Remagnetization of Upper Jurassic limestones from the Danubian Unit (Southern Carpathians, Romania): tectonic implications

CRISTIAN G. PANAIOTU[1], CRISTINA E. PANAIOTU[2] and IULIANA LAZĂR[3]

[1]University of Bucharest, Faculty of Physics, Paleomagnetic Laboratory, Bălcescu 1, Bucharest, Romania; cristian.panaiotu@gmail.com
[2]University of Bucharest, Faculty of Geology and Geophysics, Mineralogy Department, Bălcescu 1, Bucharest, Romania; cris.panaiotu@gmail.com
[3]University of Bucharest, Faculty of Geology and Geophysics, Geology Department, Bălcescu 1, Bucharest, Romania; iuliana.lazar@g.unibuc.ro

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Abstract: We present a pioneering paleomagnetic study on Upper Jurassic limestones from the Danubian Unit (Southern Carpathians, Romania). Thermal and alternating field demagnetizations were applied to define the characteristic remanent magnetization component in all six localities (81 samples). All samples have a normal polarity characteristic remanent magnetization. Negative regional and local fold tests suggest that this remanent magnetization is in fact a remagnetization produced by late diagenetic processes. The studied limestones were probably remagnetized during the collision of the Getic Unit and Danubian Unit which took place during the long normal polarity Chron C34 (82–118 Ma). The area mean direction (D = 75.5°, I = 50.0°, α_{95} = 10.2°, k = 44) implies about 75° clockwise rotation post remagnetization. Our paleomagnetic results further indicate the absence of significant relative rotation between the Getic Unit and the Danubian Unit during the Cenozoic.

Key words: Upper Jurassic, Southern Carpathians, paleomagnetism, remagnetization, limestones.

Introduction

The Danubian Unit is considered a part of the European margin scraped off the Moesian Platform in response to strong collision with the Getic Unit during late Early Cretaceous (e.g. Iancu et al. 2005; Schmid et al. 2008). After this collision both units are considered part of the Tisza-Dacia Megaunit (Csontos & Vörös 2004). Whatever model is adopted, all of them invoke a Miocene retreat of the subducted oceanic slab as the principal driving force for the final emplacement of the continental ALCAPA and Tisza-Dacia Megaunits that occupy the internal parts of the Carpathian loop (Csontos & Vörös 2004; Fügenschuh & Schmid 2005; Ustaszewski et al. 2008; Van Hinsbergen et al. 2008). Paleomagnetic results to support these models are available only from internal parts of the Tisza-Dacia Megaunit: Apuseni Mountains (Pătraşcu et al. 1990, 1994; Panaiotu 1998) and Getic Unit (Pătraşcu et al. 1992; Panaiotu & Panaiotu 2010). There is a broad agreement between paleomagnetic data and geological models concerning the sense of rotation and the timing, but not the amplitude of rotation (Ustaszewski et al. 2008).

In this study we present the first paleomagnetic results from the Danubian Unit. The initial purpose was to constrain the Upper Jurassic position of the Danubian Unit prior to the collision with the Getic Unit in terms of paleolatitude and vertical axis rotation. We selected for sampling the carbonate sequences developed within the Kimmeridgian–Tithonian of the Danubian window in the Sviniţa area (western part of the Southern Carpathians). Our study documented both the existence of a Cretaceous remagnetization, which obscured the Upper Jurassic primary magnetization of the limestones, and a subsequent clockwise rotation, which has implications for the Southern Carpathians Tertiary geodynamic scenario.

Geological setting

The Southern Carpathians are built up of a succession of nappes and thrust sheets with a complicated geotectonic structure within the Carpathian Folded Belt (Fig. 1). The studied Upper Jurassic sequence belongs to the sedimentary cover of the Danubian Unit, one of the most complex geotectonic units of the Marginal Dacides that are interpreted as part of the strongly deformed European continental margin (Săndulescu 1994). The Danubian Unit was defined first as the Danubian autochthonous and later as the Danubian nappe complex (e.g. Iancu et al. 2005 and references therein). The Danubian nappes represent the most external Carpathian units, which continue south of the Danube in Miroć (Serbia) and in the Stara Planina and Prebalkan (Bulgaria) tectonic units (Săndulescu 1994; Kräutner 1996; Kräutner & Krstić 2002). The Danubian Unit is composed of several thrust complexes: Arjana, Coşuştea, Upper Danubian and Lower Danubian (Iancu et al. 2005).

The studied sequence belongs to the Upper Danubian nappe complex which is largely exposed in the western part of the Danubian window in the Sviniţa area (western part of the Southern Carpathians, Fig. 1) and is represented by carbonate sequences developed during the Kimmeridgian-Tithonian interval, belonging to Greben Formation. The Greben

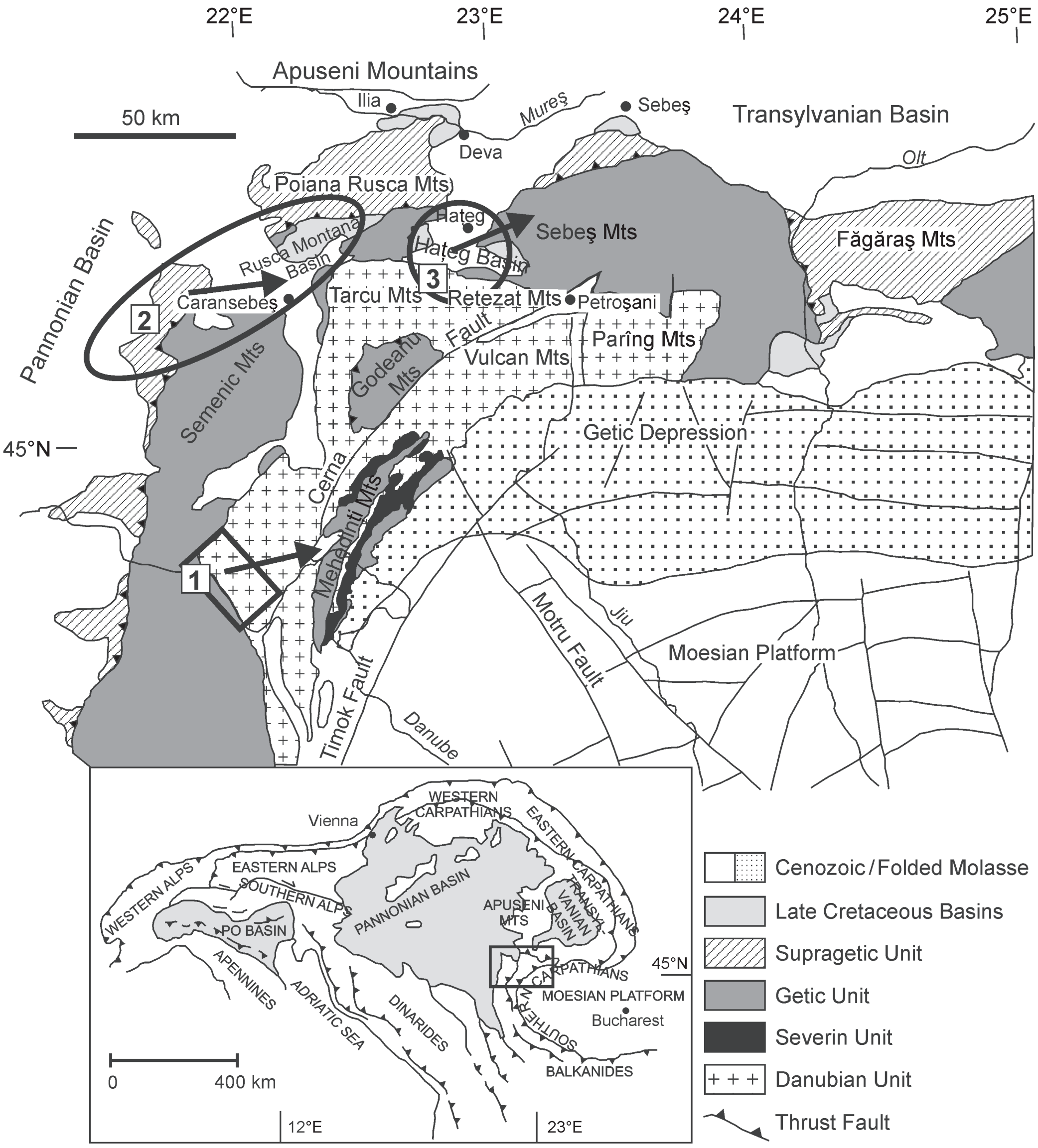

Fig. 1. Areas with paleomagnetic results within the Southern Carpathians: **1** — this study, **2** — Upper Cretaceous magmatic rocks (Pătraşcu et al. 1992), **3** — Haţeg Basin (Panaiotu & Panaiotu 2010). Arrows correspond to mean Late Cretaceous paleodeclination for each area. Maps after Willingshofer et al. (2001).

Formation was described first by Răileanu (1959) who defined within this formation two units: "upper nodular limestone horizon" and "the compact limestone horizon". The lower part of the Greben Formation (20 to 30 meters in thickness) consists of bedded red nodular and subnodular limestone (10 to 150 cm the thickness of each bed) with various textural and structural features. The upper part of this formation in the Sviniţa area (5 to10 meters in thickness) is represented by grey sub-nodular and cherty limestones (each bed 20–40 cm thick) alternating with thin marls and marly limestone beds.

From these nodular limestones a rich ammonite fauna, which proves the Late Kimmeridgian and Early Tithonian age, was described by Răileanu & Năstăseanu (1960) and Grigore (1998). They identified the following ammonite zones: *Acanthicum*, *Cavouri*, *Beckeri* and *Hybonotum*. Later, Grigore (2000) also demonstrates the presence of *Verruciferum* and *Richteri* ammonite Zones. Thus, the studied sequences that outcrop near the Sviniţa locality belong to the uppermost Kimmeridgian–Lower Tithonian interval (Grigore 1998, 2000).

Sampling and laboratory procedures

We sampled 6 localities in the Upper Jurassic limestones of the Greben Formation (Fig. 2). The lithology of the sampled localities is dominated by red nodular limestones sometimes intercalated with grey limestones. In each locality we collected several samples distributed along several meters of stratigraphic section. At locality B9, however, we sampled 35 beds distributed on a 28 m stratigraphic section. Samples were

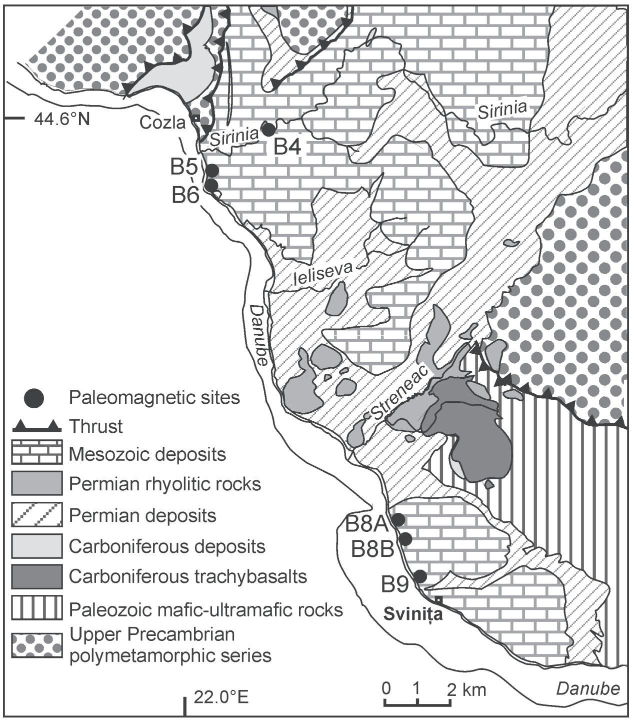

Fig. 2. Position of the sampling localities in the Mesozoic limestones of the Danubian Unit. Geological map is simplified after Romanian Geological Map scale 1 : 200,000, sheet Turnu Severin.

cored (2.54 cm in diameter) with a portable gasoline-powered drill. They were oriented in situ with a magnetic compass. Local declination was determined with a sun compass.

Cores were split in the laboratory into standard specimens (2.2 cm in length) for paleomagnetic measurements. Pilot specimens from each locality were subjected to detailed alternating field (AF) demagnetization up to 140 mT and thermal demagnetization up to 700 °C. Thermal demagnetization was performed in 50° steps up to 400 °C and 25° steps up to 700 °C. Around half the specimens were measured in the Paleomagnetic Laboratory at the University of Bucharest. Remanences were measured with an Agico JR5 spinner magnetometer. Thermal demagnetization was performed with a home built heater (triple mu-metal shields, non-inductive processor control furnace). For AF demagnetization we used a static demagnetizer (Magnon International). The heater and the magnetometer are installed inside a set of three Helmholtz coils used to reduce geomagnetic field in the working area. The degree of thermal alteration during laboratory heating was monitored by measuring magnetic susceptibility on a MS2B Bartington system. The rest of the collection was measured in the Paleomagnetic Laboratory at Utrecht University using a horizontal 2G Enterprise DC SQUID cryogenic magnetometer and a laboratory-built thermal demagnetiser. Paleomagnetic analysis was performed using Randy Enkin's paleomagnetic software (http://gsc.nrcan.gc.ca/sw/paleo_e.php) and Remasoft 3.0 (Chadima & Hrouda 2006).

In addition at the Paleomagnetic Laboratory of the University of Bucharest, we carried out a series of rock magnetic analyses in order to characterize the nature of the main magnetic carriers at each sampling locality. We analysed the acquisition of an isothermal remanent magnetization (IRM), in a succession of fields up to 2.5 T using a pulse magnetizer MMPM10, and its subsequent back-field demagnetization. After each step remanent magnetization was measured with JR5 magnetometer. The change of the magnetic susceptibility during a heating-cooling cycle from room temperature to 700 °C in argon was investigated using an AGICO CS-4 apparatus coupled to the MFK1A kappabridge. On selected specimens we measured the hysteresis properties using a VSM model 3900 (Princeton Measurements) with a maximum applied field of 1 T.

Complementary to the paleomagnetic study we did preliminary petrographic observation of polished thin sections using polarized microscope and cathodoluminescence microscopy (using equipment from the CITL model CCL 8200 MK3) to identify some peculiar aspects of the depositional and diagenetic processes influencing the magnetic minerals from the studied limestones. We focussed on observing the depositional texture and composition as well as the diagenetic compaction and chemical dissolutions/precipitation or remobilization of iron bearing minerals.

Results

Rockmagnetic results

In red limestones IRM acquisition curves saturate in magnetic fields above 1.6 T (Fig. 3A) showing dominance of hematite in these samples. Coercivity of remanence for these limestones determined from back field demagnetization of saturation IRM ranges between 70 mT and 300 mT. In some samples hematite is accompanied by magnetite. This is evident both in IRM acquisition curves and hysteresis experiments. After diamagnetic correction some hysteresis loops display "wasp-waisted" behaviour (Fig. 3B). This type of hysteresis loop is likely associated with mixtures of hematite and magnetite minerals (Tauxe et al. 1996). Variation of magnetic susceptibility with temperature is in agreement with IRM experiments. Some samples show an increase of magnetic susceptibility around 500 °C before a significant drop in magnetic susceptibility between 500 °C and 600 °C, followed by the next fall after 600 °C. We interpret this behaviour as an indication of mixture of magnetite and hematite (Fig. 3C). Other samples show only the presence of hematite (Fig. 3D). During cooling, all samples show a large increase in magnetic susceptibility showing the creation of new magnetite upon heating at 700 °C. Partial thermomagnetic runs between room-temperature and 400 °C, 500 °C, 600 °C and 700 °C show that in most samples this alteration appear after 600 °C (Fig. 3D).

In grey limestones the most effective method to identify magnetic mineralogy was the acquisition and demagnetization of IRM because their magnetic properties were significantly weaker than those of red limestones. As can be seen from the example presented in Fig. 3A the IRM curves is fully saturated in 0.4 T showing the presence of a soft coercivity mineral. Due to low values the magnetic susceptibility — temperature

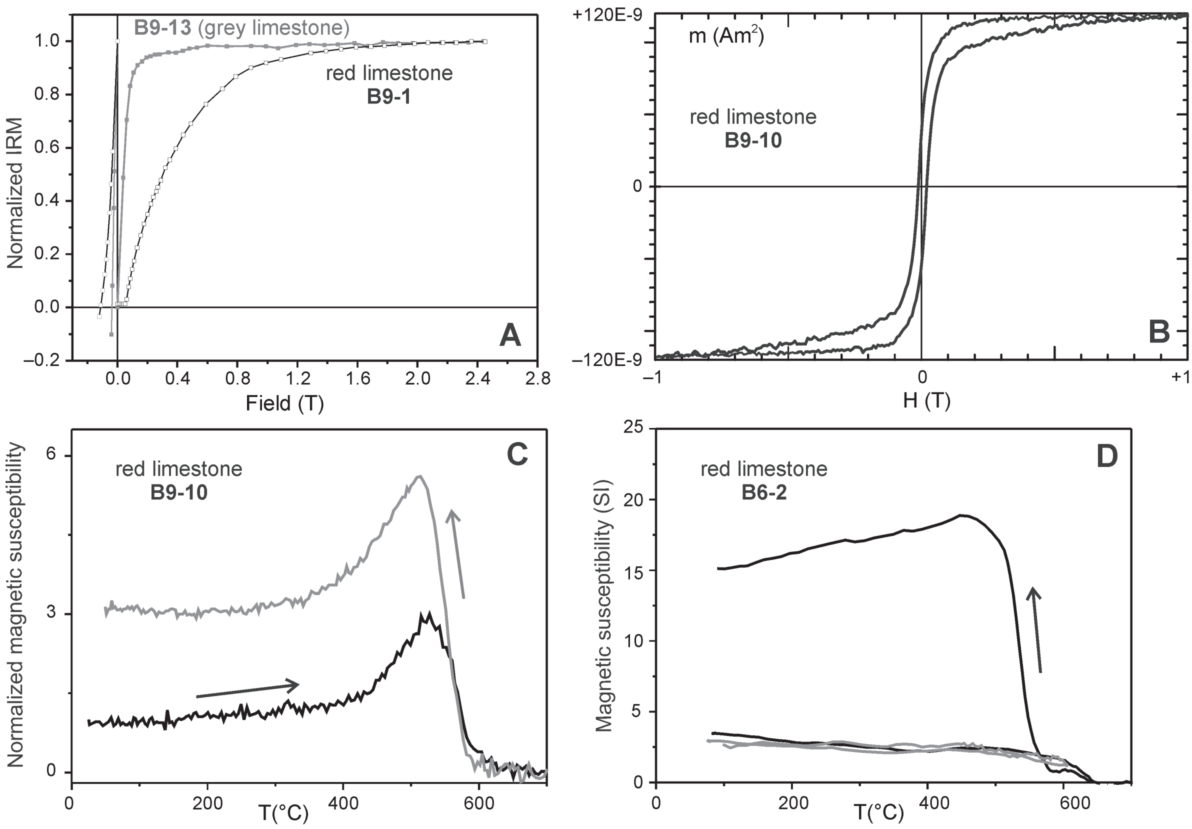

Fig. 3. Examples of rockmagnetic results: **A** — IRM acquisition and backfield demagnetization; **B** — Hysteresis loop of a red limestone; **C** — Variation of the low-field magnetic susceptibility during a heating-cooling cycle for a sample with magnetite and hematite; **D** — Partial thermomagnetic runs at 600 °C (grey curve) and at 700 °C (black curve) for a sample with hematite.

curves are noisy, but show a significant drop between 500 °C and 600 °C suggesting that this magnetic mineral is probably magnetite. Cooling curves always show an important increase of magnetic susceptibility.

Paleomagnetic results

Typical examples of orthogonal projections after thermal demagnetization are presented in Fig. 4. The samples fall into two categories. The majority of samples, after removing one or two low temperature components (below 250–300 °C), have thermal demagnetization diagrams revealing the presence of a stable and well-defined directional component with normal polarity, going toward the origin. The second category contains samples having a univectorial characteristic remanent magnetization (ChRM) also with normal polarity and pointing toward origin. All samples show erratic demagnetization trajectories starting in the temperature interval 500–600 °C when the remanent magnetization is less than 95 % of the initial natural remanent magnetization (NRM). This behaviour is accompanied by mineralogical transformation reflected in an increase of both magnetic susceptibility and remanent magnetization. AF demagnetization has isolated the same normal polarity component, but it was less efficient in specimens where hematite was the main magnetic mineral. For this reason thermal demagnetization was the preferred technique to isolate the ChRM.

The ChRM directions were determined by principal component analysis (Kirschvink 1980) in the temperature interval between 300 °C and the temperature where directional insta-

Table 1: Paleomagnetic results from the Upper Jurassic limestones rocks of the Danubian Unit.

Locality	Geographical coordinates		In situ				Tilt corrected			
		N	D(°)	I(°)	k	α_{95}(°)	D(°)	I(°)	k	α_{95}(°)
B4	44.632871°N 22.048401°E	6	**59.5**	**59.1**	**28.3**	**12.8**	104.5	38.9	14.7	18.1
B5	44.612490°N 22.006762°E	11	**79.9**	**63.7**	**131.2**	**4.0**	89.6	6.6	36.1	7.7
B6	44.609915°N 22.006956°E	4	**75.3**	**47.0**	**194.7**	**6.6**	15.4	54.0	194.7	6.6
B9	44.501817°N 44.501817°E	35	**83.6**	**37.4**	**70.8**	**2.9**	72.8	53.5	75.9	2.8
B8B	44.518843°N 22.078713°E	8	**87.6**	**44.1**	**60.1**	**7.2**	89.0	52.3	9.0	19.5
B8A	44.519744°N 22.078084°E	17	62.9	31.5	19.8	8.2	72.7	52.7	28.4	6.8
		17	58 % unfolding				**62.9**	**46.2**	**50.5**	**5.1**
Area mean										
Remagnetized Upper Jurassic limestones		6	**75.5**	**50.0**	**44.0**	**10.2**	78.5	46.5	8.8	23.9

D and I are site-mean declination and inclination calculated before and after tectonic correction; k and α_{95} are statistical parameters after Fisher (1953); N is number of samples giving reliable results or number of sites for the mean direction. Mean direction of characteristic remanent magnetization for each locality is marked with bold letters.

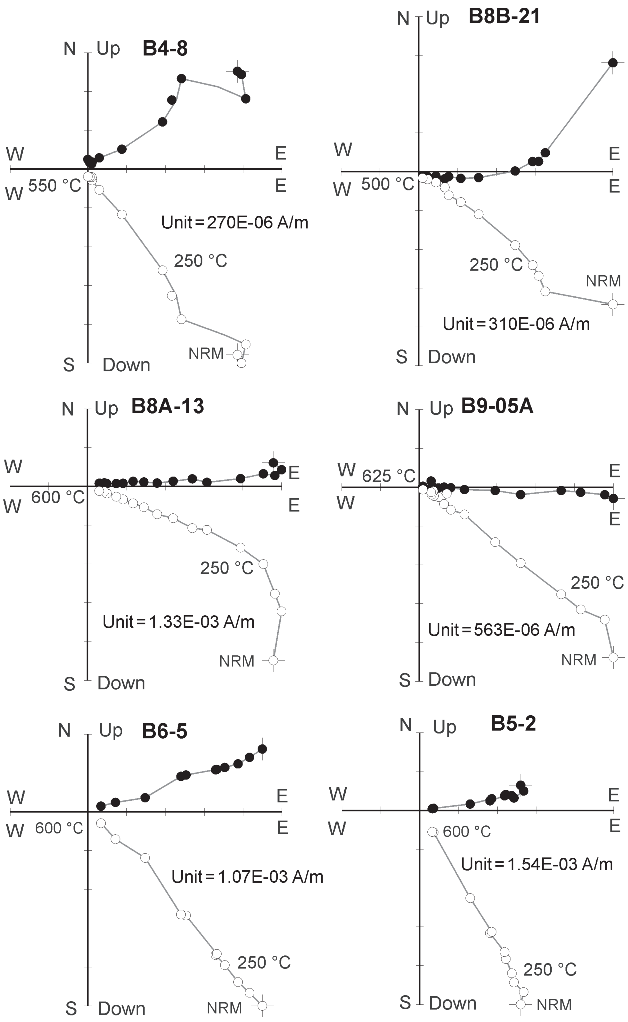

Fig. 4. In situ orthogonal plots of thermal demagnetization: multi-component natural remanent magnetization (specimens B4-8, B8B-21, B8A-13, B9-05) and univectorial natural remanent magnetization (specimens B6-5, B5-2). The maximum temperature on each plot marks the beginning of erratic demagnetization trajectories.

bility has started. The line fits were based on the following constraints: 1) minimum 4 demagnetization steps; 2) the Maximum Angular Deviation was less than 10°. The decay of ChRM during thermal magnetization is in agreement with a magnetic mineralogy dominated by magnetite, in grey limestones, and dominated by hematite, with distributed blocking temperatures, sometimes combined with magnetite, in red limestones. Locality mean directions, based on Fisher statistics (Fisher 1953), are presented in Table 1.

Petrographic results

Most of the analysed limestones are characteristic for deep shelf environment with dominant pelagic fauna (mainly crinoids and radiolarians), ranging from fine-grained mudstone to medium-grained packstone (Fig. 5A,B). Colour also varies from light grey to dark red according to the amount of iron oxide incorporated in the rock sample. The red coloured limestone shows that iron oxide was incorporated into the mud either in the matrix or filling the internal cavities and pores of the bioclasts (within the network of crinoids, in endolithic perforations within the macrofossils, inside foraminiferal and radiolarian chambers). Most probably this iron pigmentation has a bacterial origin (Preat et al. 1999; Mamet & Preat 2006) with micrometric hematite. The grey coloured limestone does not have hematite and also does not have mud matrix but calcite cement.

The observed effects of diagenesis include the syndepositional compaction with reorientation and aligning of the bioclasts followed by reorganization of the mud and possible concentration of the hematite crystals along some weakly developed and undulating lamina surfaces. This is an early diagenetic process which takes place while a large amount of pore water still exists, allowing such reorganization. The entire sequence of rocks contains no impermeable layer and the sedimentation was almost continuous without big gaps, in such conditions the pore water could have been expelled freely as the lithostatic pressure increased.

The chemical diagenetic overprints are either related to early diagenetic processes like cementation and recrystallization or to late diagenetic processes after a tilting/folding phase. All of these processes are responsible for the remagnetization. Early diagenetic cementation affected only the coarse-grained grey limestones which contain large amount of echinoderms and other shells but less mud. Around echinoderms there is often a thick rim of non-luminescent syntaxial calcite crystals (Fig. 5C). Later burial cementation is also present and can be recognized from its bright/dull luminescent calcite (Fig. 5C) typical for anoxic environments. The early and later cementation make the sediments less sensitive to further compaction and limited the fluid flows and chemical remagnetization.

Bacterial hematite from the red limestones is unstable during burial conditions and its recrystallization into larger hematite crystals is a usual process which can produce a chemical remagnetization, obliterating the primary one. Late chemical diagenetic processes are attributed to pressure dissolution with different forms of stylolite and dissolution seams. These are regarded as late diagenetic features because they cut the late burial cements and are oblique to the bedding reflecting a post tilting/folding event. Stylolites have large amount of insoluble residue like iron oxides, organic matter and clay along their irregular surfaces (Fig. 5D). The iron oxide along these surfaces is still hematite, but the crystals are larger and grouped together in lumps so this process is responsible for a new chemical remagnetization.

Discussions

Origin of ChRM

Because the Late Jurassic is characterized by a relative high frequency of reversals (e.g. Ogg 2004) we expected to find many reversals in the 28 m thick B9 section. On contrary, both at this locality and other localities the ChRM has only normal polarity. This characteristic suggests that the ChRM is probably a remagnetization.

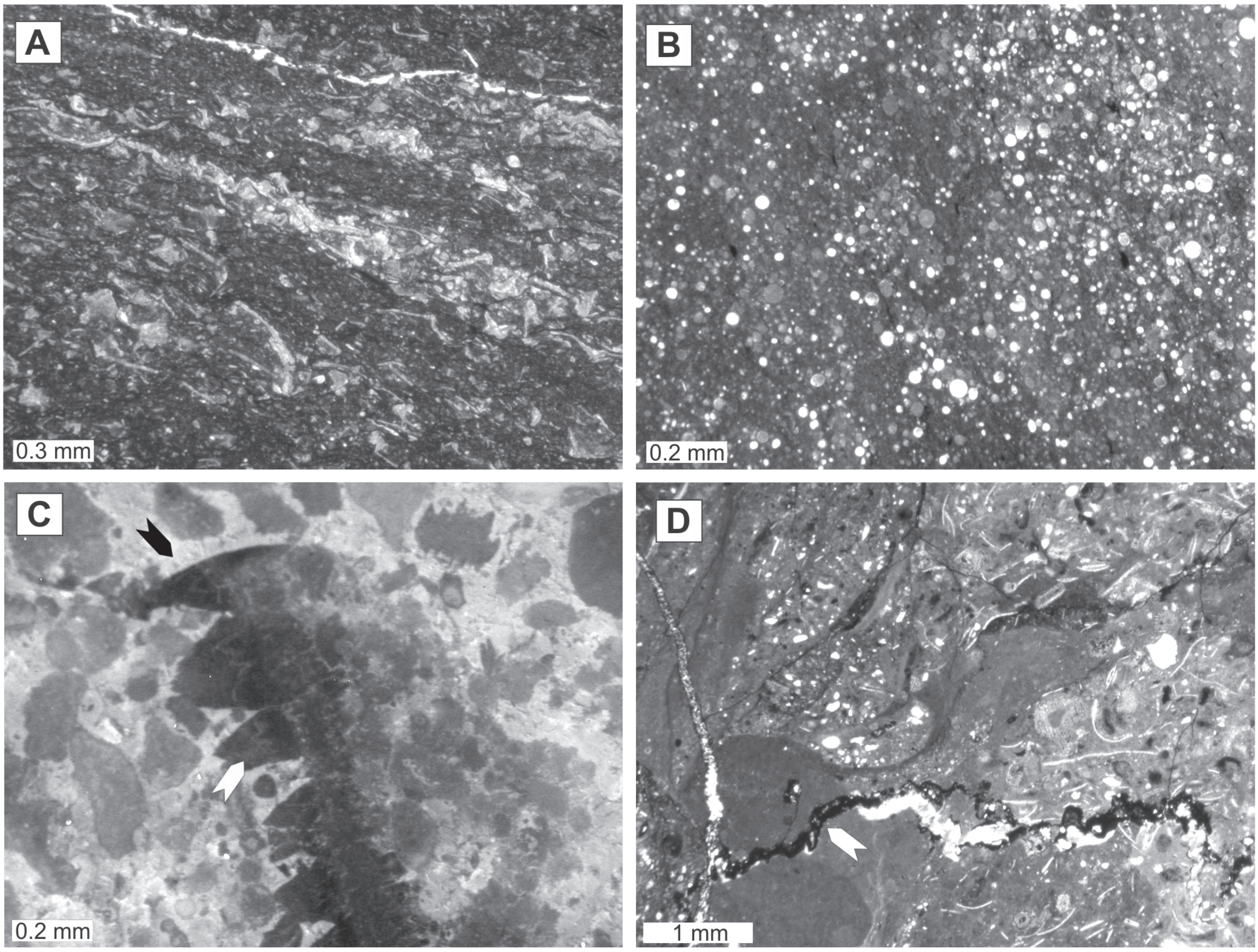

Fig. 5. Examples of sampled limestone types: **A** — Red laminated crinoidal packstone; **B** — Red radiolarian packstone; **C** — Non-luminescent syntaxial calcite cement (white arrow) around echinoderms followed by luminescent pore cement (black arrow); **D** — Stylolites (white arrow) with concentration of insoluble residue.

To constrain the age of the ChRM we performed fold tests both at locality level and regional level. In four localities (B4, B5, B8A, B8B) we sampled both limbs of a mesoscopic fold so it was possible to do local fold tests. We used two types of fold test: proportional fold test (Watson & Enkin 1993) and direction-correction tilt test (Enkin 2003). Proportional Fold Test evaluates the unfolding % which corresponds to the maximum Fisher precision parameter k as the data is progressively unfolded. The direction-correction tilt test tests whether or not the site mean directions are correlated to the bedding attitudes, and also provides an analytical method which determines the bedding correction which renders the least dispersion of the directional data. Both fold tests are negative in three localities (B4, B5, B8B) showing that the age of ChRM is post-folding (Fig. 6A). At locality B8A both tests suggest a syn-folding magnetization at around 58 % unfolding (Fig. 6B).

At a regional scale the direction-correction tilt test is negative for five localities (B4, B5, B6, B8A, B9). Both the direction-correction tilt test and proportional fold test suggest optimal untilting at around 24 % untilting so we interpret the ChRM as a post-folding magnetization. If we include the syn-folding mean direction from locality B8A the direction-correction tilt test is indeterminate, but the degree of optimal untilting is also around 24 % (Fig. 7).

Since small vertical axis rotations between the sampling localities cannot be ruled out also we performed the block rotation Fisher test (BRF) proposed by Enkin & Watson (1996). The test is negative given the following results: geographical coordinates: mean inclination = 50.2°, k = 25; stratigraphic coordinates: mean inclination = 45.7, k = 6.

Taking into account both the lack of reversed polarity magnetizations and the results of the fold tests we think that the ChRM is a remagnetization most probably acquired mainly during the final stage of folding. Pervasive and widespread remagnetizations are common in many orogens (e.g. Oliva-Urcia et al. 2008; Grabowski et al. 2009; Meijers et al. 2011). Several mechanisms and settings have been invoked to explain remagnetizations of low to moderately deformed rocks in tectonic regimes, including thermal metamorphism, migration of orogenic fluids, diagenetic mineral transformations and magnetic reorientation induced by pressure solution (McCabe & Elmore 1989; Jackson 1990; Menard & Rochette 1992; Katz et al. 1998; Oliva-Urcia et al. 2008). In our study we consider that remagnetization is produced by

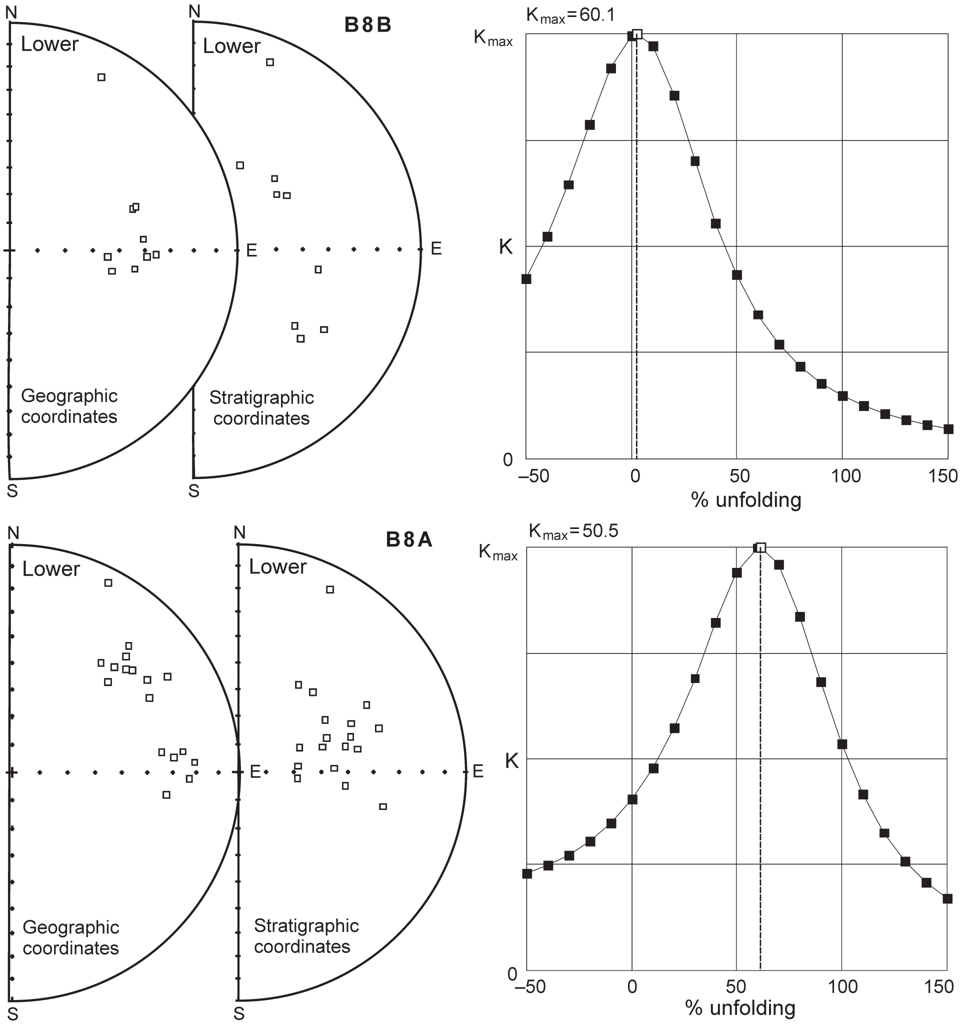

Fig. 6. Examples of local fold tests for localities B8A and B8B: equal area projections of individual samples in geographical and stratigraphic coordinates and incremental fold test (Watson & Enkin 1993) showing the variation of precision parameter k during unfolding.

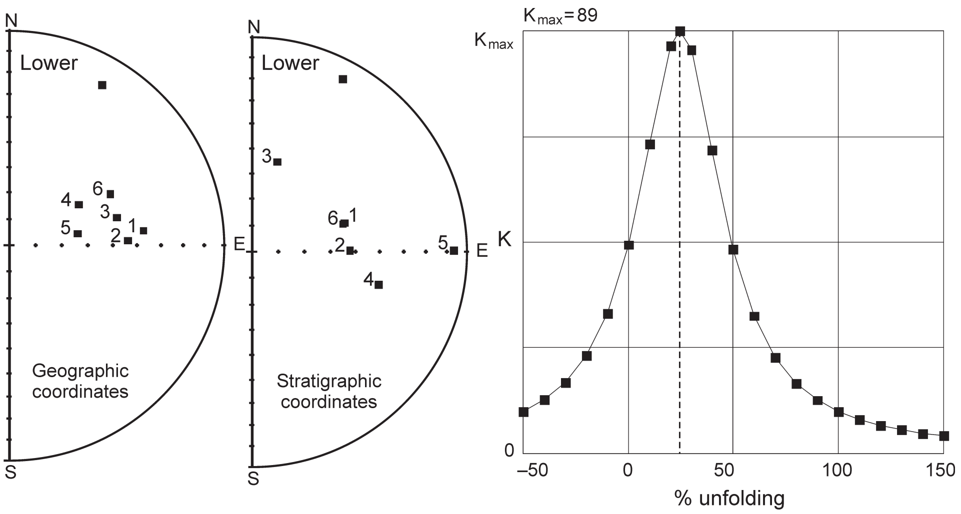

Fig. 7. Regional fold test: equal area projections of locality mean directions (1 = B9, 2 = B8B, 3 = B6, 4 = B4, 5 = B5, 6 = B8A) in geographical and stratigraphic coordinates and incremental fold test (Watson & Enkin 1993) showing the variation of precision parameter k during unfolding.

the late diagenetic processes identified in the studied limestones. As observed by detailed petrography, the remagnetization was probably acquired during or after a tilting/folding event by pressure dissolution process which liberated the magnetic minerals and concentrated them along the stylolites or dissolution seams, similar to the process described in the Pyrenees by Oliva-Urcia et al. (2008).

We computed an area mean direction based on the syn-folding direction for locality B8A and in situ directions for other localities. We think that this value is the best estimation of area mean direction (Table 1). In geographical coordinates the mean inclination of the area mean direction is practically identical with the mean inclination from the BRF test so vertical axis rotations between sampling localities are probably not significant.

The sampling localities are close to the present day boundary between the Getic Unit and the Danubian Unit in the western part of the Southern Carpathians (Fig. 1). Most probably this normal polarity remagnetization was produced during the collision of the Getic domain with the Danubian domain. This collision took place during the late Early Cretaceous–early Late Cretaceous (e.g. Csontos & Vörös 2004; Iancu et al. 2005; Schmid et al. 2008). The collision period corresponds to Chron C34 when the geomagnetic field has only normal polarity for a very long period (Cande & Kent 1995).

Tectonic implications

In Fig. 8 we plotted together area mean directions from this study, the Upper Cretaceous sediments from

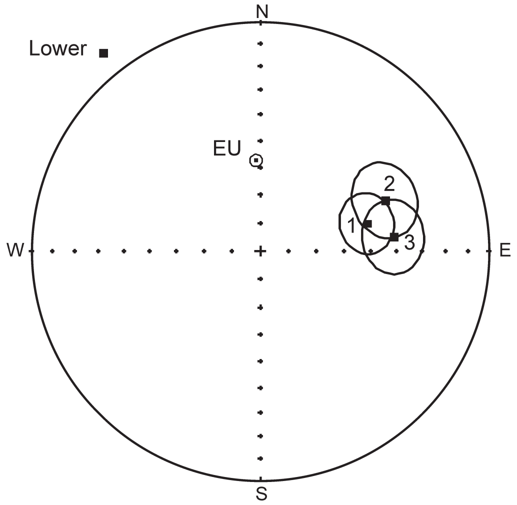

Fig. 8. Equal-area projection of area-mean directions: **1** — this study, **2** — Upper Cretaceous sediments from the Haţeg Basin (Panaiotu & Panaiotu 2010), **3** — Upper Cretaceous magmatic rocks (Pătraşcu et al. 1992); **Eu** — expected European direction for the Late Cretaceous calculated from synthetic European paleopole 70 Ma (Besse & Courtillot 2002) for geographical coordinates: 45 °N, 22 °E.

the Haţeg Basin (Panaiotu & Panaiotu 2010) and the Upper Cretaceous magmatic rocks (banatites) from the western part of the Southern Carpathians (Pătraşcu et al. 1992). The amplitude of the clockwise paleomagnetic rotation with respect to expected Cretaceous paleomagnetic direction from stable Europe (Besse & Courtillot 2002) is similar for all three areas: ~70–85° (Table 2).

To estimate if there is any tectonic motion between these areas we calculated poleward displacements and rotations using the method of Debiche & Watson (1995). The data presented in Table 2 show that both poleward displacements and rotations are not significant. These results confirm the geodynamic models for the evolution of the Southern Carpathians, which suggest coordinate rotation of Getic and Danubian Units around the corner of the Moesian Platform during the Cenozoic (e.g. Csontos & Vörös 2004; Fügenschuh & Schmid 2005; Ustaszewski et al. 2008; Van Hinsbergen et al. 2008). According to the paleomagnetic data, this rotation in the western part of the Southern Carpathians took place with little internal deformation reflected in vertical axis rotations.

Table 2: Comparison of tectonic motion between terrains from the Southern Carpathians and stable Europe.

Terrains	Poleward displacement (°)	Rotation (°)
Haţeg Basin — Danubian	8.5 ± 11.4	8.4 ± 13.2
Banatites — Danubian	7.4 ± 11.1	7.6 ± 13.0
Haţeg Basin — Banatites	1.9 ± 12.7	15.8 ± 14.2
Danubian — Europe	4.8 ± 8.4	72.4 ± 9.8
Haţeg — Europe	12.5 ± 9.4	70.1 ± 10.4
Banat — Europe	11.1 ± 10.3	85.2 ± 11.4

Tectonic motion was computed for the first terrain with respect to the second. Position of terrains is presented in Fig. 1: **area 1** = Danubian (remagnetized limestones, this study); **area 2** = Banatites (Upper Cretaceous magmatic rocks); **area 3** = Haţeg Basin (Upper Cretaceous sediments).

Our data show that the domain affected by large Cenozoic clockwise rotation extend around 300 km in a N-S direction.

Conclusions

A remanent magnetization of normal polarity has been recovered in all strata sampled in the Upper Jurassic limestones from the Danubian Unit. The lack of reversed polarity magnetizations and several negative fold tests suggests that this remanent magnetization is in fact a remagnetization acquired probably in the last phase of folding. Most probably the studied limestones were remagnetized at some stage in the collision of the Getic Unit and Danubian Unit which took place during the long normal polarity Chron C34 (82–118 Ma).

The area mean direction implies about 75° clockwise rotation post remagnetization. This rotation is similar to that recorded by the Upper Cretaceous sediments and magmatic rocks from the Getic Unit. Our new data show that the Cenozoic rotation of the western part of the Southern Carpathians around the Moesian Platform took place without major vertical axis rotations between internal blocks.

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