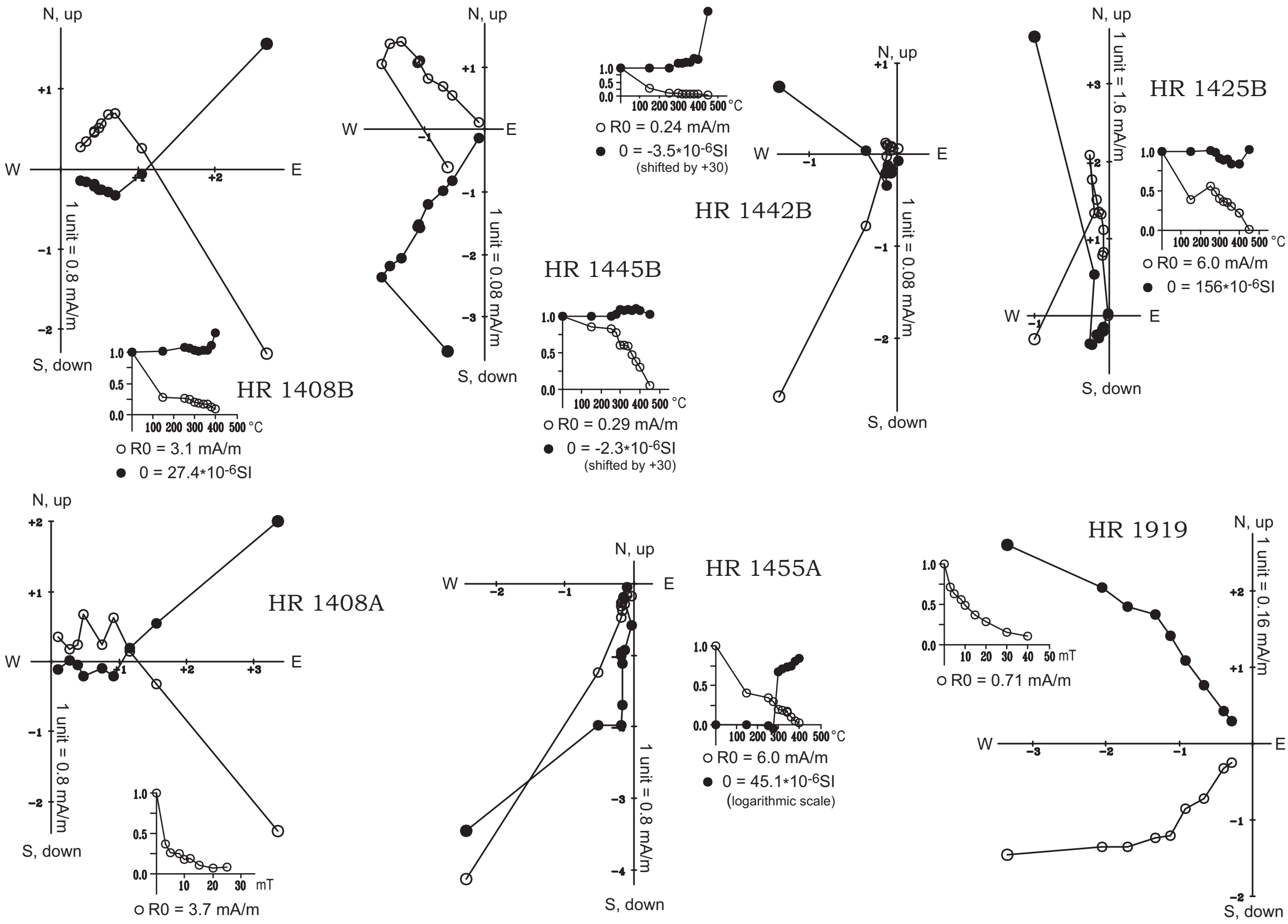

Fig. 5 Drniš and Sinj basins. Typical demagnetization diagrams in geographic coordinate system. Each orthogonal projection (Zijderveld diagram) is accompanied by normalized NRM or NRM/susceptibility versus demagnetization field or demagnetization temperature diagram. On the left side, the results of thermal (specimen HR1408b) and AF (specimen HR1408A) demagnetizations of sister specimens (from the Drniš basin) are shown. The central and left side diagrams are typical thermal demagnetizaton curves for several localities from the Sinj basin (Lučane road cut, specimen HR1445B, Lučane section, HR1442B, Poljaci marl, HR1425B, Strmendolac, HR1455B). HR1919 is a typical AF demagnetization curve for the Santonian limestone.

Key: Orthogonal plots: dots are projection of the vector onto the horizontal, circles onto the vertical plane. Normalized intensity or intensity /susceptibility diagrams: intensity - circles, susceptibility – dots

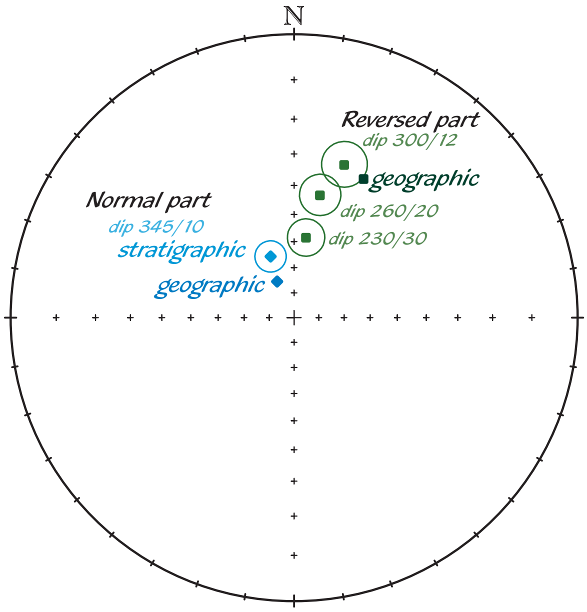

Fig. 6 Pag island, Crnika section. Mean paleomagnetic mean directions for the lower (HR1384-396, reversed polarity), and for the uppermost (HR1397-407, normal polarity) parts, before and after tilt corrections. For the normal polarity part, the dip direction/angle was unambiguous, for the reversed polarity part three post-tilted versions were calculated. 300/12° was the schistosity plane of AMS, the other two were measured in the field, close to the sampling segment of the section. All directions are plotted with $_{95}$ and the reversed polarity directions are re-calculated as normal directions.

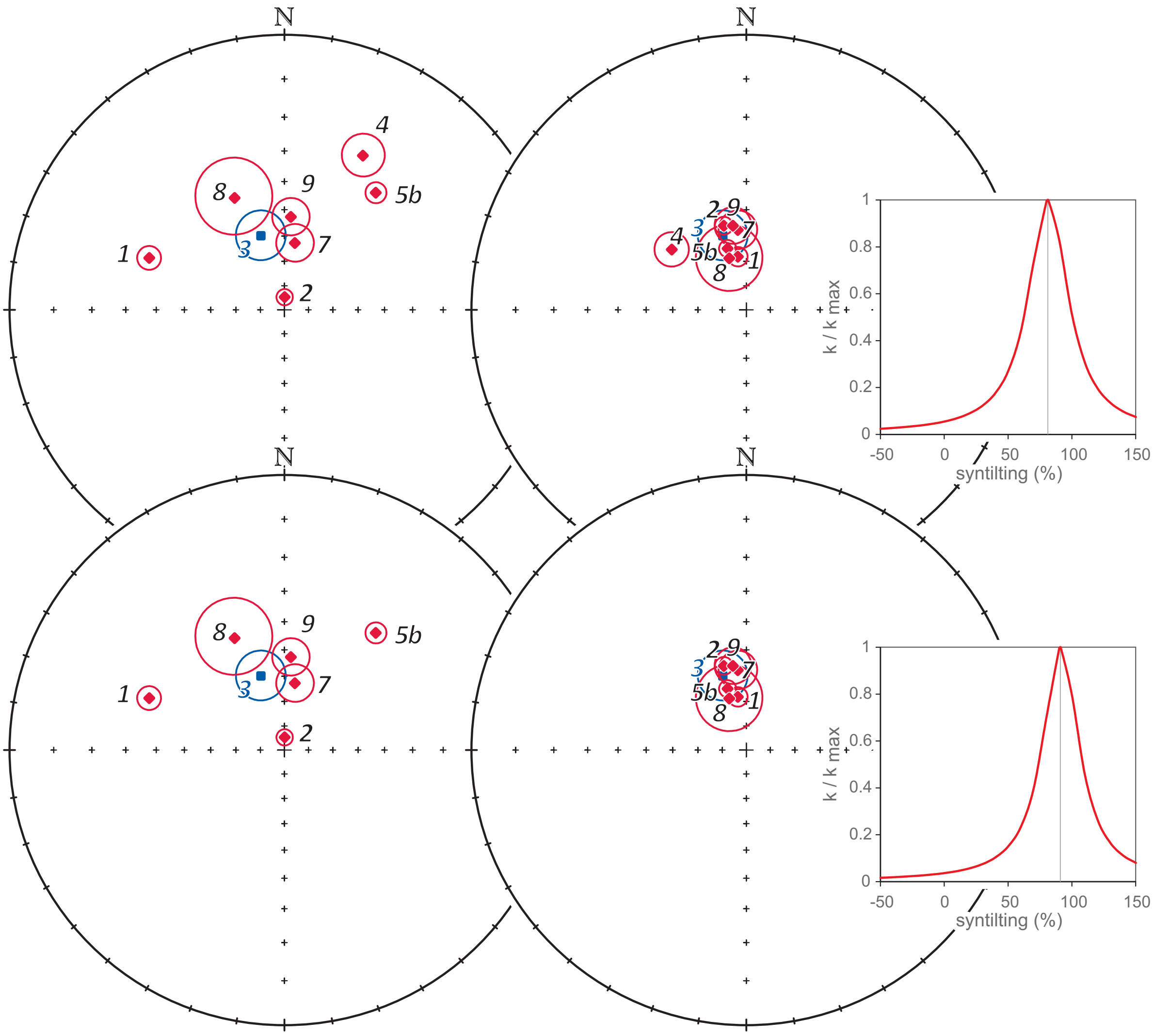

Fig. 7 Drniš-Sinj twin basins. Locality mean paleomagnetic directions (all plotted as normal polarity directions) with $_{95}$ before (left side) and after (right side) tectonic corrections. The paleomagnetic direction for the tephra (locality SD3) is included in the diagrams without tilt correction, since its magnetization is interpreted as of post-tilting age. The locality numbers are shown in the diagrams without the code SD. The upper diagrams include locality SD4, which is omitted from the lower diagrams showing only the locality mean directions which are tightly clustered after tectonic corrections. Fold/tilt test shown by the syntilting versus k/k max diagrams was carried out only for the sediments and it is positive, with a maximum of the curve close to complete unfolding (see also Table 3).