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Palaeomagnetism and rock magnetism of the Permian redbeds from the Velebit Mt. (Karst Dinarides, Croatia): dating of the early Alpine tectonics in the Western Dinarides by a secondary magnetization

Tomasz Werner [a,*], Marek Lewandowski [a,b], Igor Vlahović [c], Ivo Velić [d], Magdalena Sidorczuk [e]

[a] Institute of Geophysics, Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warszawa, Poland
[b] Institute of Geological Sciences, Polish Academy of Sciences, ING PAN, Twarda 51/55, 00-818 Warszawa, Poland
[c] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, HR-10000 Zagreb, Croatia
[d] Geolog d.o.o. and Croatian Geological Summer School, Pančićeva 5, HR-10000 Zagreb, Croatia
[e] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland

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A B S T R A C T

The studied area of the Velebit Mt., a part of the Adria microplate, belonged to a NE margin of Gondwana during the Carboniferous and Permian. While the Carboniferous to the Early Permian was characterised by deposition of clastic rocks, younger sedimentation was dominated by a thick sequence of carbonate rocks. The Lower Permian deposits of the core part of the Velebit Mt. at Košna and Crne Grede localities were investigated using palaeomagnetic and rock magnetic measurements. The main remanence carriers were recognized as haematite with an increasing contribution of SP/SD magnetite in younger subsections. The AMS fabric with low anisotropy ratio (1–3%) is strongly oblate at Košna and weakly prolate at Crne Grede, reflecting differences in the contribution of magnetic phases.

A significant remagnetization of the Permian rocks, as proved by results of a conglomerate test, probably caused by a combination of elevated temperatures and fluid migration, may be assigned to burial-related processes that affected the rocks before the final uplift of the Dinarides. Characteristic remanent magnetizations recorded in haematite are apparently similar to the Permian direction for Africa (shallow inclination with NNW declination), as expected for Velebit Mt. coordinates. Paradoxically, this orientation is observed *in situ* within the almost vertically dipping beds. We explain this relationship assuming a syn-folding Cretaceous remagnetization of the rocks at their subhorizontal position (ca. 30°S), in which a mean vector of the secondary remanence overlaps with the Cretaceous direction, expected for Africa at the Velebit Mt. geographical coordinates. Consequently, our results indirectly point to the Cretaceous time of incipient stages of the Dinaric tectonism, and suggest African geotectonic affinity of the Velebit rocks. No important vertical-axis rotation is implied by our results, in contrast to previously published data. The puzzling complete remagnetization carried by haematite at relatively low-to-moderate temperatures is also discussed.

1. Introduction

Reconstruction of a geodynamic history of the Alpine system is a complex issue (e.g. Csontos and Vörös, 2004; Neugebauer et al., 2001). Tertiary history of Alcapa, Tisza–Dacia and Adria terranes is constrained by a wealth of geological and palaeomagnetic data (Channell, 1996; Csontos and Vörös, 2004; Neugebauer et al., 2001; Satolli et al., 2007, 2008; Stampfli and Borel, 2002; Van Dijk and Scheepers, 1995). Significant progress in the Dinarides has recently been made due to works of Emő Márton and co-workers (Márton et al., 1995, 1999, 2002, 2003, 2006, 2008, 2010, 2014; see also Márton and Veljović, 1983). Palaeomagnetic data acquired in the Dinaric chain (the north-eastern part of the Adria terrane) suggest that the whole unit experienced 35° counter-clockwise rotation with respect to Africa during late Miocene–Pliocene (Márton et al., 1999, 2002 and references therein). Meanwhile, the southern continuation of the Dinaric chain (i.e. Hellenic arc) rotated clockwise with similar magnitude (Kissel et al., 1995). Consequently, a pre-rotation palaeogeographic reconstruction reveals the whole Dinaric–Hellenic unit as a straight structural domain (Csontos and Vörös, 2004). Its Palaeogene–early Miocene north-westwards movement induced right lateral shear with respect to the north-easterly situated terranes (Alcapa, Tisza), which resulted in opposite vertical axis rotations of these terranes, compensated along the mid-Hungarian zone (Márton and Márton, 1996, 1999). At the same time, the movement of

* Corresponding author at: Institute of Geophysics, Polish Academy of Sciences, ul. Ks. Janusza 64, 01-452 Warszawa, Poland. Tel.: +48 6915 765; fax: +48 6915 915.
E-mail addresses: twerner@igf.edu.pl (T. Werner), lemar@twarda.pan.pl (M. Lewandowski), igor.vlahovic@rgn.hr (I. Vlahović), ivo.velic@zg.t-com.hr (I. Velić), magdalena.sidorczuk@pgi.gov.pl (M. Sidorczuk).

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the Adria microplate resulted in collision and accretionary wedge formation in the Northern Apennines (Bettelli et al., 2004).

Palaeomagnetism is a well-recognized tool for reconstruction of crustal block movements. It may also be applied to dating of folded structures, by a reference of identified characteristic magnetization to known palaeomagnetic poles/directions. This potential will be utilized in this study with the primary goal of contributing to a better understanding of the tectonic evolution of the Karst Dinarides, using secondary magnetizations to date tectonic stages. We selected the Permian rocks of the Velebit Mt. since up to now they were not investigated palaeomagnetically in detail, although they potentially carry information useful for recognition of tectonic history of the Karst Dinarides. In this study we provide new palaeomagnetic data from the Lower Permian clastic deposits of the Velebit Mt., as well as results of rock magnetic studies on their magnetic fabric and minerals.

Better understanding of origin of geological structures of the Karst Dinarides and their tectonic evolution (Velić et al., 2002; Vlahović et al., 2005) requires more data concerning the kinematic history of crustal units, today incorporated into the Alpine orogen of Croatia. In this paper we focus on remagnetization phenomena of the haematite-bearing Permian redbeds in a low-to-moderate temperature environment and applicability of this secondary component of a natural remanent magnetization (NRM) for dating of tectonic deformation of the Karst Dinarides (Croatia).

Preliminary palaeomagnetic results (Lewandowski et al., 2009) indicated possible secondary magnetizations in Permian rocks, but available data on palaeotemperatures obtained in this part of the Dinarides did not indicate temperatures high enough for acquiring secondary thermoviscous remanence in haematite which is the main magnetic carrier. Fio et al. (2010) in their paper on the Permian–Triassic Boundary (PTB) within the neighbouring Rizvanuša section concluded that PTB level was exposed to the maximum temperatures of 110–170 °C based on conodont colour alteration index (CAI) values of conodonts found in the overlying Middle Triassic rocks in the areas NW and SE of the studied sections (CAI = 1.5–2.0, H.-J. Gawlick and S. Missoni, pers. comm.) Therefore, Lower Permian rocks studied in this paper, which were approximately buried 1–1.5 km deeper than PTB rocks should not have been exposed to the temperatures above 200 °C. Nonetheless, despite this relatively low-to-moderate temperature setting, we observe complete resetting of the original magnetization of the Permian redbeds.

2. Geological setting

The study area of Velebit Mt. (Fig. 1), a deformed part of the Adria microplate (see e.g. Schmid et al., 2008; Handy et al., 2010, 2014), belonged to the NE margin of Gondwana during the Carboniferous and Permian. The Permian deposits in the Central Velebit area are composed of two informal lithostratigraphic units (Fig. 2): Lower Permian clastic deposits (topic of this paper) and uppermost Lower Permian to Upper Permian carbonates.

Lower Permian clastic deposits are, similar to the Upper Carboniferous ones, characterized by heterogeneous lithological composition. They consist mainly of pyritic sandstones, quartz conglomerates and petromictic conglomerates in the lower part and reddish-brownish sandstones and siltstones in the upper part. For this study only petromictic conglomerates and reddish-brownish sandstones and siltstones were sampled.

Petromictic conglomerates are known as Košna deposits or Košna conglomerates (Salopek, 1942). They are cropping out NW of Brušane in c. 2 km long, narrow lens of variable thickness (up to 100 m), mostly covering quartz conglomerates and laterally pinching out into reddish sandstones and siltstones. Košna conglomerates are composed of poorly sorted pebbles (1–30 cm in size) of the Lower Permian dark grey limestones, fusulinid limestones and dolomites, pyritic and reddish sandstones, as well as small quartz pebbles. Red or gray matrix is sand-sized, composed of quartz and less calcareous particles. The outcrop of Košna conglomerates close to the Košna spring was sampled for the conglomerate test.

The uppermost unit of Lower Permian clastic succession in the Central Velebit area is composed of reddish-brown siltstones and fine-grained to coarse-grained sandstones, in places even microbreccia greywackes. Medium- to ill-sorted angular detritus consists of quartz and particles of different rocks – carbonates, clastic, metamorphic and igneous rocks, claystones, as well as muscovite and chlorite. Matrix is chlorite–sericite aggregate with or without quartz (Sokač et al., 1976). Reddish colour originates from ferrigeneous minerals (mostly pigmentary haematite), indicating a close association with terrestrial environments (including oxidation and weathering of older rocks), while in places sandstones and siltstones are greenish. Depositional environments were probably continental and deltaic/coastal. In order to indicate that the Velebit Mt. Permian redbeds are not equivalent of the Upper Permian Gröden sandstones as previously considered (e.g. Salopek, 1942), a new, up to now informal term has been coined: Brušane sandstones (after neighbouring village of Brušane). Palaeomagnetic study presented in this paper was performed in these reddish clastic rocks at two localities: valley of the Košna stream and at Crne Grede.

3. Palaeomagnetic sampling and methods

Two sections of the Permian red siltstones and sandstones were sampled at the Košna and Crne Grede localities (Figs. 1 and 2), where previously reconnaissance samples were collected (KOS and CRN respectively, Lewandowski et al., 2009).

Both sections consist of redbed deposits, showing a variety of microfacies, differing in grain sizes and mineral assemblage, although unsorted quartz grains are predominant (Fig. 3). Reddish colour, including opaque minerals, is confined mostly to the matrix.

At the Košna site 103 drilled cores (25 mm in diameter) oriented with a geological compass have been taken from three parts of the section (KO – 12 m thick, KS – 9.2 m, KA – 14.6 m) with little change in bedding orientation for overturned bedding along the section (Fig. 2, Table 1; see Table 1 for comments on orientation of bedding planes). In order to compare palaeomagnetic directions obtained from differently oriented samples, an additional ten hand samples were collected at one segment of the KO sub-section (named KOH at the 3–5 m level of KO, Fig. 2, Table 1). In the laboratory from each KOH hand samples 7 to 12 cylindrical core samples were obtained (a total of 106 cylindrical samples).

At the Crne Grede site 24 cores were collected along a continuous section (CR – 20.1 m thick) with slightly varying bedding orientation along the section (193–200/64–86, Fig. 2, Table 1).

In the Košna conglomerates underlying the Košna section (named KPO) a total of 28 clasts were sampled for a conglomerate test (clasts are relatively large, many with diameter of more than 10 cm), mostly from sandstones and limestones within the overturned section with the bedding orientation of 18/72 (Fig. 2, Table 1). The variety of grey and reddish clasts of limestones, reddish sandstones and fine-grained conglomerates were sampled.

Magnetic susceptibility and anisotropy (AMS) of all collected samples were measured with KLY2 (Geofizyka Brno, Czechoslovakia), KLY3 (Agico, Czech Republic) and MFK1A (Agico, Czech Republic) susceptibility bridges prior to the further palaeomagnetic studies. The AMS tensor was calculated for each sample and mean AMS tensors were also determined for sites based on Jelinek's (1978) algorithm (with Anisoft 4.2 software package of Chadima and Jelinek, 2008). Some additional clustering algorithms were also employed to describe the grouping of the principal AMS axes (with Spheristat 3.1 software – Stesky and Pearce, 2010).

Magnetic mineralogy of selected samples was studied with several methods: Lowrie test (Lowrie, 1990) or continuous monitoring of SIRM and magnetic susceptibility upon heating as well as the hysteresis parameters (coercivity, coercivity of remanence, Mr/Ms). For Lowrie