From post-rift phase to basin inversion – late-stage tectonic evolution of a major intra-plate shear zone of the Pannonian Basin

National Research, Development and Innovation Office (NKFIH/OTKA) project PD 104937

Final report

Aims

The beginning of the neotectonic period in the Pannonian Basin is considered to be the shift from the thermal subsidence of the post-rift phase to basin inversion and the onset of compression (Bada et al. 2007). Structural inversion started in the Late Miocene in the SW due to the pressure exerted by the Adria microplate and propagated towards the NE (Fodor et al. 2005). The shift between the stress fields was not instantaneous at any given location, instead it covered a relatively long time interval, when post-rift sag was interrupted by compressional events (Csontos 1995). The project aimed at investigating the initial period of inversion and the neotectonic events in uplifted basements blocks of the SW Pannonian Basin (Mecsek-Villány area), where syn-tectonic sediments were available and able to conserve signs of tectonic movements. The main points of the project were

- to identify tectonic events at the transition between the post-rift and inversion phases, and date them with the help of updated biostratigraphy and if possible, with radiometric methods;
- to temporally and spatially constrain flooding of the area by Lake Pannon, to distinguish climatic and tectonic effects in relative lake level changes;
- to date the change from general basin subsidence to uplift, and to relate this event temporally to the onset of detectable compression;
- to reveal the uplift history of the presently uncovered basement.

Progress, conformity with the research plan

The project was carried out generally according to the research plan. The temporal span of the project was extended with a year, partly because of difficulties with thermochronological measurements (previously unknown, unfavourable mineralogical composition of the target rocks and change in processing lab), partly because of the large amount of biostratigraphically important fossils found. A task carried out in addition to the original plan was the analysis of possibly seismically fractured clasts with Polish colleagues to gain information on otherwise undetectable Quaternary tectonics.

As planned, results were achieved in intense co-operation with various – mostly paleontologist and dating lab – colleagues and institutions. A doctoral student joined our department in Sept. 2015, the task of 3D GIS representation of the fault zone was transferred to her. As she missed a semester, this work stopped at an advanced stage for a while, thus will be finished outside the project's time span. In exchange, a more detailed model is expected to be created.

One considerable diversion from the budget plan happened during the project, adding unexpected major value to the exploitation of the project budget. A large amount of finances was spared due to free laboratory processing of thermochronology samples offered by colleagues in Germany and Poland. With the support of the Scientific Panels of the Council of Agricultural, Environmental, Ecological and Earth Sciences, this sum was used during the last year to buy one of the largest private collections of vertebrate fossils gathered mostly from Upper Miocene deposits of the Mecsek area, to save it from being sold abroad. This purchase secured the transfer of the material into a public collection; the fossils will be investigated in a next research project.

Results

Key methodology meant the integration of geological and geophysical data, from the surface and subsurface, including structures, sedimentology, paleontology and geomorphology. This resulted in a detailed picture of structural evolution of the area, discerning new deformation phases. A revised bio- and lithostratigraphy of the mostly littoral Pannonian sediments was compiled, what for the first time made it possible to tie dates to tectonic events instead of using the traditional categories of „Lower and Upper Pannonian" applied even in recent tectonic papers (e.g. Csontos et al. 2002, Konrád & Sebe 2010). The evolution history of the study area following the key aspects of the research plan is summarized here.

To analyse late Cenozoic burial and exhumation history, different low-T thermochronometers (apatite (U-Th)/He, apatite fission track, zircon (U-Th)/He) were applied to assess the uplift and partly the burial history of the Western Mecsek Mts., in combination with other thermal history data. Sampling happened along a longitudinal profile across the mountains; measurements were carried out at the Low-T Geochronology Laboratory at the University of Göttingen and at the Institute of Geological Sciences of the Polish Academy of Sciences. The results showed that the area underwent no major uplift during the late Neogene. The main, rapid uplift and exhumation happened in the Paleogene (Sebe et al. in prep a), in contrast with previous suggestions on a mid-/end-Cretaceous timing. In the old debate whether sedimens younger than Upper Triassic had ever existed in the Western Mecsek, thermal history calculations support the deposition and later denudation of these Mesozoic rocks.

At the beginning of the post-rift period the (post-)Sarmatian inversion (Horváth 2007) was the first important event. The studied fault zone (Mecsekalja Dislocation Zone, MDZ) thrust the basement onto the Sarmatian rocks (Sebe et al. 2015a) then – and/or possibly later, during the first part of the Pannonian. The inversion event affected the mountains and the foreland differently. Offshore sedimentation seems to be continuous across the Sarmatian-Pannonian boundary only in (sub)basin centres (like in the Hidas Basin in the Eastern Mecsek; Gelencsér 2016). Most areas show a hiatus, and unconformity increases towards the mountains: in contrast with uninterrupted sedimentation in the basin centres, while towards the mountains more and more is missing from the base of the Pannonian deposits and they become littoral. This may refer to large-scale folding during the Sarmatian inversion event.

Sedimentation – with open-water calcareous marls – resumed around 11-10 Ma in the transitional area between the Mecsek and Villány Hills (e.g. Székelyszabar; Sebe et al. 2015b) and in the immediate foreland of the Mecsek (e.g. Pécs-Danitzpuszta) (Rofrics et al. 2014, Csoma et al. 2016). The mountains remained subaerial until the latest Pannonian. Newly found macroflora indicated elevated topography near the lakeshore and warm climate (Hably & Sebe 2016). As a candidate for radiometric dating, a biotitic clay in the white marls was investigated and was proved to be pyroclastics; surprisingly, even its source could be identified in the Pásztori volcano now buried below the Little Hungarian Plain (Sebe et al. 2016a). The tuff, the source and the host sediments were dated with numerous methods, providing „absolute" ages as well (Fig. 1), which are very rare and much needed in the Late Miocene of the Pannonian Basin. The data did not provide a concordant picture yet but studies are continuing, including another tuff from the marls (from Nagykozár).

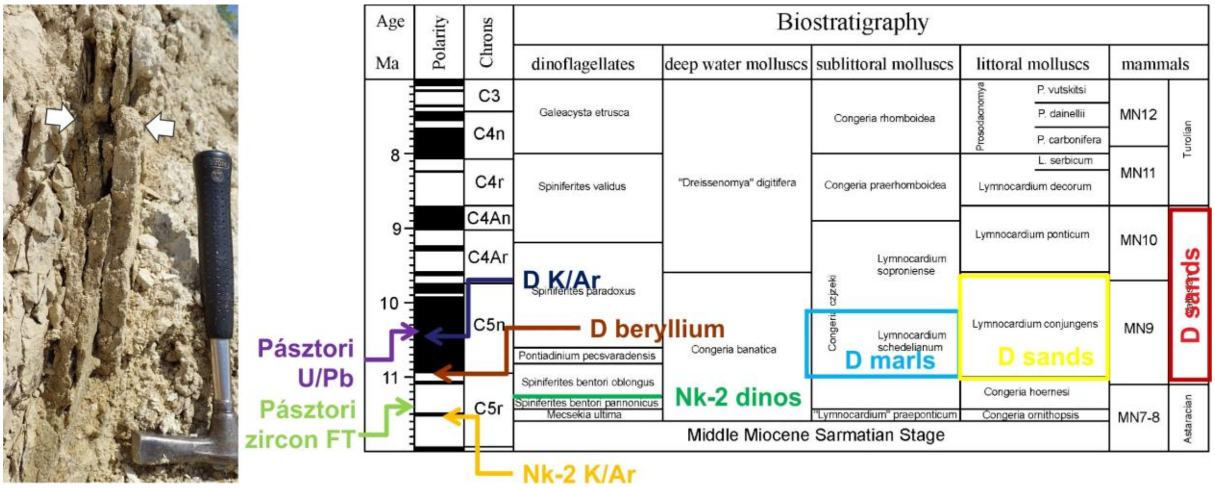

Fig. 1. Age data from and around the tuff layer at Pécs-Danitzpuszta (D), from the probable source (Pásztori volcano) and from a nearby tuff (from well Nagykozár Nk-2)

During the post-rift period generally characterized with thermal subsidence and plastic deformation (Horváth 2007), the MDZ was active and produced brittle deformation, similarly to the other important marginal fault zones of the area, like along the Northern Imbricates (N margin of Mecsek) or the Mórágy Block. Within the Late Miocene (Pannonian), at least three tectonic events can be distinguished, a transtensional and two compressional/ transpressional ones, where deformation was mostly localized along the mentioned fault zones. Seismic sections and borehole data illustrate well the different evolution history of the mountains and the foreland both in the northern and southern margins (Sztanó et al. 2015, Kovács 2016).

Signs of extension/transtension – normal faults and negative flower structures in coarse sands parallel with the MDZ – were only recorded in the oldest (11-10 Ma old) sediments

(Fig. 2). The deformed sands were dated to be much older than previously thought: thorough investigation showed that coarse sands follow the open-water calcareous marls conformably, and molluscs in both units belong to the same, above indicated time interval instead of the ~8 Ma age suggested by Kazár et al. (2007) (Sebe et al. 2015a). Compression (N-S) ensued already in the same biochron, before 10 Ma, causing strong deformation including syn-sedimentary tilting, angular unconformity and reverse faults (Fig. 2).

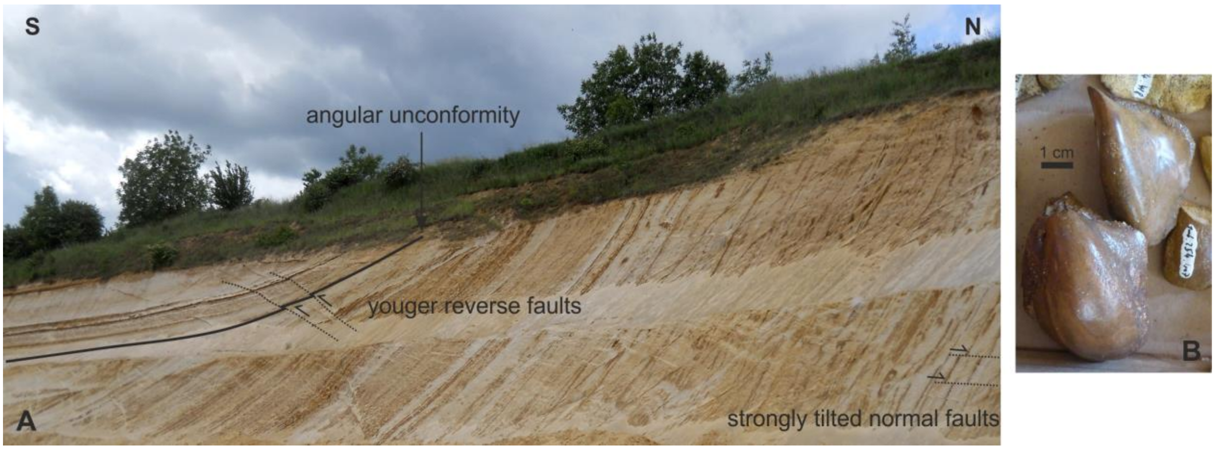

Fig. 2. Effects of tectonic events on 11-10 Ma old Lake Pannon sands (Pécs-Danitzpuszta) and some age indicator molluscs from the sand (*Congeria* cf. *pancici* and *C.* cf. *ungulacaprae*)

Spatially extensive biostratigraphic dating of littoral lacustrine sediments in the Mecsek area revealed that flooding of the mountains by Lake Pannon happened during a very short time period, practically coevally in the whole area, during the Prosodacnomya littoral mollusc biochron (8-6,5 Ma sensu Magyar & Geary 2012) (Sebe et al. 2013, 2016a, Budai et al. 2015, Sztanó et al. 2015, Kovács et al. 2016). It affected almost the entire mountains, except for maximum the highest peaks (Fig. 3). To decipher the roles of basinwide (climate-controlled) lake level increase and/or regional tectonics in a relative lake level rise of at least 300 m, a wider context should be considered. Since there are no signs of backstepping/flooding in e.g. the Transdanubian Range after 8 Ma (Sztanó et al. 2013), the basinwide lake level rise can be ruled out. Strong compressional tectonics of the period in the Mecsek area contradicts tectonic subsidence. As the mountain range is perpendicular to the progradation direction of the delta system (Magyar et al. 2013), a possible mechanism inducing submergence might be crustal flexure (downwarping) caused by loading of the sediments of the approaching delta. Sites where the relationship of locally sourced, transgressive deposits (Kálla Fm.) and sediments of the Alp-Carpathian delta system (Újfalu Fm.) is observable indicate that burial of the area by the delta system occurred shortly after the transgression (Budai et al. 2015; Sztanó et al. 2015; Nagy et al. 2016, in prep.; Kovács et al. 2016), and the mixing of the two types of sediment is also characteristic (Thamó-Bozsó et al. 2014). This supports the proposed idea; however, detailed calculations are needed in the future to decide whether this mechanism is feasible. GIS analysis of the spatial distribution of Pannonian lithostratigraphic units (Sebe et al. 2015b) revealed that sands of the Kálla Fm. overlie not only basement but also offshore Lake Pannon deposits (in the southern and northern foreland), thus they do not indicate simply transgression but an increase in erosion intensity and sediment transport into the lake.

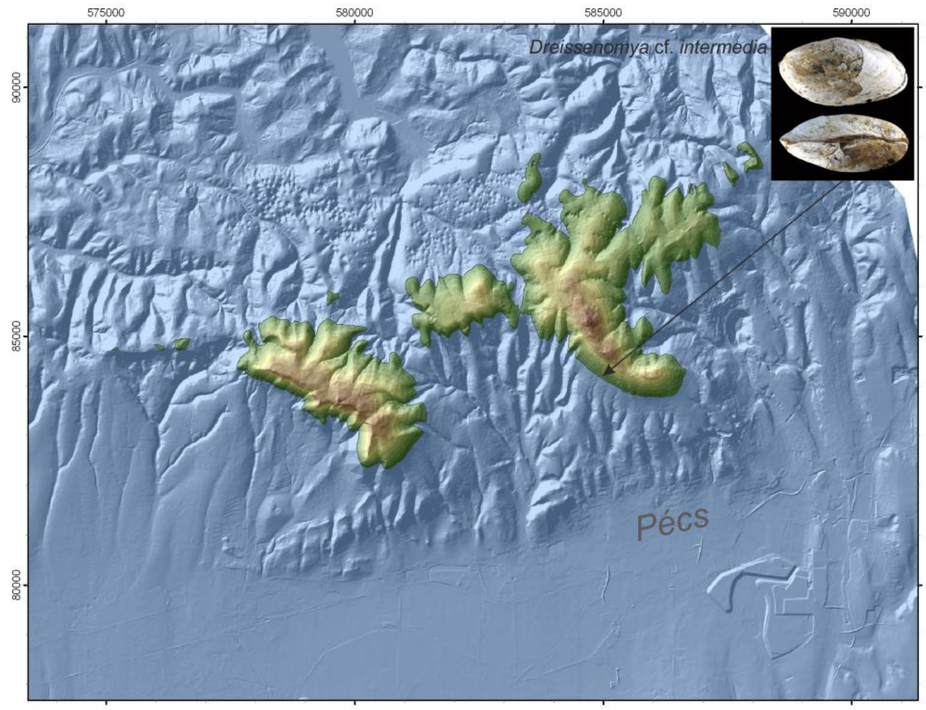

Fig. 3. Minimum flooding of the Mecsek Mts. in the Late Miocene (~7 Ma), with mollusc indicating age of the highest-lying littoral deposits

Shortly after the transgression, intense compressional (transpressional) tectonics started all over the study area, which can already be linked to the basin inversion (cf. Bada et al. 2007, Uhrin et al. 2009). It produced reverse and strike-slip faults, folding, tilting, thrusting of basement onto Upper Miocene sediments, uplift and erosion of hinterland blocks. From then on until the complete filling up of Lake Pannon in the area (~6,5 Ma, Magyar et al. 2013), a complicated interplay of relative lake level changes and tectonic movements, much more complex than in basin areas, controlled sedimentation, displayed e.g. in the reworking of Lake Pannon deposits or the alternation of littoral and sublittoral faunas (Fig. 4) (Budai et al. 2015 & in prep., Sebe et al. 2013, 2016a, Kovács 2017). Deformations seem to have been prolonged, with several generations of structures overprinting each other but still fitting into the same transpressional regime with roughly N-S aligned maximum horizontal stress. Observations highly support the statement of Horváth (2007) on the post-rift period being „most complicated and exciting", in the study area even more than in other parts of the Pannonian Basin. This can be attributed to its location in the SW part of the basin, close to the „Adria push".

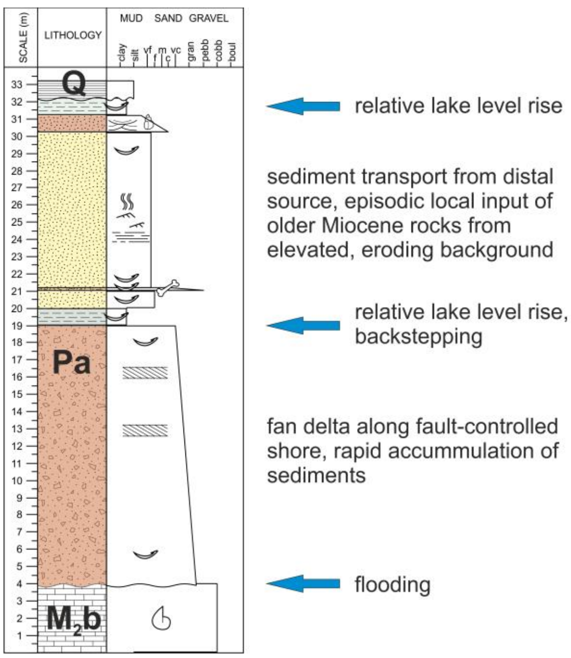

Fig. 4. Appearance of – tectonically and climatically controlled – relative lake level changes in the sediments along the S margin of the Mórágy Block (Himesháza)

Paleogeographic reconstructions for the Late Miocene revealed high relief and a rugged, often shifting, in several cases fault-controlled shoreline of Lake Pannon (Budai et al. 2015, Sebe et al. 2013, 2015b, 2016a, Sztanó et al. 2015, Hably & Sebe 2016, Kovács et al. 2016). After attempts to separate the impact of vertical tectonic movements and of lake level fluctuations on sedimentation and geomorphology, it was demonstrated that 1) surface fragments in the Mecsek had been erroneously identified as Pannonian wave-cut terraces; 2) given the similar pace of lake level oscillations and of vertical tectonic movements and the rapid formation of wave-cut terraces compared to the possible biostratigraphic resolution, terraces of Lake Pannon are not adequate to trace syn-sedimentary vertical tectonic movements (Sebe et al. 2013).

After the Pannonian, reverse and strike-slip faulting continued in the Mecsek area (Budai et al. 2015 & in prep, Sebe et al. 2016a, Kovács 2017). Though the stress field remained transpressional, the maximum stress may have turned into a more east-westerly orientation at least locally. Compression also resulted in lateral extrusion of basement blocks in the MDZ where topography allowed this (Ledő et al. 2013). Uplift of the Mecsek Mts. seems to have been less (a few tens of m-s to a few hundred m-s) than previously estimated (e.g. Hámor 1966). In the Villány Hills, the majority of the post-Pannonian uplift of the range must have happened in the first half of the Pliocene; by 3 Ma, the hills had been exhumed nearly to the same extent as they are now (Sebe et al. 2015c), and late Quaternary uplift rates are low (Szujó et al. 2017). The very low rates compared to the actively subsiding Drava Basin and to the Mecsek Mts. can be explained by the Villány Hills being located at a transitional position, at the inflexion line of large-scale folds in S Transdanubia proposed by Fodor et al. (2005). During the Quaternary, the Mecsek Mts. seem to continue slow uplift; however, deeply incised modern valleys can be at least partly results of repeated filling and re-incision during glacial and interglacial periods, respectively (Sebe 2013, Tokarski et al. in prep.). Quaternary landscape evolution is also (in some cases indirectly) fault-controlled at numerous places (Sebe 2013, Csillag et al. 2013), in accord with recent observations (Sebe 2009). The analysis of fractured clasts provided evidence of seismic shocks in the Mecsek during the Pleistocene, along the marginal faults and within the mountain (Tokarski et al. in prep.).

Public outreach, economic exploitation

As for economic exploitation, knowledge acquired during the project has already been applied during two state industrial research projects. It also turned out in the Eastern Mecsek that it is necessary to understand the structure of the area because undetected thrusting of basement rocks on the Miocene sediments can cause discrepancies in rock volume estimations of quarries. The results of the project can be used by water or hydrocarbon exploration in the area as well.

Emphasis has been placed on public outreach during the project. Field trips to Upper Miocene outcrops were organised for university and secondary school students. Using own material and that of the Komló municipal museum, an exhibition was installed at an elementary school in Pécs, where vertebrate fossils from Pannonian sediments were displayed, explained in poster and in a class presentation and the animals were reconstructed in origami by a pupil of the school (Fig. 5). The exhibition will be transferred to the university as well.

Fig. 5. Exhibition of Miocene fossils and their origami reconstructions at an elementary school in Pécs

Results from the project were integrated into university teaching materials; a new elective course was also launched in the topic. During the project several students were involved in research. The following student thesis and papers have been compiled:

BORBÁS E. 2014: A Pécs környéki felső-triász konglomerátumok vizsgálata (Study of Upper Triassic conglomerates around Pécs). Hungarian Student Scientific Competition (OTDK) paper, University of Pécs, 69 p.

BUDAI S. 2015: Hímesháza környéki pannóniai üledékek őskörnyezeti rekonstrukciója (Paleoenvironmental reconstruction of Pannonian sediments at Himesháza). MSc thesis, Eötvös Loránd University, Budapest, 77 p.

JANKÓ N. 2015: Miocén ősmaradványok a pécsváradi homokbányában (Miocene fossils in the sand pit of Pécsvárad). BSc thesis, University of Pécs, 45 p.

NAGY G. 2015: Késő-miocén molluszkafauna a Mórágyi-rög peremén (Himesháza) (Late Miocene mollusc fauna along the Mórágy Block). BSc thesis, University of Pécs, 36 p.

ROFRICS N. 2015: Pécs-Danitzpuszta késő-miocén molluszkafaunája (Late Miocene mollusc fauna of Pécs-Danitzpuszta). BSc thesis, University of Pécs, 37 p.

SZUJÓ G. 2015: A villányi Templom-hegy fedőhegységi üledékeinek szedimentológiai vizsgálata (Investigation of Cenozoic sediments at Villány, Templom Hill). BSc thesis, University of Pécs, 43 p.

GELENCSÉR K. 2016: A Hidasi-medence pannóniai üledékeinek vizsgálata (Pannonian sediments of the Hidas Basin). BSc thesis, University of Pécs, 55 p.

KOVÁCS Á. 2017: A Nagymányok környéki pannóniai üledékek vizsgálata (Pannonian sediments in the vicinity of Nagymányok). Hungarian Student Scientific Competition (OTDK) paper, University of Pécs.

NAGY G. 2017: Sekélyvízi pannóniai puhatestűek a Nyugat-Mecsekben (Littoral molluscs in the Western Mecsek Mts.). Hungarian Student Scientific Competition (OTDK) paper, University of Pécs.

The theses and papers all acknowledge the support of the NKFIH (OTKA) project. The results have partly been already published, partly are being prepared for publications.

Continuation of research

This project is continuing in the 4-year-long NKFIH project 116618 (Stratigraphy of the Pannonian Stage in southern Transdanubia, PI Imre Magyar) started in January 2016, which builds on the results of the PD project and places it in a regional context.

Based on the results and cooperation started during this project, a Croatian-Hungarian bilateral Science and Technology grant application was submitted in 2016 with Croatian colleagues aimed at the correlation and joint interpretation of Lake Pannon sediments across the border, in the Drava Basin and its margins.

To understand the Neogene evolution of the Mecsek-Villány region, it is necessary to know the Late Miocene-Quaternary history, to identify the events that must be „stripped" from the present-day scene to obtain an earlier Miocene view. The present project contributed to this topic. Then a step needs to be taken back in time. In fact, this project already included some view into earlier time intervals due to the reworked fossils and rocks present in Upper Miocene sediments. My next project plan is to study the pre-Pannonian Miocene of the Mecsek region from stratigraphical, paleogeographical as well as from structural geological points, in cooperation with paleontologist and geochronologist colleagues. Preparations for this have already begun, partly within the present project, partly independently of it (Sebe et al. 2015, Sebe et al. 2016, Jankó 2015, Gál 2016; the sampled Miocene tuffs being in the final phase of dating by Réka Harangi-Lukács; and Sr-dating of marine sediments by György Less). A major point in this project would be to identify and evaluate the Miocene vertebrate material of the area, which, though hardly known among experts, is of utmost international importance and its visibility in the scientific community should considerably be enhanced. A strong basis for this work is provided by the fossil collection bought during the present project. I plan to submit the new project application after a year's pause dedicated to the completion of 'in prep' articles, since there are still important results from the present project which deserve publication.

Pécs, 30th Nov. 2016

Krisztina Sebe, PhD
University of Pécs
Department of Geology and Meteorology

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