Time relations of large scale displacements and internal deformations of tectonic units as manifested in paleomagnetic rotations, brittle structures and magnetic fabric

Final report of the K 105245 / K128119 project

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The project started on 1st January 2013 with a project number K105245. The host institution at that time changed from "Eötvös Loránd Geophysical Institute of Hungary" to "Geological and Geophysical Institute of Hungary". Due to a new re-organization the name of the host institution became "Mining and Geological Survey of Hungary" and based on a new contract, the project continued with the number of K 128119 from 01 July 2017.

The project was to terminate at the end of 2016, but prolongation till 31st December, 2017 was granted on 15th April, 2016, on a request dated 10th March, 2016.

The project proposed to obtain first-order constraints on the Cenozoic tectonic processes in the Carpatho-Pannonian region. To this end, we planned the evaluation and assessment of existing paleomagnetic, AMS and mesotectonic data as well as obtaining new ones in some areas of special interest. In the following report, the different types of research will be clearly distinguished, but the discussion of the results will follow the development of the project.

It has to be emphasized that the project benefited very much not only from the contributions of co-operation partners abroad, listed in the project proposal, but Michal Kováč (Comenius University, Bratislava) and Radovan Pipík (Earth Science Institute, Slovak Academy of Sciences, Banska Bystrica). The study of the Dukla nappe was the subject of the MSc thesis of Dániel Kiss (Kiss, 2015), rewarded by excellent mark.

Overview of the paleomagnetic results from the Western Carpathians (Márton et al., 2015)

The paleomagnetic results of several decades were critically evaluated in this paper. The assessment of the pre-Mesozoic data in the light of the post-Oligocene CCW rotation of the Outer Carpathian Magura and Silesian nappes, the Inner Carpathian area, including the North Hungarian Miocene volcanic field pointed to several problems to be solved. Some were out of the scope of our project, like the paleomagnetic and AMS study of the Hronicum which are in progress in Slovak–Hungarian–Polish co-operation. Those relevant to this project are e.g. the research carried out in the Paleogene flysch of the Dukla nappe (Poland), in the Miocene Orava basin at the boundary of the Outer and Inner Western Carpahians (Poland and Slovakia) and in the Miocene Turiec basin of the Inner Western Carpathians.

Time relations of internal deformation and large scale rotations in the Outer West Carpathians during the Cenozoic, Magura and Silesian nappes (Márton and Tokarski, 2016. Kiss et al., 2016)

The paleomagnetic and magnetic fabric (AMS) results from the Magura and Silesian nappes led to the conclusion that the first process was the strain-induced imprint on the sedimentary magnetic fabric, still in horizontal position. This was followed by the formation of the map-scale structures (folds). Some localities preserved the remanent magnetization acquired before folding, some were remagnetized after folding. However, both populations exhibit similar CCW rotation angles. This proves that the general CCW rotation characterizing both nappe systems post-dated the deformation manifested in the magnetic fabric as well as the map scale folds.

The Dukla Nappe is the easternmost one of the Outer Western Carpathians, situated in Poland between the Magura and Silesian nappes. It is characterized by imbricated thrusts and by the presence of olisthostromes. In addition to paleomagnetic and AMS measurements, anisotropy of the remanence measurements and mineralogical investigations were carried out on samples from nine, geographically distributed localities. The paleomagnetic results indicate that the studied part of the nappe participated in the general CCW rotation characterized by the Magura and Dukla nappes. The AMS lineations are connected to paramagnetic minerals and are interpreted as reflecting the extensional direction during deformation. The lineations of the magnetic minerals are poorly defined and are probably due to weak orientation during sedimentary transport. The most interesting result of the study is that bedding strikes systematically deviate from the AMS lineations measured for the same sampling locality. This deviation suggests that the flysch was first internally deformed, imprinting the AMS fabric. It was somewhat later, in the course of the CCW rotation, when the flysch acquired the tectonic strike which is a mesotectonic feature of the deformation.

Orava basin (Tokarski et al., 2016)

In this paper the success of a novel method was documented, which is the integrated application of fractured clast analysis (for regional stress reconstruction) and paleomagnetism. Orientation of fractures were measured in a large number of clasts, while paleomagnetic measurements were made on fine grained sediments from a number of localities of corresponding ages. Two populations were distinguished in the fractures. The angle between the two sets of fractures was about 30°, while most of the paleomagnetic localities exhibited a CCW rotation of similar magnitude. In our interpretation the basin underwent a 30°CCW rotation at about 8Ma, and the change in orientation of the stress field is only apparent. As the basin is considered by some as the NE termination of the Mur-Zilina shear zone, we interpret this rotation as connected to displacement along this zone.

Turiec basin (Márton et al., in prep)

The primary aim of the study was to tie the mudstones of a 100m long drill core SLPR-1 from the restricted Turiec Basin of Miocene age to the world-wide magnetic polarity scale. The suitability of the drill core material for this purpose was proved by means of the following main steps. First, the consistency of the paleomagnetic signal was documented within five long core segments. Next, the directions of the characteristic remanent magnetizations were defined in specimens drilled also from shorter segments. The core segments were then azimuthally re-oriented to each other using silt intercalations and/or the orientation of the magnetic susceptibility (AMS) ellipsoid. The paleomagnetic direction for the drill core was finally determined by fitting the general tilt of the drill core to the one measured close to the drilling site. The early diagenetic age of remanence of the drill core, carried by greigite, was proved by means of a positive regional tilt test involving SLPR-1 and a number of outcrops from the same formation and a positive "conglomerate test". The latter was based on re-deposited core material in the form of mud cakes between 9.60 – 14.60m of the core. Eventually, the results from the azimuthally un-oriented drill core samples became equivalent to the most carefully executed studies on outcrops.

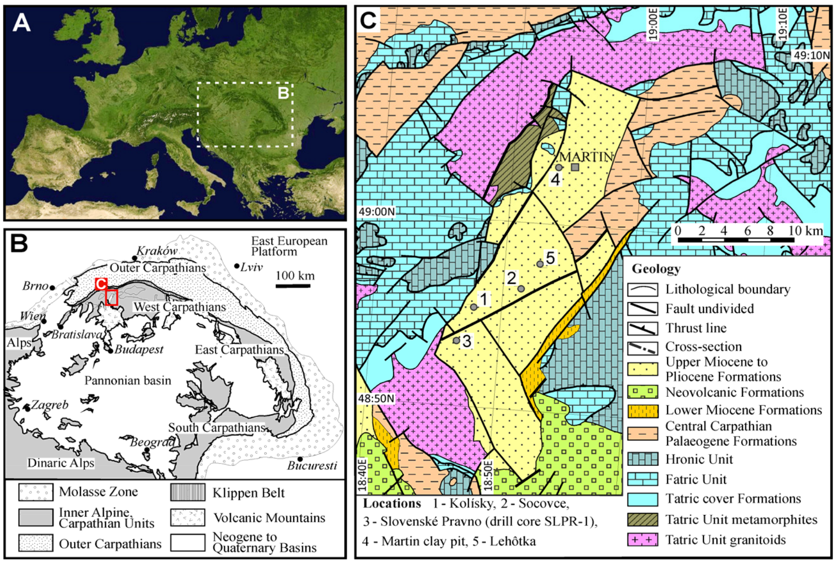

Fig. 1 Geographical position of the Carpatho-Pannonian region in Europe (A), of the Turiec Basin within Carpathian Orogenic Belt (B) and the geological map (modified after Bezák et al., 2004; Králiková et al., 2014) of the Turiec Basin and surroundings (C).

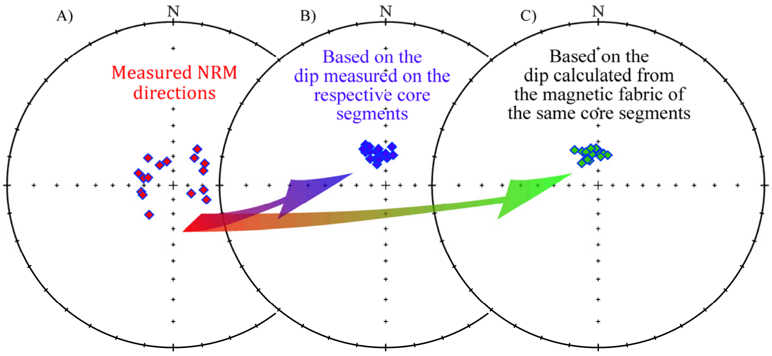

Fig.2. Drill core SLPR-1. Re-orientation of the paleomagnetic vectors to the dip azimuth of 280°, measured on the surface close to the drilling site from 16 segments of SLPR-1, containing silt intercalations. The scattered paleomagnetic directions (A) become tightly clustered on reorientation according to silt intercalations (B) and the magnetic foliation planes (C). After Márton et al. (2014).

As mentioned earlier, AMS considerably aided the reorientation of the azimuthally non-oriented segments of the drill core SLPR-1, since AMS foliation planes could be used as proxies for the bedding planes. In the 16 horizons where the bedding dip was expressed both by silt intercalation and well defined AMS foliation, the magnetic lineations (AMS maxima) also cluster close to the strike of the bedding plane. The magnetic fabrics of the outcrop localities (except one) also exhibit well clustered maxima and intermediate directions in the magnetic foliation plane and the maxima are sub-parallel to the respective tectonic strikes and to each other. As mesotectonic measurements suggest, the sedimentary fill of the Turiec basin was deformed in several extensional and compressional tectonic regimes and also affected by westward tilting (Kováč et al., 2011) after the deposition of the youngest sediment studied by us. The AMS fabrics observed in the studied localities suggest that they were imprinted before the tilting, i.e. in a horizontal position. The character of the deformation must have been compressional, as the strikes of the bedding tilts are close to the directions of the respective AMS lineations. The most likely phase of deformation imprinting the magnetic fabric should be very young, i.e. about 6Ma. At his time inversion in the South Pannonian basin took place, producing dominantly E-W oriented structures, due to N-S compression generated by northward moving Adria. The AMS lineations in the Turiec basin, however, suggest E-W compression, i.e. point to the influence of a local stress field on the basin fill. Concerning the problem of possible general rotation of the basin after the deposition of the studied Pannonian through Early Pliocene sediments, the mean paleomagnetic declination deviates 10° to the west from the present N, but considering the error angle, the deviation is not significant.

Transdanubian Range (Sipos-Benkő et al., 2014 OTKA project number is in the erratum)

The paper jointly evaluates the earlier obtained results of the magnetic fabrics (AMS) measurements and the markers of the brittle deformation affecting Eocene through Late Miocene sediments. The main results are as follows. As the AMS measurements suggest, the Eocene through Early Miocene clay-rich deposits suffered weak ductile deformation, and the direction of the extension shown by AMS lineations is aligned with the NNE-SSW extension during a strike-slip phase (30-19Ma) or with the NE-SW extension of the main rifting phase of the Pannonian basin (19-14Ma). It suggests that the ductile deformation and the following brittle deformation are closely related, i.e. the same stress field is responsible for both. The Late Miocene sediments do not show any sign of ductile deformation, but several phases of brittle deformation were identified between 10 and 4 Ma before the neotectonic strike-slip phase. This is a striking contrast to the same types of sediments in the south Pannonian basin where the AMS measurements documented widespread ductile deformation (Márton et al., 2012), even at localities where markers of brittle deformations were lacking. The reason may be the larger distance of the Transdanubian Range from Adria, which is responsible for the compressional deformation detected in the south Pannonian basin.

Paleomagnetic constraints on the mid-Jurassic – Eocene displacements of Adria (Márton et al., 2017) **and its relevance to the development of the Carpatho-Pannonian region**

The Transdanubian Range is defined as a tectonic unit of Southern Tethyan origin, closely related to Adria till its escape from between the Eastern and South Alpine region. It implies that the pattern of the apparent polar wander path for Adria and the Transdanubian Range should be similar up to the time of separation and different afterwards. The above publication, apart from extending the APW for stable Adria with new Jurassic results, critically evaluates earlier published data and constructs an APW based on those, which are coming from strictly autochthonous areas and are based on geographically distributed localities of similar ages. The important aspect of the new APW for the present project is the confirmation of a Late Cretaceous CW and the post-Eocene CCW rotation of Adria, with respect to Africa. The time of the latter is not constrained directly, but the CCW rotations measured in several areas of the circum-Adriatic region and the tectonic inversion in the Pannonian basin s.l. point to its being very young, around 5-6 Ma.

The problem of an earlier not defined extensional phase predating the first Miocene CCW rotation affecting the area N of the Mid-Hungarian Zone

In recent years extensive structural work was carried out in NE Hungary, partly in connection with this project, partly with OTKA 81530. It was found that deformation bands provided the most important information about the structural evolution, since they helped to discriminate deformation events at variable state of consolidation, i.e. during progressive burial. The earliest elements are dilational deformation bands, which record NE-SW extension during the late Oligocene, ca 25 Ma (Petrik et al. 2014). However, this indication occurred only at a single site, in an overall contractional setting of NW-SE compression (Petrik 2016). NE-SW extension was also observed in the Darnó Zone (Kis-hegy) as the earliest element (disaggregations bands), around 20.5-20 Ma (Beke 2016, Beke et al. in prep). In this site other type of bands and also brittle fractures, calcite veins were superimposed on the early event during successive evolution, between 20-18.5 Ma. One of these events can be connected to the escape tectonics of the Alcapa block. In this way, we can verify that extension preceded extrusion tectonics, at least in some parts of the Pannonian Basin. In other closely located sites extension was related to the Pannonian Basin formation from 18.5 Ma (Petrik et al.

2016). From these observations we infer that extrusion was preceded and followed by extensional tectonics. It is still to be evaluated how much of the pre-extrusion extension of this locally observed structures influenced large-scale basin evolution.

This evolution implies a slight CCW change of the maximal horizontal stress axes from NW-SE to WNW-ESE before rifting. This could also mean a slight clockwise rotation of rocks around 20 Ma if one assume stable stress field and rotation around vertical axes. Although, the pre-volcanic sediments seem to show somewhat smaller CCW rotations than the oldest volcanic level, the large statistical error, basically due to the small number of the sedimentary outcrops so far yielding results, prohibits regarding the difference significant. Obviously, additional paleomagnetic data are needed from sediments, which requires searching for suitable outcrops. Unfortunately, good paleomagnetic result can not be expected from the best structural sites due to the coarse grained nature of the deposits.

It is also a question if this succession of the above events could be projected to the Transdanubian Range, where we related all NE-SW extension to Pannonian syn-rift phase (Sipos-Benkő et al. 2014). In the light of north-eastern Hungarian data, it is possible that a similar, late Oligocene(?) to early Miocene extension, with identical stress axes, also occurred in the Transdanubian Range. This supposition can be supported by the fact, that the NE-SW extension was registered by AMS of the Oligocene sediments. It is logical to assume that this ductile deformation closely followed deposition, i.e. can be considered as active around 25 Ma, before the onset of the extrusion.

The problem of the punctuated or continuous character of the rotations in NE Hungary

In the Mátra Mts and in the Bükk Foreland the products of the Miocene silicic volcanism were sampled. The area is now in the focus of OTKA project K115472 and it is only the aspect related to this project which is reported here. The new results from several sites (some of them comprising several horizons of ignimbrites and tuffs) support the punctuated character of the rotations (Márton et al., 2018). They also permit to conclude that results obtained from strongly welded ignimbrites must be excluded from tectonic reconstructions due to extreme flattening of the inclinations, unless a method for correcting them is developed.

The method of stratigraphic correlation based on the combination of magnetic polarity and paleomagnetic declination was presented as a contribution to the geological features of the Ipolytarnóc area of the Bükk National Park (Márton, 2016).

The products of the Miocene silicic volcanism were also investigated from a different aspect. Photo-statistic and AMS method was combined in order to reconstruct paleoflow directions in the Keserűs Hill lava dome complex (Visegrád Hills) and thus prove the existence of a central edifice-topped syn-eruptive topography (Bíró et al., 2015).

Research of the Cenozoic in the South Pannonian basin (Lesić et al., submitted, Lesić et al., 2014) **and in the Dinarides** (Márton et al., 2016)

In **Serbia**, a large number of sites in Oligocene and Early Miocene volcanic and intrusive magmatic rocks were studied from the wider Rudnik and from the Kopaonik areas. Both areas are considered to belong to the West Vardar zone, but the wider Rudnik area is also regarded as part of the South Pannonian basin. The studied rocks were formed after the closure of the Vardar zone, yet they exhibit moderate, but significant CW rotation with respect to the present North. The rotation of the stress field direction in the above areas, mainly from mesoscale brittle deformation features would require CCW rotation. Thus our observations can not be interpreted as due to rotations of blocks bounded by faults within the West Vardar zone. However, CW rotations are observed E of the West Vardar zone, implying that the CW rotation characterizes a larger block and is connected to the opening of the South Pannonian basin.

In an attempt to obtain paleomagnetic constraints for the termination of the large-scale displacements in central and western **Serbia** (the area involved the northern part of the Rudnik-Kopaonik belt) we studied Badenian through Pontian sediments from 11 localities (Lesić et al., 2014, extended abstract). As the AMS measurement showed, the sediments could have suffered only weak deformation. The remanent magnetization was acquired after tilting of the strata, therefore providing information about possible rotations after the tectonic event responsible for tilting. This event took place during the Pliocene, and the main conclusion is that the study area did not rotate after the Pliocene deformation.

In the Pohorje and Kozjak Mts., Mura and Slovenj Gradec basins in **NE Slovenia** we applied combined methodology (measurements of AMS, the anisotropy of the remanence, mesoscopic an microscopic markers of deformation) to unravel the connection of different deformation elements. As the research progressed, results were presented at several conferences (Fodor et al. 2014, 2015a, b, c) and one summary paper, with the co-authorship of Slovenian co-operation partners is to be submitted to an international journal in the near future (Fodor et al. in prep). However, comparative analysis of the magnetic and mesoscopic fabric for a few sites was already published in Sipos et al. (2018).

From the above area we studied plutonic rocks, dykes and sediments of Miocene age. The obtained data depict a coherent deformation story. The Pohorje pluton was deformed just after emplacement, during imminent cooling by a dominantly extensional deformation field, at ~18.5-18Ma. First crystalplastic then brittle extension continued during cooling, up to ~15 Ma. The subsequent emplacement of different dyke generation occurred during the cooling path, from 18.2-17 Ma. Deformation style varied from ductile to brittle. AMS and ductile structural fabrics are sub-parallel. The markers of brittle deformation developed after the imprint of the magnetic fabrics. During the same time, sedimentation of the syn-rift suite started and the deposited, still unconsolidated sediments underwent extensional deformation, followed by brittle faulting during the progressive cementation. Finally, dacite dykes were intruded still in the same extensional field, but strictly in brittle regime. All these deformation happened before ca. 14 Ma, and are related to the syn-rift phase of the Pannonian Basin.

From the Miocene intramontane basins of the **External Dinarides**, we carried out paleomagnetic and AMS measurements on oriented samples collected in the Pag and the Drnis-Sinj twin basins. Following extension in the External Dinarides, the basins were filled with dominantly calcareous mud. Paleomagnetic results obtained by de Leeuw et al. (2012) from one section from each of the mentioned basins were interpreted as evidences for the absence of tectonic rotation after the deposition of the mud. We revisited the long Crnika section in Pag island, and documented, partly based on AMS results, partly on field observation of active slumping (the section was revisited after the AMS measurements revealing discrepancy between different segments of the section) that the paleomagnetic results from this section are unsuitable for tectonic interpretation. In the Drnis-Sinj basin, we collected samples from several outcrops of Miocene sediments, including gently tilted as well as strongly deformed strata (including a plungig syncline). Our results, based on remanences acquired before the Pliocene deformation, suggest 13-20° CCW rotation. It is an open question at the moment if this rotation is connected to major neotectonic zones or represent a displacement involving a larger portion of the High Karst zone.

Miocene basin evolution of the Western Carpathian–North Pannonian domain based on chronostratigraphic, stress field and paleomagnetic data (Kováč et al., 2017, 2018)

In recent years, important progress was made in the above research fields. Due to the enlarged data sets and reliable constraints on some events, it was possible to construct new palinspastic-paleogeographic and paleotopographic maps and relate the formations of basin depocentres to the CCW rotations of the ALCAPA Mega-Unit segments. From paleomagnetic point of view, the highlights are as follows. The openings of the basins started during the Early Miocene and lasted till the late Miocene in a roughly constantly oriented stress field and the present map view of the basins is due to significant amount of CCW rotations of different segments at different times, documented by paleomagnetic data. The most important features of the process are:

1. About 30° CCW “domino-style” rotation affecting the intramontane basins of the Eastern Alps (Márton et al., 2000)
2. The about 50° ”en bloc” CCW rotation of the crustal wedge built up from Northern Pannonian domain, from the Central Western Carpathians, from the Pieniny Klippen Belt and from the Outer Western Carpathians (Márton et al., 2015 and references therein)
3. During the Middle Miocene final stage of the collision of the Western Carpathians with the European Platform “domino-style” CCW rotations of about 30°, starting in the Northern Danube basin in the middle Miocene and ending in the Eastern Slovak Basin close to the Middle and Late Miocene boundary.

New statistical method (Sipos et al., 2018)

In the project proposal a new statistical method that shows the strength of correlation between the AMS and the stress axes of sediments with approximately identical ages was aimed. In general, the most probable AMS and stress tensors that explain the observed data should be retrieved from the measured data, including the confidence region of the solution. In mathematical terms, the inherently non-linear problem is solved via multiple linear equations over the equidistantly discretized space of candidate solutions. In this way the confidence intervals of the most probable solution can be accurately computed. This idea extended the classical methods of AMS data evaluation to nearly rotationally anisotropic data sets. Later it was further developed to establish a new, stochastic stress-inversion method for fault-slip analysis, which is free from ad-hoc optimality conditions. Similarly to the classical stress-inversion procedures, this new method is also based on the so-called Wallace-Bott hypothesis, but unlike the solutions in the literature, it provides statistical information for the data set, not just the principal directions of the best fit stress tensor are obtained.

The two methods above enabled us to introduce a new statistical framework for integrated evaluation of AMS data sets with fault-slip data. The integrated evaluation is particularly useful, when the available AMS and/or fault-stria data are scarce. It helps to study the transition of ductile-to-brittle behaviour of progressively cemented sediments or solidifying rocks, as this was demonstrated on real data sets collected in the Pannonian Basin. The evaluated data made it clear, that the integrated evaluation tighten the range of possible extensional direction and it can be used to decide about the deformational origin of the AMS data set.

Our results were presented at the international conference IUGG 2015 in Prague in the IAGA A10 section on 25th June, 2015 (Sipos et al., 2015). The method to evaluate nearly rotationally AMS data was published in (Sipos, 2014). The procedure for stochastic stress inversion and the integrated method was published in Tectonophysics (Sipos et al., 2018).

In the course of the above elaborations the principal axes of the AMS data were treated as strictly precise. In reality, they are handicapped by statistical errors. Therefore, it is necessary to set a limit to the errors permitted and filter the data accordingly. The automatization of this procedure have recently been solved by a computer program, written by Gábor Imre, which can be used in combination with the AMS measuring program used in the laboratory of the MBFH as well as the commercially available one (Anisoft, Chadima and Jelínek 2008, Chadima et al., 2018).

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