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First rock magnetic and palaeomagnetic analyses of the Pre-Cenozoic rocks of the Velebit Mt. (Croatia): prospects for applications in palaeogeographic and geotectonic studies

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ABSTRACT

Post-Carboniferous deposits of the Karst Dinarides were analyzed in terms of their palaeomagnetic and rock magnetic properties in order to identify the best sections for comprehensive palaeomagnetic studies on the geodynamic and palaeogeographic evolution of this mountain belt. A total of eighteen reconnaissance rock samples have been collected from the Permian red beds and dolomites, and Triassic, Jurassic, Cretaceous and Eocene carbonates. Most come from Velebit Mt., part of the Dinaric orogenic belt finally uplifted in the Oligocene–Miocene, and stretching NW–SE along the NE Adriatic coast. Experimental studies comprised identification of potential carriers of a natural remanent magnetization (NRM) by means of their properties of Curie temperature and coercivity accompanied by SEM and microprobe studies, demagnetization of standard palaeomagnetic specimens by means of alternating field and thermal cleaning, as well as the measurement and analysis of magnetic susceptibility and its anisotropy. Haematite (in Permian red beds) and Ti-magnetite (in carbonates) and sporadically goethite have been identified as remanence carriers. The state of preservation, ascertained by SEM observations, suggests a detrital origin of NRM in most of the samples. Characteristic NRM components (ChRM), both of high coercivity and unblocking temperatures, could be clearly identified in most of the specimens. These components show smeared distribution on the sphere and do not cluster around any known palaeomagnetic direction expected for the Velebit area from apparent polar wander paths, neither for Eurasia nor for Africa. This outcome suggests lack of overall remagnetization of the studied part of the Karst Dinarides after the last tectonic event and/or important contribution from tectonic rotations to the observed pattern of ChRM distribution.

Keywords: Palaeomagnetism, Rock magnetism, Karst Dinarides, Adria, Velebit Mt., Croatia

1. INTRODUCTION

Mesozoic and Cenozoic plate tectonic reconstructions of the Carpathian–Dinaride–Hellenic regions have been recently a matter of several syntheses, involving geologic and palaeomagnetic data (VAN DIJK & SCHEEPERS, 1995; NEUGEBAUER et al., 2001; STAMPFLI & BOREL, 2002; CSONTOS & VÖRÖS, 2004). The main crustal units of this area are the Alcapa, Tisza–Dacia and Adria composite terrains, from which a wealth of palaeomagnetic results have been collected during the past decades (see VAN DIJK & SCHEEPERS, 1995; BESSE & COURTILLOT, 2002; CSONTOS & VÖRÖS, 2004; MUTTONI et al., 2005 for references). A particular gap in this palaeomagnetic data set of Adria is due to relatively restricted palaeomagnetic research in the territory of Croatia and neighbouring countries, although significant progress has recently been made due to the works of Emő Márton and co-workers (MÁRTON et al., 1995, 1999, 2002, 2003, 2008; see also MÁRTON & VELJOVIĆ, 1983).

The main purpose of this study was to check the general rock properties of the different units, in order to be able to plan further activities enabling a better insight into a complex tectonic and palaeogeographic evolution of the Karst Dinarides. Therefore, to learn more about the pre-Cenozoic history of the Croatian part of the Adria plate, we performed reconnaissance palaeomagnetic studies in the wider area of Velebit Mt. in Lika and Northern Dalmatia (Fig. 1), which are characterized by rocks of a very wide stratigraphic range. It was particularly important to check a working hypothesis on the possible post-tectonic remagnetization of the Velebit structure that would prevent us from undertaking a more in-depth palaeomagnetic study on the palaeogeographic and geotectonic evolution of the Adriatic Carbonate Platform and its underlying and overlying units.

2. PREVIOUS PALAEOMAGNETIC STUDIES

There has been some previous palaeomagnetic study of the Karst Dinarides, but the complexity of their geological history requires a systematic approach. In Northern Croatia, (part of the Pannonian Basin), somewhat more palaeomagnetic measurements were performed in Neogene deposits, including those by MÁRTON et al. (1999, 2002, 2006), MÁRTON & FODOR (2003), BABINSZKI et al. (2007) and VASILIEV et al. (2007).

Most of the previous palaeomagnetic investigations of the Karst Dinarides were either performed a relatively long time ago (e.g. MÁRTON & VELJOVIĆ, 1983; MÁRTON & MILIČEVIĆ, 1994; KISSEL et al., 1995; MÁRTON et al., 1995), or the area of the Karst Dinarides was not a major focus of the investigations (e.g. MAURITSCH et al., 1995; CHANNELL, 1996). Only recently, have papers on the palaeomagnetic study of the relatively stable areas of the Karst Dinarides been published by MÁRTON et al. (2003, 2008), in which the youngest Jurassic, Cretaceous and Palaeogene rocks were studied. MÁRTON et al. (2008) indicate general concordance with the African polar wander path during the youngest Jurassic and Cretaceous, but with a slight displacement interpreted as a consequence of about 10° CCW rotation of Istria in comparison with the African motion. In the earlier paper MÁRTON et al. (2003) concluded that the area of stable Istria must have been 30° CCW rotated in the Tertiary relative to Africa and stable Europe, but also indicated that Maastrichtian–Eocene platform carbonates from Central Dalmatia were subsequently remagnetized, either during the Late Eocene–Oligocene tectonic deformation or by Miocene hydrocarbon migration.

A recent study by SATOLLI et al. (2008) also indicated coherent movement of Adria with respect to Africa during the Late Jurassic and Early Cretaceous, and the difference in the position of their apparent polar wander paths for this period was interpreted as being a consequence of a subsequent 26° CCW rotation, probably connected with Apenninic orogenesis.

Rocks selected for the purpose of this study have not been, up to our knowledge, palaeomagnetically studied yet.

3. GEOLOGIC SETTING

The area of the Karst Dinarides is composed of a thick sequence of deposits, representing a wide stratigraphic range (Carboniferous to Recent). Most of the rocks cropping out in Central, Western and Southern Croatia originated from the ancient Adriatic Carbonate Platform, which lasted from the Late Early Jurassic to the end of the Cretaceous (see discussion in VLAHOVIĆ et al., 2005). Others include the rest of the basement rocks and relatively thin overlying carbonate and siliciclastic deposits. The entire sequence is probably up to 10 km thick, but due to the intense tectonics the thickness may only be estimated.

The target rocks, comprising clastics and carbonates of Permian to Eocene age, crop out in the central part of the Karst Dinarides (Fig. 1). They include thick carbonates and some clastics (Fig. 2), deposited in different palaeogeographic settings, from mixed siliciclastic–carbonate environments of the epeiric sea to a more or less isolated intraoceanic carbonate platform. Palaeogeographic positions varied from equatorial latitudes in the Permian to progressively more northern latitudes during the Mesozoic and Cenozoic. Different areas were also submitted to different diagenetic conditions (especially regarding burial depths, which vary from several hundred metres for the youngest to several thousand metres for the oldest rocks). Furthermore, it was apparent at the beginning of the investigation that it was necessary to sample rocks of such a wide stratigraphic range (from Middle Permian to Eocene, i.e. from approximately 265 to 50 MY) in order to check whether the area of Velebit was remagnetized during the important tectonic event connected with the collision and the final uplift of the Dinarides.

The general succession of deposits in the central part of the Karst Dinarides, i.e. in the Velebit Mt. and neighbouring area, is presented in Fig. 2. For more information on the succession and its stratigraphy see VELIĆ et al., 2002; VLAHOVIĆ et al., 2005; VELIĆ, 2007 (and references therein). Sampling localities are shown on Fig. 1, and logistic data are included in Table 1.

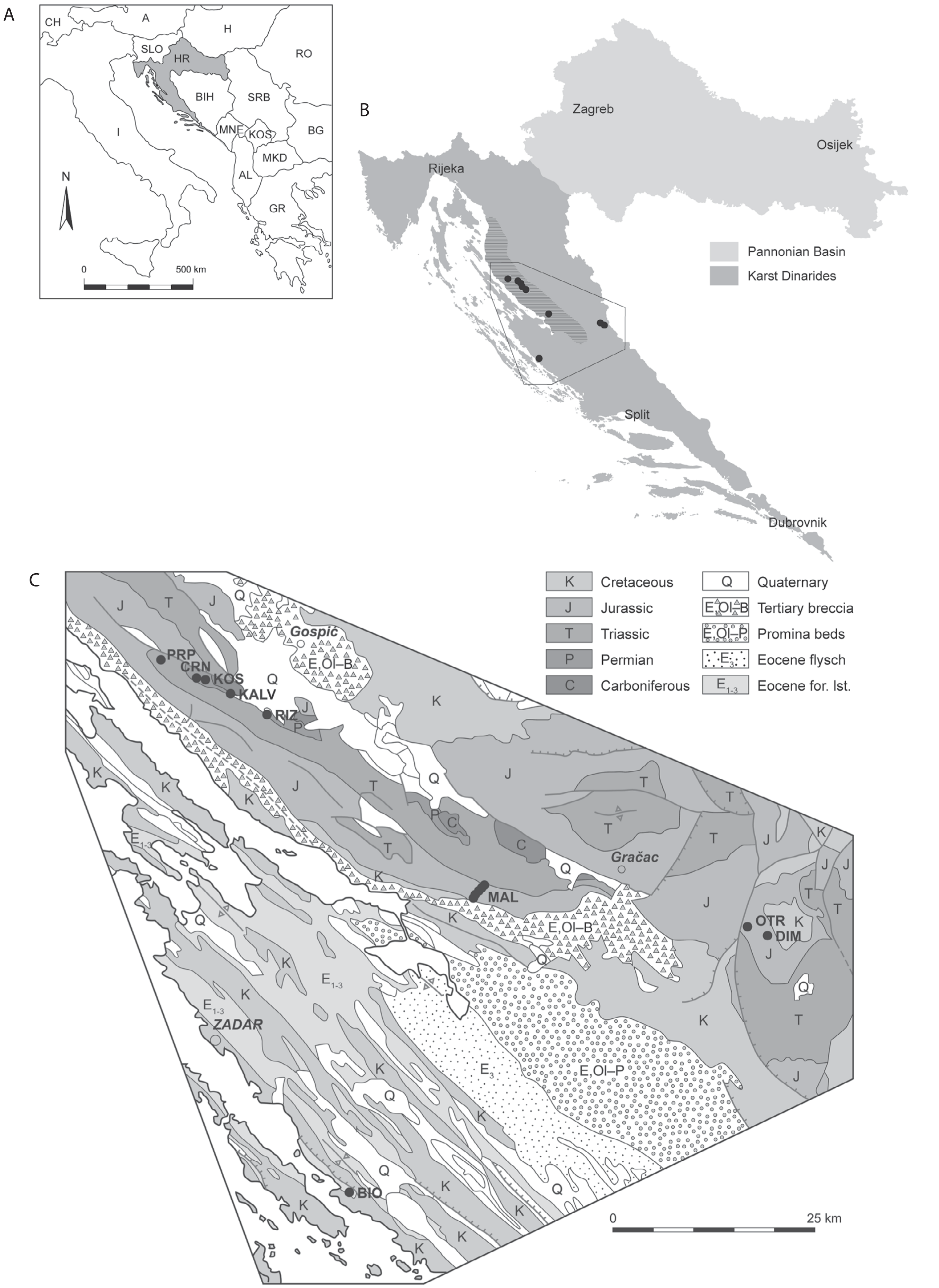


Figure 1: Geographical position of the studied area (A, B – shaded area represents Velebit Mt.), and schematic geological map (simplified after FGI, 1970) showing the positions of the samples (C). Legend: PRP – Prpići, CRN – Crne Grede, KOS – Košna, KALV – Kalvarija, RIZ – Rizvanuša, BIO – Biograd, MAL – Mali Halan, OTR – Otrić, DIM – Dimići.

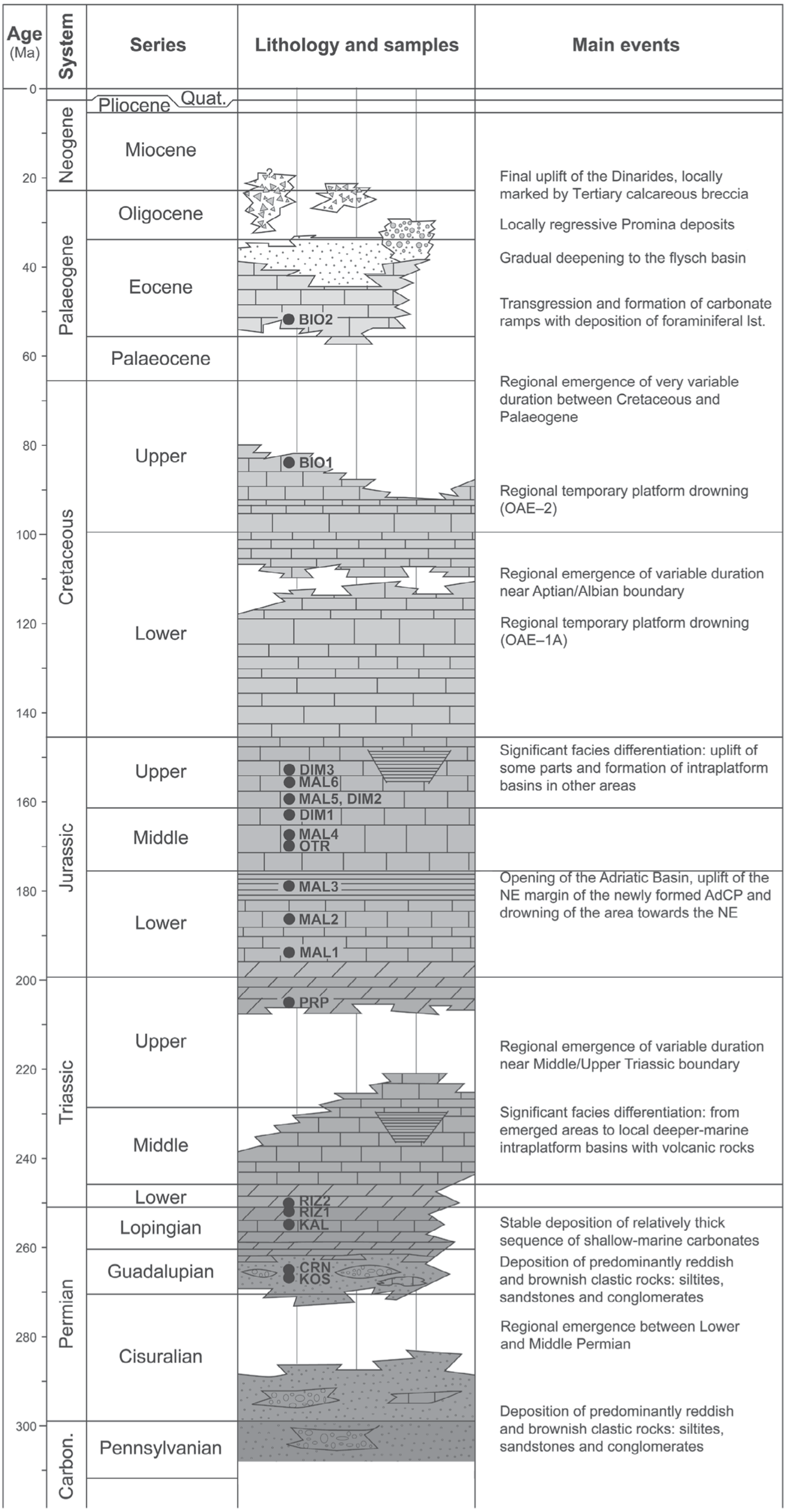


Figure 2: A schematic geological column of the Velebit Mt. area illustrating the stratigraphic position of the sampling localities of this study (see Fig. 1 for symbols description). Time scale after GRADSTEIN et al. (2004). Palaeogene/Neogene events and deposits, which are not a topic of this paper, are presented very simplified.

The oldest sequences of rocks cropping out in the Karst Dinarides were deposited from the Carboniferous to the regional emergence in the Early Permian, and from the Middle Permian to the next regional emergence in the Middle/Late Triassic (Fig. 2). Of these, the oldest cropping out in the area of Karst Dinarides are the Upper Carboniferous, (Moscovian), predominantly clastic deposits. Similar deposition continued into the Permian, then after an emergent phase in the Early Permian, it continued until the end of the Middle Permian. This part of the sequence was sampled at Košna (sample KOS) and Crne Grede (sample CRN). A thick succession of carbonates, with only a sporadic and relatively weak input of clastic rocks, is composed of Middle/Upper Permian dolomites (samples Kalvarija – KALV, and Rizvanuša – RIZ), Lower Triassic dolomites and Middle Triassic recrystallized limestones. All these rocks were deposited in mixed siliciclastic–carbonate environments of the epeiric sea, probably along the NE margins of Gondwana (see discussion in VLAHOVIĆ et al., 2005).

After a long emergent phase, lasting between the Ladinian or Early Carnian (in places even Anisian), until the Late Norian, a thick succession of pure carbonates was deposited. These represented part of a huge carbonate platform on which regionally important and recognizable facies, including the Main Dolomite (*Hauptdolomit*) and Lithiotis Limestones were deposited throughout the area of present southern and southeastern Europe, and elsewhere. This sequence, which continued until the end of the Early Jurassic, was sampled at the Prpići locality (sample PRP).

During the Toarcian, the huge former platform was dissected into several small platforms surrounded by drowned basinal areas, including the Adriatic Carbonate Platform which was probably connected towards the south to the Kruja, Gavrovo–Tripolitza and Menderes platforms in present Albania, Greece and Turkey. This huge area was isolated from direct continental influences because it was surrounded by a deep Tethyan ocean, but frequent occurrences of dinosaurs indicate at least temporal connections with Africa until the Mid-Cretaceous, and with Eurasia during the Late Cretaceous, when the platform finally disintegrated heralding the beginning of collision with the European plate. This sequence was sampled in Mali Halan (samples MAL), Otrić (sample OTR) and Dimići (samples DIM), while the youngest Cretaceous rocks (Upper Santonian) were sampled at Biograd (sample BIO1).

After the shorter or longer emergent phase, deposition was renewed only in the deeper parts of the pre-existing palaeorelief. As a result of intense tectonics, shallow marine, ramp carbonates, (Foraminifera Limestones – sample BIO2), were gradually replaced by deeper-marine flysch sediments in elongated basins. Regressive Promina deposits are only visible in some locations, and end with thick alluvial deposits. The tectonic stress, oriented NE–SW (in present-day geographic coordinates), intensified during the Late Eocene resulted in the Oligocene and Early Miocene with the intense uplift of the Dinarides. This uplift is marked in places by massive Tertiary carbonate breccia, while the change of tectonic stress in the younger, neotectonic phase, was charac-

Table 1: Basic data for sample collection. Legend: S.A. – sample azimuth; S.D. – sample dip; B.A. – bedding azimuth, B.D. – bedding dip.

LOCALITY	HAND SAMPLES					LITHOLOGY	AGE	UTM COORDINATES	
	SYMBOL	S.A.	S.D.	B.A.	B.D.			x	y
Rizvanuša	RIZ1	294	62	214	85	Dolomite	U. Permian	5524541	4926595
	RIZ2	284	81	208	81	Dolomite	L. Triassic		
Košna	KOS1	138	52	138	52	Red sandstone	M. Permian	5519453	4929872
Kalvarija	KALV	128	50	205	89	Dolomite	U. Permian	5521786	4928382
Crne Grede	CRN1	10	120	190	60	Red sandstone	M. Permian	5517390	4929628
Prpići	PRP1	111	70	240	10	Dolomite	Norian	5512127	4932680
Mali Halan	MAL1	6	51	202	40	Limestone	Hettangian	5552426	4905346
	MAL2	10	135	190	55	Limestone	Pliensbachian	5552337	4904942
	MAL3	120	123	197	57	Limestone	Toarcian	5551459	4904986
	MAL4	50	131	230	49	Limestone	M. Jurassic	5551437	4904819
	MAL5	101	0	225	69	Limestone	Oxfordian	5551705	4903297
	MAL6	216	70	216	70	Limestone	Kimmeridgian	5551512	4902925
Otrić	OTR1	305	75	76	37	Limestone	M. Jurassic	5586321	4899795
Dimići zapad	DIM1	220	73	39	23	Limestone	Callovian	5588429	4898868
	DIM2	348	16	57	10	Limestone	Oxfordian	5588726	4899063
	DIM3	46	15	71	11	Limestone	Kimmeridgian	5588878	4899184
Biograd	BIO1	230	42	210	55	Limestone	U. Santonian	5537087	4866758
	BIO2	232	114	232	55	Limestone	L. Eocene	5537089	4866756

terized by a N–S oriented stress and mostly stike-slip movements, which finally shaped the Karst Dinarides.

4. ANALYTICAL PROCEDURES

Eighteen magnetically oriented hand samples, treated as a reconnaissance collection, were taken from rocks of varied ages from the Permian to the Eocene (Table 1). Hand samples were cored in the laboratory into standard palaeomagnetic cores, 1” diameter, yielding a total of 59 cores. Of these, 48 cores yielded sound palaeomagnetic results, enabling the identification of components of the natural remanent magnetization (NRM). Stable, characteristic components of NRM (ChRM) were used for the preliminary assessment of the relative rotations of the succession from the Velebit area with respect to Eurasia and Africa. The magnetic mineralogy was assessed using the method of LOWRIE (1990), supported by SEM and microprobe studies for better understanding of the nature of NRM. The Lowrie test was performed on standard-sized specimens, which were initially stepwise pulse magnetized along the z axis up to 2.7 mT to obtain the coercivity characteristics in a form of an induced remanent magnetization (IRM) curve. Next, the same specimens were pulse magnetized along the z, y and x axes in nominal fields of 2.7, 0.4, and 0.12 mT, respectively (LOWRIE, 1990), and, subsequently subjected to thermal demagnetization, providing information on unblocking temperatures (Néel temperature, T_{ub}) for each of the IRM three-components. Changes in the low-field susceptibility (κ) during the thermal demagnetization experiment were routinely monitored using the low-field KLY–2 susceptibility bridge. Variation of the initial magnetic susceptibility along the lithostratigraphic column was used to infer changes of paramagnetic minerals influx into the sedimentary basin. The anisotropy of the magnetic susceptibility (AMS) of 75% of the specimens was measured, and the density distribution of the principal components of the AMS ellipsoids was calculated using the SpheriStat package (STESKY, 1995). AMS study was performed to check the potential effects on internal rock deformation induced by tectonic stress (see TARLING & HROUDA, 1993).

All cores were subjected to thermal demagnetization in a Magnetic Minerals MM–1 furnace. Each specimen was heated in steps up to 580°C, except for the haematite-bearing rocks, which were heated up to 670°C. After each demagnetization step, cores were cooled in a zero magnetic field and measured on a 2G SQUID cryogenic magnetometer with a residual internal field below 3 nT and a noise level of less than 10^{-7} A/M (compared to 2 x 10^{-6} A/M of the most advanced spinner magnetometers). These characteristics ensure the complete demagnetization of the sampled rocks and identification of the most subtle NRM components, preventing unfavourable mineralogical changes in a course of thermal demagnetization. The cores exhibiting spurious magnetization and/or an NRM intensity close to the magnetometer noise level were excluded from the demagnetization procedure. Both the furnace and the SQUID magnetometer were operated inside a pair of Helmholz coils, reducing the ambient geomagnetic field by at least 95%. Some specimens were demagnetized by means of alternating field (AF), using magnetically shielded solenoids, combined with the SQUID.

Palaeomagnetic Data Analysis (PDA) software by LEWANDOWSKI et al. (1997), employing principal component analysis (KIRSCHVINK, 1980), was used to calculate the characteristic NRM components (ChRM) from the demagnetization data of each specimen, and to plot the orthogonal demagnetization diagrams. ChRM components with angular standard deviation greater than 8° were excluded from further analysis. Standard FISHER (1953) statistics were used to calculate the characteristic mean direction for the remaining ChRM populations. GMAP by TORSVIK & SMETHURST (1999) has been used for recalculation of the palaeomagnetic directions from apparent polar wander paths (APWP).

The rock samples (approximately 2 kg each) were dissolved in acetic acid (cf. HOUNSLOW & MAHER, 1999), and magnetic minerals were extracted from the insoluble fraction by a neodymium magnet placed in a removable, thin latex envelope. The extracts were analyzed by scanning electron microscope with EDX, JEOL JSM–6380LA. Thin sections were analyzed by electron microprobe with a Cameca WDX SX 100 device in order to identify the chemical composition of ferrimagnetic grains.

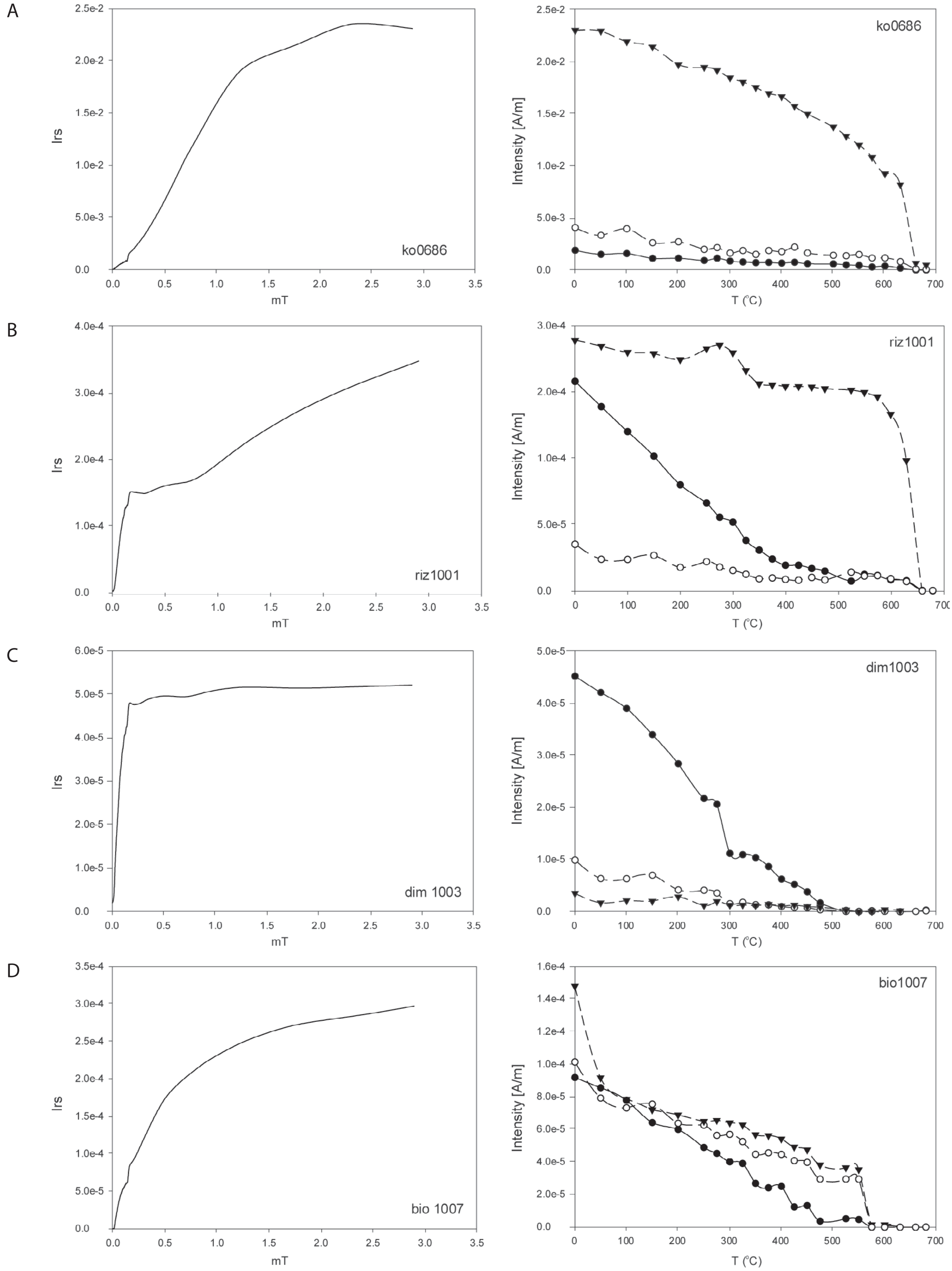
5. RESULTS

5.1. Rock magnetic results

Rock magnetic studies revealed the presence of both soft and hard magnetic phases in the studied rocks. Permian red beds of the Košna unit (Fig. 3A) do not contain any magnetite. Specimens were not saturated up to the field of 2.7 mT, and the maximum of T_{ub} for each of three induced components was in the range of 670°C, unequivocally demonstrating the presence of haematite.

In contrast to the Košna deposits, the Upper Permian limestones of Rizvanuša (Fig. 3B) contain a mixture of low and very high coercivity mineral phases. It is clearly demonstrated by the bimodal trend of the IRM curve, showing a steep slope up to the 0.2 T field, followed by a remanence plateau up to 0.9 mT, and continued by a gradual increase of the remanence, yet not saturated in the highest field. The presence of two different magnetic phases is confirmed by the Lowrie test, where the hard magnetic phase has a T_{ub} of ca. 670°C, while the soft one shows a T_{ub} of the order of 540°C, implying the presence of haematite and Ti-poor magnetite, respectively. Callovian limestones of Dimići (Fig. 3C) show the presence of a single magnetic phase with a low coercivity, easily saturated with the magnetic field of 0.2 T. This phase shows a T_{ub} around 540°C, characteristic for Ti-poor magnetite.

Upper Santonian carbonates of Biograd (Fig. 3D) show an IRM arcuate shaped curve up to the highest imposed magnetic field. This is indicative for the presence of a hard coercivity mineral, which was still unsaturated in the field of 2.7 T. Thermal demagnetization shows a low unblocking



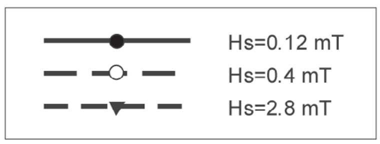


Figure 3: Results of the Lowrie test of typical samples. Induced remanence acquisition curves (left plots) and thermal demagnetization of the remanence induced along z (triangles), y (open circles) and x (full circles) specimens axes (right plots). See text for more detailed descriptions of diagrams.

temperature for the high coercivity phase (T_{ub} ca. 150°C), coexisting with a phase of T_{ub} near 580°C, characteristic for goethite and magnetite, respectively.

5.2. Susceptibility results

Magnetic susceptibility varied from site to site, and generally, three groups of susceptibilities can be distinguished (Fig. 4A): group L, with very low values, ranging from –12.78 to +4.61x10^{-6} SI, group I with intermediate susceptibilities (+30.9 to +84.9x10^{-6} SI), and group H, characterized by high susceptibilities (from +109.7 to +194.2x10^{-6} SI). Group L has susceptibilities comparable with typical platform carbonates, with a very low content of ferrimagnetic grains, while group I has values comparable with the susceptibilities of pelagic limestones (cf. LEWANDOWSKI et al., 2005). Group I comprises the Upper Permian and Lower Triassic rocks, as well as the Middle Jurassic carbonates. Group H comprises carbonate deposits spanning the Upper Triassic to the lower parts of the Middle Jurassic, having susceptibility values comparable with the red beds of the Middle Permian age. Older and younger carbonates all display the L category of susceptibility.

Anisotropy of magnetic susceptibility is of generally low values (Fig. 4B), which is rather an unexpected result for the rocks relatively strongly affected by tectonics. The degree of anisotropy (Pj, JELINEK, 1981) does not generally exceed 3%. The exception are rocks of Crne Grede and Otrić (Middle Permian and the Middle Jurassic age, respectively), both having the L category of susceptibility. Their Pj values indicate a strongly developed foliation (Fig. 4B), for the deformation of sphere exceeding 10%, up to 40% with a positive value of the shape parameter T (JELINEK, 1981). These data indicate an increased degree of internal deformation of rocks of Crne Grede and Otrić sites, located close to the major fault and regional nappe system margin, respectively, although a heightened influx of clay minerals to the sedimentary basin may also be important.

5.3. SEM and electron microprobe results

Insoluble residuals of Velebit Mt. carbonates contain a variety of magnetic fractions. The most interesting for study were those magnetic phases with the potential of representing remanence carriers. Most of the identified magnetic grains of this group were magnetites/Ti-magnetites, with different

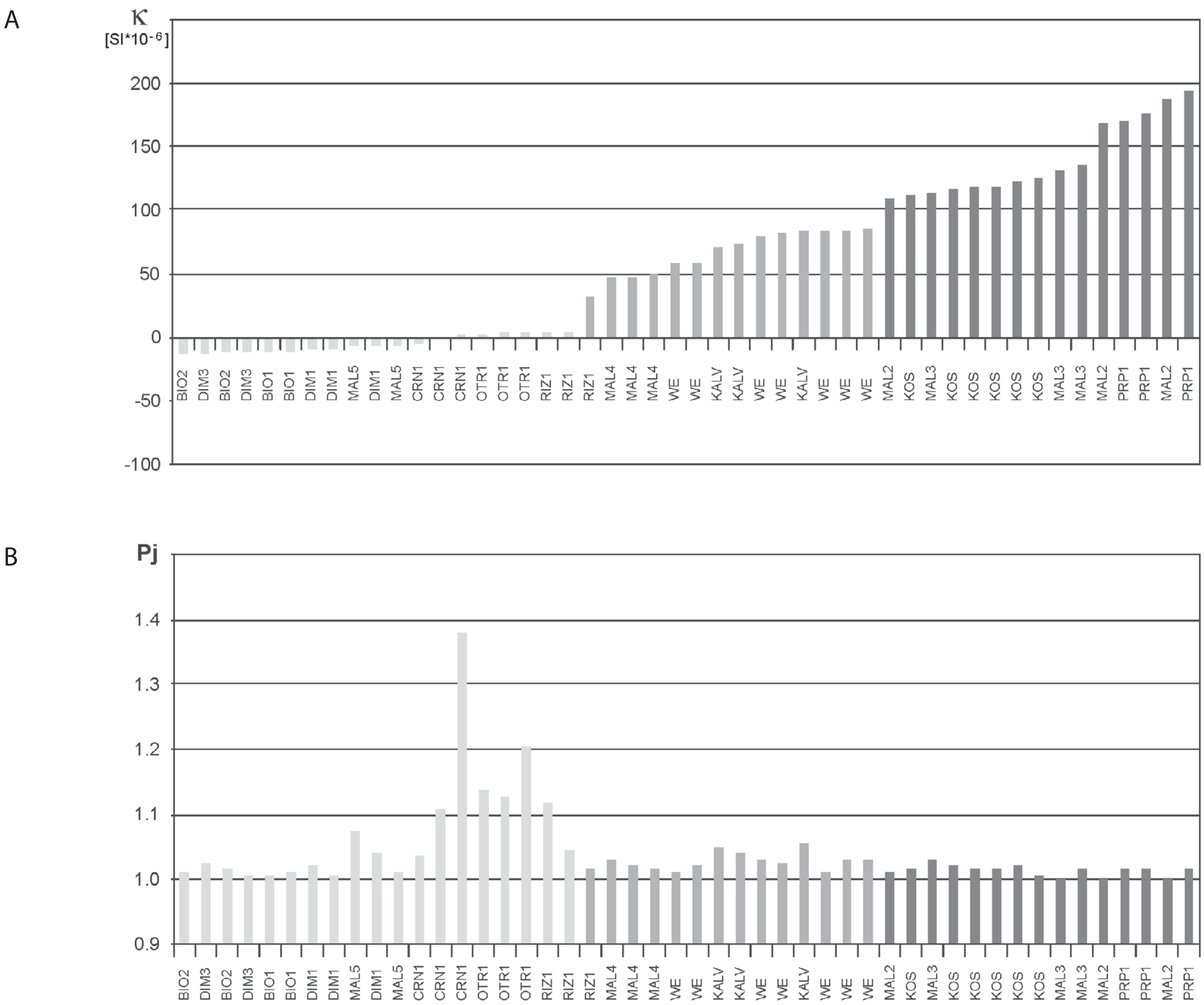


Figure 4: (A) Variation of the magnetic susceptibility parameter κ; (B) Anisotropy of the magnetic susceptibility – variability of magnetic foliation Pj (JELINEK, 1981). Ranges of categories of susceptibilities are shown: L (low) – light grey, I (intermediate) – medium grey, and H (high) – dark grey.

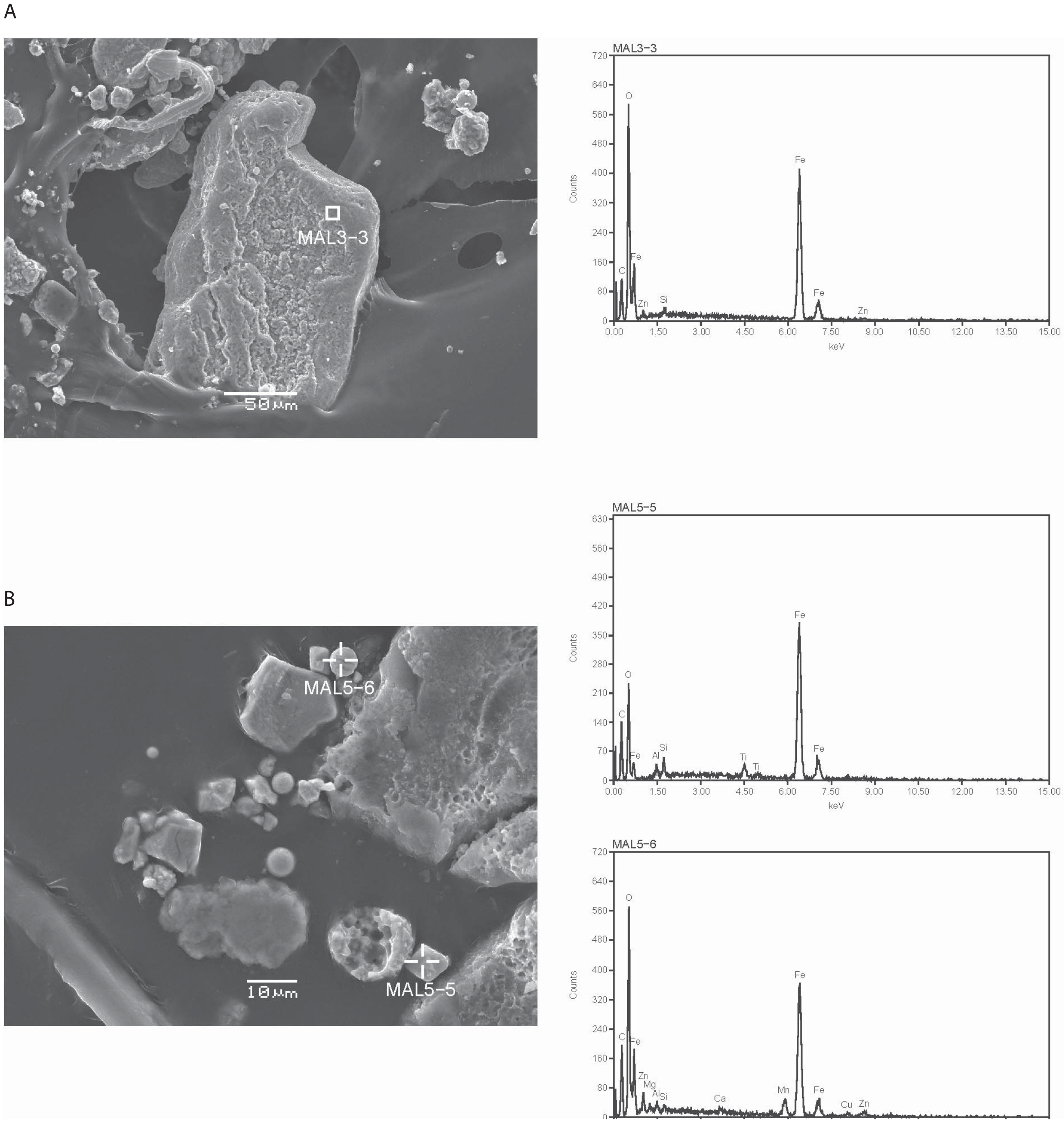


Figure 5: (A) Well sorted, detrital Ti-poor magnetite (MAL3–3), indicative of a distal source; (B) Ti-poor magnetite (MAL5–5) and magnetite spherule (MAL5–6) of a pseudo-single-domain dimension, potential carrier of a stable NRM (Lower Jurassic carbonates, Mali Halan).

Ti contents. The gain shapes frequently indicate a detrital origin, with sharp edges possibly indicating proximal sources. Grains with rounded edges suggest more distal transport, but some diagenetic influence due to dissolution by reducing fluids cannot be excluded. Spheres of diagenetic magnetite/maghemite with an exclusive iron composition, probably after pyrite replacement, were also observed, as well as framboidal pyrite spheres formed by aggregated subcrystals. Grain dimensions, on average, span between pseudo-single-domain states (dozen µm) to multidomain grains (>20 µm). Typical examples are shown in Figs. 5–7.

5.4. Palaeomagnetic results

The overall mean NRM measured for 45 specimens has the orientation D=14°, I=51° (present-day coordinates – Fig. 8), and is very similar to the present-day direction of the regional geomagnetic vector, expected for the mean sampling localities coordinates of 45°N/15°E from the geocentric, axial dipole model (D=0°, I=63°). This result proves that sample orientations were correct and that the present-day geomagnetic vector may have had an important contribution to the total remanence acquired in the rocks of the Velebit area.

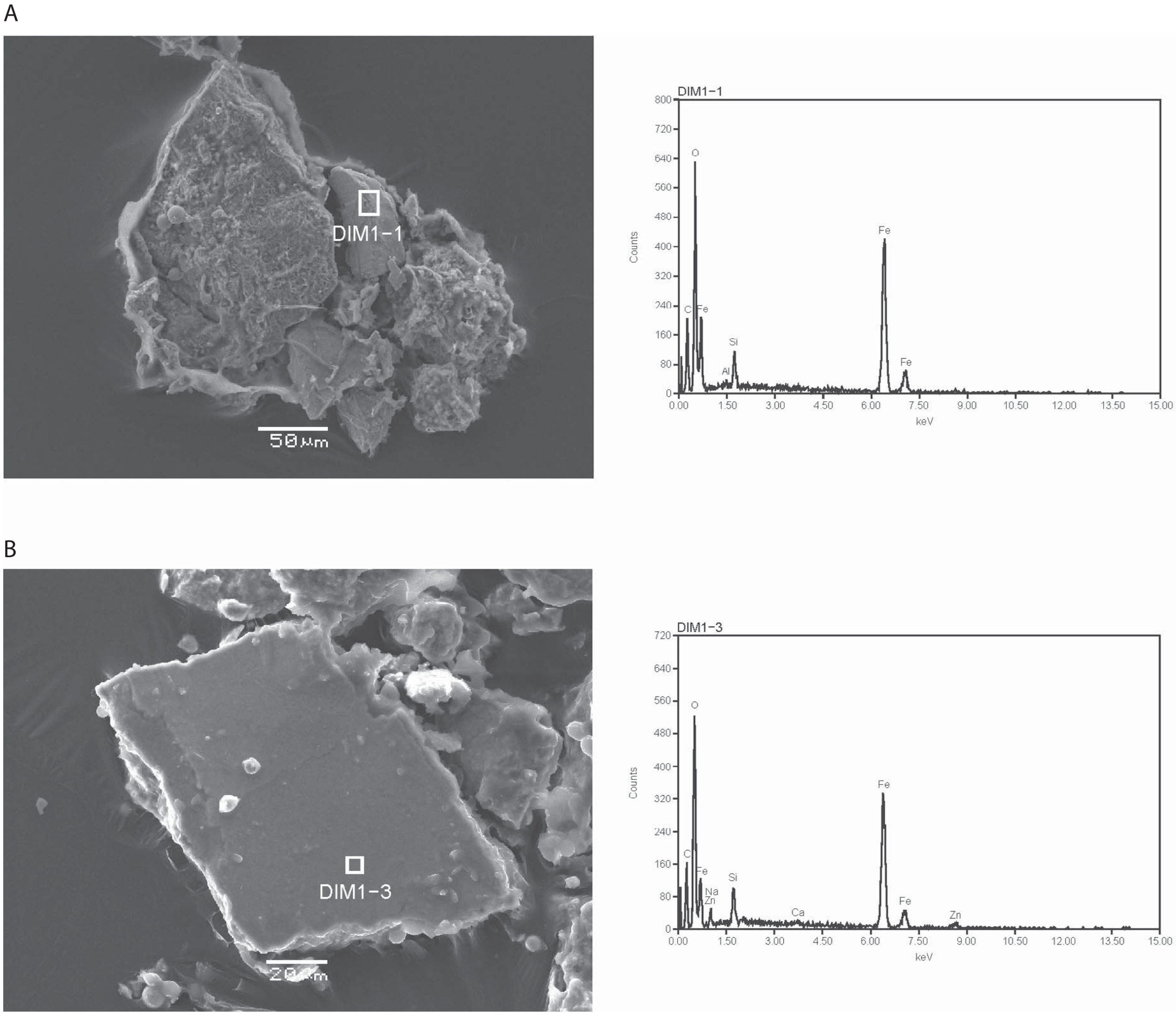


Figure 6: (A) Magnetite grain of Callovian carbonates of Dimići; DIM1–1 iron oxide (magnetite?), incorporated into a group of clay minerals; (B) DIM1–3 detrital iron oxide, probably magnetite, with attached surface coats of clay minerals, as indicated by EDS spectra.

5.4.1. Results of alternating field demagnetization

Most of the specimens responded very well to AF cleaning due to the presence of Ti-magnetite, although chaotic trends in demagnetization curves could also be encountered.

The Middle Permian limestones of Crne Grede (Fig. 9A) show a two-component structure of NRM. While the initial intensity is very low, the specimen could be successfully demagnetized almost to null values of the magnetization intensity. A low coercivity component is close to the present-day geomagnetic vector at the sampling site and can be regarded as a contemporary overprint. The stable component, identified in the range of 25–40 mT, has a northerly direction with a shallow inclination (geographical coordinates, Fig. 9A).

Upper Permian limestones of Kalvarija (Fig. 9B) show a similar NRM structure, but due to a stronger (by an order of magnitude) initial value of NRM, its components could be much more precisely determined.

The Lower Triassic limestones of Rizvanuša (Fig. 9C) mainly show a zigzag demagnetization trend, except for a soft, steeply inclined component.

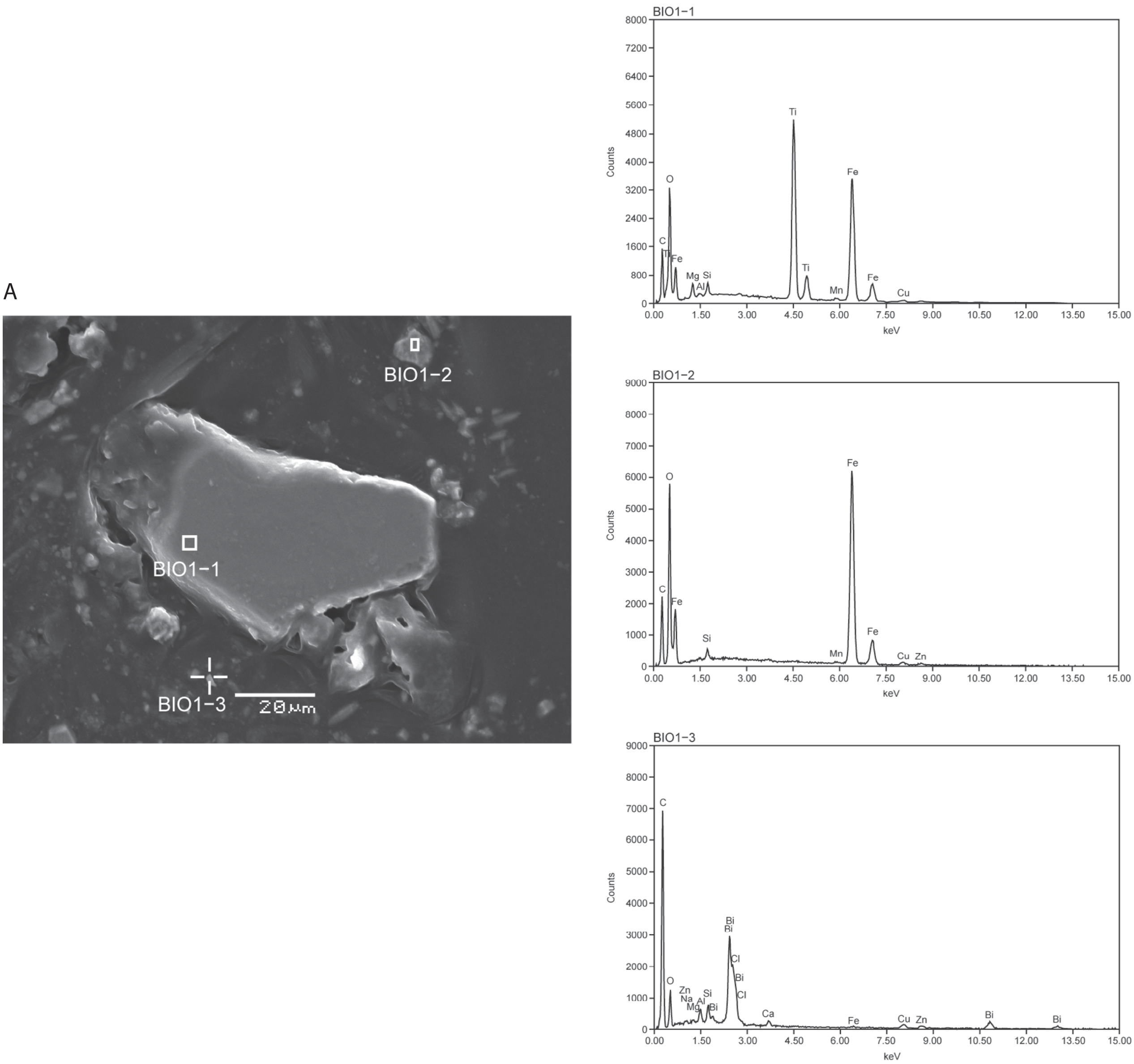
The Upper Triassic limestones of Prpići (Fig. 9D) contain two components with similar orientation toward the North and moderate inclination. The nonlinear shape of the demagnetization path indicates overlapping coercivity spectra, which makes precise identification of these components impossible.

Middle Jurassic limestones of the Mali Halan section (Fig. 9E) show generally nonlinear demagnetization paths, characteristic for components with overlapping coercivity spectra. Nonetheless, linear segments of demagnetization trajectories can be seen, enabling identification of two ChRM components. The soft one is directed along the ambient, present-day geomagnetic vector, while the harder component points to the North with intermediate inclination (geographical coordinates, Fig. 9E).

Middle Jurassic limestones from Otrić (Fig. 9F) also have a bimodal NRM structure and similar characteristics to those from the Mali Halan. Similarly, the inclination of the ChRM component is steeper than within Permian carbonates.

Kimmeridgian limestones of Dimići (Fig. 9G) contain two components of NRM. The soft one (up to 15 mT) is of

A



B

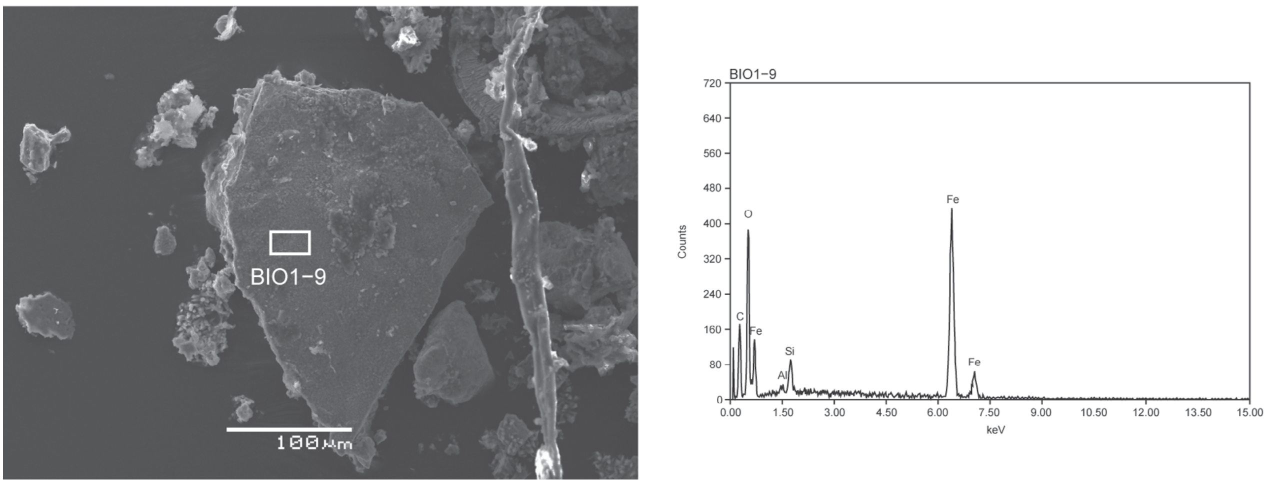


Figure 7: Poorly sorted, Ti-magnetite grains of the Upper Santonian carbonates (Biograd). (A) BIO1–1 Ti-rich magnetite grain, BIO1–2 magnetite(?) and BIO1–3 an unidentified mineral phase containing Bi; (B) BIO1–9 magnetite exhibiting sharp edges, suggesting detrital origin from a proximal source.

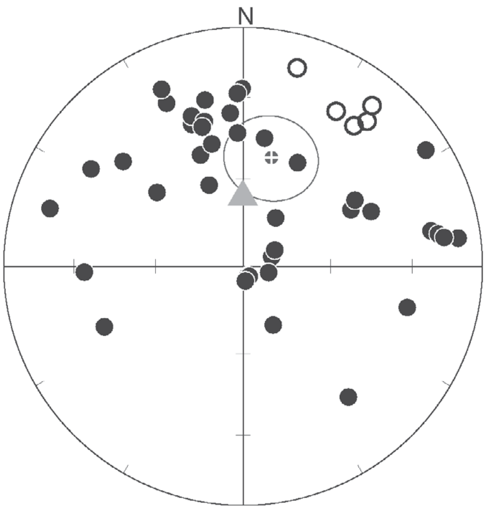


Figure 8: Distribution of NRM direction, measured for undemagnetized specimens. Open/full symbols represent upper/lower hemisphaere, present-day geomagnetic field vector (PDF) is marked by a grey triangle. Overall mean (marked by crossed dot) with associated α_{95} confidence limit is shown for comparison with PDF direction.

viscous, present-day origin, while the stable, higher coercivity component of reversed polarity shows a SSW orientation with shallow inclination (after tectonic correction, Fig. 9G).

A good example of the chaotic trends in demagnetization is the specimen of the Eocene limestones of Biograd (Fig. 9H). Santonian limestones of the same locality, however, show linear trends enabling determination of two NRM components, while the third component resides in a hard coercivity phase and it cannot be resolved by AF demagnetization (Fig. 9I).

5.4.2. Results of thermal demagnetization

Middle Permian Košna red beds were not treated by the AF method, since only haematite has been identified by the Lowrie test. Thermal demagnetization (Fig. 10A, B) reveals a bimodal structure of NRM with the characteristic remanence component pointing NWN with rather shallow inclination (geographic position).

In general, thermal cleaning was also fairly effective in revealing NRM composition, although the AF method seemed to be better in some cases. For instance, thermal demagnetization of Middle Permian Crne Grede limestones (Fig. 10C) yielded a rather poorly defined component residing in grains of moderate T_{ub} (150–350°C). Although a general direction of ChRM is similar to the one identified by AF (Fig. 9A), the quality of the latter is definitively higher. Also, thermal cleaning of the Upper Permian carbonates of Kalvarija was less effective than AF demagnetization (cf. Fig. 10D and Fig. 9B) and yielded results that could not be interpreted.

Upper Permian carbonates of Rizvanuša (Fig. 10E) show weak magnetization. Despite low reliability due to higher A.S.D. values (up to 10°), ChRM orientations are relatively coherent at the sample level. Maximum T_{ub} suggests a Ti-magnetite carrier of NRM, and do not confirm the presence of haematite, ascertained by the Lowrie test. This may be a result of the inhomogeneous distribution of haematite in these rocks. A steep, generally southwesterly directed ChRM (palaeohorizontal) could be determined, which makes thermal cleaning more successful than AF in this case.

Thermal cleaning was quite effective in the case of the Middle Triassic Prpići rocks (Fig. 10F), where NRM components could, in contrast to AF cleaning, be isolated due to the linear trajectories of the demagnetization paths. Values of 500°C for maximum T_{ub} suggest the presence of Ti-magnetite.

Upper Jurassic limestones of Dimići (Fig. 10G) responded fairly well to thermal cleaning, despite a low intensity of NRM. Maximum T_{ub} is around 475°C, suggesting Ti-magnetite as the main remanence carrier. ChRM show a northeasterly orientation with moderately shallow inclination (geographical coordinates, Fig. 10G) and is similar to the ChRM obtained by the AF method.

Mali Halan limestones (Fig. 10H, I) show a similar NRM structure, recorded in rock samples collected at different sites. A stable ChRM component shows a moderately steep, northerly orientation, in line with results obtained from the AF method. This component features T_{ub} of ca. 450°C, suggesting the presence of Ti-magnetite.

Results obtained from the rocks of Otrić (Fig. 10J) are again essentially the same as for the AF method, both in the shape of the demagnetization path and in the direction of ChRM. Despite a very weak remanence, thermal cleaning could be performed down to the SQUID noise level, since, fortunately, no secondary magnetic phases were formed in the course of thermal cleaning. A maximum T_{ub} of ca. 450°C is indicative of Ti-magnetite grains.

Thermal demagnetization of the Santonian limestones of Biograd (Fig. 10K) yielded only one component, in contrast to the three components of NRM ascertained by means of AF cleaning. A thermal demagnetization diagram demonstrates a straight line segment for almost the whole range of temperatures, thus indicating the presence of a single component. Notably, specimens treated with temperature show a component of opposite polarity to that demagnetized by AF.

5.4.3. ChRM directions – a general interpretation

A small number of independently oriented samples per stratigraphic site exclude any reliable calculation of overall characteristic directions and a virtual palaeopole position for each sampled unit. This, however, does not preclude a general interpretation of all individually isolated ChRMs, based on their comparison with a reference path of palaeomagnetic directions expected for the studied area, on the basis of an assumption on the structural coherence of the Velebit Mt. rocks either with Gondwanian or European crust. The reference path (RP) can be established by recalculation of post-Carboniferous palaeopoles of Gondwana and Eurasia (data for Carboniferous and Triassic after VAN DER VOO (1993), and from BESSE & COURTILLOT (2002) for younger geologic ages) at the reference site (coordinates 45°N, 15°E), as

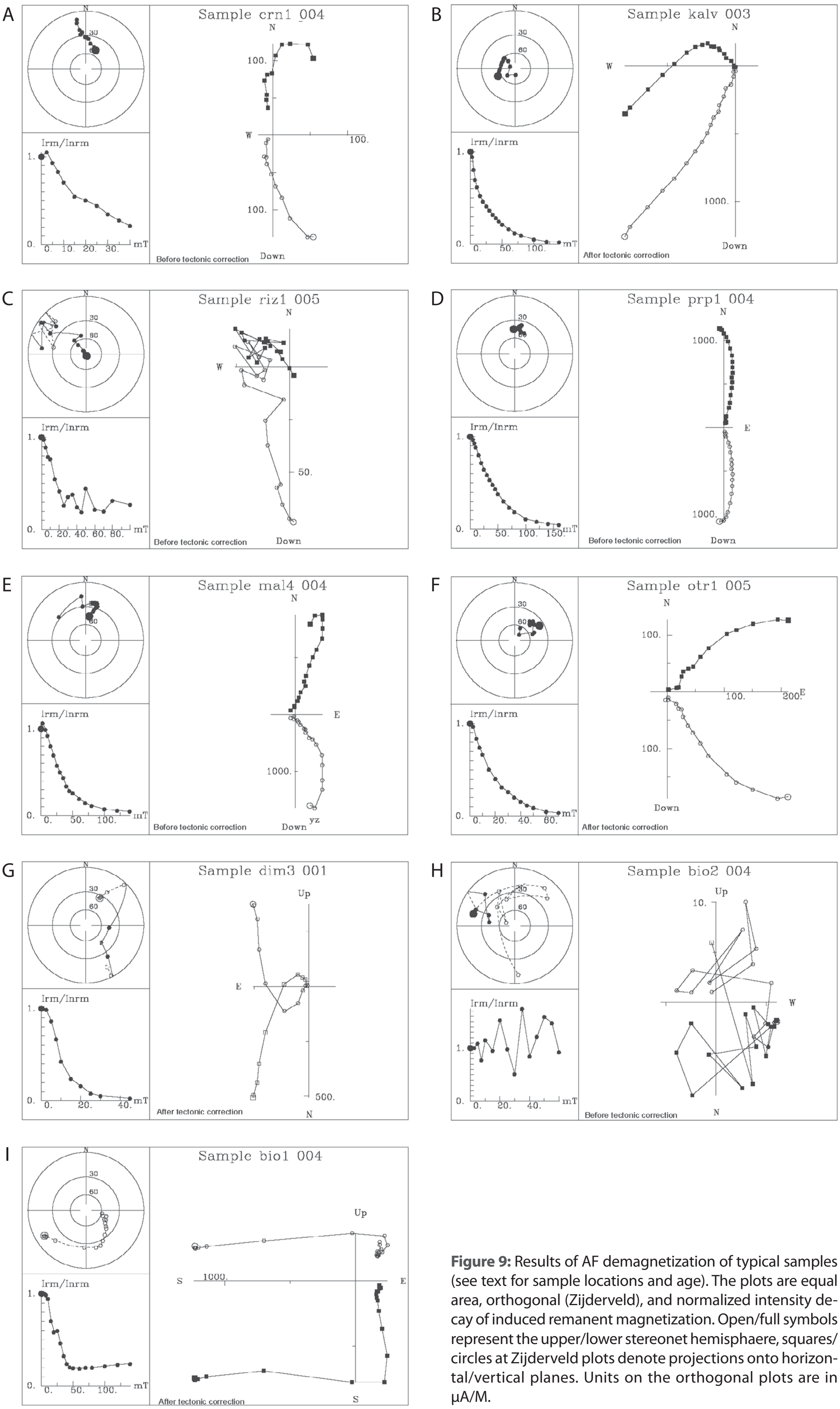


Figure 9: Results of AF demagnetization of typical samples (see text for sample locations and age). The plots are equal area, orthogonal (Zijderveld), and normalized intensity decay of induced remanent magnetization. Open/full symbols represent the upper/lower stereonet hemisphaere, squares/circles at Zijderveld plots denote projections onto horizontal/vertical planes. Units on the orthogonal plots are in μA/M.

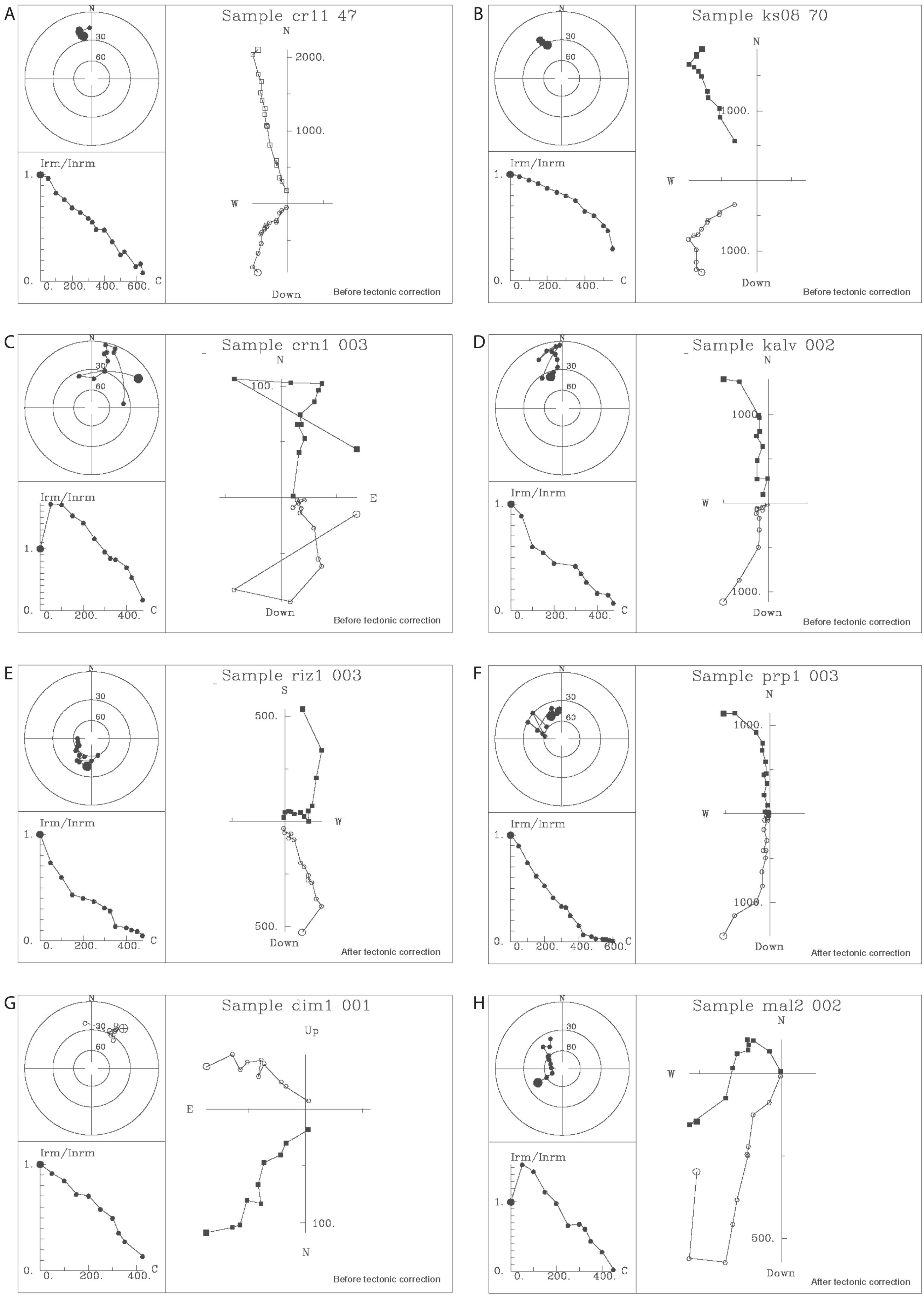
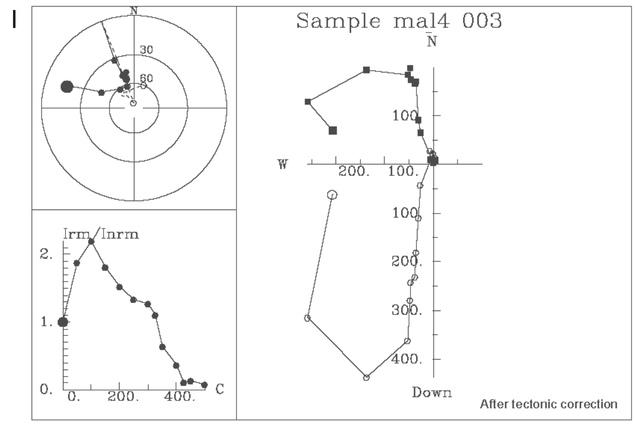
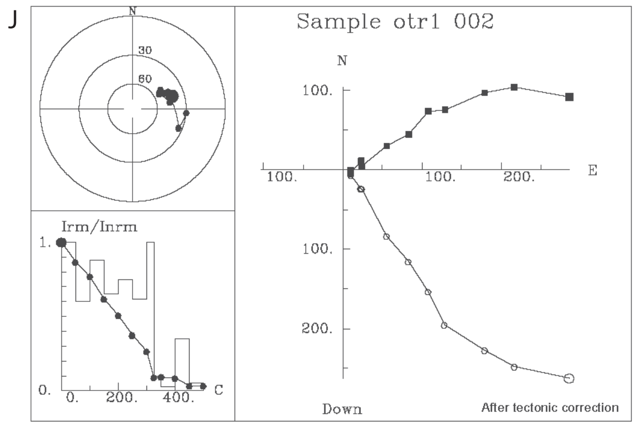


Figure 10: (continued on the next page)





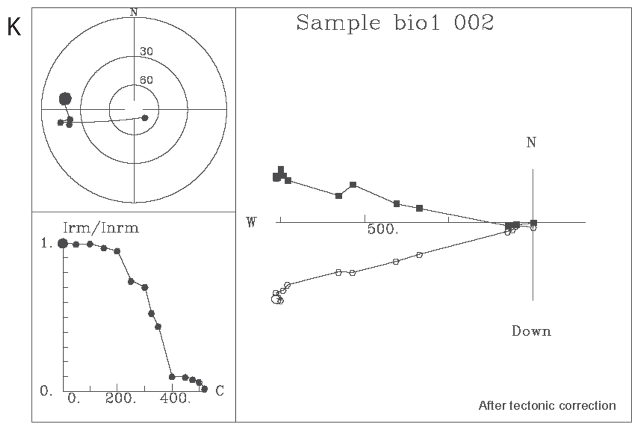


Figure 10: Results of thermal demagnetization (continued from the previous page). See Fig. 9 for symbols explanation.

shown in the Fig. 11. In the Fig. 12, in turn, ChRM directions are depicted both in their geographic coordinates (i.e. before correction for tilt) and in a palaeohorizontal frame (i.e. after correction for tilt), to be confronted with RPs. In the palaeohorizontal frame (Fig. 12B), most ChRM vectors show steep inclinations, incompatible with the known palaeogeographic history of Adria, which remained constantly at equatorial to moderate palaeolatitudes during Mesozoic–Cenozoic time (DERCOURT et al., 2000; GOLONKA, 2000). We suppose, therefore, that these directions do not represent primary NRM components.

In the geographic frame (Fig. 12A), however, the Permo-Triassic deposits of Košna, Crne Grede, Rizvanuša, and Kalvarija show low-to-moderate inclinations and smeared declinations within the NNW–ENE sector, rotated at a different degree from the coeval directions of the RPs of Africa and Eurasia. The same applies to the Middle Jurassic rocks of Mali Halan and Dimići. In general, Fig. 12 depicts a scattered distribution of ChRM vectors, meaning that there was no common post-tectonic remagnetization of all the studied rocks. Although the monoclinal structure of the investigated strata precluded fold tests, the smeared distribution of the characteristic components suggests an important, tectonic involvement of the rocks in question, the nature and meaning of which remains an open question.

Future investigations will therefore focus on more detailed palaeomagnetic and rock-magnetic studies of available fold structures along the range of Velebit Mt. and their time-equivalent rocks in the south-easternmost part of Croatia.

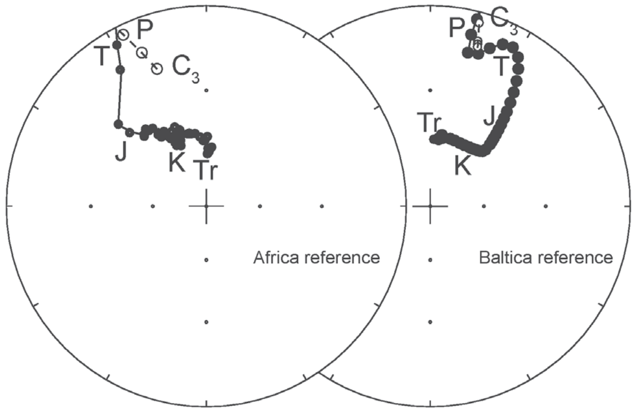


Figure 11: Outline of palaeomagnetic reference directions, recalculated for the site 45°N/15°E (Gospić area, Velebit Mt.) from current APWPs for Africa and Eurasia (see text for details). Legend: open/full symbols and broken/solid line represent upper/lower hemisphere, respectively; C_3 – Upper Carboniferous, P – Permian, T – Triassic, J – Jurassic, K – Cretaceous, Tr – Tertiary.

These planned studies should help in the identification of primary (pre-folding) and secondary NRM components, making the geotectonic history of Dinarides better bracketed in the palaeogeographic frame.

6. CONCLUSIONS

Taking into account the results obtained in this study, the following conclusions can be drawn:

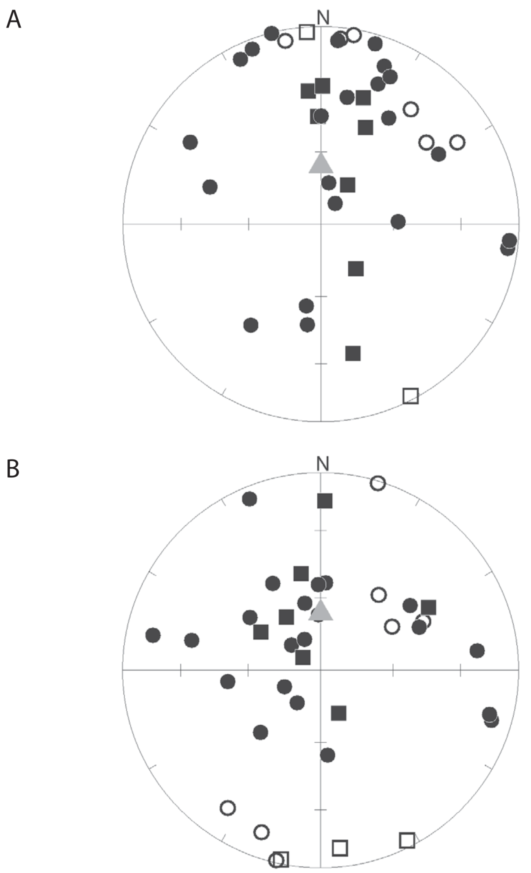


Figure 12: Characteristic remanent magnetization in geographic (A) and palaeohorizontal (B) frame, obtained in this study. Note the lack of a distinctive direction governing overall vector distribution. Dots/squares are directions obtained due to thermal/AF cleaning, respectively. Other symbols are explained in the Fig. 8.

(1) In most cases, rocks of Velebit Mt. yielded interpretable palaeomagnetic results.

(2) The area of Velebit Mt. was not completely remagnetized during the latest (Neogene) tectonic event, since ChRMs do not exhibit a normal (Fisherian) distribution around the palaeomagnetic direction, expected for the Velebit region in the Neogene.

(3) The Upper Triassic to Middle Jurassic deposits show a higher magnetic susceptibility than older and younger rocks. This may be attributed to a higher influx of magnetic grains due to geotectonic and volcanic processes, initiated by the break up of Pangea.

(4) Ti-magnetite and haematite were the principal magnetic carriers; most of the grains are of detrital origin.

(5) Both AF and thermal cleaning were efficient for isolation of NRM components.

(6) AF cleaning yielded particularly good results for the Upper Triassic of Prpići, the Upper Permian of Kalvarija and the Middle Jurassic of Mali Halan.

(7) Thermal demagnetization was particularly successful for the Upper Triassic of Prpići and the Callovian limestones of Dimići.

(8) The characteristic components obtained for Permo-Triassic and Middle Jurassic rocks display declinations within the NNW to ENE sector with moderate to shallow inclinations, when observed in geographical coordinates. Such overall distributions, compared with the expected direction for Adria in Mesozoic–Cenozoic time, suggest tectonic rotations with respect to Gondwana.

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