APPENDIX C

DETAILED RESEARCH PLAN

TECTOP-Hungary
Ongoing deformation pattern and tectonic topography in Hungary:
Active structures, seismotectonic habitat, river network development and dynamics of basin inversion

1. Introduction - state-of-art in neotectonic research in Hungary

Hungary, located in the central part of the Pannonian basin system, is a most adequate natural laboratory for active tectonic studies due to the availability of high-quality multidisciplinary data sets, and its peculiar tectonic history. Extensional basin formation within the Alpine orogenic belt started in the early Miocene, whereas structural inversion has been taking place since late Pliocene-Quaternary times (cf. Horváth et al., 2005). Basin inversion is related to changes in the regional stress field, from a state of tension that controlled basin formation and subsidence, to a state of compression resulting in fault reactivation, seismicity and a peculiar development of surface morphology (Horváth and Cloetingh, 1996; Bada et al., 1999; Gerner et al., 1999). Earthquake data indicate intense deformation in the vicinity of the contact zone between Adria and the Alpine-Dinarides orogen (Tóth et al., 2002). It has been also recognised (Bada et al., 2001,2005; Fodor et al., 2005, Horváth et al., 2005) that tectonic stresses are transferred into the interior of the Pannonian basin, resulting in a complex stress and strain pattern in Hungary (Figure 1).

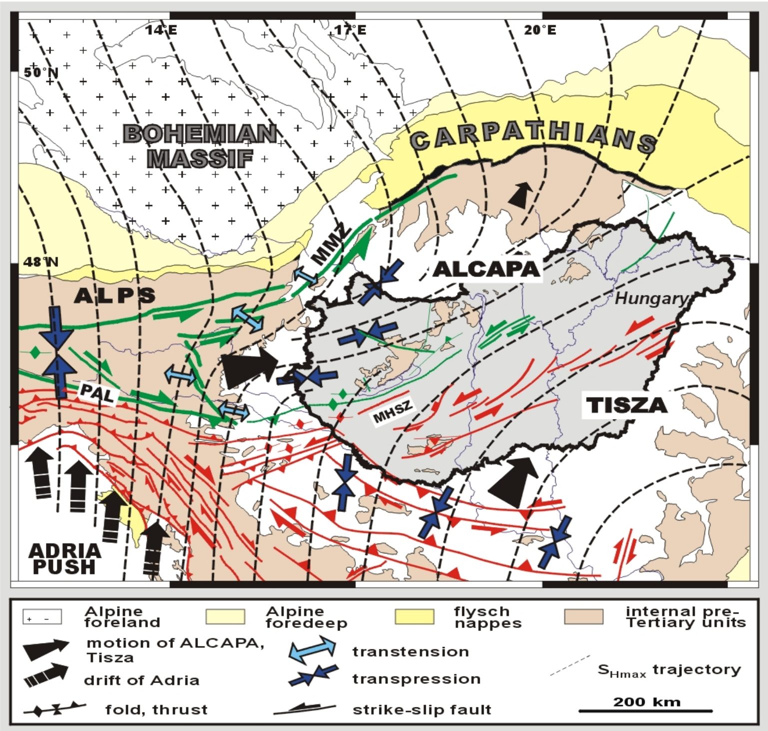

Figure 1 Contemporaneous stress and strain pattern in Hungary and surrounding areas (modified after Bada et al., 2001; velocity field after Grenerczy et al., 2005). Due to Adria push, crustal wedges are currently squeezed out from the axial zone of Alpine collision towards the hot, weak and thinned Pannonian lithosphere. The E-NE motion of the extruding ALCAPA block has a strong influence on the kinematics and spatial distribution of seismotectonic faults and the recent stress pattern indicated by S_{Hmax} trajectories. MHSZ: mid-Hungarian shear zone, MMZ: Mur-Murz-Žilina fault zone, PAL: Periadriatic lineament.

Due to intra-plate compression, the Pannonian lithosphere exhibits large-scale bending manifested in Quaternary subsidence and uplift that largely control the recent morphological features of the basin (Horváth and Cloetingh, 1996). The extended, hot, and hence weak lithosphere underlying sedimentary basins is prone to reactivation under relatively low compressional stresses, which argues for much more intense active deformation than hitherto assumed. The Pannonian basin has been interpreted as a well documented case of irregular lithospheric folding (Cloetingh et al., 1999), with a wavelength spectrum ranging from a few kilometres (local basin inversion) to hundreds of kilometres (whole lithospheric folding). Folding of the Pannonian lithosphere is often manifested in rapid differential vertical motions (i.e. co-existence of uplifting and rapidly subsiding areas in close vicinity) defining the overall landscape habitat and topography features in Hungary (Horváth and Cloetingh, 1996; Fodor et al., 2005; Ruszkiczay-Rüdiger et al., 2005a). The importance of late-stage compression and basin inversion for explaining anomalous topography and intraplate seismicity has been recognised, and a novel model for the structural reactivation of the back-arc type Pannonian basin has been developed (Horváth et al., 2005). Paleostress data (Fodor et al., 1999) indicate a characteristic temporal as well as spatial variation of both the stress and the strain fields. Accordingly, the structural styles in Hungary vary both in time and space, resulting in a complex pattern of ongoing tectonic activity (Bada et al., 1999).

In recent years significant national and international scientific efforts have been made for the analysis of active tectonic processes in Hungary and its tectonic environ, the Pannonian basin (see Appendices F1 and F4). The results obtained so far have demonstrated the key importance of recent crustal deformation, both in terms of seismoactive faulting and the remarkable differential vertical motions taking place during Quaternary through Holocene times. The present-day knowledge on the recent evolution of the Pannonian basin has been recently summarised in the form of a thematic map series, prepared in the framework of an OTKA project completed in this year (T03492). This project aimed at the synthesis of the available data and models on the present-day geodynamics of the Pannonian region. A geodynamic atlas with 9 thematic maps have been constructed depicting the most important geological and geophysical data sets relevant for the evaluation of neotectonic and active tectonic processes. The map series have been produced in a GIS platform, i.e. using layers of various databases in a uniform projection and co-ordinate system. Individual maps show crustal and lithospheric thickness, heat flow, gravity anomalies, seismicity, recent stress and rheology, morphotectonic features, neotectonic geological structures, and horizontal and vertical motions of the crust. Various elements of the atlas and related databases have been exposed and discussed in several scientific conferences and peer-viewed scientific journals. By the integration of a great variety of data, essential for active tectonic studies, the following main conclusions have been made:

1. The Pannonian basin is characterised by medium level of tectonic activity, in between the levels observed in the "active" Alpine orogen and the "passive" European foreland.
2. The Pannonian lithosphere is a subject of compressional tectonic stresses. As a result, the basin system has been actively inverting since late Pliocene - Quaternary times.
3. From the frontal zone of “Adria-push” in the Dinarides towards the interior of the Pannonian basin the dominant style of deformation gradually changes from pure contraction through transpression to strike-slip faulting.
4. Mechanical strength of the hot and extended Pannonian lithosphere is extremely low and, thus, it is prone to further deformation, structural reactivation and strain localisation.
5. GPS data indicate that contraction is taking place at an strain rate of about 4 ppb/yr averaged over the entire Pannonian basin.
6. Most active structures are controlled by the reactivation of pre-existing (Alpine) basement faults and shear zones. In the west, reverse faulting results mainly in folding of the overlying (Neogene to Quaternary) strata. Towards the east, the style of deformation becomes strike-slip faulting with either transtensional (local extension) or transpressional (local shortening) character.

7. Numerous (seismo)active faults can be identified in the Pannonian basin. However, their surface expression, exact geometry, mechanical properties and reactivation potential are ill constrained and, thus, rather obscure.

These conclusions are of crucial importance and they offer our main motivation for further neotectonic studies. The GIS based data sets behind the geodynamic atlas provide solid basis for such research. In addition, the pool of expertise in the selected research team ensures a most productive use of the accumulated data. All this can be seen as a warranty for a successful research programme. Our intention is to keep together the core of this team and to make a major step ahead together towards the reconstruction of the present-day 3D deformation pattern in the territory of Hungary. This can be achieved only by making additional dedicated research efforts, building on the results obtained so far, and by the efficient co-ordination of activities in various fields of geosciences. The details of our research plans are described in this proposal.

2. Principal scientific objectives

The principal objective of the proposed research programme is the quantitative analysis of active tectonic processes in the territory of Hungary, with an outlook to its wider tectonic environment, the Pannonian basin system. Mapping and quantifying the Quaternary to Recent 3D deformation pattern will be carried out within the framework of a coherent, process oriented research programme that will build on a fully integrated and multi-scale approach, both in time and space. The process oriented character of our research is essential as phenomenological observations alone, either obtained from the geological record (e.g. fault mapping) or based on historical records (e.g. seismicity), do not provide a complete assessment of active deformation processes. Research activities will aim at coupling processes operating on 3D lithospheric scale with those active at or near the Earth's surface. The close interaction and feedback mechanisms between neotectonics and surface processes will be also addressed. In order to focus on specific problems and to concentrate capacities, five fundamental research themes are identified. Each of these topics, addressing different aspects of the same processes, are considered vital in the analysis of active tectonic deformation. With the aid of a great variety of observation techniques, we will zoom in on selected study areas representing the most actively deforming parts of Hungary (Figure 2). The selected localities are situated in different morphotectonic domains, i.e. both in the uplifting and subsiding areas in Hungary. The difficulties in the identification and in the correlation of active geological structures between areas of different style and scale of deformation, call for methodical development in active tectonic studies, particularly in the uplifting and strongly eroded regions. Keeping in mind the above scientific ambitions and challenges, the following principal scientific objectives are defined in the framework of the following main themes:

1. Mapping of active structures: Methodology development and GIS based catalogue
2. Controls on fault reactivation: Tectonic stability and seismotectonic habitat
3. Active tectonics vs. hydrography: Tectonic controls on lake and river network development
4. Temporal aspects: Reconstruction of vertical vs. horizontal strain rates
5. Dynamics of basin inversion: Rheology and stress field in the Pannonian lithosphere

As the wider tectonic environ of Hungary, the Pannonian-Carpathian system, attracts considerable international interest, the presented scientific plans are well connected to ongoing European research programmes and aimed to serve as a good starting point for additional external funding. This is considered as an essential aspect (described in details in Appendix F4) to exceed the goals of the proposed project.

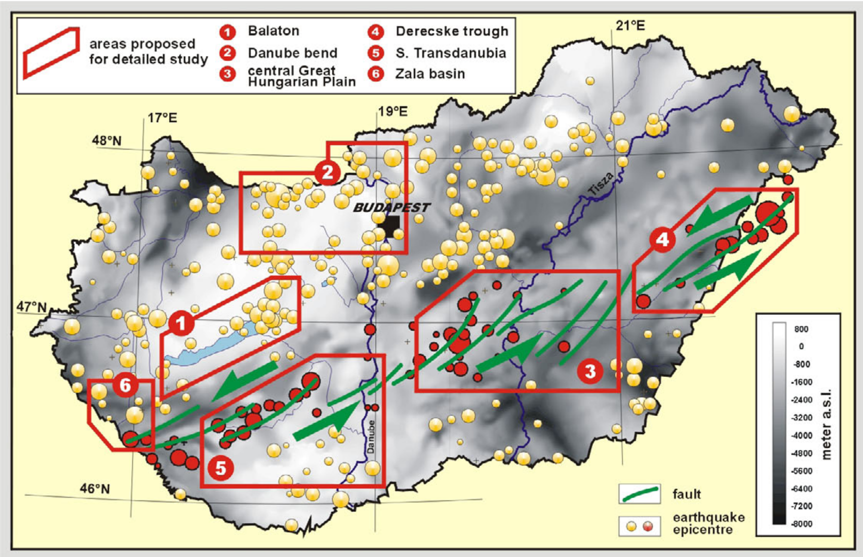

Figure 2 Pre-Neogene basement depth and seismicity in Hungary. The areas proposed for detailed tectonic analysis are indicated by numbering (see text). The NE-SW trending left-lateral (seismo)active fault zone, running through the central part of the country, is a main target of the project. Mapping the exact location of individual faults within this shear zone is of key importance. The indicated, yet tentative fault geometry is based on morpho- and seismotectonic considerations (in the west), and the interpretation of reflection seismic profiles (in the east). The orientation of some segments are quite tentative.

3. Research themes and methodology

In this section we provide the detailed description of the scientific objectives of the project by defining the related research themes and the applied methodology. The proposed areas for detailed tectonic studies, as well as the validation of site selection are also presented.

3.1. Mapping of active structures: Methodology development and GIS based catalogue

In the uplifting, western part of the Pannonian basin, including entire Transdanubia and the northern parts of Hungary, the identification, mapping and characterisation of active geological structures are often hampered by the absence of continuous syn-deformational Quaternary strata, or by the poor chronostratigraphic framework of the available alluvial and/or eolian Quaternary sediments. The problem is well illustrated on a seismic profile showing a young fault zone beneath lake Balaton (Figure 3a). The lake is located in the axial zone of the uplifting Transdanubia and is characterised by intense erosion and, thus, an unconformity and a major stratigraphic hiatus developed between the upper Miocene sequence and the overlying latest Pleistocene and Holocene mud of the lake. As a result, the exact age of faulting often cannot be determined, only a lower time bracket can be given (i.e. younger than 6-8 Ma). Locally, however, deformed Quaternary rocks and landforms can be observed. The faults on Figure 3a deform the gently folded upper Miocene strata and affect a thin layer of terrestrial sediments of likely Quaternary age. Given the strong seismicity in the direct vicinity of this fault zone (see Figure 2), this fault zone can be characterised as potentially active. Better conditions exist in the currently subsiding eastern parts of Hungary (Great Hungarian Plain), where the presence of the quasi continuous Pliocene through Holocene alluvial sequence of river Tisza and its tributaries allows precise dating of deformation (Figure 3b).

The general problem of the assessment of fault (re)activation due to poor time constraints can only be tackled by the application of a multidisciplinary approach, i.e. the involvement of a great variety of geo-information. It also includes the involvement of top quality imaging tools from various fields in geo-technology. In addition, a step from stand-alone phenomenological observations towards process oriented reconstruction of sub-surface geometries of active structures is also of utmost importance. Therefore, as a first step, we propose methodology development in the mapping of active geological structures, which will be subsequently tested in carefully selected target areas (Figure 2).

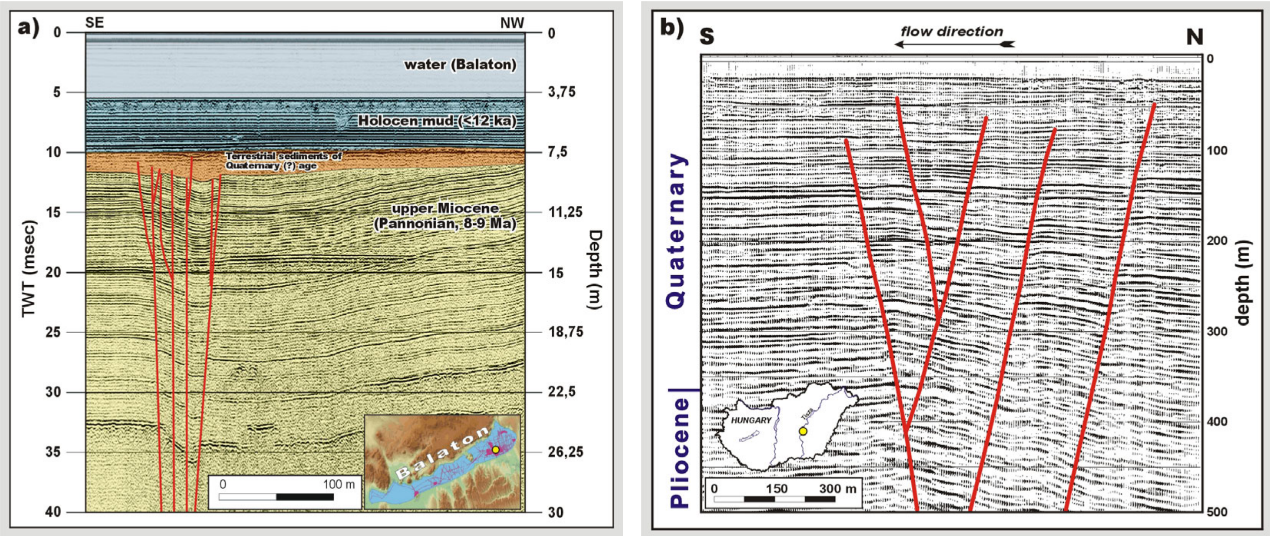

Figure 3 High-resolution reflection seismic profiles measured on (a) lake Balaton (unpublished) and (b) river Tisza (after Tóth and Horváth, 1998), and their structural and stratigraphic interpretation (study areas #1 and #3 in Figure 2, respectively). For location of profiles, see yellow circle in inserts.

Methodology development will be centred around the application of a multidisciplinary approach in a GIS environment. In the framework of this work package, large amount of available as well as new data will be employed to identify, map and characterise active and potentially active geological structures (folds and fault systems). The challenge of mapping faults in poorly exposed areas, characterised by dense vegetation and intense agricultural/urban land use, will be met by the integration of independent data including geological, digital elevation (DEM), remote sensing (monochrome, multispectral and radar scanners), geophysical (2D and 3D seismic, gravity, geomagnetic and geoelectric), seismological data and microtectonic observations obtained by structural geology methods applied in recent and Quaternary strata. Such complex integration requires the extensive use of GIS-based digital image processing tools under the supervision of tectonic experts in order to secure correct evaluation and weighting of the individual data. Active kinematics will be interpreted from overlays of the mapped fault patterns with existing geodetic data indicating active strain, and by using the existing models for past kinematics as guides towards the understanding of present deformations. The project will benefit from a wealth of seismological, geological and geophysical data, which are available for the territory of Hungary. These data include extremely detailed geological and tectonic data on the Miocene to Quaternary evolution, which may be regarded as a "guiding model" when assessing active tectonics. Detailed tectonic maps, kinematic data, strain and strain rates (fault offset and mean Miocene slip velocities), and paleostress databases will also be used. Main parts of the data to be analysed are in hands, whereas some others (industrial seismic sections, and borehole data) are accessible through the national database of the Hungarian Geological Survey.

Remote sensing, as a powerful tool for detecting recent vertical and horizontal crustal movements, will be also employed for the recognition of active structures. Since Hungary is a heavily populated country, with intensive agriculture land use, moderate climate and vegetation, conventional remote sensing data can be used in geosciences only after careful processing. The elimination of non-geological effects and the decomposition of these phenomena requires multitemporal, multispectral remotely sensed data. Pre-processing of raw images is essential for the efficient use of multitemporal data. Pre-processing will focus on geometrical correction (i.e. transforming aerial photography and high-resolution satellite imagery into map projection) and spectral correction (elimination of the effect of different illumination conditions, fog, haze from images). High-resolution

MODIS satellite imagery with 250 m ground resolution is received daily at Eötvös University Satellite Tracking Station, and will be used widely in the project for the characterisation of surface parameters. In addition, aerial photography and high-resolution satellite images will be also utilized, partly for the correction of existing digital elevation models (DEM), and partly for investigating landforms and micromorphology of the surface that are not affected by intensive agriculture.

Central in the project is the extensive use of reflection seismic profiles. Such high- to ultrahigh-resolution geophysical fault mapping, complemented with interpretations of available industrial seismic data will be carried out to (a) image sub-surface structures and deformation patterns in the youngest (preferably Quaternary) strata close to potentially active faults in order to confirm or reject current tectonic activity, (b) describe the 2D or 3D geometry of active fault systems, and (c) reconstruct the spatial and temporal evolution of sub-surface fractures. To optimize results in detecting active geological structures, the combination of three seismic profiling techniques will be used to image faults on different scales and in different depth. Available industrial seismic sections are essential to analyse tectonic features at greater depth, beneath approximately 300 m. As supplements, high-resolution multichannel and ultrahigh-resolution single channel seismic surveying will be carried out on rivers and lakes at carefully selected localities to image the architecture of the uppermost strata and to find the link between basement fractures and surface faults. This novel methodology offers two fundamental advantages. First, the underlying strata are imaged from right below the water bottom, in sharp contrast to land based seismics. This allows the interpretation of geological structures at the very top of the sedimentary sequences. This is a key in judging whether a fault is active and/or capable to cause surface rupturing. Second, it provides at least an order of magnitude higher resolution than standard on-land surveys. In the case of the multichannel survey, which provides 1-1.5 km penetration under favourable conditions, the resolution is 1-3 metres in the shallow part, and 5-10 metres at greater depth (Figure 3b). The single channel configuration, reaches 20-50 m penetration with an optimum resolution of 0.1 m (Figure 3a). The combination of different seismic profiles techniques offers an outstanding opportunity for high-resolution tectonic studies to accurately map the 2D or, preferably, 3D geometries of active faults. To complement available seismic data, additional acquisition, partly in international co-operation, will be carried out on lake Balaton (study area #1 in Figure 2), on river Danube (study area #2 in Figure 2), and on the Tisza and Körös rivers (study area #3 in Figure 2). These areas are selected on the basis of previous analysis that indicated sings of young (potentially active) deformation. In addition, the research team is in the possession of considerable seismic data from these areas, which will be integrated with the newly acquired data sets. Available industrial seismic profiles will be obtained from the Hungarian Geological Survey for all study areas. Seismic data will be processed and interpreted on state-of-the-art seismic workstations, and through the involvement of geological data (e.g. borehole data, digital maps, surface observations, etc.) and remote sensing information (radar images, satellite photometry, digital elevation models, etc.).

Besides acquisition and interpretation of high-resolution seismic data, seismogenic faulting and related active deformation will be constrained by the analysis of field exposures and, for selected sites, geoelectric sounding. At suitable sites, trenching across active faults will be used to quantify and date prehistoric seismic events. Such paleoseismic analyses at active faults with quantitative geomorphology, geophysical prospecting, shallow boreholes and trenching across the faults will be used to characterise the long term behaviour of seismogenic faults, and estimate the rate of deformation. In addition, morphotectonic investigations will be carried out to uncover the intimate link and feedback mechanism between active tectonics and lake and river network development.

As a major objective, a GIS based catalogue of active geological structures in Hungary will be created. To date, a parametric catalogue of active and potentially active faults in Hungary is not yet available. In this context, "parametric" means a set of various attributes, such as location, 3D geometry, age of activation, kinematics, slip rate and reactivation potential, often assigned with their probability character (certain, likely, probable, unknown, etc.). The catalogue is considered as one of the most important deliverables of the project, which will be first exposed in conferences and then published in international peer-reviewed journals. Finally, it will be made available as a public database on the Internet.

3.2. Controls on fault reactivation: Tectonic stability and seismotectonic habitat

In order to analyse the interplay between active tectonic processes and regional fault structures, numerical modelling will be carried out for the mechanical characterisation of faulting and folding, scaling relationships, and the interactions among faults. The principle aim is to determine the reactivation potential of the reconstructed active structures and, consequently, to assess the tectonic stability and seismotectonic habitat of different parts of Hungary. This analysis will improve the understanding of kinematics and dynamics of continental deformation, and the relationship between seismicity and geologic structures. In addition, it will provide direct input for subsequent seismic hazard assessment studies, which is considered as a an important aspect of the project. Our “fault-based” research strategy will effectively help to provide physically based estimates and predictions on the locations, magnitudes, recurrence times and temporal sequences of earthquakes. This “geo-logical” approach therefore provides a necessary complement to purely probabilistic methods, which are primarily based on earthquake catalogues and definitions of seismogenic areas.

After the catalogue of active structures (section 3.2.), has been created, their reactivation potential will be determined. 3D geometrical fault models give the opportunity to study the 3D pattern of forces acting along faults in the prevailing tectonic stress field (section 3.5.). Using these models, in combination with assumptions of the tectonic stresses around the fault, the shear and normal stresses at every location of the fault can be calculated. The calculated pattern of resolved stresses constrains the spatial pattern of fault reactivation: slip occurs in the direction of the resolved shear stress, provided it is larger than the frictional resistance of the particular fault segment (Jaeger and Cook, 1976; Wórum et al., 2004). This numerical approach, thus, allows to constrain the 3D pattern of fault reactivation. Taking advantage of the knowledge of the tectonic stress field, the ratio of the resolved shear and normal stresses (defined as slip tendency), as well as the direction of the shear stress is determined at every location on the faults modelled by triangulated surfaces. Although the calculated contact stresses represent only a first order approximation of real stresses, comparison of the 3D pattern of slip tendency with a realistic range of frictional resistance along the fault can provide useful constraints on the probability of fault reactivation. In other words, this method allows to delineate structural trends and fault arrays with high likelihood (hazard) of seismic fault reactivation. Besides, by resolving the direction of shearing along the faults will provide useful insights into the kinematics of faulting and the seismotectonic habitat of the specific area.

Coupling between field data and modelling enables quantitative testing and validation of elaborated tectonic concepts. Focusing on how a faulted volume reacts to applied stresses will, among others, help to quantify rheological fault parameters, which is a key to estimate (repeated) tectonic reactivation. Modelling aims at the qualitative and quantitative understanding of the latest episodes of tectonic evolution, the characteristics of the seismic cycle, and fault interaction in seismogenic regions. Understanding will be achieved in terms of stress magnitudes, strain rates, rheological strength distribution and fault properties. Given the 3D geometry and the specific rheological properties of proven active faults, predictions of potential earthquake hazard under the observed present-day stress field can be made. The implementation of the geometries of the crustal structures and fault systems, obtained from mapping and seismology, and of the rheological parameters of the crust-lithosphere system, obtained from independent tectonic modelling, will help to separate the coseismic, postseismic and aseismic components of the seismic cycle in the bulk deformation along active faults. Our integrated methodology will allow to model the pattern of stress accumulation and release during the seismic cycle and to characterise the style of fault interaction in the seismogenic region. The likelihood of reactivation along elements of the active fault catalogue will be, thus, a major deliverable of the project.

3.3. Active tectonics vs. hydrography: Tectonic controls on river network development

Topography is considered as an important expression and sensitive indicator of active deformation processes that are acting in a 3D space. Beside of some climatic and lithological effects, the topographic pattern is largely determined by the (paleo)stress field through tectonic deformation of rock masses. Deformational features are the subjects of (selective) erosional processes at the surface. Thus, topography will be an important sign of ongoing deformation. Tectonic processes form the surface in a cumulative manner, i.e. we observe the integrated effect of present-day deformation superimposed on past tectonic episodes. Due to the “memory" of topography, therefore, it is not a simple task to determine which features are due to the (sub)recent deformation and which ones are relict forms. To separate active deformation from the effects of ancient processes, sophisticated methods are to be applied to analyse morphology. In the last decade, the research team has worked out several methods that can help to solve this task. Digital geomorphic expertise in the evaluation of high resolution digital elevation models (DEMs) is of key importance. The visualisation and numerical processing of DEM data can show the effects of active tectonic processes in topography development. The shaded relief map in Figure 4 demonstrates how topographic analysis can reveal neotectonic control. In the Sió-Cinca area, south of Lake Balaton in central Hungary, the domain ESE from the southernmost red line is eroding by incision of a small valley system. Further to the NNW along the red lines (indicating subordinate faults) this process has just recently started implying the propagation and of the stress regime and active deformation further to NNW.

High-resolution topographic analysis will be carried out to analyse the intimate interplay between active tectonic processes and lake and river network development. The selected study areas (Figure 2) offer challenging targets to reconstruct the evolution of hydrography through time. Our landform studies will be centered around the morphotectonic analysis of available high-resolution DEMs. Additionally to the remote sensing database analysis (section 3.1.), these DEM-based morphotectonic studies will be carried out to investigate the geometry of river valley networks and the spatial variation of valley slope gradient. Quantitative geomorphology will also target the study of cumulative tectonic displacements by means of geomorphic markers (e.g., drainage pattern, slope distribution maps, river profiles, terraces, piedmont-mountain front junction profiles and active fault scarps). Radiometric age dating of geomorphic (surfaces) offsets will be carried out to assess the nature, pattern and rate of young vertical deformation.

In addition to morphotectonic investigations, the fractal analysis of the hydrography will be also carried out. The fractal structure of river networks seems quite obvious and numerous studies have been carried out in the last few decades to determine the self affinity of river networks. Adequate stream ordering techniques and the state-of-the-art GIS methods allows to prove the fractal characteristics of these features. Worldwide examples indicates that drainage networks tend to have a fractal dimension about 1.8-1.85, regardless of their scale. Such calculation will be applied to the Tisza drainage system. A key question is why rivers mould fractal trees, what the driving physical processes might be. With the aid of numerical modelling of these processes, estimates will be provided on how stochastic parameter, such as tectonics and climate forcing, influence drainage network development. This type of investigation, beyond providing a reconstructional tool, may as well be implemented the development of long term flood defence concepts.

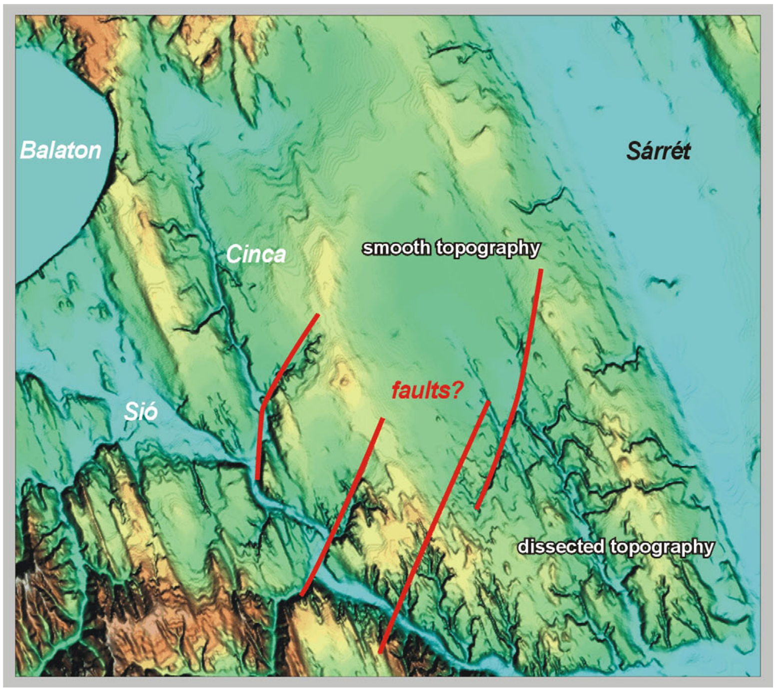

Figure 4. Shaded relief map of the hilly landscape in central Hungary, SE from lake Balaton, indicating signs of ongoing tectonic activity on the topography. Note the change of the style in the topography E of the easternmost red lines (active faults?) and the incision of short valleys further to the NW.

3.4. Temporal aspects: Reconstruction of horizontal vs. vertical strain rates

Besides the characterisation of active deformation, the quantification of recent strain and strain rates, both in the horizontal and vertical sense, is considered as an essential objective of the project. This information will be related to the geometry and reactivation potential of fault zone, which provide important constraint on how ongoing strain is distributed beneath Hungary, and on the mode and rates of deformation at the edges and within the crustal blocks constituting the Pannonian lithosphere. Preliminary data indicate active deformation rates in the centre of the basin system in the order of 1-2 mm/yr horizontally (Grenerczy et al., 2005), and 0.4-1.5 mm/yr vertically (Horváth and Cloetingh, 1996; Ruszkiczay-Rüdiger et al., 2005a,b).

To estimate the direction and rate of ongoing horizontal deformation, the results of GPS monitoring campaigns, carried out over the last 15 years, will be used. The Hungarian GPS Geodynamic Reference Network (HGRN) was established in 1989 and monumented in 1990-91. In order to obtain high precision GPS data for crustal deformation monitoring, carefully designed GPS campaigns have been carried out. Selection of the appropriate period for the measurement campaigns, number and length of sessions, receiver and antenna distribution and other parameters are of basic importance. Except for the first two HGRN campaigns, three times 24 hours in the summer season are observed. Measurements have been performed annually since 1991. From the HGRN95 campaign on, the campaigns were all carried out with 3 times 24 hour daily sessions simultaneously at all HGRN stations, and from 1999 at two more Frame Network sites as well. For data processing the Bernese GPS Software (version 4.2) is routinely used. In order to describe the accuracy of the positions obtained, RMS repeatabilities, based on daily coordinate estimates, are calculated in all three coordinate components. Accuracy of positions proved to be generally 1-2 mm in the horizontal direction, based on the RMS daily repeatabilities. Given the long time series of GPS data, HGRN provides a very reliable framework for crustal motion monitoring, at an average significance level of about 0.5-1 mm/yr. The obtained high-accuracy GPS velocities will be used to determine the overall horizontal velocity field in Hungary. This will be complemented with the map of active structures (section 3.1.) and the map of the released seismic energy (section 3.2.) to determine how strain is distributed over the country and to pinpoint the most actively deforming areas. In addition, strain rate data will be used to constrain the modelling results on the rheology of the lithosphere and the recent stress field (section 3.5.).

Unlike horizontal strain rates, the amount and rate of vertical motions can be assessed mainly on the geological time scale. In general, the territory of Hungary can be divided in uplifting and subsiding areas. Neotectonic deformation is connected to the uplift of vast regions, mainly in Transdanubia and northern Hungary. These uplifting areas underwent complex denudation processes, combined with local terrestrial sedimentation. In consequence, Quaternary deformation and landscape development have been intimately linked, and these processes can be reconstructed only in a combined way. Active surface uplift results in erosion and the formation of various landforms. Dating of these landforms of various age can result in high-resolution, step-wise reconstruction of uplift history and denudation processes. The combination of exposure and burial age dating using cosmogenic isotopes (He, Ne, Be, Al) and low-temperature geochronology (fission track and (U-Th)/He systems), the U-dating of cave formation will provide important constraints on the uplift and thermal history, and surface development in Hungary. The quantification of vertical motions and erosion rates has been started in the framework of international co-operation, supported also by OTKA (project #F043715). Exposure age dating of strath terraces in the Danube bend at Visegrád suggest ~1.6 mm/yr incision rate for the last ~270 kyr (Ruszkiczay-Rüdiger et al., 2005a). This surprisingly high deformation rate is supported by the preliminary age data from correlative Danube terrace sediments, obtained also by cosmogenic isotopes. Our intention is to continue with further dating studies in the Zala basin, SW Hungary (study area #6 in Figure 2). This area has undergone continuous folding and related surface uplift since early Pliocene times. Borehole samples will be analysed by means of fission track and (U-Th)/He measurements to reconstruct the final episodes of thermal history. Age of cooling of the Miocene strata, to be further constrained by modelling of heat flow, maturation and erosion history (the latter determined by exposure dating), will give the time path of vertical motions, i.e. both the magnitude and the rate of net uplift during basin inversion. In addition, with the aid of seismic sequence stratigraphy analysis, the amount of erosion will be also determined. The combination of uplift and erosion rates will serve as input data for subsequent landscape evolution (river network development) modelling (section 3.3.).

The uplifting regions surround the Great Hungarian Plain to the east, which show considerable Quaternary subsidence and ongoing fluvial sedimentation. Sediment accumulation fully covers older landform and, thus, the applicability of morphotectonic methods is limited. Instead, the dating and/ astronomical calibration of the continuous Quaternary strata offer the opportunity for the reconstruction of accommodation space through time. With the aid of modelling studies, this allows the separation of the tectonic vs. compaction driven component of surface subsidence. The analysis will provide approximate vertical strain rates on the geological time scale, i.e. for the late Pliocene - Quaternary period. These values will be jointly analysed with the obtained uplift rates from

Transdanubia, and will be together interpreted as differential vertical surface motions.

3.5. Dynamics of basin inversion: Rheology and stress field in the Pannonian lithosphere

Forward basin modelling shows that an increase in the level of compressive tectonic stress during Pliocene-Quaternary times can explain the first-order features of the observed pattern of accelerated subsidence in the centre of the Pannonian basin, and uplift of the basin flanks at peripheral areas. Therefore, both observational data (Horváth et al., 2005) and modelling results (Horváth and Cloetingh, 1996) appear to confirm that compressive stresses can cause considerable amount of differential vertical movements across the basin/orogen system. Possible sources of compression have been investigated by means of numerical modelling (Bada et al., 2001). The state of recent stress and deformation in the Pannonian basin, particularly in its western and southern parts, is controlled by the complex interaction of plate boundary and intraplate forces. These are the counterclockwise rotation and northward indentation of the Adriatic microplate (Adria push) as the dominant source of compression, in combination with buoyancy forces associated with an elevated topography, and crustal as well as lithospheric inhomogeneities along the Alpine, Carpathian and Dinaric orogens.

Besides the proposed fault reactivation studies (section 3.2.), the relation of tectonic stresses and the resulting strain field will be analysed through the rheological modelling of the Pannonian lithosphere. In view of its rheological structure, the continental lithosphere can be regarded under certain conditions as a two-layered visco-elastic beam. The response of such a system to the build-up of tectonic stresses depends on the thickness, strength and spacing of the two competent layers, on stress magnitudes, the strain rates and the thermal regime. As the structure of continental lithosphere is heterogeneous, its weakest parts start to yield first once intraplate stress levels reaches their strength limit. This leads strong strain localisation, which is indirectly linked with deformation at or close to the surface, i.e. the main target depth of the proposed project. In other words, modelling of the rheological behaviour of the deforming lithosphere will aid the understanding and quantification of active tectonic processes. The knowledge of present-day lithospheric dynamics is rapidly growing due to high spatial resolution in quantification of earthquake hypocenters and focal mechanisms, and surface vertical motions and horizontal strain. The time integrated approach, to be applied in our project, will allow to access in detail the geological memory of lithospheric properties on present-day geodynamics, which is a key parameter influencing present-day deformation. This way the gap can be bridged between historic and geological time scales in analysing lithospheric deformation response.

Pronounced lateral heterogeneities exist in the mechanical properties of the European lithosphere (Cloetingh et al., 2005). Large-scale modelling indicates that the Pannonian basin, mainly due to its increased heat flow and attenuated lithosphere, appears to be one of the weakest parts of the European continent, though displaying pronounced lateral as well as vertical variation (Figure 5). The basin system appears to be an area of pronounced lithospheric weakness since Late Cretaceous on, shedding light on the high degree of strain localisation in this region. A marked contrast in recent rheology between the Pannonian basin area, the surrounding Carpathian orogen and the foreland lithosphere is directly related to crustal configuration and thermal properties. Pre-existing structures and pre-rift rheology of the lithosphere play a key role in basin formation and subsequent deformation, explaining anomalous features in subsidence characteristics and inferred thinning factors.

Building on previous modelling studies (c.f. Lankreijer, 1998), our main objective is to calculate the integrated mantle and crustal, and as a sum, the whole lithospheric strength for the Hungarian part of the Pannonian basin system in a dense, uniform grid. As the mechanical strength of the lithosphere is mainly dependent on its thermal conditions, calculations will be supported by the top quality thermal database (heat flow, geotherm, etc) available at the hands of the research team (c.f. Dövényi and Horváth, 1988). Geometric constraints on the lithosphere (depth of Moho, thermal layers and base, etc.) will be adopted from earlier basin-scale studies (c.f. Horváth, 1993).

In addition to the estimates on the rheology of the Pannonian lithosphere, information on the present-day stress field will be used to analyse the recent strain pattern in Hungary. Do date, more than 700 entries have been included in the stress database, updated regularly by members of our research team, which provides one of the highest resolution data coverage in Europe. Numerical modelling will target the interplay and casual relationship between the stress and strain fields through the estimated rheological properties of the crust/lithosphere system. Our main objective is to understand and quantify the dynamics and kinematics of deformation, the transfer of stresses and strain into the interior of the Pannonian basin (Hungary) generated by the deformations active at the system boundaries. Lithospheric and crustal folding and the near surface expression of deformation in terms of active faulting, horizontal contraction, and surface deformation are also key targets. Through this our main objective is to better identify sources of the rather complex contemporaneous stress field in the system, which shows significant lateral as well as vertical variations. Numerical modelling of the present-day strain field will be tested against the latest results of space geodesy (GPS - section 3.4.), which will add valuable constraints for system models, which have great amount of intrinsic uncertainties.

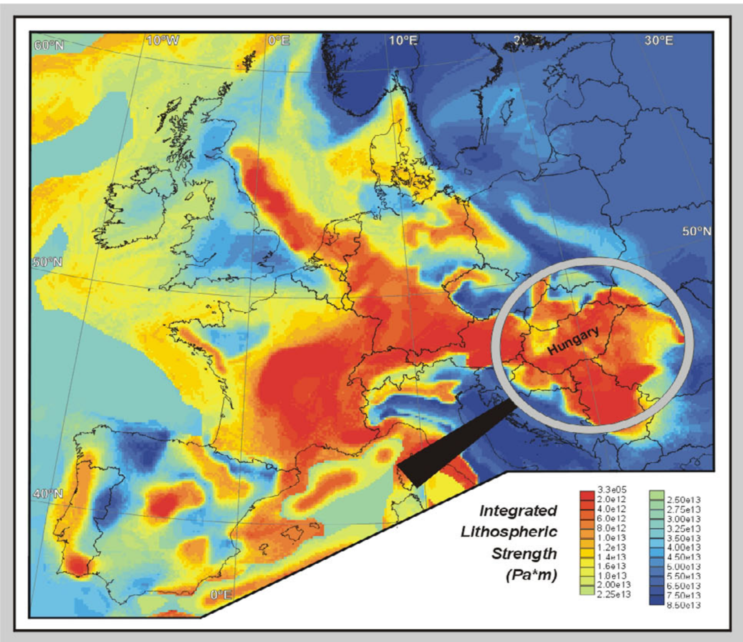

Figure 5 Integrated lithospheric strength of the European continent, based on depth-dependent rheological calculations. Note the high strength differences between the weak Pannonian basin (vicinity of Hungary) and its surroundings. Within the framework of the proposed project, we will zoom in this area to better constrain the thermomechanical parameters of the deforming Pannonian lithosphere.

4. Societal aspects

Active crustal deformation in Hungary has generated great scientific interest and attention in recent years. Research activities, on national as well as international level, have led to the growing recognition of the increasing societal importance of neotectonic and related landscape-forming processes. Understanding and quantifying related natural hazards, such as earthquakes, slope instability, and flooding in the vulnerable environment of Central Europe is a serious challenge for the scientific community. Besides hazards, however, active deformation and basin inversion can for instance result in a better prospect for the petroleum industry. The diversity of neotectonic processes in Hungary and the evaluation of their societal impact require sensible and careful analysis. Geoprediction in this actively inverting sedimentary basin requires a multidisciplinary approach and, therefore, the interaction and collaboration of researchers from a significantly broader field of geo-expertise than hitherto considered. One of the main challenges is to understand the solid Earth as a dynamic system by improving the quantification of recent lithospheric deformation and the controls and feedback mechanisms of neotectonic processes. This is a prerequisite for a proper response to the needs and safety of humanity in this vulnerable environment.

In the framework of the proposed project, our research team will make an attempt to contribute to the understanding of the numerous societal aspects of active tectonic processes in Hungary (Bada et al., 2005). In this context, our target deliverables (see section 5.) will provide input for quantitative seismic hazard assessment and tectonic stability studies of crucial facilities (waste disposal, power plants, urban facilities, etc.). Identification of areas of active subsidence in the light of flood defence strategies is of key importance. In regions of ongoing surface uplift, combined mapping of active or exposed (older) faults and areas of high topographic gradients will provide input for delineating zones of increased slope instability. Active tectonic processes also strongly influence the habitat of natural resources (water and hydrocarbons). All these aspects give an essential societal context for the proposed project, which will be evaluated and disseminated as a final task.

5. List of expected key deliverables

- Improved methodology in mapping of active geological structures, using a multidisciplinary approach in GIS platform. Testing of improved methodology in selected target areas.

- A parametric catalogue of active and potentially active geological structures (mainly faults and fault zones). Parameterisation will include location, 2D and 3D geometry, age of activation, kinematics, slip rate, reactivation potential, and will be assigned with probability character.

- Tectonic stability in various parts of Hungary in terms of the reactivation potential (slip tendency) of the reconstructed (active) fault pattern. (Re)located earthquakes on selected active faults. Identification of faults with high earthquake potential/seismic slip probability, characterisation of seismic/aseismic slip along active faults.

- Reconstruction of active tectonic control on lake and river network development in selected localities.

- Reconstruction of Quaternary to present-day horizontal and vertical crustal deformation, including estimation of absolute motions and strain rates.

- Strength map of the Pannonian lithosphere (crustal, mantle and whole lithosphere rheology). Supplemented earthquake focal mechanism solutions and in-situ recent stress orientations. Reconstruction of the dynamics and kinematics of basin inversion through modelling.

- Evaluation of the societal relevance of active deformation processes in Hungary.

6. On the composition of the research team

Our consortium is in a leading position in neotectonic research in Hungary as well as on international level, as evidenced by the personal achievements of the research team (see Appendices D1 and D2). Members of the research team have been selected on the basis of their scientific achievements on one hand, and by the individual skills in order to achieve an optimal pool of expertise for the successful implementation of the project objectives. Complementarity of expertise in the scientific consortium is considered as a major asset.

The co-ordination of the project will take place at the Dept. of Geophysics at the Eötvös L. University (ELTE). This unit has a proven record of high-quality research in the field of neotectonic studies in the Pannonian basin. The Dept. of Geophysics has the expertise to integrate various disciplines in the field of high-resolution geophysics e.g. acquisition, processing and tectonic interpretation of high-resolution seismic data, structural geology, neotectonics, seismic hazard assessment, gravity and geothermal studies, and basin modelling techniques. The Department, partly financed from OTKA funds (projects #F043715 and #T047104), has also built strong positions in the field of landscape evolution research, i.e. river network development and reconstruction of uplift and denudation paths. In addition, remote sensing, through the Space Research Group, also constitute to the core business of the Department. The principal investigator of the project, Prof. F. Horváth, head of Department, is an internationally acknowledged expert in integrated basin studies. He has over 30 years of experience in basin analysis, plate tectonic reconstruction, the analysis of active and neotectonic processes, the reconstruction of stress and strain in the lithosphere. He participated in and led numerous international research projects and consortia, many of them sponsored by OTKA and the European Union. As a result, the various working co-operations with external institutes and organisations make the Dept. of Geophysics strongly embedded in the European streamline of science. The excellent working co-operation with top European scientific institution will ensure the high quality of the proposed research on one hand, and the involvement of external funding. All these aspects are considered essential for the successful implementation of the project (see also Appendix F4 on international co-operation). In the framework of the project, the full-time employment of a post-doc researcher seems necessary. The candidate, Dr. G. Bada, has the intention to return to Hungary and bring home the expertise and international contacts accumulated during his post-doc fellowship at the Vrije Universiteit Amsterdam, the Netherlands over the last few years. In this position, he has been investigating active tectonics and landscape development in the Pannonian basin system. He has worked on the reconstruction of the present-day and paleostress fields and numerical modelling of lithospheric stress and deformation. This includes geodynamic problems, fault behaviour and gravitational stresses. In addition, he holds expertise in the reconstruction of deformation history, analysis and mapping of active structures, structural interpretation of seismic data and stability and seismic hazard assessment of key industrial facilities. Finally, we consider the involvement of talented PhD students in the research programme as a great value, which gives an essential educational component to the project.

Besides the Dept. of Geophysics at ELTE, the involvement of two additional research units seems crucial. The Seismological Observatory at the Hungarian Academy of Sciences has wide experience with the design and operation of seismic monitoring networks. Earthquake data from high-sensitivity networks will be an essential input for the proposed research. Similar is the case with the FÖMI Satellite Geodetic Observatory, which is co-ordinating repeated GPS campaigns for the study of present-day crustal motions in the Pannonian region. The obtained recent velocity field is of key importance and is considered as a major contribution for the reconstruction of active tectonics.

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