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Palaeomagnetic Results from the Sarmatian/Pannonian Boundary in North-Eastern Croatia (Vranović Section, Našice Quarry)

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Abstract

The Sarmatian/Pannonian boundary in the Central Paratethys basin is marked by a major regressive event, which isolated the basin from the open sea and resulted in a palaeoenvironmental change from restricted marine to brackish water ecosystems. The exact age of this environmental change is still ambiguous since direct age control on the boundary interval is lacking, mainly due to the scarcity of suitable sections. The Vranović section in the Našice Quarry in Croatia, however, is relatively long and continuously exposed. A detailed sedimentological and biostratigraphic study indicates that it contains the Sarmatian/Pannonian boundary and that it reflects the same palaeoenvironmental trend as other Paratethyan sequences. Here, we present palaeomagnetic and rock magnetic results from the Vranović section, based on 183 sampled levels distributed along 55 m of cyclically bedded limestones and marls. Rock magnetic data indicate the presence of maghemite or haematite in the Sarmatian deposits and low contents of magnetite in the Pannonian rocks. Thermal demagnetization results indicate dominantly normal polarities, and the mean direction closely coincides with the present-day field direction at Našice. We conclude that magnetostratigraphic age control cannot be derived for the Vranović section because of a dominant secondary (post-tilt) magnetization. Consequently, a firm numerical age based on magnetostratigraphy cannot be assigned to Sarmatian/Pannonian boundary events from this section.

1. INTRODUCTION

One of the most important palaeogeographic changes in the geological evolution of the Central Paratethys basin occurs at the Sarmatian/Pannonian boundary. During the Sarmatian (s. str.), the Central Paratethys was part of an epicontinental marine water mass (e.g. PILLER & HARZHAUSER, 2005; STEININGER & RÖGL, 1985) and water exchange was suggested to have taken place with the open seas and with the Eastern Paratethys basins (e.g. MAGYAR et al., 1999). The straits between Central Paratethys and the global seas caused a severe separation of water bodies resulting in aberrant isotope signatures, high salinities and elevated alkalinity (e.g. PILLER & HARZHAUSER, 2005). The Sarmatian/Pannonian boundary interval is marked by a major regression, which isolated the Central Paratethys from the sea, transforming it into the large, long-lived, brackish water body of Lake Pannon (e.g. PILLER & HARZHAUSER, 2005). The cause of this regression is still highly debated, and the main hypotheses are (1) eustatic sea level lowering (VAKARCS et al., 1994; HARZHAUSER & PILLER, 2004), (2) tectonic events in the Carpathians and Dinarides (e.g. SANDULESCU, 1988), and (3) intraplate stress (HORVÁTH & CLOETING, 1996). Without an accurate time frame for this event, it is at present difficult to solve this controversy and to understand the underlying mechanisms.

The age of the Sarmatian/Pannonian boundary is at present largely based on observation of the fossil remains of the three-toed equid *Hippotherium* in the lower part of the Pannonian sequences (e.g. BERNOR et al., 1988; RÖGL & DAXNER-HÖCK, 1996). Correlation with the dominantly reversed polarity palaeomagnetic data from the *Hippotherium*-bearing sediments of Kastellios Hill on Crete (SEN et al., 1986) resulted in an approximate age of 11.5–11.6 Ma for the base of the Pannonian (STEININGER et al., 1990, 1996). Later, however, detailed palaeomagnetic studies indicated that *Hippotherium* only commonly appeared in the lower part of chron C5n at an age between 10.8 and 10.6 Ma, in Asia (BARRY et al., 1982, 1985; KAPPELMAN et al., 1996; WOODBURNE & SWISHER, 1995) as well as in Spain (GARCÉS et al., 1996, 1997, 2003; KRIJGSMAN et al., 1996). Consequently, it was shown that the Kastellios Hill magnetostratigraphy correlates best to chron C4Ar at an age between 10.7 and 9.1 Ma (GARCÉS et al., 1996). To date, no palaeomagnetic data have been reported from the Pannonian *Hippotherium* sites, probably because of outcrops being unsuitable for magnetostratigraphy. Radiometric ages do exist from the early *Hippotherium* sites at Höwenegg in Germany (10.8±0.3 Ma; BARANYI et al., 1976) and the Vienna Basin (11.1±0.5 Ma; BERNOR et al., 1993a, b). Hence, there seems to be a general agreement on

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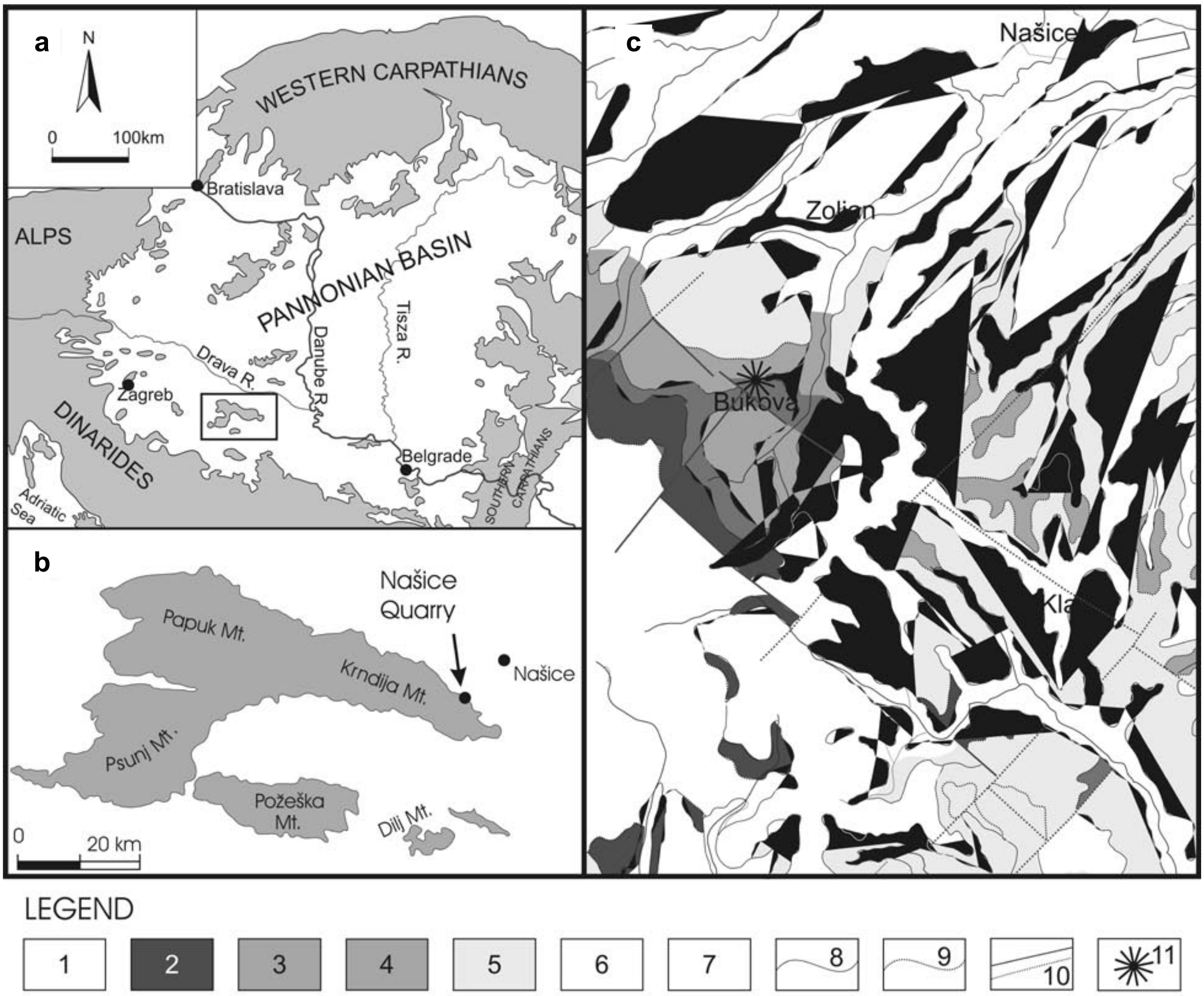

Fig. 1 Location of the studied area: (a) Pannonian Basin; (b) Study area; (c) Geological sketch map after KOROLIJA & JAMIČIĆ, 1988. Legend: 1) Pre-Miocene; 2) Badenian; 3) Sarmatian; 4) Lower Pannonian; 5) Upper Pannonian – Plio–Quaternary; 6) Pleistocene; 7) Holocene; 8) normal stratigraphic boundary; 9) transgressive boundary; 10) faults; 11) location of the sampled section.

the so-called *Hippotherium* datum, occurring at an age younger than 11.1 Ma (e.g. AGUSTÍ & MOYÀ-SOLÀ, 1991), but, remarkably, the age of the Sarmatian/Pannonian boundary was never revised accordingly.

The relative sea level drop at the Sarmatian/Pannonian boundary caused large areas in the central part of the Central Paratethys basin to dry up, and only small, scattered patches of the originally thin Sarmatian deposits escaped complete erosion (e.g. MAGYAR et al., 1999). It is therefore difficult to find exposed sections of uninterrupted sedimentation through the marine/lacustrine boundary. In the southern part of the Central Paratethys basin, a conformable transition from the Sarmatian to the Pannonian deposits has been found much more frequently than an unconformable one. A relatively long and excellently exposed section, comprising the Sarmatian/Pannonian boundary, exists in north-eastern Croatia in a quarry near Našice (Fig. 1). The Vranović section expresses a noticeable sedimentary cyclicity of alternating limestones and marls (Fig. 2). The regularity of this cyclicity suggests a relationship with astronomically induced changes in palaeoclimate (Milankovitch forcing). The section has previously been studied for sedimentological and biostratigraphic purposes which resulted in detailed palaeoenvironmental and lithostratigraphic interpretations (PAVELIĆ et al., 2003; KOVAČIČ, 2004; BAKRAČ, 2005; KOVAČIĆ & GRIZELJ, 2006). Here, we present palaeomagnetic results, including a detailed rock magnetic characterization, of this exceptional Sarmatian/Pannonian boundary section in the Central Paratethys, with the aim to develop a reliable chronostratigraphic framework for the entire interval using integrated bio-cyclo-magnetostratigraphic techniques.

2. GEOLOGICAL SETTING

The Pannonian Basin is presently surrounded by the Alps, Carpathians and Dinarides, and belongs palaeogeographically to Central Paratethys (Fig. 1). The basin formed in the Early Miocene, as a consequence of continental collision and subduction of the European Plate under the Apulian Plate (TARI et al., 1992; HOR-

Fig. 2 Photograph of the lower part (Sarmatian–Early Pannonian) of the Vranović section that contains clear sedimentary cycles. The carbonate-rich layers can be observed. The average thickness of a basic limestone–marl cycle is 0.7 m.

VÁTH & CLOETINGH, 1996; KOVÁC et al., 1998; ROYDEN, 1988). Miocene deposits of the southern part of the Pannonian Basin, unconformably overlie a strongly tectonized Palaeozoic–Mesozoic–Palaeogene basement of magmatic, metamorphic and sedimentary rocks. From the Early to the Middle Miocene (Middle Badenian), in the syn-rift phase of basin formation, deposition of clastic and carbonate sediments was accompanied by strong tectonic and volcanic activity. The post-rift phase of basin formation (Upper Badenian to recent) is characterized by subsidence due to lithospheric cooling, with occasional inversions of the basin generated by intraplate stress that affected the entire Pannonian Basin (HORVÁTH & CLOETINGH, 1996).

During the Late Sarmatian, tectonic compaction occurred in the southern part of the Pannonian Basin. Contemporaneously, the connection between the Pannonian Basin and the Mediterranean was closing, and Lake Pannon formed as a separate depositional system with low salinity waters (STEININGER et al., 1988; RÖGL, 1996). However, recent studies indicate isotope trends suggesting a simple system of an alkaline lake with steadily declining salinity (HARZHAUSER & PILLER, 2007; HARZHAUSER et al., 2007).

At the beginning of the Pannonian, under conditions of low tectonic activity, limestones and marls were mostly deposited. Lake-level rise during the Pannonian caused flooding of previously emerged regions. Progradation of deltaic clastic systems, shallowing and finally infilling of the basin during Pontian times was probably caused by deceleration of basin subsidence. During Mio–Pliocene times, and more intensively in the Quaternary, another compressive phase took place in the Pannonian Basin, uplifting and exposing its southern margin in Croatia (JAMIČIĆ, 1995; HORVÁTH & CLOETINGH, 1996; PRELOGOVIĆ et al., 1998; MÁRTON et al., 2002).

3. NAŠICE QUARRY – VRANOVIĆ SECTION

The Našice quarry is located on the northern slopes of Mt. Krndija, which belongs to the southern part of the Pannonian Basin (Figs. 1 and 2). Sediments of the Croatian margin are characterized by widely different lithologies, starting with Upper Badenian (~14 Ma) carbonates and ending with Pontian (~5 Ma) siliciclastics. During this period, the depositional environment changed from fully marine, to reduced marine and finally brackish (PAVELIĆ et al., 2003). The Vranović section is located in the northern part of the quarry. It measures 55 metres in thickness and comprises Upper Sarmatian and Pannonian sediments as evidenced by the occurrence of specific palynomorphs (BAKRAČ, 2005). The sedimentary succession is divided into three informal lithostratigraphic units: (1) 'Kasonja Formation', (2) 'Croatica Formation', and (3) 'Pavlovci Formation' (Figs. 2 and 4).

The 'Kasonja Formation' is only exposed in the lowermost 4 metres of the section, and represents the Sarmatian part of the sequence (Fig. 2 and 4; up to V6). It consists of horizontally laminated marls. The marls are well bedded, with bed thickness varying between 10 and 70 cm (Fig. 4). Horizontal lamination is generally varve-like suggesting seasonal changes in sedimentation. In some places the marls are massive or contain intercalations of clays and limestones. The marls were deposited from suspension in a relatively deep, calm sedimentary environment. Fossil associations indicate a transition from a reduced marine to brackish water environment, which is a similar trend to other Sarmatian–Pannonian sequences (PAVELIĆ et al., 2003). Palynomorph assemblages consist of marine dinocysts that are tolerant to decreased salinity: *Hystrichosphaeropsis obscura*, *Polysphaeridium zoharyi*, *Lingulodinium machaerophorum* (Fig. 3a), and brackish-water dinocysts *Spiniferites bentori budajenoensis* (BAKRAČ,

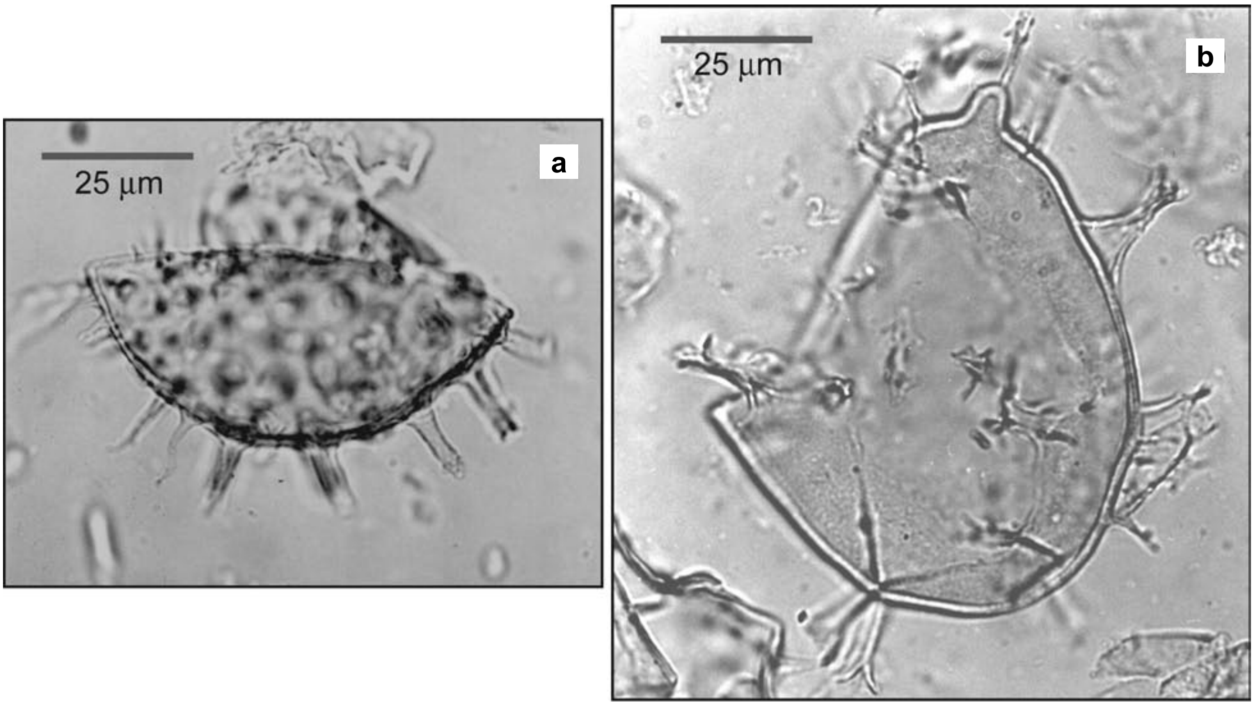

Fig. 3 (a) The Sarmatian dinocyst *Lingulodinium machaerophorum* (DEFLANDRE & COOKSON, 1955) WALL, 1967; (b) The Pannonian dinocyst *Spiniferites bentorii pannonicus* SÜTŐ-SZENTAI, 1986.

2005). This assemblage is also typical of the Late Sarmatian deposits in Hungary (SÜTŐ-SZENTAI, 1988).

The 'Croatica Formation' consists of horizontally bedded, marly limestones, intercalated with massive marls, and represents the lowest Pannonian part of the succession (Fig. 2). Bed thickness ranges between 10 and 30 cm (Fig. 4) and the fossil association in the lower part indicates an earliest Pannonian age ('Croatica beds' – PAVELIĆ et al., 2003; KOVAČIĆ, 2004; KOVAČIĆ & GRIZELJ, 2006). The sediments were deposited from suspension under oscillating warmer and cooler temperatures that generated high carbonate production. Deposition of the carbonates is thought to have occurred in a littoral zone in brackish–lacustrine environments, while the marly intercalations indicate water-level oscillations that temporarily formed deeper lake levels. During that time, salinity was so low that the environment became oligohaline, and locally even fresh. Such environmental conditions enabled the expansion of endemic species. Ecological conditions were unfavourable for dinoflagellates, which is evidenced by the absence of dinocysts in these sediments. Consequently, prasinophyte algae *Mecsekia ultima*, *Mecsekia spinosa* and *Mecsekia incrassata* dominate the phytoplankton assemblages (BAKRAČ, 2005).

The 'Pavlovci Formation' is predominantly composed of massive marls of Early Pannonian age ('Banatica beds'), and represents about 50% of the succession (PAVELIĆ et al., 2003; KOVAČIĆ, 2004) (Fig. 4). The marls form units 0.3–6.0 m thick. They are bioturbated and yellowish to light grey in colour. The calcite content is high, reaching up to 77%. The marls were deposited in a deeper zone of the brackish lake than the marly limestones of the 'Croatica Formation'. The lake bottom was oxygenated, enabling colonization by benthic organisms that produced bioturbation. The dinocyst assemblage of *Spiniferites bentori pannonicus* (Fig. 3b), *Spiniferites bentori granulatus*, and *Impagidinium spongianum* characterizes these deposits, and can be correlated with the assemblage of Spiniferites bentori pannonicus zone in Hungary (SÜTŐ-SZENTAI, 1988). Within the succeeding deposits, *Spiniferites bentori pannonicus* and *Spiniferites bentori oblongus* dominate the palynomorph assemblages. *Nematosphaeropsis* sp. and membranous forms of *Spiniferites bentori* indicate water-level rise and a distal environment. This assemblage is similar to that of the Spiniferites bentori oblongus zone from Hungary (SÜTŐ-SZENTAI, 1988).

4. PALAEOMAGNETIC RESULTS

4.1. Methods

In the field, at least two standard palaeomagnetic cores were drilled at 183 individual sample levels with an electrical drill and a generator as power supply. In the laboratory, rock magnetic experiments were performed to characterize the carrier(s) of the magnetization. Thermomagnetic runs in air were measured with a modified horizontal translation type Curie balance with a sensitivity of approximately 5×10^{-9} Am^2 (MULLENDER et al., 1993). A few milligrams of bulk sample were put into a quartz glass sample holder and were held in place by quartz wool. The measurements were carried out up to 700°C for samples for diverse lithologies. An alternating gradient magnetometer (MicroMag Model 2900

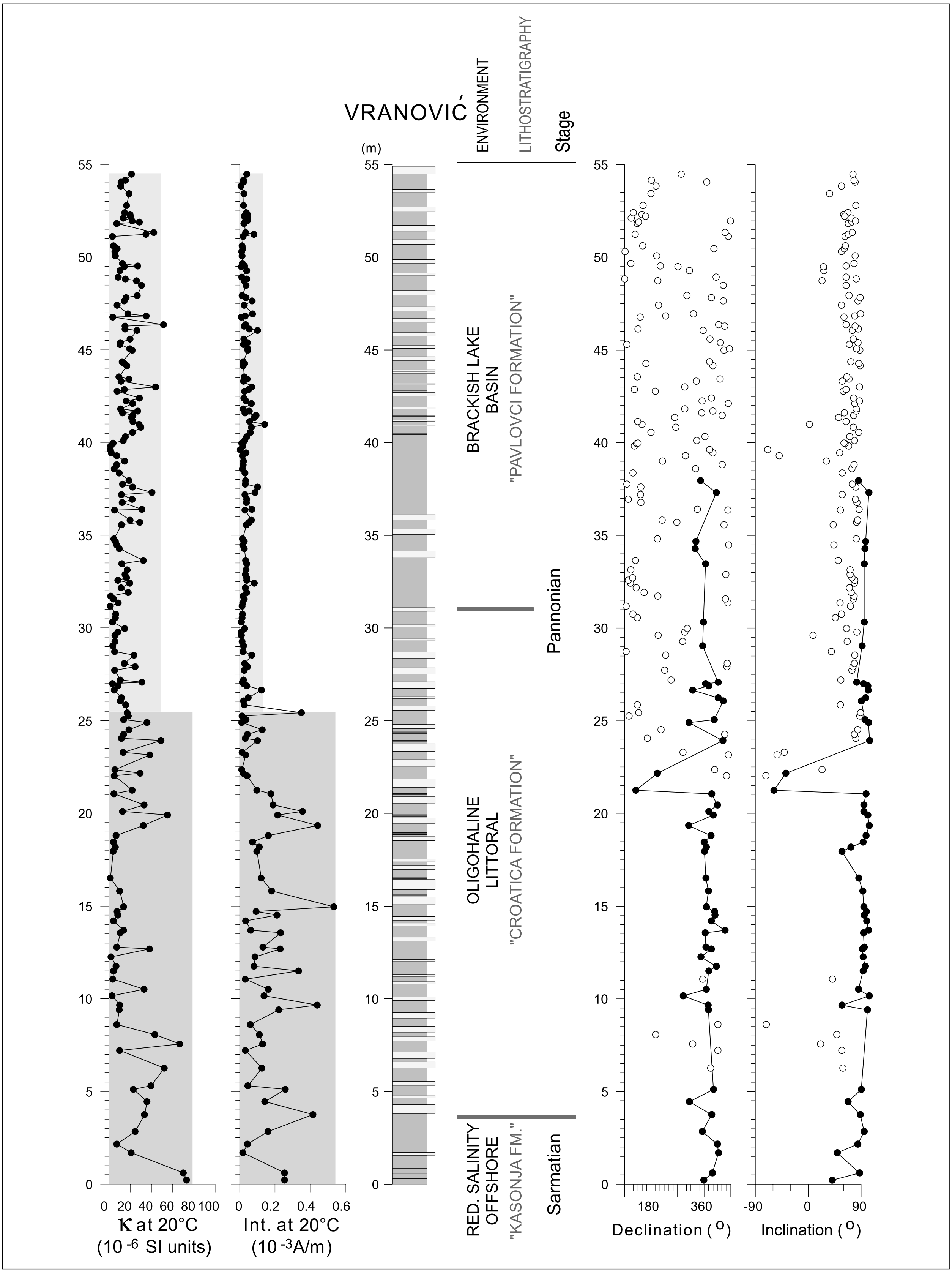

Fig. 4 Low-field magnetic susceptibility, NRM intensity, lithological column, and palaeomagnetic declination/inclination record for the Vranović section. The initial NRM intensity correlates with (low) χ_{in} for the samples collected above 25.5 m, which is highlighted with light-grey shading; no correlation is observed for the samples below 25.5 m (darker-grey patch). Light-grey beds in the lithological column correspond to the indurated limestones; darker-grey beds represent marls; the very dark shadings are organic rich layers (close to a sapropel type). On the right-hand side of the lithological column is an environmental interpretation, lithostratigraphy and the stages identified in the section (according to PAVELIĆ et al., 2003). In the declination–inclination record, the solid symbols represent directions obtained from Zijderveld diagrams with the maximum angle deviation MAD<15º and with coherent demagnetisation trajectories; the open symbols represent the directions obtained from Zijderveld diagrams with MAD>15º and with noisy demagnetisation diagrams, also associated with the lowest susceptibility and NRM-intensities.

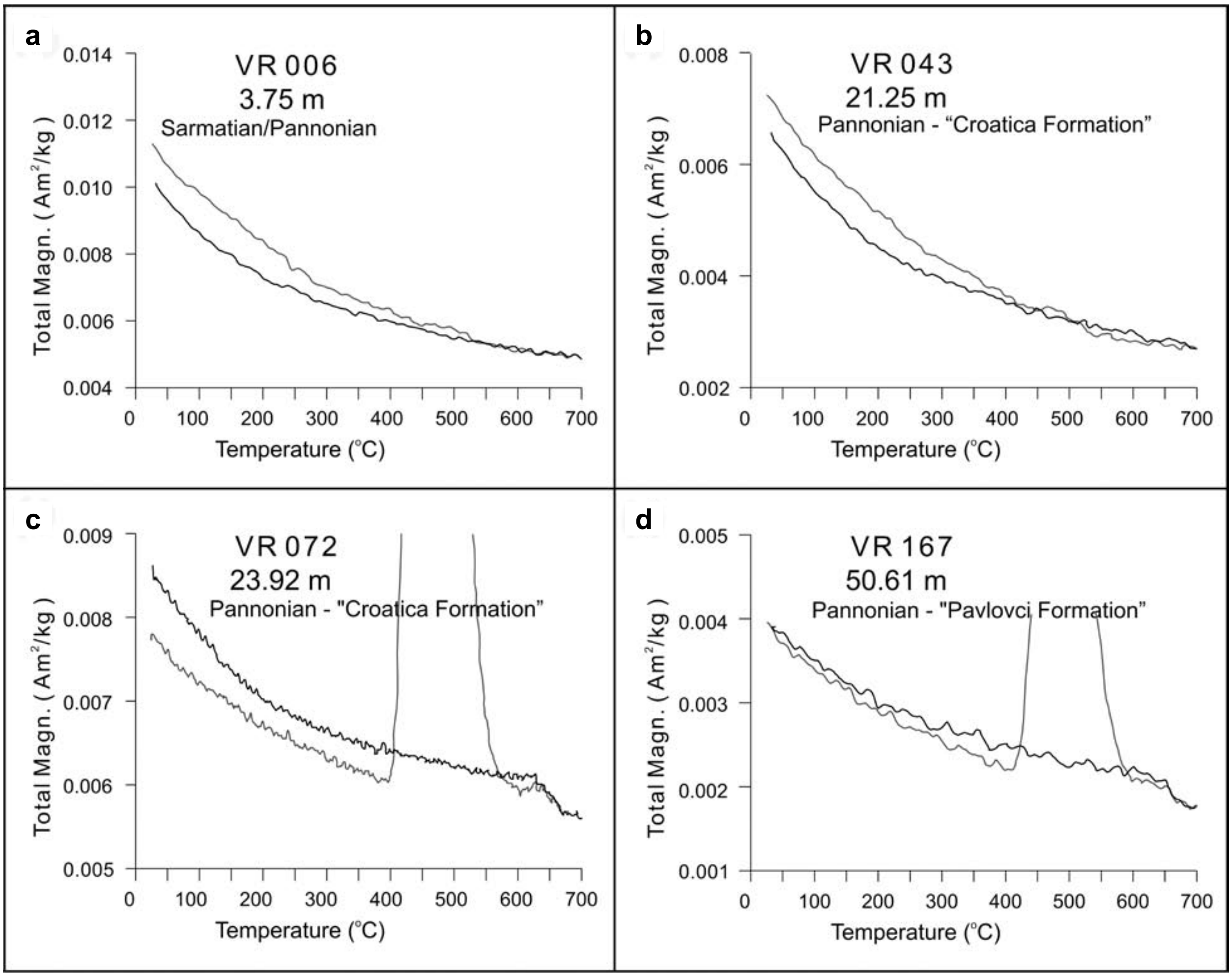

Fig. 5 Representative thermomagnetic runs for the analyzed samples. Heating is represented by a grey line and cooling by a black line. Data in (c) and (d) show major alteration after heating above 400ºC most probably as the effect of the pyrite transformation to magnetite. The drawings do not show the entire heating curve because the out-of-scale trend would limit viewing of the shape of the heat–cool cycle. Below the samples codes the stratigraphic level and the stages are indicated.

– Princeton Measurements Corporation, noise level 2×10^{-9} Am^2) was used at room temperature to make the following measurements: (1) hysteresis, (2) isothermal remanent magnetisation (IRM) acquisition, and (3) back-field curves. The sample mass ranged from ~0.2 to ~0.5 grams. The hysteresis loops of selected lithologies were recorded to determine the saturation magnetisation (M_s), remnant saturation magnetisation (M_{rs}) and coercive force (B_c). The values were read after paramagnetic slope correction and on a mass-specific basis. Because of the partial saturation of the pole shoes, the response of the MicroMag Model 2900 is not linear above 1.6 T. Therefore, we only report the values for a maximum field of 1.6 T. Back-field curves allow determination of the coercivity of remnance (B_{cr}) after application of the maximum positive field. IRM acquisition curves, containing 300 data points, were noisy and contained little useful information.

Stepwise thermal demagnetisation has been applied to one sample from each stratigraphic level to determine the palaeomagnetic directions of the NRM. Demagnetisation was performed with temperature increments of 5–30°C up to a maximum temperature of 380°C. The samples were heated and cooled in a magnetically shielded, laboratory-built furnace with a residual field less than 10 nT. After each step, the bulk susceptibility was measured on a KLY–2 susceptometer (AGICO, Brno, noise level 4×10^{-8} SI) in order to check for possible mineralogical changes during thermal treatment. The natural remnant magnetization (NRM) was measured on a horizontal 2G Enterprises DC SQUID magnetometer (noise level 3×10^{-12} Am^2).

4.2. Rock magnetism

Several rock-magnetic experiments were carried out on unheated bulk rock samples to determine in which magnetic mineral(s) the remnance is residing and how it was acquired. Thermomagnetic runs show that the initial total magnetisation is low in all measured samples (Fig. 5). All hysteresis loops are affected by noise, but the general shape can still be distinguished (Fig. 6). The hysteresis loops are generally narrow-waisted (Fig. 6a–c), which is typical of multi-domain magnetic behav-

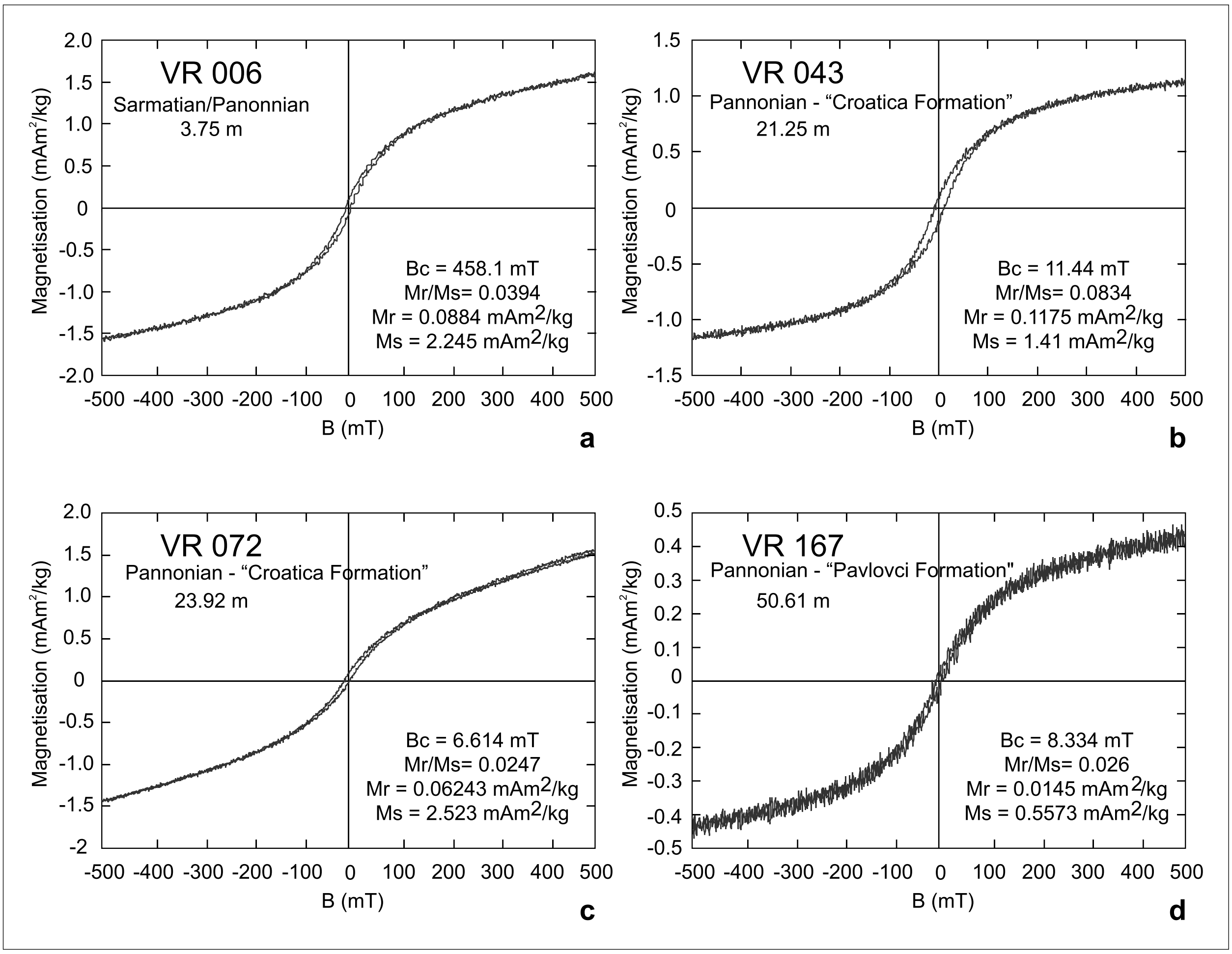

Fig. 6 Hysteresis loops for characteristic samples measured for -2T≤B≤2T. The figures show the result up to ±500 mT (the important part of the loop) with applied paramagnetic contribution and mass correction. Below the sample codes the stratigraphic levels and the stages are also indicated.

iour (DUNLOP & ÖZDEMIR, 1997). Samples from the Sarmatian 'Kasonja Formation' reveal hysteresis loops that are not closed in fields of 300 mT, indicating the presence of a high coercivity mineral. The high value of B_c = 458.1 mT (Fig. 6a) points to the presence of a high coercivity mineral like maghemite, goethite or haematite (usually formed as a result of alteration). In the thermomagnetic runs from the 'Kasonja Formation' and the lowest part of the Pannonian 'Croatica Formation', only the paramagnetic matrix contribution was detectable (Fig. 5a, b) and the data suggest the existence of very low contents of magnetite. The hysteresis loops of the middle and upper parts of the 'Croatica Formation' indicate the presence of a low coercivity mineral with low values of B_c (Fig. 6b, c), which most likely represents multi domain magnetite. In the upper part of the section ('Pavlovci Formation'), a thermally induced pyrite to magnetite transformation occurs (Fig. 5c, d). The presence of pyrite was already presumed because macroscopic pyrite crystals could be distinguished in the upper part of the Vranović section.

4.3. Thermal demagnetisation

NRM intensities are generally low in the basal part of the section, with maximum values of 0.53 mAm^{-1}, but they are even lower in the upper part, with a maximum value of 0.14 mAm^{-1}. The initial (low) NRM intensity correlates with the (low) initial susceptibility χ_{in} and a significant change to lower values is observed above 25.5 m in the section (see Fig. 4). Stepwise thermal demagnetisation diagrams (Fig. 7) and the normalized intensity versus temperature curves (Fig. 8) indicates that one remnance component is commonly removed at the relatively low temperatures of 100–160°C. This indicates the presence of either a large laboratory-induced viscous remnant magnetisation (VRM) or a (sub)recent secondary chemical remnant magnetisation (CRM). The random character of this component suggests a laboratory-induced remnance. Approximately 80% of the samples from the lower part of the section retained a magnetisation above 160°C, and only 13% of the samples do so from the upper part of the section (Fig. 8). After removal of the 160ºC component the intensities decrease to less than 20% of the initial

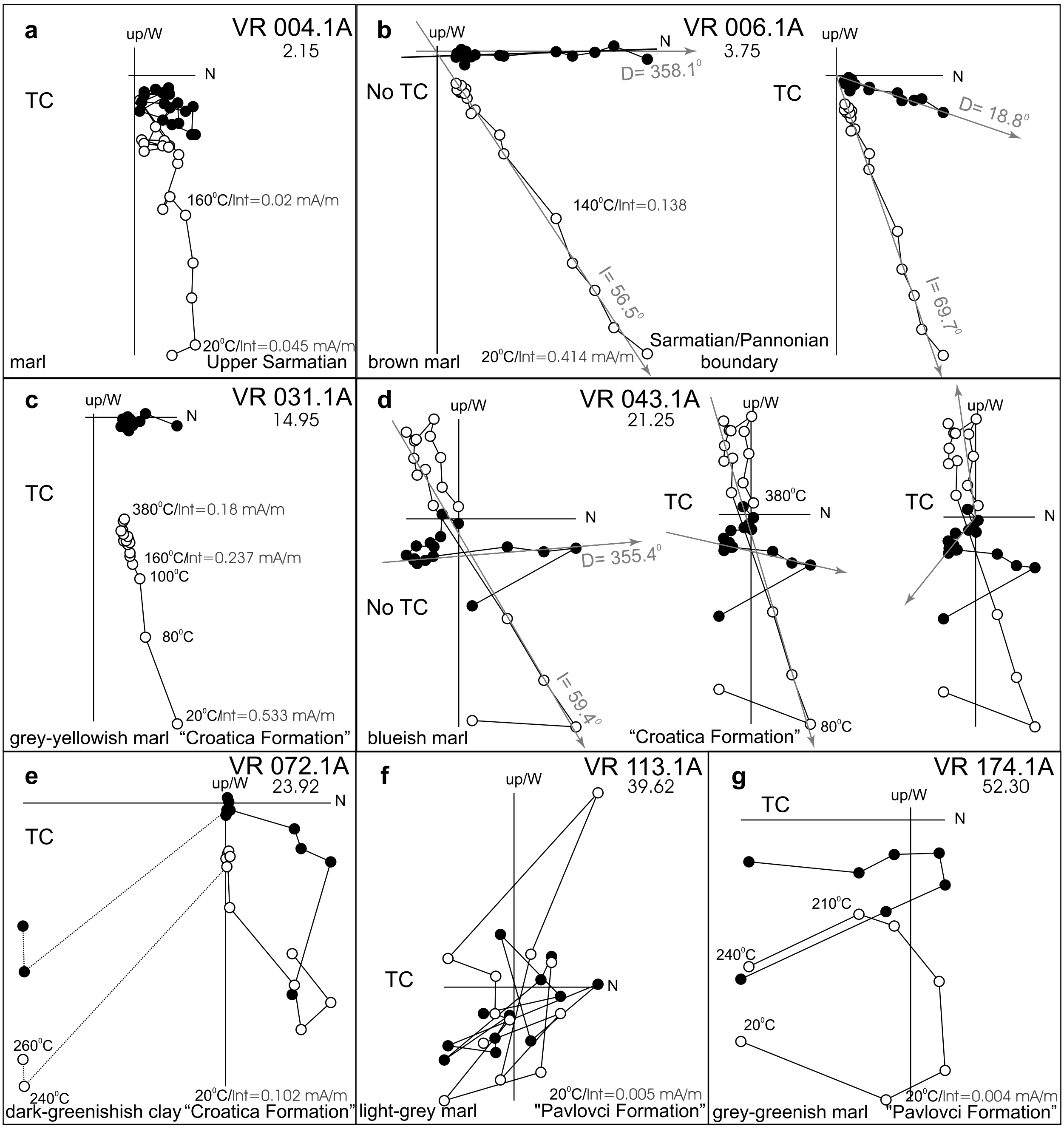

Fig. 7 Representative thermal demagnetisation vector diagrams of some selected samples. Solid (open) circles denote projection on the horizontal (vertical) plane and the attached numbers indicate temperatures in ºC. Stratigraphic levels are written below the sample codes (in capital letters); lithologies are in the lower left-hand corner and next to them are the stages for the different rocks.

NRM at 250–320ºC (Fig. 7), generally approaching the accuracy level of the magnetometer. Demagnetisation at higher temperatures yields inconsistent results and only directional scatter is obtained.

Directions of the NRM components were determined with principal component analysis (KIRSCHVINK, 1980) using at least four temperature steps for each component, from steps higher than 180ºC and always including the origin. All directions with a mean angle deviation (MAD) >15º were rejected. The remaining dataset is presented in a declination–inclination plot (Fig. 4). The lower part of the Vranović section has mainly normal polarities and few reliable, consistent results can be obtained from the upper part of the section. Only two levels at 21.25 and 22.15 m show clear indications of reversed polarity (Fig. 4, 7). In these cases, a small viscous and randomly oriented component is removed at 100ºC, and a relatively large secondary – it has approximately a present-day field direction before applying of the bedding tilt correction – component at 200–210ºC (Fig. 7d). The NRM is removed at 380ºC.

When palaeomagnetic data from sedimentary sequences reveal dominantly normal polarities, it is crucial to investigate if these normal directions could result from a present-day field overprint. In the Vranović section, the bedding tilt/strike of the sedimentary strata is

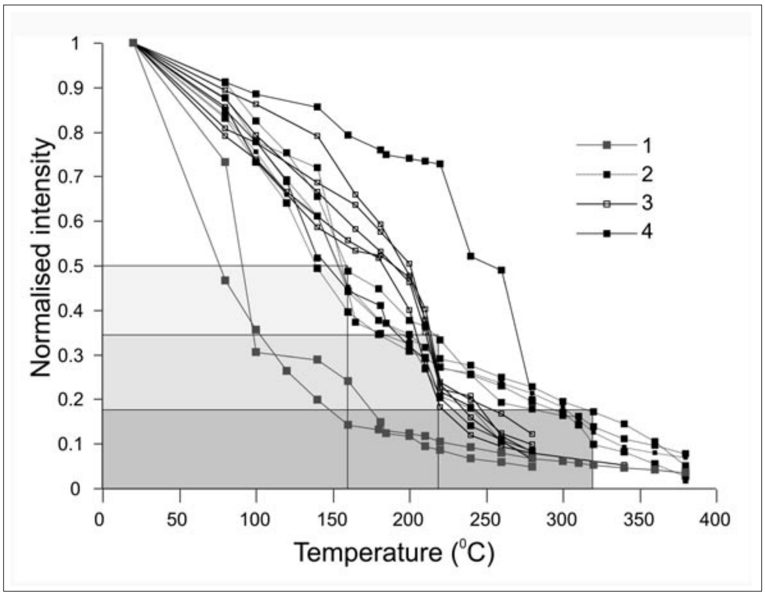

Fig. 8 Normalized intensity versus temperature for selected samples. Symbol 1 indicates samples with intensities that drop below 40% after heating at 100ºC; symbol 2 indicates samples with intensity decreasing in two steps, the first at 160ºC and the second at 220ºC; symbol 3 indicates samples with intensity dropping suddenly when heating to 220ºC; symbol 4 indicates (a few samples) with intensity decreasing rapidly after heating at 270ºC.

approximately 65°/15° dipping SE, which is helpful for distinguishing primary from secondary components. The normal polarity directions that passed the MAD selection criterion scatter around the geocentric axial dipole field direction for the present latitude of the section when no bedding tilt correction is applied (Fig. 9a). After using the statistical cut-off (VANDAMME, 1994) to this dataset, the calculated mean direction is: declination = 354.5°, and inclination = 62.9°. This is close to the expected present-day field inclination (63.8°) for the latitude of Našice (λ = 45.5º). This strongly suggests that the normal polarity directions are of (sub)recent origin, and most likely related to the present-day earth's magnetic field. In this case, we would also not expect any inclination error related to compaction of the sediment. Applying the E/I correction method for inclination error (TAUXE & KENT, 2004) on our normal polarity dataset, we confirm that the palaeomagnetic directions are not flattened (Fig. 9c). The E/I corrected mean inclination of I** = 63.7° is even closer to the expected inclination of 63.8° at Našice.

Although all of this evidence strongly points to a secondary overprint for the normal polarities at Vranović, we also investigated the possibility that these directions could have been of primary (pre-tilt) origin. Hence, we also calculated the mean of the individual directions after applying a bedding tilt correction (Fig. 9). The result, after using the VANDAMME (1994) cut-off, suggests a mean palaeomagnetic direction with declination = 15.9° and inclination = 76.5°. If true, this implies that the southern margin of the Central Paratethys was located at a palaeolatitude of λ = 64.4°N (i.e. somewhere in central Scandinavia) during the Sarmatian/Pannonian boundary interval. This clearly demonstrates that the remnance in the Vranović section is of secondary origin, which clearly postdates the tectonic tilting of the section.

5. DISCUSSION AND CONCLUSIONS

Detailed sedimentological and palynological studies of the Vranović section at Našice demonstrates that it comprises the Sarmatian/Pannonian boundary interval, which is characterized by a major palaeoenvironmental change from reduced marine to brackish water conditions. Sarmatian palynomorph assemblages consist of marine dinocysts that are tolerant to decreased salinity and brackish water. In the earliest Pannonian, prasinophyte algae dominate the phytoplankton assemblages, and ecological conditions had become unfavourable for dinoflagellates. Higher in the sequence, the dinocyst assemblage indicates oxygenated environments and an increase in the water level. The observed biostratigraphic and palaeoenvironmental trend is similar to that observed in Hungary (SÜTŐ-SZENTAI, 1988), which suggests that it is typical for the entire Central Paratethys basin.

Rock magnetic data from the Vranović section indicates that the initial magnetization is weak and characterized by multi-domain magnetic behaviour. Hysteresis loops and thermomagnetic runs indicate the presence of a high coercivity mineral like maghemite, goethite or haematite in the Sarmatian deposits, while the Pannonian rocks are typified by low contents of multidomain magnetite. Thermal demagnetization reveals a remnant magnetisation component that shows dominantly normal polarities and that has, before bedding tilt correction, a mean direction closely coinciding with the expected present-day geocentric axial dipole field directions at Našice. This indicates that the remnance of the Vranović samples is of secondary origin and that no magnetostratigraphic age control on the Sarmatian/Pannonian boundary could be derived from our samples. Nevertheless, two stratigraphic levels contain evidence for reversed polarities.

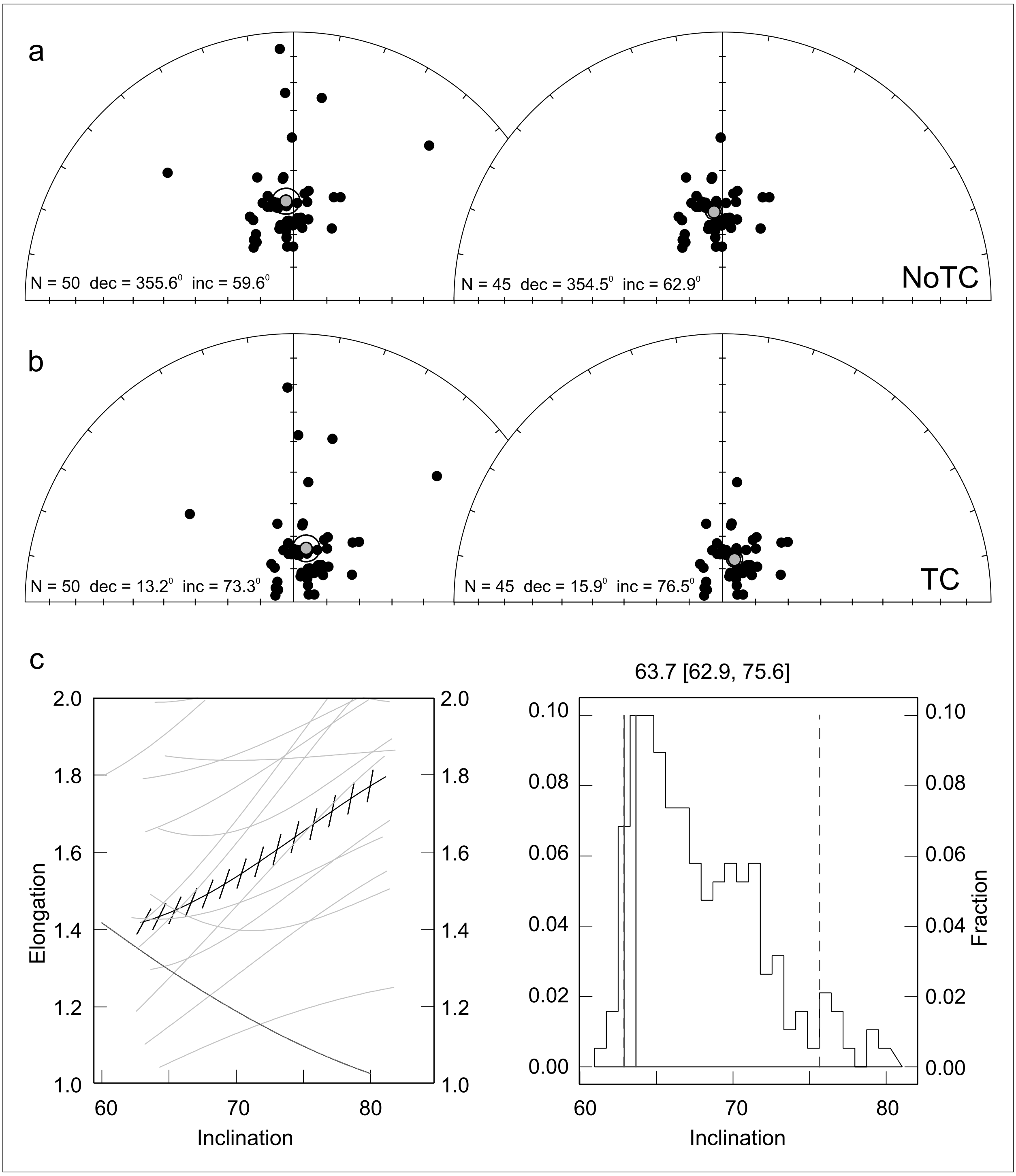

Fig. 9 Characteristic remnant magnetisation before (panel a) and after (panel b) bedding tilt correction. The left-hand sides of the panels a and b include all the solid-symbol points from Fig. 4 from the declination–inclination column. The right-hand sides of the panel (a) and (b) contain all the points after applying the VANDAMME (1994) cut-off. The left-hand side diagrams of the (b) and (d) panels are presented with no tectonic correction (NoTC). (c) Correction for the inclination error using the method of TAUXE & KENT (2004). On the left-hand side is the plot of elongation versus inclination for the TK03.GAD model, where the black curve shows the variation of the elongation of the dataset distribution with respect to mean inclination when affected by flattening factor ranging from 0.4 to 1.1; the light grey curve is the same for the dataset generated from bootstrap analysis. The corrected inclination is given by the intersection with the dashed line (expected elongation from the TK03.GAD). Top right-hand diagram from panel c indicates the distribution of the corrected inclinations with a 95% confidence limit.

A consequence of this study is that the Sarmatian/Pannonian boundary remains undated by direct magnetostratigraphic or radiometric techniques. Nevertheless, we conclude that it is necessary to re-evaluate the age of 11.6–11.5 Ma for the Sarmatian/Pannonian boundary that figures in the commonly used geological time scales of Central Paratethys (STEININGER et al., 1990, 1996). This age is mainly the result of multiple cross correlations with well-dated Mediterranean Miocene sections, but also largely depends on the first appearance of the three-toed equid *Hippotherium* in the lower Pannonian, at the beginning of the local Papp zone C (PAPP, 1948, 1951; NAGYMAROSY & MÜLLER, 1988; RÖGL & DAXNER-HOCK, 1996; STEININGER et al., 1996). By definition, the first appearance datum (FAD) of *Hippotherium* marks the beginning of the Vallesian stage and is indicative of Neogene Mammal zone MN 9. Other basal Pannonian faunas of Rudabanya, Gaiselberg, and Comanesti–2 also correlate with MN9 (FERU et al., 1980; BERNOR et al., 1988, 2002, 2003; STEININGER et al., 1990, 1996; RÖGL & DAXNER-HOCK, 1996). The base of the Vallesian has, however, recently been directly dated by magnetostratigraphy at 11.1 Ma (chron C5r.1r) in the Vallès–Penedès Basin (GARCÉS et al., 1996, 1997; AGUSTÍ et al., 2001), but the Sarmatian/Pannonian boundary has not been revised accordingly. We therefore conclude that caution is warranted when using an age of 11.5–11.6 Ma for the environmental change from marine to brackish waters in Central Paratethys, and that more research should be done to obtain better age constraints on the Sarmatian/Pannonian boundary.

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