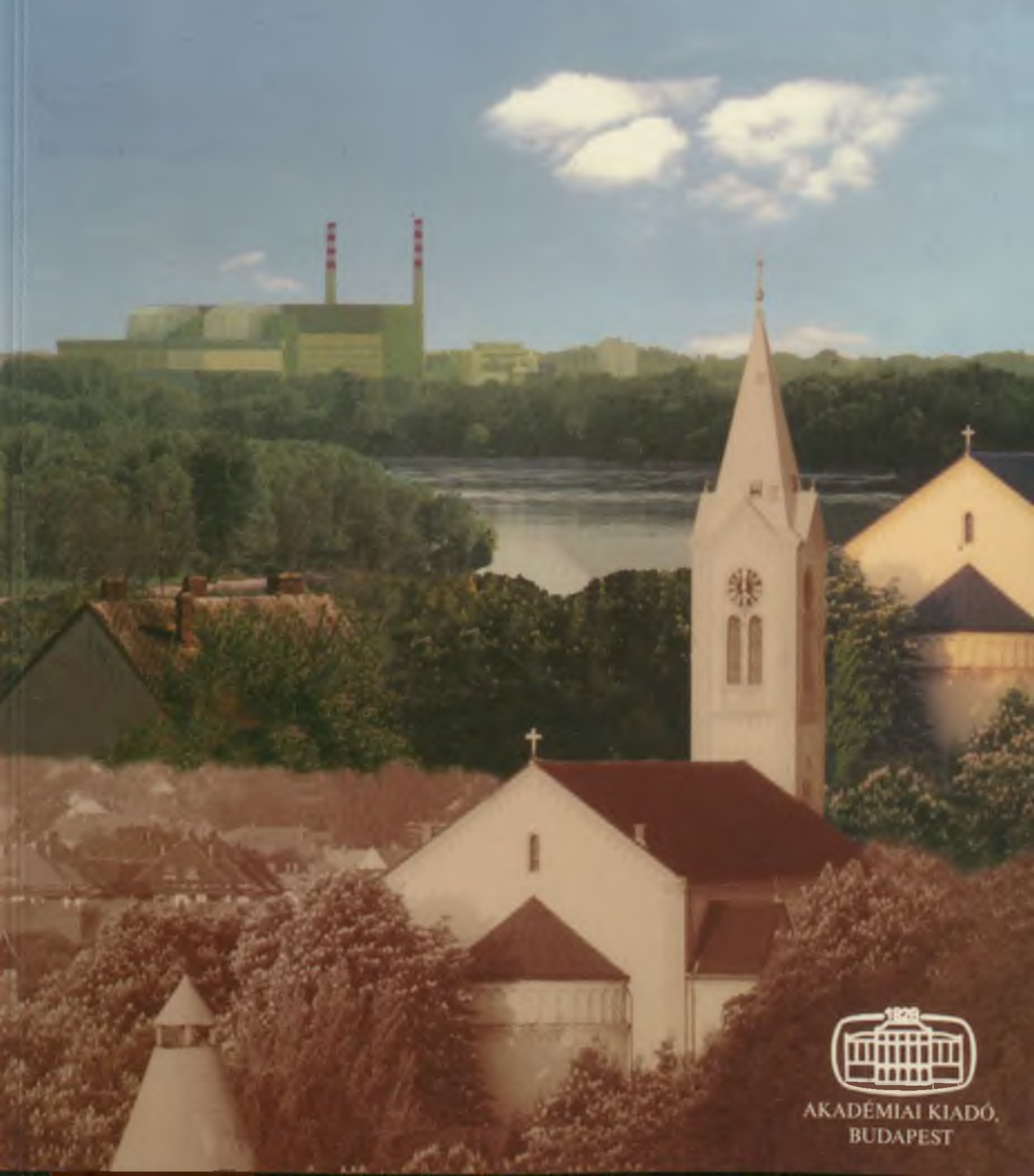
SEISMIC SAFETY OF THE PAKS NUCLEAR POWER PLANT



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SEISMIC SAFETY OF THE PAKS NUCLEAR POWER PLANT

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Preface

This book presents a selection of papers relating to the re-evaluation of the seismic safety of the Paks Nuclear Power Plant. Seismic safety analysis is understood as the quantitative estimation of the earthquake hazard at a site. Engineering solutions are generally available to mitigate the potential vibratory effects of quakes through design. However, there are no adequate solutions for mitigating the effects of permanent ground displacement phenomena such as surface faulting, subsidence etc. For this reason, in the re-evaluation process the potential for surface faulting has been investigated with special care. Publications of the International Atomic Energy Authority (IAEA) provide guidelines and recommends procedures to adopt in the consideration of earthquakes and associated topics for nuclear power plant siting but there are no internationally accepted procedures for the evaluation of the seismic hazard which would be appropriate for assessing the seismic performance of existing nuclear power plants. The seismic safety re-evaluation, therefore, has been based on a thorough analysis incorporating geological, geophysical, seismological and earthquake engineering information in a systematic way, similar to those applied for assessing the seismic condition in nuclear power plant siting.

In the evaluation of the probability and intensity of future quakes the study of past events and processes are essential. Approximations differ from each other concerning the remoteness of the past as well as in their direct or indirect relation to earthquakes. Evidently, the more recent these events and processes are and the closer they are related to quakes, the more reliable conclusion can be drawn. History of past earthquake activity show the closest relation with seismic hazard. Hungary belongs to the regions of low to moderate seismicity where the prediction of future seismic activity should only be based on an interval of observations with the duration of thousand years, much shorter than the return period of large destructive intraplate earthquakes. Réthly (1952) collected all events registered since 456 AD in his catalogue of earthquakes in the Carpathian basin. However, even this catalogue is far from being complete, moreover, only data from the last two or three centuries might be regarded reliable. Obviously one should involve additional data in the evaluation of seismic hazard; geological, geophysical, geomorphologic data alike.

On behalf of the Paks Nuclear Plant Co. Ltd. comprehensive investigations have been conducted in the area of the power plant and in its wider surroundings for more than ten years to evaluate seismicity and to assess safety of its operation. In the course of these studies a great amount of geological, tectonic, geophysical, seismological, geotectonical and geomorphological data and knowledge have accumulated in the form of reports, maps and publications.

Recognizing that the value of the accumulated material may have significance beyond a single industrial application, the Paks Nuclear Plant Co. Ltd. decided to publish a concise summary of the research work of the last ten years thus making the results of investigations available for the domestic and international audience of geosciences and experts in nuclear energetics. A volume of invited papers, summarizing the results seemed to be a proper tool for demonstrating possibilities offered in various fields of earth sciences for the assessment of seismic safety. Each of the invited contributions has a character of a summary, since authors should outline the methods, key points and conclusions of several reports on previous extensive mapping activities or measurements sometimes comprising several hundred pages. In spite of its tutorial character we hope the volume can be useful for geoscientists as well, due to the fact that no synthesizing work of this kind has been published yet. Most of the studies are compiled by project leaders and among the authors are listed most of those who have contributed to the assessment of the earthquake hazard. The description of geological surveys of the wider and closer surroundings and a summary and evaluation of tectonic and neotectonic evidences are followed by a summary of various geophysical measurements and the evaluation of seismological data. Seismic measurements carried out on the Danube constitute a separate chapter because of its vital importance in deciding the presence or absence of capable faults (transgressing youngest subsurface geological formations). A chapter on geomorphology serves as the closing part of the investigations.

Introducing their topics some of the authors found it necessary to present the general scope and significance of their research and to provide a short historical overview as well as an insight into the methodical details. Evidently these descriptions sometimes overlap. Similarly, some items occur in more than one list of references. However the editors deliberately avoided cutting redundant information since their aim was not so much to publish a monograph but to prepare a collection of authoritative articles, also usable as stand-alone studies, that collectively comprise or affect the seismic safety of a nuclear power plant. This also implies that the authors of the volume should be considered as independent experts taking all competence of and full responsibility for the conclusions in their exclusive field of research.

A glossary of terms has been compiled in order to help the nonspecialist.

We wish to express our sincere thanks to the staff of the Paks NPP Co. Ltd. for the support provided for the research activities as well as the publication of the present volume. We are especially grateful to Jenő Balogi, development manager, for his help and assistance. At last, let us express our hope that specialists and nonspecialists should both be served by the collection of review papers of this volume.

Budapest, May 1997

Editors

Geological research in the Paks region 1985–1994

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1. Introduction

The Hungarian Geological Survey has been taking part in the geological research in the environs of the Paks Nuclear Power Plant since 1985. Most of the results in the area W of the Danube were supplied by geological investigations to support examinations concerning the NPP's seismic safety. In the surroundings of the NPP geological works for the planned extension and for the support of seismological examinations, carried out by numerous institutions and experts were the most productive. Activities of the Transdanubian Division of the Geological Institute of Hungary (MÁFI), of the experts from different divisions of the Hungarian Geophysical Institute (ELGI), from the Geodetical and Geophysical Research Institute (Sopron) (GGKI), from the Department of Geophysics Eotvos Loránd University (Budapest) (ELTE), from the Geophysical Exploration Company (Budapest) (GKV), and of A. F. Gracsov and his colleagues from the Geophysical Institute of Moscow should be mentioned, who took part in the assessment of seismic safety of the area between 1985 and 1991. In cooperation with the measuring team of ELGI and considering the recommendations of the Scientific Coordination Committee, Hungarian Geological Survey issued a summary in 1992 based on the elaboration of earlier data. In 1994 an other important work was published summarizing the geological conditions in the area, evaluating tectonical conditions and adapting the results of the accomplished projects to GIS. The present study summarizes the results and methods of the geological studies in the surroundings of the NPP *(Figure 1)* pointing out information about the surface and near-surface geological formations. It provides an outline of the main characteristics of installing and using the GIS database which contains the results of the geological investigations carried out in the area in a unified system.

The main purpose of the studies ordered by different authorities during the ten years were to collect the basic geological data needed for the assessment of seismic hazard in the surroundings of the NPP, to supply certain missing data and to accomplish the geological synthesis of them. We also used the results of earlier geological-geophysical studies for the final synthesis (Chikán et al. 1994a). A part of the considered data originates from areas more remote from the NPP; the clarification of the distribution, development and interrelationship of certain formations made this outlook necessary. The most important aims set eventually and reached were the possibly most exact cognition of the geological conditions in the region, the construction of a geological map of high accuracy and the specification of the main characteristics of the geological formations influencing earthquake liability. An opportunity of the edition of a geological map of increased accuracy presented itself by using the information gained continuously during these ten years of research. Our map which was edited as a result of the geological synthesis is the base of numerous map versions arranged in the GIS (Turczi 1994). A simplified version of this map of 1:25.000 scale is shown by *Figure* 2.

The results of the completed geological research are grouped below by topics. The *surface geological mapping*, the elaborated *borehole surveys*, the establishment of *artificial exposures*, the synthesis of the results of our survey are to be dealt with separately; the works performed in relation with the structural conditions are covered to the extent they contributed to the better understanding of the geological conditions. Their tectonic evaluation can be found in the next essay of the present volume (Balla et al. 1997). The introduction of the *GIS database* is placed in a separate chapter.

2. Surface geological mapping

The basis of the geological research is the geological map, which describes the geological formations, and their relation to each other within the region to be studied. Explanatory notes are attached to this map, introducing the most important features of the formations. The region around the Paks NPP belongs to those areas of the country, where no geological mapping had been performed before (not considering the plain mapping of the 1950's), and as a consequence an adequate detailed geological map essential to the seismic safety evaluations was not available. To remedy the lack of this map geological survey was accomplished in the region three times. In the first step in 1985, as a result of which a geological map of 1:50.000 scale was completed for the closer environs (Chikán et al. 1985), then in 1992, when a 1:50.000 scale geological map of a 30 km radius circle around the NPP was constructed (Chikán 1992) (further on this area is referred to as "region"), and at last such surface geological mapping was carried out in 1994, when the 1:25.000 map of a 10 km area around the NPP (further we refer to this as the "closer region" of the NPP) was compiled (Chikán et al. 1994a, b *Figure 2*). In relation to these works, the Survey carried out structural-geological examinations and analyses (Dudko 1992, Chikán and Dudko 1992, Gerner 1993, Dudko and Maros 1994) and these geological studies contributed also to evaluation of seismic hazard (Balla et al. 1993.). Naturally, besides the results of the surface mapping we also used the results of other surveys done partly by MÁFI, partly by other researchers, consequently the reliability of our maps (parallel to the enlargement of the map scale) has risen continuously. The results of the surface mapping, and the geological conditions can be summarized as follows.

The area investigated is located in the middle part of the Pannonian basin. In its geological setting, three major sequences can be distinguished which are as follows:

A Paleo-Mesozoic basement,

Neogene formations,

Quaternary overlying deposits.

The amount of information available concerning the *Paleo-Mesozoic basement* is highly limited and sporadic. Stemming from the complicated structure of the mountains areas, it is obvious that the small number of boreholes reaching the basin basement (8 in a circle of 30 km radius: Miske-1, 2, 3, Németkér-1, Szekszárd B-17, Tengelic-1, Tolna B-47 and Vajta-3) have only given an informative picture concerning the actual geological and tectonic setting of the basement. The rocks it consists of are partly metamorphic, partly sedimentary and have a development which is conform to that of rocks of similar age in the Mecsek Mountains. No data suitable for clarifying the relation between the metamorphic and sedimentary developments has been found in the area.

The *Neogene rocks filling the basin* were reached, or penetrated by several boreholes. The data obtained from these boreholes are inhomogeneous in several aspects: very few boreholes reached the older part of the Neogene and also the basement (12 in a circle of 30 km radius), while upwards in chronology the amount of data shows an increasing tendency; the Upper Pannonian rocks were reached by 900 boreholes. Nevertheless, the major part of data from the boreholes have been obtained from hydrological exploratory boreholes using intermittent coring, and only a few boreholes using continuous coring studied and documented in details are found in the area. The Upper Pannonian sediments cannot be studied in surface exposures over the area. The Miocene rocks are of sedimentary and volcanic origin, and the Upper Pannonian beds are known as an average basin facies. The data concerning these formations gained as new during the survey are reported at the chapter reviewing borehole research.

The *Quaternary sedimentary cover* is the most studied sequence subjected to most detailed examinations in the area. This volume of our report is devoted, first of all, to the geological setting of this sequence. As far as the western and lastern parts of the region in concern regarded the facies features of the deposits are rather diverse in which the role the fluvial, eolian and slope deposits play is of the greatest importance. During the study of the Quaternary sequence both geographic and geological considerations were included, thus, we have sets of data and examinations suitable for a versatile interpretation. These deposits were formed during the past 2.5 million years. In our study the lower boundary of the Pleistocene is represented by the 2.43 million years old Gauss-Matuyama boundary, whereas the border between Early and Middle Pleistocene is the 700,000 years old Matuyama-Brunhes boundary. The boundary between the Middle and Late Pleistocene is represented by the 125,000 years old Riss-Würm thermal peak. The beginning of the Holocene is dated to 12,000 years. For the appearance, facies, and the most typical mineralogical-lithological features and regional extent of each sediment, see the comment of the geological map (Chikán et al. 1994) and the expert report about the area (Kókai 1988). The data available concerning the interrelationships between the deposits have allowed to outline the present picture created by the geological development of the area, and to reconstruct the relevant processes. The evaluation of data sets enabled a better understanding of the chronological and facies conditions of the sedimentation, and to get to know horizontal and vertical relations. However, even today there are some problems concerning correlation.

At the boundary between the Upper Pannonian and the Pleistocene, a considerable erosional activity took place in the area which caused a large amount of Upper Pannonian deposits to be removed from the area. Only borehole Paks-4b has provided data concerning the presence of the Lower Pleistocene, (or in another opinion Pliocene (see in our present volume Balla et al.) Tengelic Red Clay Formation described in boreholes Tengelic-2 is found W of the area. However, no evidence to the age of this formation, supported by examinations exceeding the bedding and macroscopical features is available, therefore this occurrence was represented as part of the loess sequence in our log Dszgy-1 also crossing the borehole concerned. This solution is even more justified because during our present examinations it is the loess sequence for which, concerning its classification, dating and chronological subdivision, the most data could be collected.

Based on the comprehensive studies of the key profile at the Paks brickyard, carried out over a period of some years, an approximately precise picture of age and facies conditions of the series exposed here is available to us. Being a profile exposing the largest, best studied and thickest Pleistocene sequence in the area, It provides an excellent basis for an attempt to classify the Pleistocene deposits found in the area chronologically, by relying on comparisons with this sequence.

According to the present classification (Pécsi 1993), the lowermost beds in the Paks loess profile are dated to be about 1 million years old, thus they are as old as Early Pleistocene. According to the original study of the Paks key profile (Kriván 1955), deposits older than that and lying between the Upper Pannonian beds and the lowermost beds of the brickyard can also be found S of the brickyard. With regard to its age, this sequence would correspond to the Tengelic Formation. However, no data from the area concerning such an old Pleistocene deposit is available to us, although it can also be imagined that the deposits penetrated between the Pleistocene fluvial deposits and the Upper Pannonian sediments in borehole Paks-4b can also be assigned here.

In the loess sequence, a further classification and correlation are made possible, on one hand, by the analysis of paleosols, and on the other hand, by the macrofauna that occurs at some sites. The lithological features of the sequence are not too suitable for correlation purposes (particularly, in the case of minor exposures), although some signs indicate that the consolidation status, and thus the textural feature of the deposits exhibit a certain consistent change upwards the profile. The correlation of the different levels in the loess sequence were tried to be solved by establishing artificial exposures dealt with later.

Within the loess sequence, the interrelationship between the sediment types is so occasional, and the loess formations of different age perform so similar properties, that it is impossible to map each level, and, in the case of minor exposures the lithological features are insufficient for dating. That is why loess sequence was represented in a uniform manner as a single element on the map. However, in the profiles, on the basis of data and results obtained from the evaluation of exposures, each loess presumed to be older than Würm was distinguished using a marking 18R, and the loess likely to be of Würm age was distinguished with a marking 18W *(Figure 3)*. A formation that is in a special relation to loess is the Pleistocene drift sand found in the area. This deposit type was formed at the same time when the loess sequence. As a function of changes in climatic conditions, loess always contains a certain amount of sand, but marked drift sand levels were only formed at some places. However, this drift sand generally has a more limited areal extent than the regional scale, and in most cases it wedges out horizontally. As a result, it rarely can be determined whether two drift sand occurrences distant from each other in space belong to the same bed, or not.

Upwards along the Paks key profile, the number of sand beds shows a decrease. During the investigations, several concepts concerning the development of sand beds found here were formed: some researchers (Ádám et al. 1954) deemed that the sand beds were of fluvial origin. Kriván (1955) considered sand horizons of eolian origin. Pécsi (1993) supposed that the most typical sand beds in the Paks exposure were formed as derasional valley fillings. On the basis of their facies the Pleistocene wind blown sands found W of Paks both in surface exposures and in boreholes cannot be clearly correlated with the sand layers found in the key profile. Had we taken into consideration, however, the climatic conditions that led to the development of drift sands, and the sedimentary conditions that had been able to supply sufficient amounts of sediments for drift sand development, it could be made probable that the best conditions for the forming of this drift sand started to prevail near the Riss-Würm boundary, or in the beginning of the Würm.

Of geological profiles compiled on the basis of surface exposures, boreholes penetrating each sediment, and the geoelectrical logs, it is log Phsz-2 attached as an annex to the GIS, and profiles 5 and 6 *(Figures 4* and *5)* that show which setting position can be assumed for these rocks on the basis of data available at present. It should be noted that for a part of drift sand occurrences, only the thickness and properties of soils formed on them provide opportunities for dating.

The bedding conditions of the Pleistocene slope deposits are only rarely doubtful: their development is likely to have taken place during the entire Pleistocene, however, in most of the cases, as loess sequence they are represented in the form of reworked soil levels, delles, valley infillings. Only the younger talus deposits likely to have been formed during the final stage of the Würm were represented in the map with a separate symbol. Their position matches with the present terrain conditions and they were accumulated in a larger amount particularly at the bottom of the terrain elements having already formed during the Pleistocene and along the valley sides. Their altitude with respect to sea level does not have relevance since it is the current base level that plays an important role in the evolution of the valleys, and its alterations also influence the emergence of slope deposits.

The topics concerning the dating and stratigraphic position of Pleistocene fluvial deposits including their relationship with deposits of other facies should considered to be problematic. Both in the exposures containing fluvial deposits and in the boreholes, the development conditions of the sediments could be relatively well assessed. However, no exposure at all could be found in the region that would allow for a precise determination of the relationship between the fluvial deposits and the loess sequence. As far as the chronology is concerned, there exist different opinions. The sporadic biostratigraphic data (Jaskó and Krolopp 1991) refer, at some sites, to an Early Pleistocene origin whereas at other sites to a Late Pleistocene one. Consequently, it can be stated that in a part of the area fluvial sedimentation also took place simultaneously with loess formation during the Pleistocene. However, the lateral contact and relationship between the two facies are unknown to us. This also means that although in some cases the age of the sequence can be dated in vertical profiles, its correlation with deposits of a different facies is difficult. This represents a significant problem not only concerning this particular geographical area but also within the Quaternary studies in Hungary.

Based on data concerning chronology and bedding, two types of Pleistocene fluvial deposits are distinguished. The age and classification of deposits of the Danube valley can be evaluated on a sedimentary or on a biostratigraphic basis (Jaskó and Krolopp 1991). Beds with an age and facies similar to the part assigned to the Upper Pleistocene can be found NW of Paks, in a valley stretching towards Cseresnyés and in a sequence in the row of hills between Tengelic, Szőlőhegy and Pusztahencse. Beneath the latter, the Lower Pleistocene levels can also be found W of the area, in boreholes found in the vicinity of the Training Center at Tengelic.

Based on the aforesaid, the solution selected in geological profiles was to represent the boundary between fluvial deposits and loess as an erosional boundary and the sedimentary terrains of fluvial deposits were represented as erosional troughs that partly existed earlier *(Figure 6)*.

On the surface of the Pleistocene fluvial sand, the conditions of drift sand development were created at several places due to a change in the climatic factors. At those parts of the area where Pleistocene drift sand overlies the fluvial sand, generally the two facies cannot be separated sharply. In many cases, sand dunes of material blown out from a relatively small distance are found in the area. As a function of changes in the wind intensity and the paleomorphological conditions, at some places blow-outs are found, whereas at other sites larger dunes were built by the wind. This situation also allowed small lakes to form at the end of the Pleistocene. The relation between Pleistocene fluvio-eolian sand and Pleistocene drift sand is still not clear. They have a similar mineralogical composition, thus the blow-out terrain level and the place of origin of the original deposit may be the same for both sequences, however, their regional extents show some differences. It is not excluded that the two deposits may be of the same age but there is no direct evidence to it, and no deposits overlying the fluvio-eolian sand and indicating new inundations by the river have been found either.

In the whole area, there is an unconformity between the Pleistocene and Holocene deposits. Even in the areas where the sedimentary conditions were similar during the two periods (such as near the Danube), there is a hiatus between the facies, thus there is no continuous transition between the Pleistocene fluvial deposits and Holocene fluvial deposits.

Among the Holocene deposits, the fluvial deposits are considered to be the oldest. In the area they occur at several levels, in the form of channel and flood plain deposits alike. Their interrelationships and the changes in granulometric composition are determined mainly by phenomena associated with water streaming and water level fluctuation. The only usable order as to the age of deposits of different grain size can be set up in that bed deposits in the area W of river Danube are older than the flood plain deposits also found here, whereas in the vicinity of the present bed, the youngest ones are, of course, represented by the bed deposits.

The Holocene sedimentation is characterized by a relatively quickly changing facies and limited horizontal and vertical extents. In the vicinity of the Danube, due to the development of the flood plain, generally, at the bottom the bed deposits, then flood plain deposits are found. Overlying them fluvial-paludal sediments deposited in the small remaining lakes, under stagnant water environment are found. In local sedimentary basins, farer from the Danube, limnic deposits were formed. For the whole area is typical, that the older deposits are covered by a relatively thin Holocene drift sand in a significant regional extent. The underlying bed outcrops partly in small spots, partly regionally. It is typical that wind acts as a destructive rather than a accumulative element on hill ridges exposed to it the most. At these sites, drift sand is only rarely found, and blow-outs are rather typical.

The sediments formed due to an anthropogenic activity not represented in the map but yet supplying a significant amount of deposits should also be noted. Even disregarding any activities resulting in deposits differing from those described before indirectly, due to a transformation of the environment (for instance, the damming of fish ponds), youngest Holocene deposits are found over a large area and, at some places, in a considerable thickness. For the deposits resulting from human activities, two significant types can be distinguished: one of them is a reworked rock of geological formations, considerable rock masses of former periods, such as the backfill that was used to provide a foundation for the Nuclear Power Plant and that attained, at some places, a thickness of 2 m, and the other one is the accumulation of wastes, by-products resulting from human activities. Unfortunately, its thickness, in the area concerned, also attains several meters at some sites, and not only in officially established, controlled waste disposal areas but also in the illegal waste disposal sites.

3. Borehole survey

The first boreholes were deepened to support the geological mapping of the area around the Paks NPP in 1985. In relation to the geological mapping of an approximately 720 m^2 large area, 20 mapping coring boreholes of 30 m depth, and 99 shallow boreholes of 10 m depth were deepened around the NPP, all of them on the west bank of the Danube. The boreholes were aimed at complementing the mapping, and helped to solve the stratigraphical and facies problems having arisen during the field survey. Part of this material were subject to laboratory tests (Chikán et al. 1985, Chikán et al. 1986).

Out of the boreholes only 9 transversed the Quaternary formations, and all of these stopped in the Toronyi Formations of the Transdanubia Main Group. The petrological development of the Pannonian formations are typical: there were found partly sequences characterized by prevailing sand, partly alternating sand, silt, clay and marl; in some cases the Ostracoda fauna confirmed the Upper Pannonian age of the formations.

By evaluating the sequences exposed by shallow and mapping boreholes, a significantly more accurate picture could be presented about the distribution of the formations, and about their relationship.

In connection to the examinations concerning seismic safety, 4 all along coring boreholes and a coring borehole between 150–300 m were deepened in 1986, in the immediate surroundings of the Power Plant. It was MÁFI's task to analyze and evaluate the borehole data in detail. The Paks-2/a borehole was deepened on the region of the NPP, the Paks 3 borehole northeast to Dunaszentgyörgy, the Paks 4/a and 4/b boreholes were deepened southwest to the NPP. The evaluation of the Paks 4/c borehole deepened in the immediate neighbourhood of the last two boreholes was carried out by the staff of the National Geological Research and Drilling Company (Miskolc). The formation groups transversed in the boreholes could be correlated easily *(Figure 7).*

The detailed evaluation of the deep boreholes brought numerous new results, both in describing the geological formations found near to the Power Plant, in clarifying their stratigraphical position, both in relation to the structural-geological information about the region. The detailed reports about the boreholes (Chikán 1986, Chikán et al. 1987a, b contain all the basic data produced during the evaluation, and the attached explanations as well. In the present essay emphasis was put only on the most important elements of the geological results.

Stratigraphically it is important, that the earlier known, Szilágyi Claymarl Formations of Badenian age, which were transversed by the Paks-2 borehole deepened in 1979 in the region of the Power Plant (Jámbor et al. 1982), was also reached in two boreholes set southwest to the power plant, in the Paks-4/a and in the Paks-4/c ones. But the Badenian Formations were reached in the Paks-3 borehole, in the form of another facies, namely the Leitha limestone sequences to be correlated with the Pécsszabolcs Formation. At the same time, the Sarmatian formations ovelying the Badenian ones reached in the Paks-2 borehole were missing from all of the further boreholes partly due to their washing away (Paks-3), partly for structural reasons (Paks-4/a, 4/c). Consequently the Lower Pannonian formations settle discordantly on the underlying bed in all the three boreholes reaching the Badenian. Being of average basin nature petrologically development are, they contain alternating claymarl silt and silty claymarl. The Paks-4/c borehole transversed the Upper Pannonian Formations with full segment, in the other boreholes the sediment sequence of average basin facies can be characterized by well comparable data, which is formed by the series within the Somlói, Tihanyi, and Toronyi Formations. The thickness and the distribution pattern of the three formations is varied according to bottom configuration and flow patterns of the former Pannonian inland lake, and depending on the coast distance and the nature of the transported clastic material; in some places they tend to grow or to diminish at the expense of each other. In some places, for example near to the NPP, the geophysical measures and the borehole data equally showed, that the formation was affected by structural movements. One possible interpretation of the tectonic phenomena exposed here is shown in *Figure 8.*

In all cases there is a significant hiatus between the Pleistocene formations superimposing the Upper Pannonian formations discordantly and the underlying bed, but the thickness of the sediment missing cannot be established exactly. The Quaternary formations in all of the three boreholes consist of Danube sediment mainly, with the exception of the Paks-4/b borehole, where under the Danube sandy pebble, ancient silt sediment of loess origin is found between 31,8–36,9 m.

From the structural-geological point of view, the Paks-4/a and the Paks-4/c boreholes brought new results. In the two boreholes settled on the flower-structures outlined on an earlier measured seismic section on the region, a tectonic zone was exposed indicating a considerable displacement between the Lower Pannonian and the Badenian layers. Furthermore, in the whole borehole succession faults, or joints were identified in a downward increasing quantity, referring to tectonic effects. Fault-scratches were observed on a significant part of joints, which are of relatively flat dip and, as a consequence, they refer to a displacement with a considerable horizontal component.

4. Artificial exposures

In the course of investigations carried out in the environs of the NPP, the age of the presumed or rather, observable structural phenomena was coming to the fore gradually. The fundamental question, whether the structural phenomena exposed by seismic measurements and boreholes had been renewed during the Quaternary or not, was to be solved by the application of several methods. The analyses of the joints measured in the natural exposures (Chikán and Kókai 1989) have not yielded convincing results. Because of this, after a significant geophysical preparation (Meskó et al. 1993) a trenching research was executed in the region, in the framework of which along a section of 500 running metre length, qualified as a zone of disturbance by the geophysical measurements, trenches were deepened down to an average 2 m, and documented in detail (Don et al.1992, Chikán and Jedlovszky et al. 1992). These experiments proved, that tectonic, structural phenomena affecting the surface cannot be identified on the section qualified as a zone of disturbance by the geophysical measurements. At the same time the data referring to the stratigraphic conditions of the formations studied in the course of the trenching could be used when the geological map was constructed.

To the stratigraphical analyses and paleogeographical reconstruction of the region's Quaternary formations, and to the final evaluation of the geological-geophysical-geomorphological data received in the course of the geological works carried out in the neighbourhood of the Power Plant in 1994, supplementary examinations were necessitated in order to get to know the basic characteristics of the most typical Quaternary formations in the region in more details, their interrelationship, and to provide a more accurate dating and history of evolution.

To attain this goal, 10 groups of formation of the earlier investigated exposures were chosen, exposing the widest spread layer groups in the region, and their detailed palaeonthological and sedimentological examinations had been carried out. For the sake of the later evaluation and comprehensive examinations an artificial exposure was created for comparative studies, which was established at the place of a landslide of the Danube bank having occurred in January 1994, at Dunaföldvár. During data processing, the sequences of the exposures were described from the top, and – in order to be able to compare it with the section of the Paks brickyard – a downward sampling was executed with a frequency of 20 cm.

The results of the completed evaluations were summarized in two reports (Chikán et al. 1994b, Kókai et al. 1994). These reports contain the detailed data and examination results of the analyses by the individual exposures. The present essay focusses on the most relevant results used for the synthesis of the formations and the construction of the geological map.

From our artificial exposures we had received data regarding age from the exposures signed Gy-I, Gy-II and T-3 These formations have proven to be presence older than Würm, i.e. they represent Middle Pleistocene loess formations. The loess found in exposure T-1 proved to be the oldest of them, where the fauna indicated an age older than Würm, but the palaeomagnetic measurements and paleosol properties made the presence of the double soil of Paks presumable. The surface distribution of this group of formation cannnot be mapped because of the relatively minorlithological differences. In the loess sequence of the Gy-I and Gy-II exposures a younger fauna, still older than Würm, i.e. of Riss or rather Riss-Würm age could be identified, and the paleosol exposed here corresponds partly to the Mende Base, partly to the Basaharc soil complex. Loess formations found higher in the profile fully correspond to Würm; the youngest loess formations also can be found in the western area of the region, near Györköny: in our opinion, the sandy loess of the Magas-hegy of Györköny is the youngest loess horizon of the whole area, probably even younger, than that on the top of the section of the Paks brickyard.

As it has already been mentioned the age of the Pleistocene quicksand is uncertain at some places. The exposure T-2 and T-4 of Tengelic are examples, where neither the relationship of the Pleistocene quicksand to the loess can be determined, nor it contains faunasuitable for dating, therefore its ranging is based on the thickness and characteristics of the recent soil developed on it.

The Pleistocene fluvial sand formations are partly of Early-, partly Late Pleistocene age. The Paks-I, Paks-II, and Tengelic-2 artificial exposures showed younger fluvial sand. A somewhat differing evolution and stratigraphic position is documented by the Gy-III exposure at Györköny, which settles higher, than the previous formation group, with Pleistocene quicksand and loess on it; therefore it is possible, that this also represents the older part of the Pleistocene. The horizontal development of this formation is not known. The fluvial layers observed in the exposure probably indicate the alluvial fan sediment depositedbetween the older and the younger loess series.

5. Synthesis of the geological formations

Summarizing the statements and results of the abovestudies, a synthesis of the region's surface and subsurface formations was completed in 1994 (Chikán et al. 1994a). This is partly summarized by the explanatory notes complementing the information available about the surface formations found in the immediate neighbourhood of the Paks NPP, at some places with references to materials systematized in earlier reports. It also publishes a reduced version of the region's geological map of 1:25,000 scale, and describes the spatial relationship of the individual formations to each other in numerous sections. The introduced geological map became part of the space information database containing geological data about the region, as the basic map representing the geology of the region.

6. GIS database

In the course of the summary and analysis of geological information about the NPP's surroundings of 10 km radius a wealth of data of different content and resolution accumulated. The handling, structuring and effective operation of this data set need precise work in informatics and powerful software-hardware environment. Adaptation of the spatial data to GIS seemed to be logical. GIS plays a significant integrating role, as place is a natural connecting point for every (not only geoscientific) subtopic. The organizing of GIS database makes it possible, that autonomic information can be integrated, the necessary parergon of which is homogeneous and standardized database content. With the help of the database the cognition of complete information series is possible at the points within the examined area, also to determine logical filters including different subsets of the topics and to represent the results on maps.

According to the given tasks basic and concluded graphic and describing data of fixed topics, prepared by different research institutions (MÁFI, ELGI projects and divisions), have been adapted to the GIS. The accomplishment occurred in Intergraph MGE environment. Below the principles and the description of the system is reviewed. The text refers to the documentation of used standard Intergraph applications, the explanations below only contain the absolutely indispensable information.

The principles of developing the database were as follows:

The data series are fitted into *the MGE environment of Intergraph*, therefore the database (its graphic and alphanumeric part) follows the MGE standard.

The data structure and data types ensure full compatibility to other Intergraph modules and applications. The graphics does not use such modules (arc, curve, B-spline), which might cause problems when running other modules. The alphanumeric tables contain data fields built from basic types (char, integer, real). This ensures the openness of the data series in a wider sense.

The data are maximally classified. Classification is one of the most important elements of the GIS database. This makes the widest range application and representation possible. Every object represented on the map can be reached both autonomically and according to its logical status. The objects are separated according to *LEVEL* in the graphics, and according to their identification or characteristics in the database tables. In other words: every object that can be represented on map is separate either graphically or alphanumerically (record linked to graphic element).

Digital maps reflect database approach. This means that the forming of map-intelligence always supervises the cartographic viewpoints. In other words: the main task of the graphic element is the expression of spatiality and not the traditional delineation according to key definition. The information needed for cartography is ensured by the classification and the linked database information.

A major viewpoint is to accomplish a multipurpose system and to avoid redundancy.

It was attempted to reach identification minimum at every topic of the database. This means that the minimal demand concerning the database information linked to graphic elements is the record of unique or type identification. By using this as key field, the data table can be related to any describing data. The database functions as basic data collection in its current condition, but it is also prepared for answering combined questions.

The *MGE data model* ensures the hierarchic classification and grouping of the information. The highest unit of the model is the *PROJECT. The PROJECT* is the totality of maps, alphanumeric data and data type definitions. The next level is the totality of maps which are included in *INDEX*. The maps are part of different thematic groups *(CATEGORY).* One map can only belong to one category. Maps can be defined as graphic representation of the objects of the real world. Every graphic unit belongs to one determined *FEATURE* class. The FEATURE is the totality of the object's further undividable characteristics.

The highest level classification form in the hierarchy is *INDEX.* Although the basic data series is supported by traditional profiles, there are continuous maps appearing in the database. So the aim of using INDEX is not to edit a virtual continuous map, but to install feature combinations of master-reference files.

All thematics have been ordered in a so called paks10 *category.* The categorization does not mean that we have to give up classification; it happens on the *FEATURE* level. The main reason for that is that nothing justifies the strict separation of the thematics on CATEGORY level. The sole paks10 CATEGORY can be inaugurated to further *MGE* modules without any restrictions.

The topics are equally classified on *FEATURE-ATTRIBUTUM* level. The logical homogeneity of FEATURE can be tracked based on the terminology.

There is a determined software and hardware environment belonging to operating the GIS database, and the reference system also belongs to its build-up and usage as main characteristic. *The software environment is represented by Intergraph MGE.* The MGE environment is the totality of many different but coordinated and connected with each other softwares. The two separate parts of the database are the graphic and alphanumeric data series, in other words the maps and the describing data connected to the map elements. At first approach graphic data are processed by *MicroStation,* alphanumeric ones are processed by an *RDBMS* (in our case ORACLE). These basic softwares support more application groups and modules. To handle the database of the surroundings of the NPP of 10 km radius the following modules are necessary:

MicroStation
MGE Basic Administrator
MGE Basic Nucleus
MGE Base Mapper
MGA Analyst
MSM Terrain Modeller
RIS-RDBMS (Oracle)

The recording, editing and representation of digital data is the task of *MicroStation.* Alphanumeric data manipulation is carried out *by RIS/ORACLE. RIS* is a surface between Intergraph modules and the database processors which ensures the independence of the database. In other words the user meets only *RIS* when processing alphanumeric data, and does not even need to know, what the concrete database processor tool is. *MGE* modules carry out database administration, cleaning of contours, connection keeping with *RDBMS* and basic queries. Database administration is a planning procedure before filling up the system with data. The classification, definition and recording of the graphic and alphanumeric data structure is the plan of the GIS. One of the tasks of this document is to publish and explain the administrated records. The MGA module is responsible for creating topology, and carries out topologic queries and representations. The *MSM* module creates, queries and represents digital relief map.

The hardware environment is determined by partly the used softwares, partly the demands of the handled mapping and numeric data series. The developing tool is Intergraph Clipper based Workstation (InterPro 2700). The operation system is unix (clix). The necessary storing space (considering only data) is 40 Mb, the memory need is minimum 64 Mb.

The GIS data series of the surroundings of Paks of 10 km radius is built on *EOV reference system,* this includes 24 profiles. The resolution of the reference system is 1:10,000. The thematic maps were edited on the 1:10,000 base, but their resolution is different. The unit of measure of the coordinates included in the system is metre.

Mapping thematic is the determining and key factor, holder of the database connection in the GIS. Most of the graphic elements constituting the map plays an important role in information supply beside the representation of the real world. The information connection is built on the relations between database tables and on topology. The system only answers questions which are able to be concluded and calculated from the built-in information *(MGA).* The wording of the questions is the user's task. Some technical data of the major mapping thematics are described below.

Topography was digitized by profiles of 1:10,000 scale. With regard to the fact, that this is the most complex thematic, separate digitizing rules and handling tools were set up, the present description refers to these cardinal points. The following objects and graphic element types can be separated on the topographic map:

–linear elements,
–areas,
–point elements,
–inscriptions.

The lined elements are in most cases boundaries of areas (branch of cultivation, vegetation). According to cartographic rules only the one of highest priority appears in case of matching lines. The digitizing technology followed this principle. But to meet both the representation and the GIS demands, every line-section (from one crossing to the other) is an autonomic graphic element, with a describing note linked to it (attribute record). This note makes the enumeration of every function concerning one line section possible. If e.g. there is a road on the boundary of a forest and a ploughland, then the road *(linear feature)* covers the vegetation boundary *(area boundary feature)* according to priority. Both functions of this section is noted in the database. The elements of the topographic maps are not up-to-date, they reflect conditions from 1979. According to agreement the full scale process of this condition would be an unnecessary investment and false. Therefore we can qualify the topographic base as follows:

–it reflects the present situation,
–its database intelligence is on graphic element level,
–topologic intelligence (interrelationship of graphic elements, qualification of regional elements according to branch of cultivation, vegetation) is prepared, but its accomplishment is only reasonable after updating based on air-photos,
–the linear structure of the topographic system is suitable for orientation, it is the base of professional thematics.

The base of the *digital elevation model* is the vertical contour drawing of the topographic map. In order to be able to handle data only each tenth contour was digitized. At places where the preciseness of morphology made it necessary, the bisecting contour was digitalized also. The contour drawing has *ATTRIBUTUM*, "Z" value was ordered to every line. This linear structure is the base for the modeling module *(MSM)*. The area E of the Danube with elevations of 90 m a.s.l. can practically be considered as flat. This area is registered as constant level *(PLANAR AREA)*. The deep valleys, quays, mainly bordered by abrupt loess walls are marked with separate auxiliary lines. These auxiliary lines modify modeling and make it more precise. A part of the relief map are numerous spots elevation, which also serve to improve the model.

Boreholes can be found in two logically linked tables. The primary table contains global data concerning the borehole, such as the primary key field and the identification of the borehole. The sequence table contains the transversed geological units and their underside depths. The primary table contains the measured coordinates of the boreholes and the ones that was edited on the layout. The borehole-point map can be generated from the database table. The appearing text at the borehole point can be any information of the primary table in the graphics.

The so called *FTV boreholes* exposed the settlement of the NPP. The database was made by the FTV Rt. *in MicroStation-dBase* format. The structure of the database is created in primary table-sequence table system. The available data were converted to MGE environment. No changes has been made to the original data, new columns were inserted to identify boreholes and EOV coordinates.

The *observation map* records the spatial position and form of the observation spots. The extension of the observation is often minimal, point-like. In this case a little square symbolizes the shape of the exposure in order to make unified handling possible. A lot of information connect to the observation place: tectonic measurements, layout plan and description with text. Their representation is carried out with the help of an external order, it can be defined as similar to shallow boreholes concerning their data structure. At the observation point the identification of the exposure and the exposed rocks are enumerated. As a completion, layout, stereogram, rose diagram and grain dispersion graphs belong to the text. These partial data are not parts of the actively accessible database, but the basic information can be introduced to reach the element. The operating tool of this function is not part of the standard *MGE* applications, it is an external *MDL* development.

The *geological map* represents the formations found in the area and the lines of the edited profiles. The types of geological formations were separated according to age, genesis and composition by numeric codes in the table attached to the map. An intelligent map was created with the help of the topology generating module of the MGA application, in which the mentioned types can be accessed one by one or together based on abbreviated thematic identifications given in the linked table. We edited a colour map by using topologic data structure, the key of which is conform to the generally accepted colour types of geologic maps. Identifications of the *geologic profiles* belonging to the geologic map are stored in a separate table, connected to each other by profile lines. The identifications appear in the center of the profile lines as labels. Colour maps were edited about the profiles with the help of the topologic data structure. The profiles can be visualized from the geological map by pointing to their lines or identification labels, with the help of the MDL application described in the previous chapter.

The *geomorphological map* separates the morphologic types occurring in the area. The lines depicted on the map also themselves bear thematic information and have two different functions from GIS viewpoint. Most of them separate closed, morphologically interpretable spots, but part of them appears as individual line. Accordingly we ordered separate data tables to them, in which we represented their coded types and the kind of their spot creating function. These can be accessed with the help of *MGE GeoDatabase Locate* module. We edited a colour spot-map based on the topologic data structure generated from the codes given in the spot map table. The types of this spot map can be accessed based on abbreviated thematic identifications. The *paleoenvironmental map* separates the morphologic types in the area according to their age and landform types. As each line on the map borders closed spots, their separation according to their spot creating characteristics was not necessary. The applied series of techniques is identical to the geomorphologic map concerning thematic filters and colouring.

The adaptation of *geophysical data* (seismic, gravity and VESz measuring data series) into GIS database have created numerous problems. All three geophysical measurments produced large data mass on basic and interpreted data level. The presence of these data would increase the size and passive knowledge of the system. Only edited result maps can take part in problem solving accesses and logical combinations. In case of seismic and VESz measurments geophysical layouts identify place and measurings, while the identification supports the preparation of data connection. The result of gravity measurements is the isoline map. The isolines are separable according to value, similarly to map relief, and are processable by the *MSM Terrain Modeller* module. The surface created this way is comparable with other maps and can be processed by the standard *MGA overlay* technique.

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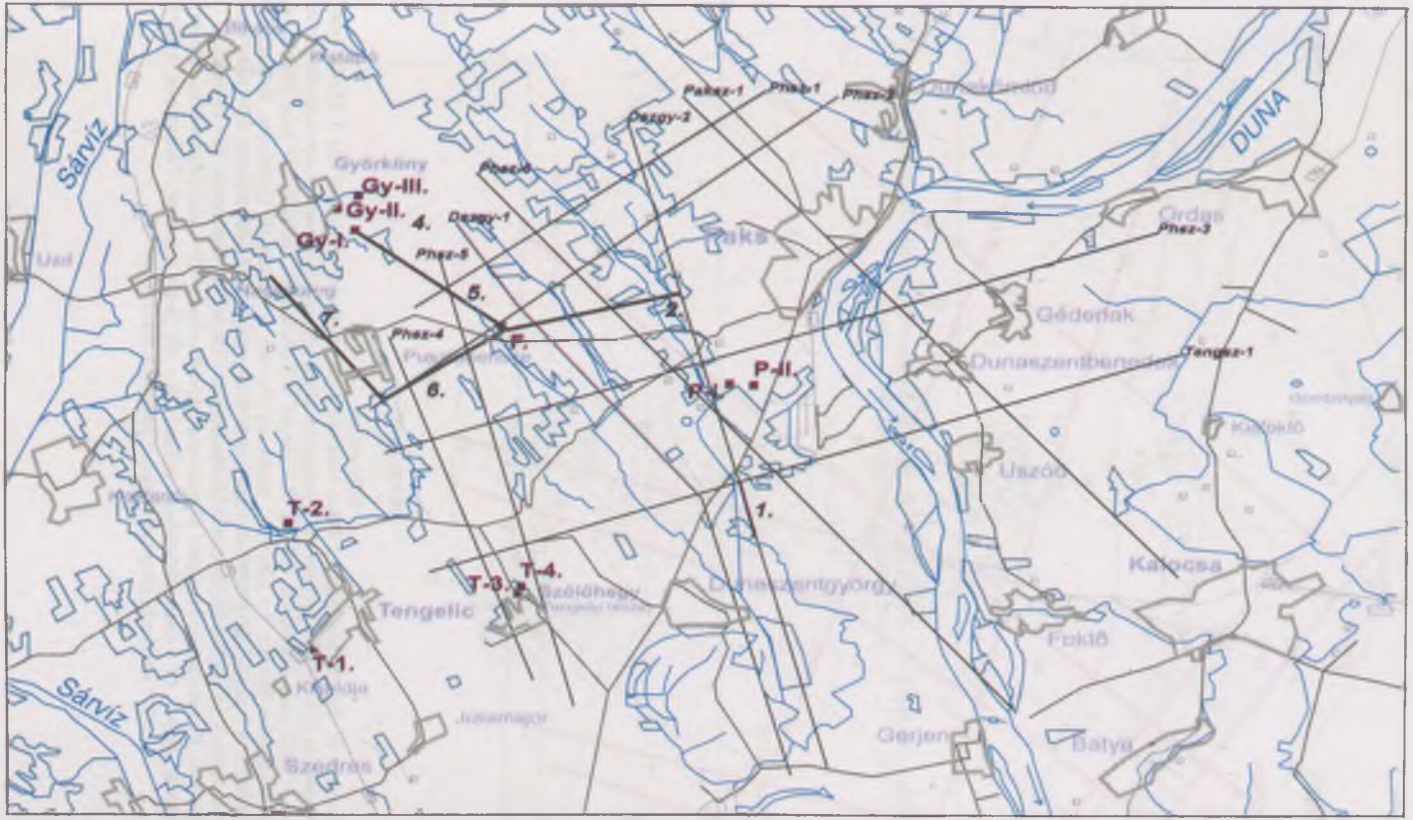

Fig. 1. Summarizing map of the surroundings of the NPP Paks – F, Gy–I-III, P–I-II, T–1-4 = position and denomination of artificial exposures created during the research; Dszgy–1-2, Paksz–1-2, Phsz–1-6, Tengsz–1 = 1:10,000 scale geologic profile inserted in the GIS database; 1-7 = 1:25,000 scale geologic profile inserted in the present volume

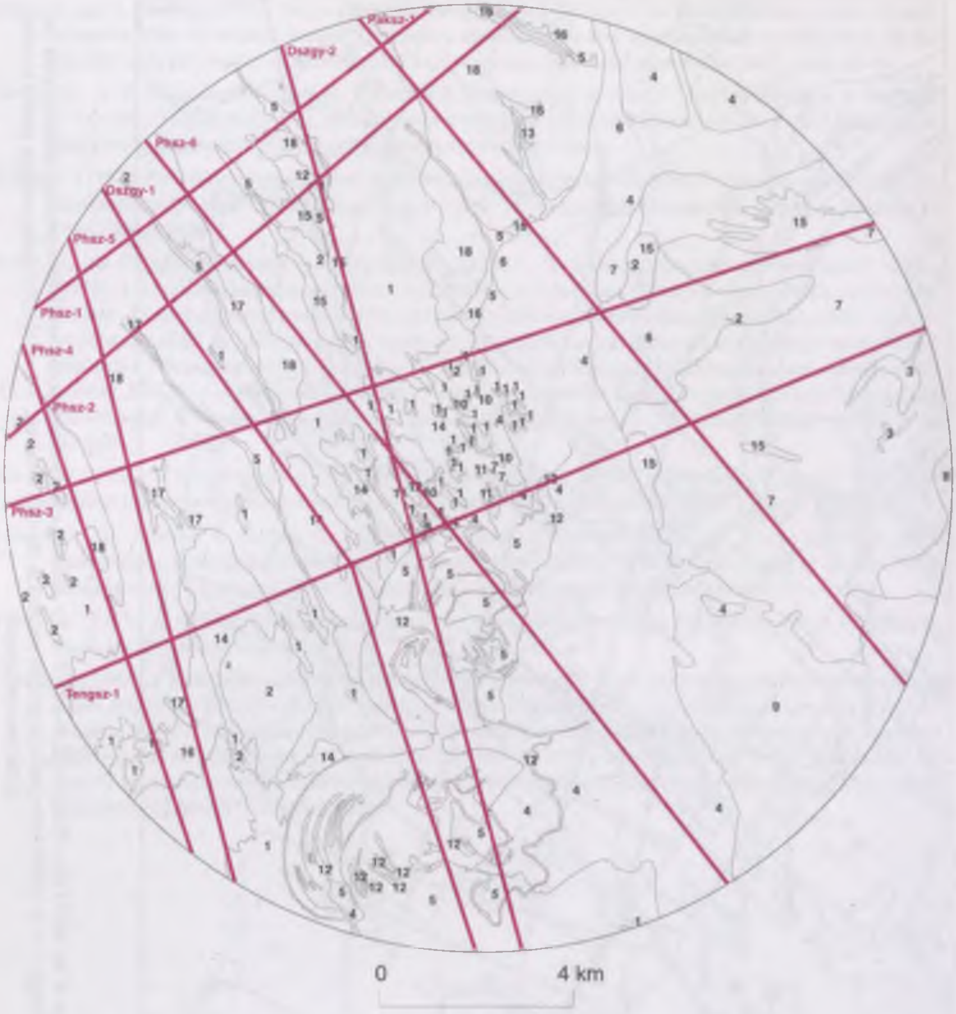

Fig. 2. Geologic map of the surroundings of Paks; simplified and reduced version of the 1:25,000 scale geologic map inserted in GIS (On the profiles the numeration of the separated formations corresponds to that on the map). – 1 = drift sand (Holocene, eolian); 2 = clayey silt (Holocene, limnic); 3 = peat (Holocene, limnic); 4 = sand (Holocene, fluvial); 5 = silty sand (Holocene, fluvial); 6 = sandy silt (Holocene, fluvial); 7 = silt (Holocene, fluvial); 8 = clayey silt (Holocene, fluvial); 9 = silty clay (Holocene, fluvial); 10 = silty sand (Holocene, fluvial-limnic); 11 = silt (Holocene, fluvial-limnic); 12 = clayey silt (Holocene, fluvial-limnic); 13 = silty sand (Holocene, fluvial-slope); 14 = sand (Pleistocene, fluvial-eolian); 15 = sand (Pleistocene, fluvial); 16 = silt (Pleistocene, slope); 17 = sand (Pleistocene, eolian); 18 = silt (loess sequence; Pleistocene, eolian); 19 = sand, silt, claymarl (Upper Pannonian, limnic)

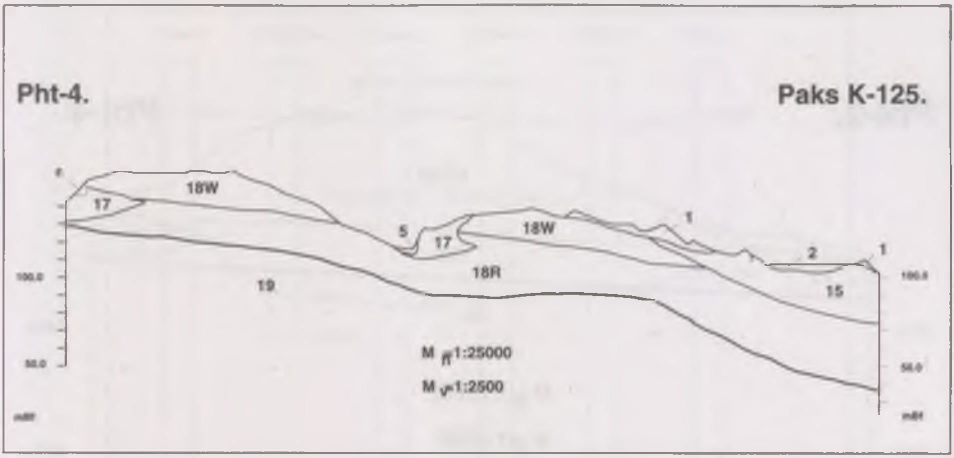

Fig. 3. Geologic profile between Pusztahencse-mapping-4 and Paks K-125 boreholes, representing the exposure of Földespuszta (F) (Profile No. 2)

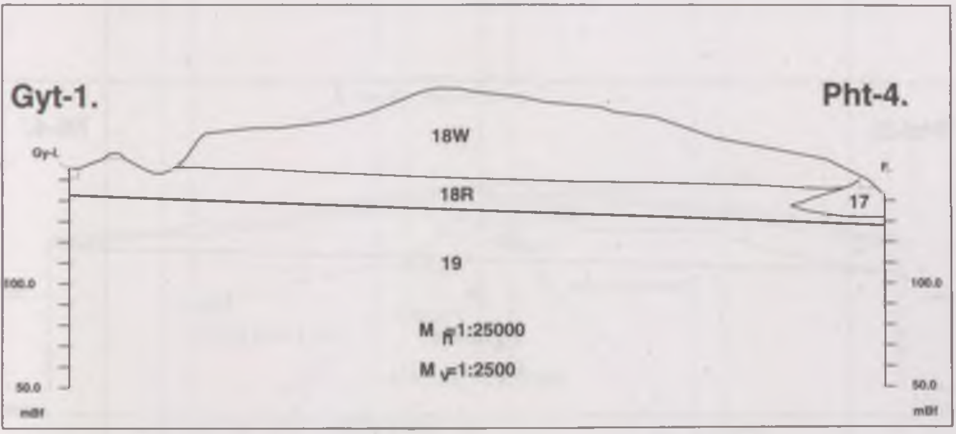

Fig. 4. Geologic profile between Györköny-mapping-1 and Pusztahencse-mapping-4 boreholes, representing the exposure of Györköny Gy-I. and Földespuszta (F) (Profile No. 5)

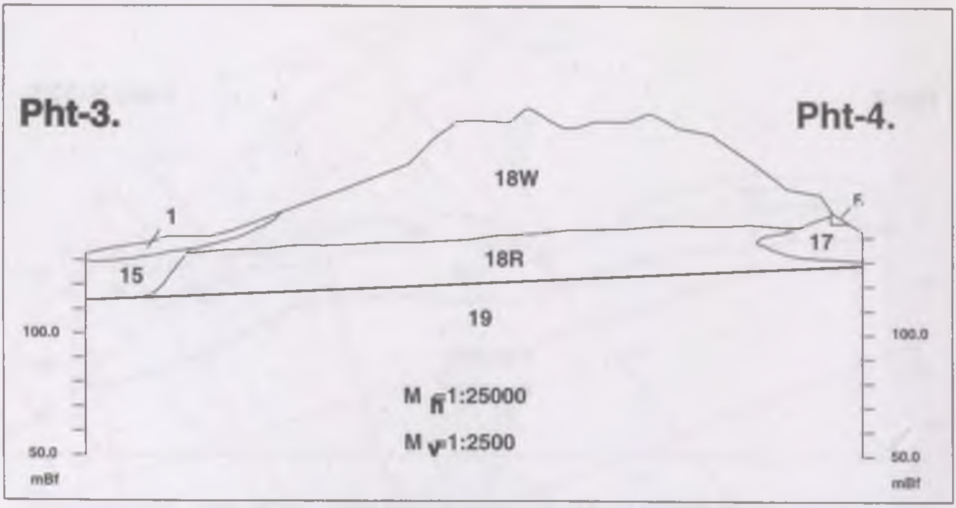

Fig. 5. Geologic profile between Pusztahencse-mapping-3 and Pusztahencse-mapping-4 boreholes, representing the exposure of Földespuszta (F) (Profile No. 6)

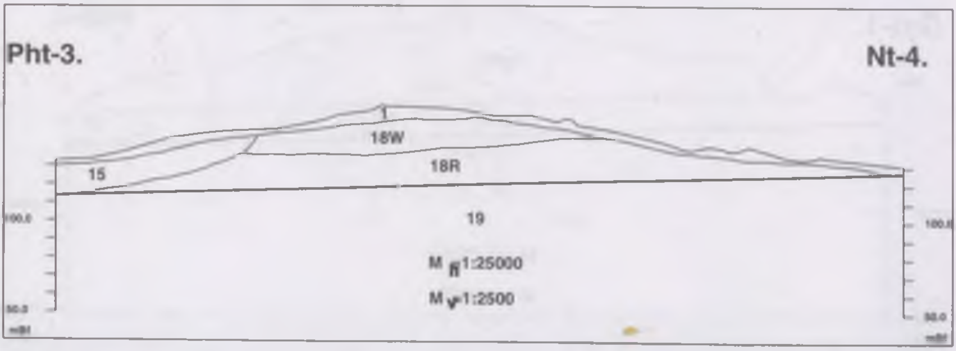

Fig. 6. Geologic profile between Pusztahencse-mapping-3 and Nagydorog-mapping-4 boreholes (Profile No. 7)

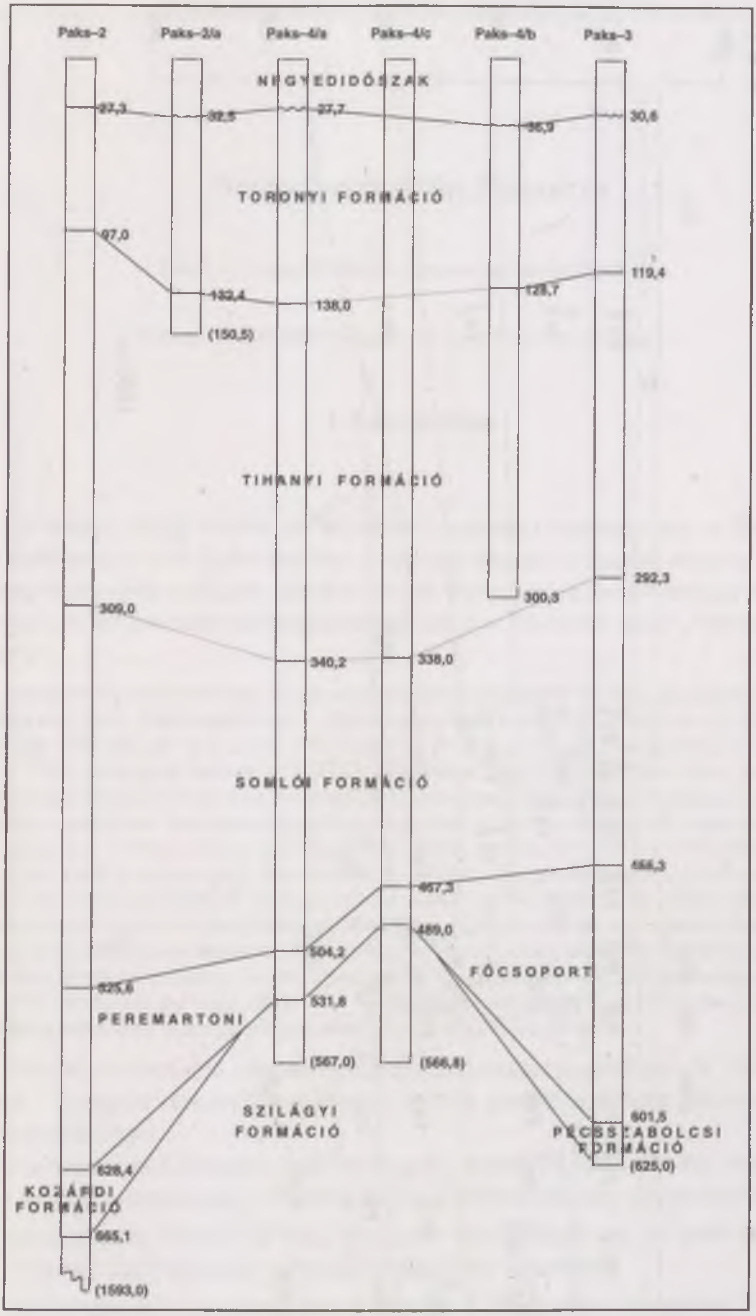

Fig. 7. Lithostratigraphic correlation of sequences from the boreholes deepened close to the Paks NPP

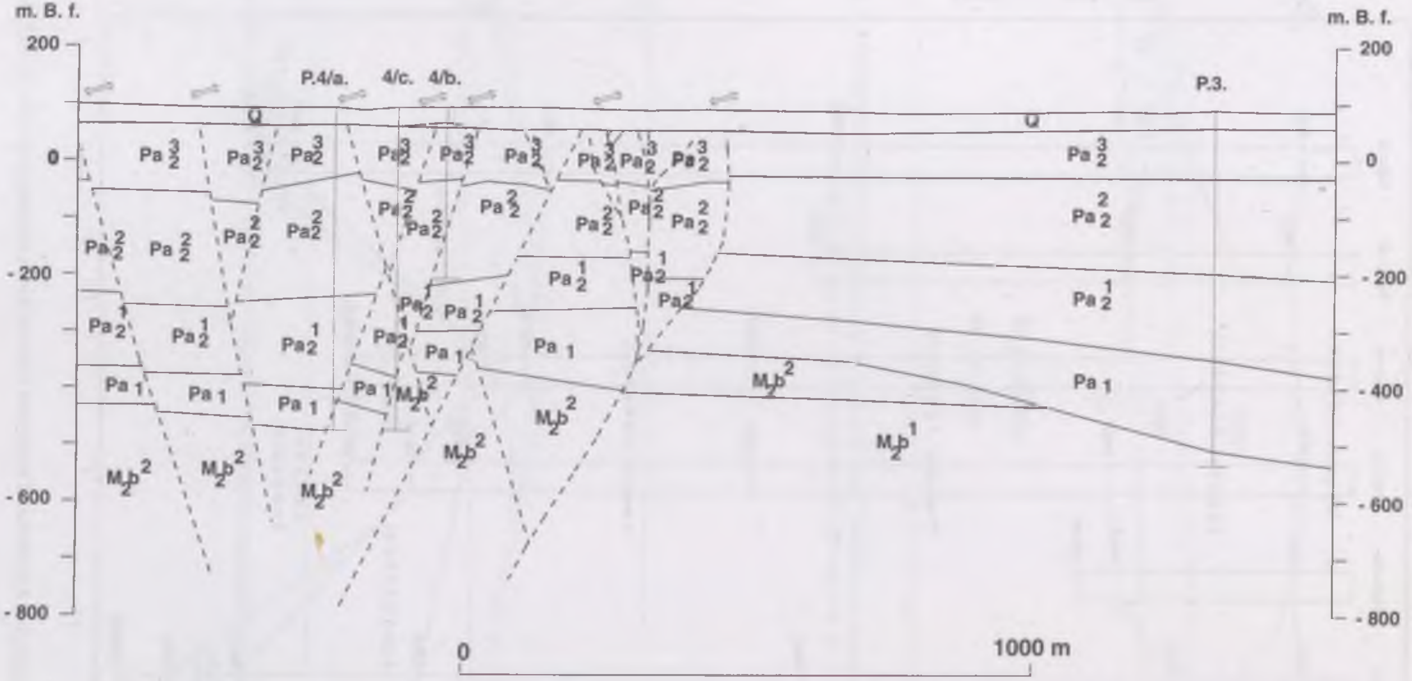

Fig. 8. Geologic profile between Paks-4/a and Paks-3 boreholes (Profile No. 1)

Neotectonics of the Paks area

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1. Introduction

In seismic safety studies, neotectonics is regarded important due to the connection of the earthquakes with faults and due to the fact that the youngest tectonic movements including those upon faults are subjects for the neotectonics. In the present study "fault" is used as a collective term for displacements such as "reversed fault", "strike-slip fault", "upthrow".

Neotectonics of the Paks area was intensely studied in late eighties and early nineties (Balla 1988, 1991, 1993, Balla et al. 1993, Chikán and Kókai A. 1989, Dudko 1992, Gerner 1993, Gracsov et al. 1987, 1989, Gúthy and Hegedűs 1990, Horváth et al. 1990, 1993, Meskó et al. 1993, Prónay and Gógh 1992, Újszászi and Zalai 1992). In 1994, Geological Institute of Hungary summarized and interpreted "geological, geophysical and geomorphologic data available for the area of the Paks nuclear power plant" and – involving numerous institutions from outside – performed "supplementary geological, geophysical and geomorphologic studies" (Bodrogi et al. 1994, Chikán et al. 1994a-b, Dudko and Maros 1994, Gúthy and Jánvári-Kántor I. 1994, Kókai et al. 1994, Kovacsvolgyi 1994, Kummer 1994, Schweitzer et al. 1994a-b, Stickel and Zalai P. 1994, Szabó et al. 1994, Szabó-Kilényi 1994) and compiled "a report with the analysis and summary of the results" (Balla 1995a) that was intended to be "basis for further studies in seismic risk assessment of the site of the Paks nuclear power plant". Data and results were incorporated in to GIS database (Turczi and Tullner 1994). For supplementary study of the faults in the Quaternary sequence, in 1995 detailed high-resolution reflection seismic survey was carried out (Gúthy 1995, Wittmann and Imre 1995). New results were correlated with those obtained earlier, and the neotectonic features were characterized in a more detailed way (Balla 1995b).

Below, neotectonic conclusions from the studies carried out in 1994–1995 are outlined. "Youngest" means "Quaternary", and the general approach consisted in distinct ideas was as follows:

- earthquakes in Hungary take place in the depths of numerous km, within pre-Cenozoic sequences, so controlling faults should be searched for within the basement;
- unambiguous proof for the "youngest" movements can be provided by faults bearing displacements within the Quaternary sequences;
- possibility to connect features in these two levels offers a working hypothesis on the generation of faults within the Quaternary sediments by rejuvenation of older faults in underlying sequences.

In harmony with these ideas, an analysis in an upward direction will be performed, starting with the basement and continuing with Miocene sequences – with the Pannonian sediments among them – and passing over to the Quaternary sequences based on knowledge from older formations. It will be investigated whether there are traces of the Quaternary rejuvenation of faults in deeper horizons.

We accept location of the Pliocene-Pleistocene boundary on 1.8 Ma. This simplifies the text since the red and variegated clay sequence ("Tengelic Formation") in the top of the Pannonian can be named "Pliocene" whereas the overlying sand and loess sequences, "Pleistocene". If the same boundary is located – in accordance with an alternative view – on 2.4 Ma, the lower boundary of the Quaternary would "shift" into the time span of the Tengelic Formation, but the age of that formation would not become closer to those 500,000 years that are considered lower boundary of the age of any tectonism to be taken into account in seismic risk assessment for nuclear power plants. In that case, changes would happen in the terminology ("Pliocene to Early Pleistocene" instead of "Pliocene" and "Middle to Late Pleistocene" instead of "Pleistocene"), but not in the conclusions themselves.

2. Tectonics of the basement

Tectonics of the basement will be analyzed in two steps, from the general gravity and magnetic anomaly pattern, in the first, and from the gravity effect of the basement, in the second step.

2.1. Gravity and magnetic anomaly pattern

In the Bouguer anomaly map *(Figure 1)*, a WSW-ENE oriented structure is visible. In the residual anomaly map *(Figure 2)*, it is clearly seen that an approximately 20 km wide strip, that is traceable from the SW corner up to the middle of the eastern frame of the map, is governed by WSW-ENE oriented structures whereas north of it there are SW-NE trending linear anomalies at about 40^o to it. The strip in question is the *"main zone"* in further discussion.

The most impressive magnetic anomaly of the area is located at Paks *(Figure 3)*. Based on the seismic section Du-6 cutting this anomaly Szabó-Kilényi (1994) supposed Miocene volcanites as the source rocks. The anomaly is trending in a SW-NE direction similarly to the gravity anomalies. A much less expressed magnetic anomaly chain is traceable across the whole area, approximately along the WSW-ENE oriented strip in the residual gravity anomaly map that support the structural distinction of the strip.

2.2. Gravity effect of the basement

In a gravity anomaly map that is free of the basement depth variations and of the effects imposed by density variations of basin fill, the Δ**g** values first of all reflect density distribution within the basement in an indirect way, displaying *gravity effect of the basement.* Since limitations owing to data insufficiency cannot be overcome, so application of precise and complex methods is doubtful, the simplest way – analysis of the Δ**g-h** relation – was chosen.

Dots, representing two-layer models with horizontal and infinite boundaries, with constant lowest-layer boundary and with the upper-layer thickness as the only variable, are arranged along a straight line with the directional tangent depending on the density difference between the two layers. This is the usual approach for the studies which analyze the Δ**g-h** relation in sedimentary basins and try to conclude on depths from gravity data for areas with no boreholes and seismic profiles. All the scientists clearly realize that results obtained that way are only valid in a statistic sense and approximately, nevertheless, regard these results satisfactory in cases when the dots are dispersed within relatively narrow zones. Large dispersion of the dots is a firm sign for variations beyond the basement depths. Due to the approximate nature of the method, the study below was restricted to a visual analysis and attempts to outline significant changes.

Δ**g** values have been read from the Bouguer anomaly map *(Figure 1)*, basement-topography data have been taken from boreholes (**h**, depth) and from seismic sections (**t**, travel times) interpreted by Szabó-Kilényi (1994).

30 boreholes reached the basement in the study area. Δ**g** values for different boreholes *(Figure 4)* have been compared in a following way. The density contrast on the sediment/basement boundary was taken 0.3 g/cm^3, and all the dots, each of them representing a single borehole, were shifted to the same depth along lines corresponding to that value. 1000 m b.s.l. has been chosen as the correlation depth since it crosses the dot population along its center. Δ**g** values read at this depth have been used in further manipulations.

Along the seismic profiles, both Bouguer anomalies and travel times have been read each 500 m and correlated in accordance with their position. Seismic data are arranged along a line, this made possible to analyze variations along the profile not only in a statistic way but also in a spatial sense. For this reason, dots have been connected with lines as they follow each other.

From the viewpoint of the Δ**g-t** correlation, those profile sections have been regarded "normal" in which the dots have fallen within a relatively narrow zone corresponding to the density contrast 0.3–0.4 g/cm^3. The fundamental idea of the analysis was that the "normal" dot arrays are characteristic for distinct geological models with no more details whereas the "anomalic" sections between them fall above model boundaries. The sections have been correlated by comparison of "normal" arrays and connecting "anomalic" sections. In he same way as in the case of the boreholes, Δ**g** values have been taken for the same travel-time level to make them free of depth variations. From the drilling data on the profiles, it became clear that 1000 ms in seismic sections approximately corresponds to 1000 m b.s.l. for boreholes. This made possible to compile gravity data corrected by drilling and seismic depths.

Most of the Δ**g** values for 1000 m b.s.l from boreholes in the eastern and southeastern segments of the study area fall on or is close to a surface that dips towards the north *(Figure 5).* In the south, where the gravity level is high, crystalline rocks are dominant in borehole cores whereas in the north, with low gravity level, Mesozoic rocks are typical. The boundary of these two domains can be located on 7–8 mGal in the diagram (1000 m b.s.l.) and between the boreholes Sol.1 and Sol.7, in the map. Based on data derived from seismic sections, the gravity "slope" can be extended onto the southwestern segment of the study area, and it seems possible to cover with it the main zone and its southeastern limb.

Within the 5–10 km wide strip accompanying the main zone from the north, from the seismic section marked "Pa" up to the section Ki-39, the Δ**g** values projected to the 1000 m b.s.l. horizon only vary between 2 and 6 mGal. In the northeast, this would fall within the "slope" trend for the main zone and its southeastern limb, however, in the west, in the immediate neighborhood of the high-gravity-level sector outlined by the southern sections of the seismic profiles and Pak-4, data from the "Pa" seismic sections indicate low gravity level. Accordingly, the northern boundary of the main zone is sharply expressed in the distribution of the Δ**g** values projected to 1000 m b.s.l. dividing a north-directed gravity slope from a strip with a constant gravity level for at least 40 km.

The relatively low (0,4 mGal/km) gradient of the gravity slope probably indicate deep source, so that statistic relationships between the gravity subdivision and the basement rocks are only probable. That is why the fact that the Δg values for the boreholes Sol.1, Sol.5 and Kk.K.1 slightly and that for the borehole Kec.1 significantly differ from the corresponding slope value as well as the fact that these boreholes and the borehole Kec.Ny.1 penetrated Mesozoic, not crystalline rocks can be interpreted in terms of local disturbances. The same is true for the fact that boreholes Solti.1 and Solti.3 reached crystalline, not Mesozoic rocks within the low-gravity-level strip.

Within the northern limb farther of the main zone, data from the profiles Du-6, Ki-63 and Ki-57 indicate an area of high gravity level with an excess up to 8–10 mGal as compared to the low-level strip. This area can be also contoured in the Bouguer anomaly map.

2.3. Conclusions

In gravity and magnetic anomaly maps *(Figures 1–3),* a 20 km wide zone running in a WSW-ENE direction can be outlined. In the map reflecting the gravity effect of the basement *(Figure 5),* it is accompanied in the north by a 5–10 km wide low-level strip. They together correspond to the first-order tectonic boundary of Hungary which follows the Kapos Line and then merges with the northern edge of the Szolnok Flysch Belt (Balla 1989). Along a line within the zone, gravity effect of the basement displays a sharp change that with a high probability can be related to crustal structure. This change is explainable in terms of large-scale strike-slip displacement upon the main zone so that basement domains now contacting on the zone arrived from large distance. In further discussion, the line cutting in the southeast the series of the SW-NE oriented residual gravity anomalies and at the same time limiting in the northwest the north-dipping gravity slope in the basement effect will be named "*main fault*".

Accompanying zone along the main fault is visible on the southeastern side in the original gravity maps whereas on the northwestern side in basement gravity effect map. The probable reason for this difference may consist in multistage evolution of the tectonic zone and its surroundings (various maps display information on various stages).

In the gravity effect of the basement *(Figure 5)*, northwest of the low-level strip a high-density area is visible, the Paks magnetic minimum being on its southern side. The southeastern boundary of this low is so straight that probably follows a fault. The contours of the high-gravity area seem to indicate a 17 km sinistral displacement, however, the displaced continuations of the magnetic low is absent. The fault approximately coincides with the inflexion line of a residual gravity anomaly couple.

3. Tectonics of the Miocene sequences

In the discussion of the structural pattern of the Miocene sequences, first, the faults will be analyzed, then, individual analysis of the distinct sequences will be given.

3.1. Faults

Faults are first of all known from seismic sections. Seismic sections of the Paks area have had several interpretations (e.g. Gracsov et al. 1989 or Horváth et al. 1990, 1993). The present analysis is based on faults in interpretation by Szabó-Kilényi (1994). Seismic profiles in the Paks area are subparallel and do not form network, so that the correlation of the sections generate special problems. Like in the study by Szabó-Kilényi (1994), gravity and magnetic maps *(Figures 1–3)* have been taken as a basis, however, some of the faults have been correlated in a new way. The most important element of the fault network at the base of the Pannonian sequence *(Figure 6)* is the main fault (**D**) depicted from the gravity and regional data. South of it, there are faults (**L, E, C'**) of the same SW-NE strike as north of it (**B, B', F', F**). As a consequence, three groups of faults are distinguished: the main fault, and the accompanying faults north and south of it.

The main fault is continuously traceable across the whole of the study area, although its expression in the basement topography is changeable. The youngest sequence cut by this fault is Late Pannonian in the eastern and middle parts of the area, west of the Danube, however, it becomes older; it is Early Pannonian in the Du-1 and Late Miocene in the Pak-4 sections.

The existence and position of the *northern accompanying faults* is clear within Miocene sediments and at their base, dip of them, however, usually being awkward. Faults are well-expressed in the basement topography so that they are traceable in gravity maps. Generation of the basins can be related to local extension, so that their relationships with the main fault can be interpreted in terms of sinistral strike slip upon the latter. The faults already existed at the beginning of the Pannonian, their rejuvenation – as flower structures within the Pannonian sediments – diminishes farther of the main fault: the flower pattern becomes simpler and passes over to single normal fault or to an uncertain pattern.

The *southern accompanying faults* are within the main zone delineated from the gravity and magnetic anomaly maps and running south of and parallel to the main fault. The faults cross the zone obliquely. Their orientation is similar to that of the northern accompanying faults, but they are poorly expressed in the residual anomaly pattern and do not play controlling role in the generation of the Miocene basins. It seems probable that the southern accompanying faults unlike the northern ones have only been generated due to the rejuvenation of the main fault.

The position of the fault **L** in the profile Pak-4 approximately falls on the southwestern continuation of the fault **B**, both of them having been rejuvenated. The fault **B** is markedly expressed in the pre-Pannonian Miocene basin structure, consequently, Pannonian sediments were faulted due to rejuvenation of a formerly existing fault. At the same time, the existence of the fault L in the pre-Pannonian Miocene structure is doubtful. It is a fundamental question whether the fault **L+B** existed before the Pannonian. The southwestern continuation of the Miocene basin in the northwestern limb of the fault **B** – as seen in the Bouguer anomaly map – turns onto the northern limb of the main fault, not continuing towards the fault **L**. As seen is the seismic section, the fault **B** controlled the evolution of the neighboring basin from the very beginning, probably, induced by the sinistral displacement upon the main fault. So, the fault **L** only got into the imaginary continuation of the fault **B** by the end of the strike-slip displacements and previously was situated west of its present-day site relative to the fault **B** at a distance corresponding to the magnitude of the horizontal displacement. In other words, the present-day relative position of the faults **B** and **L** seems to be accidental and cannot be used as an argument in favor of their connection. In spite of this, they could act in a similar way when the rejuvenation took place.

The *age of the rejuvenation* seems to be younger than the youngest Late Pannonian sediments in seismic sections since the faults either decease within or run out of the uppermost processed levels of the sections. This fixes the age of the faults within the time span from the latest Miocene up to the recent times but leaves open the question of the real age within this at least 4–5 Ma period.

The age would only be determinable more precisely in the case of documented upper age limits, but in the whole study area one single datum of this type exists: for the fault array E in the seismic section Pak-2, Szabó-Kilényi É. revealed that at 150 ms the uppermost layers unconformably cover faults and undulations in the deeper strata *(Figure 7)*. The unconformity is located 135 m below the base of the Quaternary, within the Pannonian sequence. This upper age limit is not necessary valid for any of the faults but clearly shows that at least some of the faults cutting Pannonian were formed not in the Quaternary, even not in the Pliocene, but within the Pannonian time. Consequently, it would not be reasonable to regard the faults running out upwards from the Pannonian strata in seismic sections as *proofs* of the Quaternary tectonism since these faults only demonstrate *possibility* of that tectonism.

3.2. Sequences

In subdivision of the Neogene basin fill, interpretation of seismic sections by Szabó-Kilényi (1994) has been accepted. The Pannonian sequence was best distinguishable. It is usually unconformly superimpose an older, also Miocene sedimentary sequence arranged by Szabó-Kilényi (1994) into Upper Badenian and Sarmatian. Below it, a sedimentary and a volcanic sequences are visible which can substitute each other and may be in various vertical relationships. Szabó-Kilényi (1994) arranged both of them into Karpathian and Lower Badenian. Tectonic character of the distinct sequences deduced from thickness maps.

Thickness distribution of the Pannonian sequence is demonstrated by its base topography map *(Figure 6)*. The base of the Pannonian is usually well seen in seismic sections, basins and highs are expressed in it, faults on their boundaries can be supposed. Upwards the basins and highs mostly disappear, displacements upon the faults diminish or cease.

Thickness distribution of the *Upper Badenian to Sarmatian sequence (Figure 8)* in general – sometimes with a shift – reflects the system of highs and lows in the base of the Pannonian in the northwestern limb of the fault **B**, in the southeastern limb of the fault **B'** in the profile Pak-2 and northeast of it, in the wedge between the faults **F** and **D** (main), and along the whole of the southeastern limb of the fault **D**. At the same time, there is a significant difference in the thickness distribution of those two sequences in the wedge between the faults **B** and **B'**, in the southeastern limb of the fault **B'** in the profile Pak-1 and southwest of it, as well as in the block between the faults **F'** and **F**.

Extension of the *Karpathian to Lower Badenian* sequence is much more restricted than that of either the Pannonian or the Upper Badenian to Sarmatian sequence. It is striking that in the northeast it wedges out in the strip where the profile "Pak" changes to "Ki", i.e. these profiles belonging to completely different sets, that is why this wedging out seems to be not quite proven. The thickness distribution *(Figure 9)* northwest of the fault **B**, furthermore, in the southeastern limb of the fault **B'** and northwestern limb of the fault **E** in surroundings of the profiles Pak-2 and Pak-3 shows an inverse pattern relatively to that of the Upper Badenian to Sarmatian sequence. These two distributions are also quite different in the wedge between the faults **B** and **D** west of the profiles Du-6 and Pak-3 as well as in the southwestern part of the block between the faults **L** and **E**, and they only resemble each other in the northeastern part of the block between the faults **B** and **B'**.

According to model calculations by Kovácsvölgyi (1994), the Paks magnetic low can be related to the remnants and root zone of a Miocene volcano. This low approximately falls onto the thickness maximum of the Karpathian to Lower Badenian sequence, i.e. the basin here is mainly filled with volcanites.

3.3. Conclusions

The governing structural element of the Paks area is the main fault (**D**) corresponding to the Kapos-Szolnok lineament. Towards the northeast and the southwest, accompanying faults divert from it, they control distribution of the basins demonstrating sinistral displacements upon the main fault. The structural pattern of the Karpathian to Lower Badenian, of the Upper Badenian to Sarmatian and of the Pannonian sequences is adjusted to this fault network. Some of the elements of that network (western ending of the fault **D** and the fault **F'**) are only expressed in the Pannonian as flexures.

Domes and basins of the Pannonian mainly arose in places of similar structures in the Upper Badenian and Sarmatian that is interpretable in terms of *inheritance*. At the same time, the most of the Upper Badenian to Sarmatian domes are superimposed onto Karpathian to Lower Badenian basins and *vice versa* that can be regarded as *inversion*. If the thickness contour lines in the areas of bad correlation with both evolution types is not due to errors in their location, both the inheritance and inversion should be considered partial.

Karpathian to Lower Badenian basins sometimes are partially or completely filled with volcanites which *in statu nascendi* could form topographic highs, so that further sedimentation could take place first of all nearby. This could result in inversion with no significant tectonic changes. Judging from the magnetic anomaly pattern, this is the case with the basin at Paks, and. from the reflection seismic pattern, with the section of the profiles Pak-3 and, maybe, Pak-2 between the faults **B'** and **D**, practically lacking in magnetic anomalies. It seems possible that the intra-Badenian inversion is not connected with a change in the sense of tectonic movements, but for a firm decision much more information would be needed on the distribution of volcanites.

Fault **B** is an important element of the tectonic pattern in general. It forms the boundary between the Pannonian and Badenian sediments in the core log of the borehole Paks-4a-c (Chikán 1997) and limits in the southeast the Paks magnetic low, i.e. Miocene volcanites, that – together with the Bouguer low in its southwestern continuation up to the profile Pak-4 – does not allow any transversal strike-slip displacement upon NW-SE trending faults like the assumed tectonic continuation of the Mór Trough (Horváth et al. 1990). Fault **B** is expressed in the gravity effect of the basement as a 17 km sinistral strike slip. It can be supposed that the strike slip occurred before the volcanism (that is why the magnetic source is not displaced) and was rejuvenated as a normal fault.

The main fault (**D**) was the site of a tectonic rejuvenation affecting the whole of the Pannonian sequence east of the Danube. West of the Danube, the rejuvenation is restricted to older and older sequences and probably vanishes in the west within 10 km. The rejuvenation becomes slighter along the accompanying faults, i.e. moving away of the main fault indicating a close relationship with the evolution of the latter. In the vicinity of Paks, the rejuvenation of the main fault finished earlier than that of the fault B, this pointing to the complex nature of those relationships.

4. Tectonics of the Quaternary sequences

In deep horizons of the Quaternary sequence, attempts to reveal faults have been made by high-resolution seismic survey. In *near-surface layers*, faults and joints have been studied in outcrops and artificial exposures, including trenches. In geomorphic and geologic maps which characterize the *Earth's surface*, there are a lot of linear structures, they have been studied in satellite images.

4.1. Deep horizons: high-resolution seismic sections

Of the high-resolution seismic sections surveyed in 1989 for detecting faults (Gúthy and Hegedűs 1990) the section Pa-8 produced results worth of disputing. It crossed fault **B** which in 1994–1995 was crossed by the profiles Pa-12, 13, 14 and 15 (Gúthy and Jánvári-Kántor 1994, Gúthy 1995) as well.

After the loose, disintegrated, sandy cores from the Quaternary sediments, Pannonian sediments appear in solid cores of constant shape that is a significant, even visually well recognizable mechanical change occurs on the sequence boundary. In high-resolution seismic sections, this boundary alone cannot be identified and can only be drawn putting borehole data in the section. The reflection pattern of the Quaternary sediments is usually far of that which could be described in geological terms. For instance, the most general feature of the fluvial sediments, i.e. the lenticular structure, is practically absent, and in the fragments with seemingly good stratification there is no marker horizon. This generate doubts concerning the idea that the reflectors in the sections everywhere coincide with layers, so that the most convincing criterion for tracing faults in sedimentary sequences, i.e. displacement of marker horizons, seems to be loosen.

In the structure of the Quaternary sediments displayed in high-resolution seismic sections, two remarkable features are seen: a zone poor in signals (in stacking sections) and a trough-like depression (in migrated sections). In the sections Pa-8 = Pa-12, Pa-15 and Pa-13, they occur together and follow in a map a filled-up Danube ox-bow (Figure 10). Here, the grounding conditions may get impoverished on the marshy ground, on the other hand, in a lens wedging out along the profile loose sediments, badly conducting seismic waves can be present. In both cases, local deficiency in energy – seismic shadow – is expectable, it is probably reflected by the vertical zone poor in signals.

Based on the static correction curve for the profile Pa-12, it can be supposed that between 82 and 90 m a.s.l. there is a velocity low that points to a change in lithology. In the geoelectric sounding curve (Stickel and Zalai 1994), a low-resistivity layer is detected at 84–90 m a.s.l., and a high-resistivity layer, at 63–75 m a.s.l. Both of them point to the presence of lenticular bodies within the Quaternary sequence with lithological composition different of that of the surrounding rocks. These lenses may have seismic velocities needed to consume energy In the sections Pa-15 and Pa-13, the velocity anomaly is absent, this being only true for the layer removed from-above the section during the processing, and in the near-surface horizon of the sections, this lens can be present. Local velocity low results in increasing travel times, and if it is not taken into account during the processing (this is the case with the sections in question) reflectors in deeper horizons will be pushed down. The trough-like depression is probably related with this phenomenon.

It can be concluded that there are unsolved problems in the seismic display of the Quaternary sediments, so that the direct structural interpretation of the reflection pattern is not convincing. Help can be given by the good stratification of the Pannonian sequence: those of the faults within the Quaternary sediments can only be accepted which fall onto the direct upward continuation of the faults which displace Pannonian sediments. In the high-resolution seismic sections of the Paks area, however, no case of this type can be proven.

4.2. Near-surface horizons: measurements of joints

The first joints – 104 in 12 Pleistocene exposures – were measured by Chikán and Kókai (1989). During the geological mapping of the 30 km area around the nuclear power plant (Chikán 1992), 1379 joints were measured in 167 outcrops of Quaternary sediments

(Dudko 1992). The results were processed and interpreted by Dudko (1992), Gerner (1993) and Balla (1994). In 1994, more 634 joints were measured in 6 outcrops (Dudko and Maros 1994), so, the total data volume exceeded two thousand.

The surface of the joints is smooth or slightly undulating. For the geologists, this was an evident proof of the shear, *i.e.* tectonic origin of the joints. In combination with the prevailingly steep, subvertical position of the joint planes this fact suggested shear stress in early interpretations (Horváth et al. 1990, Balla 1991).

The values in the summary rose diagram for the joints measured in 1992 *(Figure 11)* are dispersed between 3.75 and 7.70%, *i.e.* within a very narrow interval around the 5.56% expectable for the completely uniform distribution, not showing any definitely preferred orientation. That is why the data were filtered for the tectonic interpretation: removed were joints qualified already in the field as "slump-derived" (Dudko 1992) or those which could be related to the slope and outcrop orientation (Gerner 1993) also recorded in the field. The remaining data assemblage showed three maxima, in a WSW-ENE, WNW-ESE and NNE-SSW directions.

Although this induced attempts in tectonic interpretation (Dudko 1992, Gerner 1993), the fact that joints are not concentrated in a some km wide strip above the main fault generated heavy doubts concerning the tectonic origin of the whole of the joint assemblage or even of its significant portion (Dudko 1992).

The angles between the three maxima *(Figure 11)* are roughly 60°, and the weight of the three maxima is approximately the same. This depicts a hexagonal system which is similar to that originated from the contraction of sheet-like rock masses, *e.g.*, in cooling of basalt lava flows (Balla 1994). 165 of the 167 outcrops and 1335 of the 1379 joints were in loess, consequently, the measurements first of all characterize *loess.* It seemed to be possible that the hexagonal system is related with the desiccation of the loess.

In order to throw light upon the problem, in 1994 all the outcrops were documented in details: the exposure bottom line and the position of the joints were fixed in plans. In the outcrops studied, each 1–3 m a joint occurred, their frequency being changeable, mostly as a function of the exposition. 83% of the 634 joints measured in 1994 were in two neighboring outcrops *(Figure 12)* with different distribution. Since the orientation maxima are different even in the outcrops located in some hundreds of meters, they cannot characterize a stress field stable in space. The dominating in 1992 directions could not be reproduced even in outcrop groups within some km^2.

The rather high frequency, depending on the exposition features, the low representativity and the bad reproducibility are in harmony with the non-tectonic origin. In the framework of this idea both the frequency and the preferred orientation are due to local factors: most of the joints are planes bordering slumped blocks or desiccation fissures. The joints originated from slumping limit rectangular blocks. Hexagonal jointing was nowhere observable directly, its existence could only be inferred from rose-diagrams and still needs to be confirmed by data beyond the statistics.

In 1992, an attempt was made to reveal faults by trenching. Trenches were excavated after two-stage geophysical survey in the sites which seemed to be most suitable (Meskó et al. 1993). In the approximately 1800 m^2 rock surface exposed in the 500 m trenches, there were absolutely no joints or faults (Chikán-Jedlovszky et al. 1992). This fact is in sharp contrast with the fact that in the outcrops usually in each 1–3 m there was a joint. It seems therefore probable that the joints are not present as distinct planes within the original rock mass and only appear subsequently, near the earth's surface that is possible due to both desiccation or disintegration/loosen but as a consequence of tectonic stresses. In some of the outcrops, joints which were well visible in the wall disappeared within the rock mass when the wall was being demolished, so that the near-surface origin of the joints could be directly proven.

4.3. Earth's surface: lineaments on satellite images

The advantage of the lineaments in satellite images consist in they can be studied evenly whereas their disadvantage is due to the fact they can be originated in various ways. Interpretation of the lineaments in satellite images for the Paks area can be found in works by Horváth et al. (1990, 1993) and Bodrogi et al. (1994), here the latter is used.

Numerous attempts in the field of automatic processing of digital satellite images Landsat TM and SPOT P were made in order to reveal possibilities to detect tectonic lineaments. In the highly variable pictures obtained, the faults known from the seismic sections are usually not recognizable. In some areas, the question of the relationships with some of the faults can be put *(Figure 13)*, but the connection is highly uncertain. This is best reflected by the fact that none of the pictures alone or any combination of them would form basis for delineating concrete faults: there are too many similar "lineaments" far of any of the faults.

4.4. Conclusions

In the high-resolution seismic section Pa-8 = Pa-12, a zone poor in signals is visible above the fault **B** in the Pannonian sediments; primarily it was regarded as a proof of the Quaternary rejuvenation of the fault. Later sections made clear that the zone in question follows a Danube ox-bow and its origin is probably due to grounding problems and lithological screening. The reflection pattern of the Quaternary sediments is rather uncertain in seismic sections, convincing features in favor of faults – first of all, displacements of marker horizons – are not available.

Distribution of the joints in exposures and lineaments in satellite images is similar: only some of the preferred orientations can be related to the known faults, not the spatial position and distribution of them. Most of the concrete lineaments in satellite images and joints in exposures conform to the elements of the present day topography. Consequently, the fact that their tectonic origin is full of doubts confirms at the same time the reservations concerning the direct relationships between the topography and tectonics (Balla et al. 1993).

5. Summary

From the gravity and magnetic anomaly pattern, a 25–30 km wide WSW- ENE trending dislocation zone has been delineated in the basement of the Paks area which can be identified with the Kapos-Szolnok lineament. From the same anomalies as well as from seismic sections, a definite fault or narrow fault zone – the "main fault" – has been detected. It is accompanied from both limbs by SW-NE striking faults with Miocene basins within the northwestern limb. This depicts sinistral displacement upon the main fault and normal faults on the basin boundaries. Three generation of the basins have been distinguished: a Karpathian to Early Badenian, a Late Badenian to Sarmatian and a Pannonian one. Inversion between the first two and inheritance between the last two seem to have taken place.

The Pannonian sequence is crossed by flower structures above almost all the earlier faults, these structures have been related to the rejuvenation of the tectonic movements. Most of the faults "run out" upwards from the seismic sections which do not reach the Quaternary sequence. The fault network and the anomaly pattern excludes any significant displacement upon occasional NNW- SSE trending faults. The rejuvenation of the main fault is traceable from the ENE up to the Danube, then it ceases within 10 km, and is transferred onto SW-NE trending faults in each of the limbs. Of them in the northern limb the fault B runs below the nuclear power plant.

Numerous high-resolution seismic profiles were surveyed in that area for studying the deep horizons of the Quaternary sequence, but no convincing trace of the Quaternary tectonism was visible in them. In natural outcrops and artificial exposures of the Quaternary sediments, there were more than two thousands of measurements of joints. Position and orientation of the joints did not reflect the fault network known in the Pannonian sequence. In several cases, wedging out of the joints towards the interiors of the rock masses was observed, and no joints were detected in newly excavated trenches. Consequently, most of the joints or even all of them were generated after the exposition and are non-tectonic in origin. Lineaments obtained from the automatic and manual processing of the digital satellite images also did not reveal convincing relationships with the faults in the Pannonian sediments. As seen, no firm traces of the tectonic rejuvenation have been found in Quaternary sediments. At the same time, most of the joints in exposures and lineaments in satellite images are in certain relationships with the present day topography, thus, the elements of the latter also cannot be related to the faults.

Fault-related tectonic movements within the Pannonian to Quaternary sequence can be expected first of all in the time span corresponding to the deposition of terrestrial red to variegated clays in the Pliocene (maybe, up to the Early Pleistocene), therefore, faults in the Pannonian can be aged as Pliocene. Possibility of a later, Quaternary rejuvenation cannot be excluded as well, but convincing data would be needed for the confirmation; they are not available for the time being.

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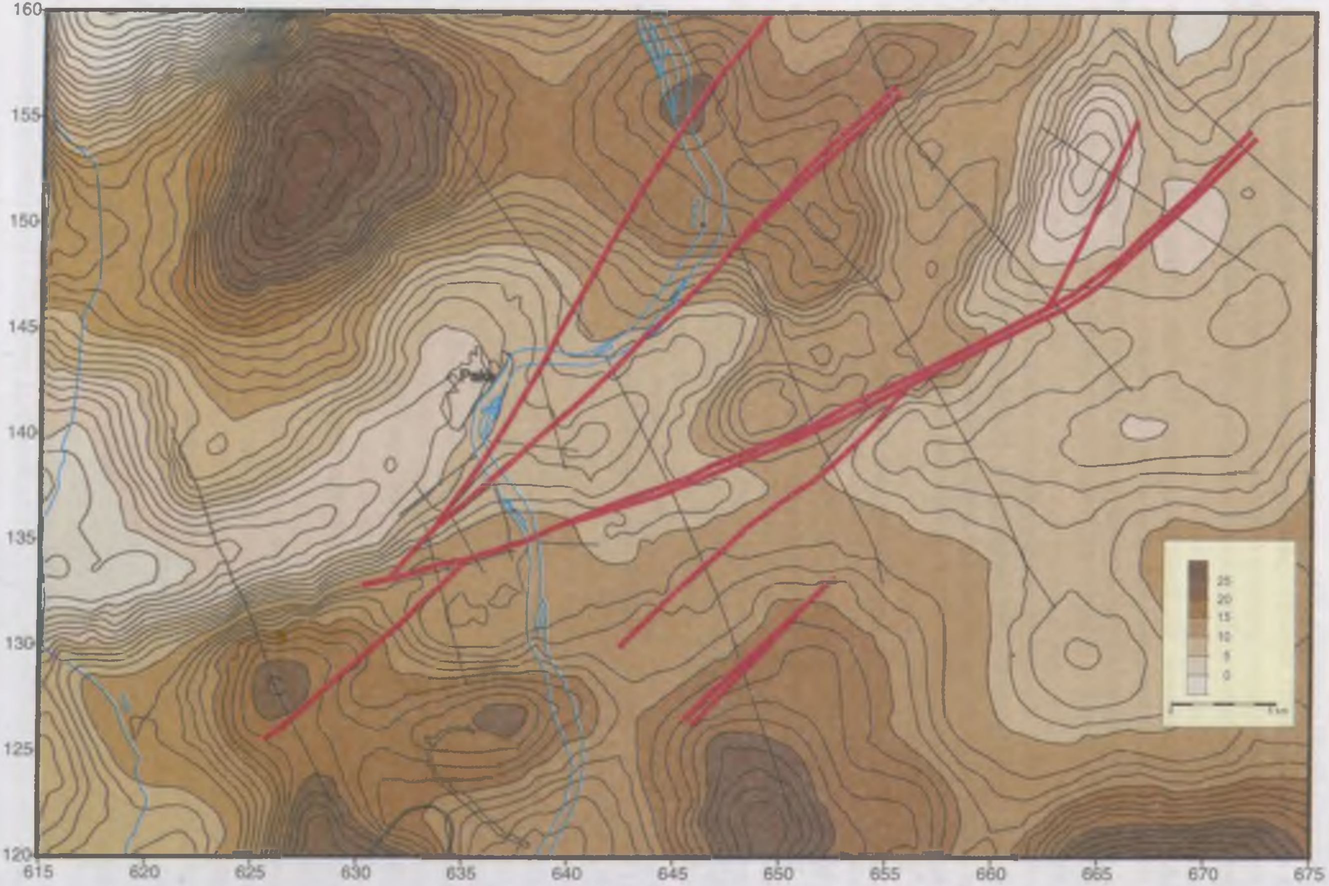

Fig. 1. Bouguer anomaly map for the Paks area. Compiled by S. Kovácsvölgyi from the database ELGI 1995a; faults from *Figure 6*. For location, see insert in *Figure 9*. Contour line spacing = 1 mGal, color spacing = 5 mGal

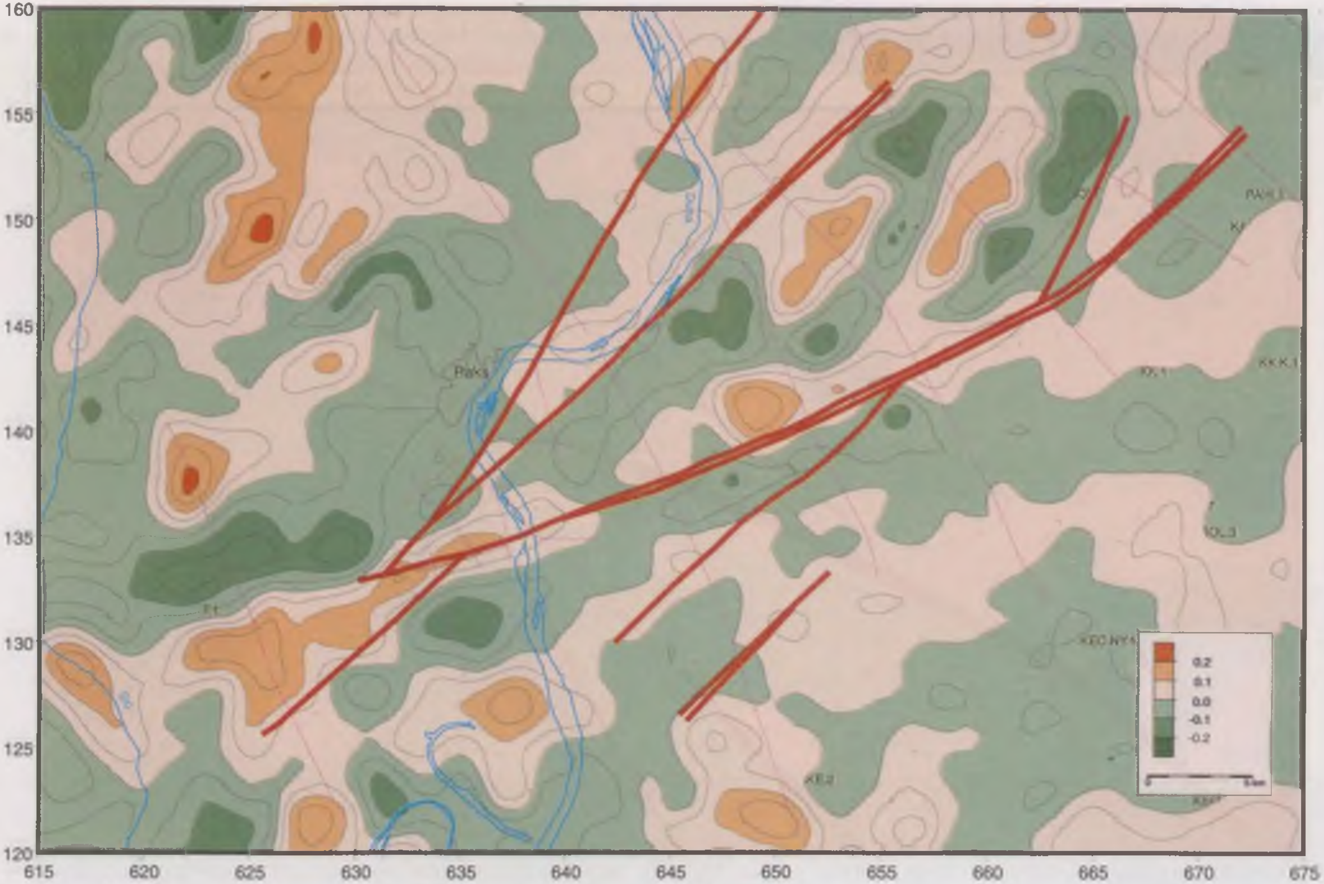

Fig. 2. Residual gravity anomaly map for the Paks area (κ=9-8). Compiled by S. Kovácsvölgyi from the database ELGI 1995a using filtering parameters given by Z. Páncsics; faults from *Figure 6*. For location, see insert in *Figure 9*. Contour line spacing = 0.1 mGal, color spacing = 0.5 mGal

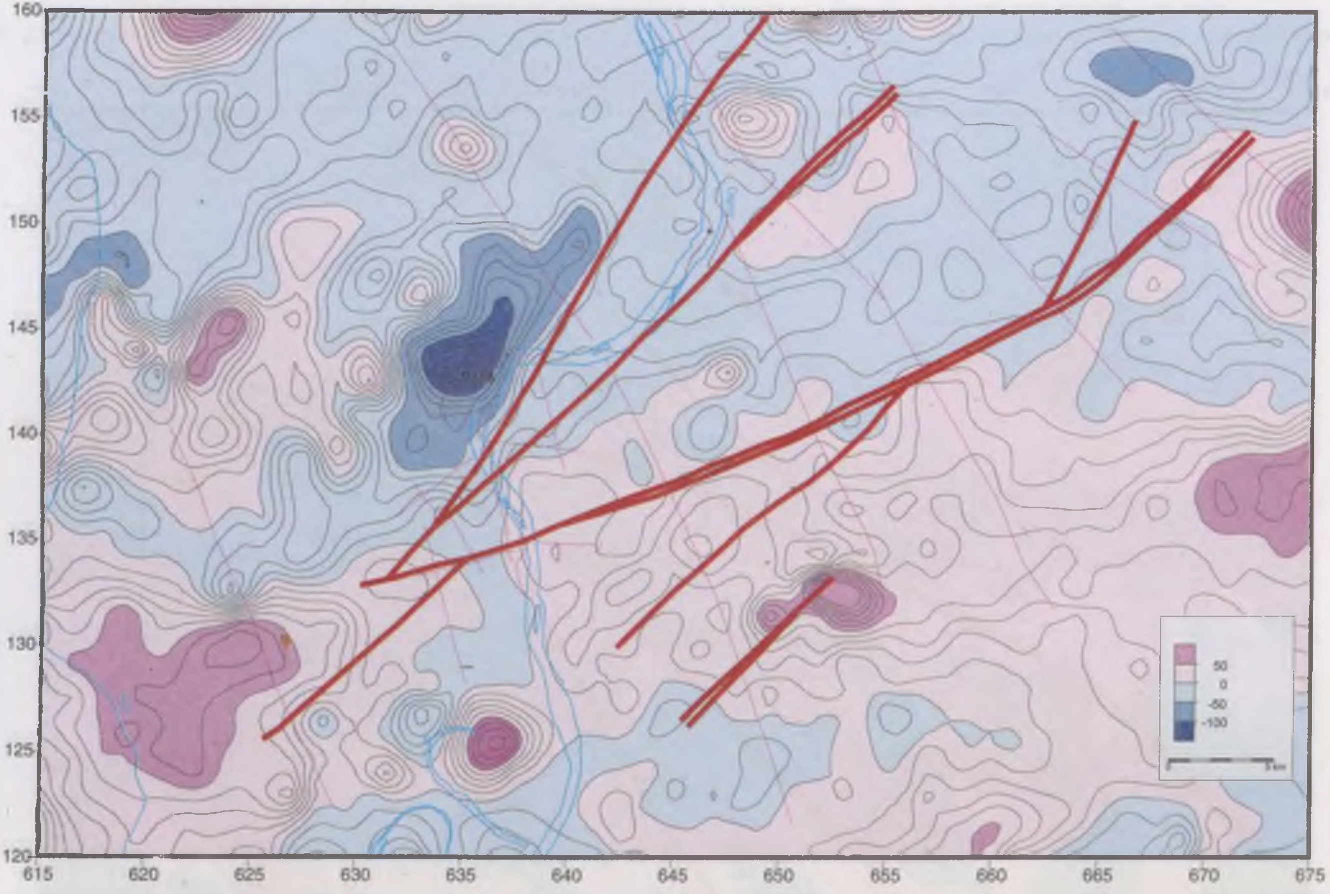

Fig. 3. Geomagnetic ΔZ anomaly map for the Paks area. Compiled by S. Kovacsvölgyi from the database ELGI 1995b; faults from *Figure 6*. For location, see insert in *Figure 9*. Contour line spacing = 10 nT, color boundaries = 50, 0, 50, and 100 nT

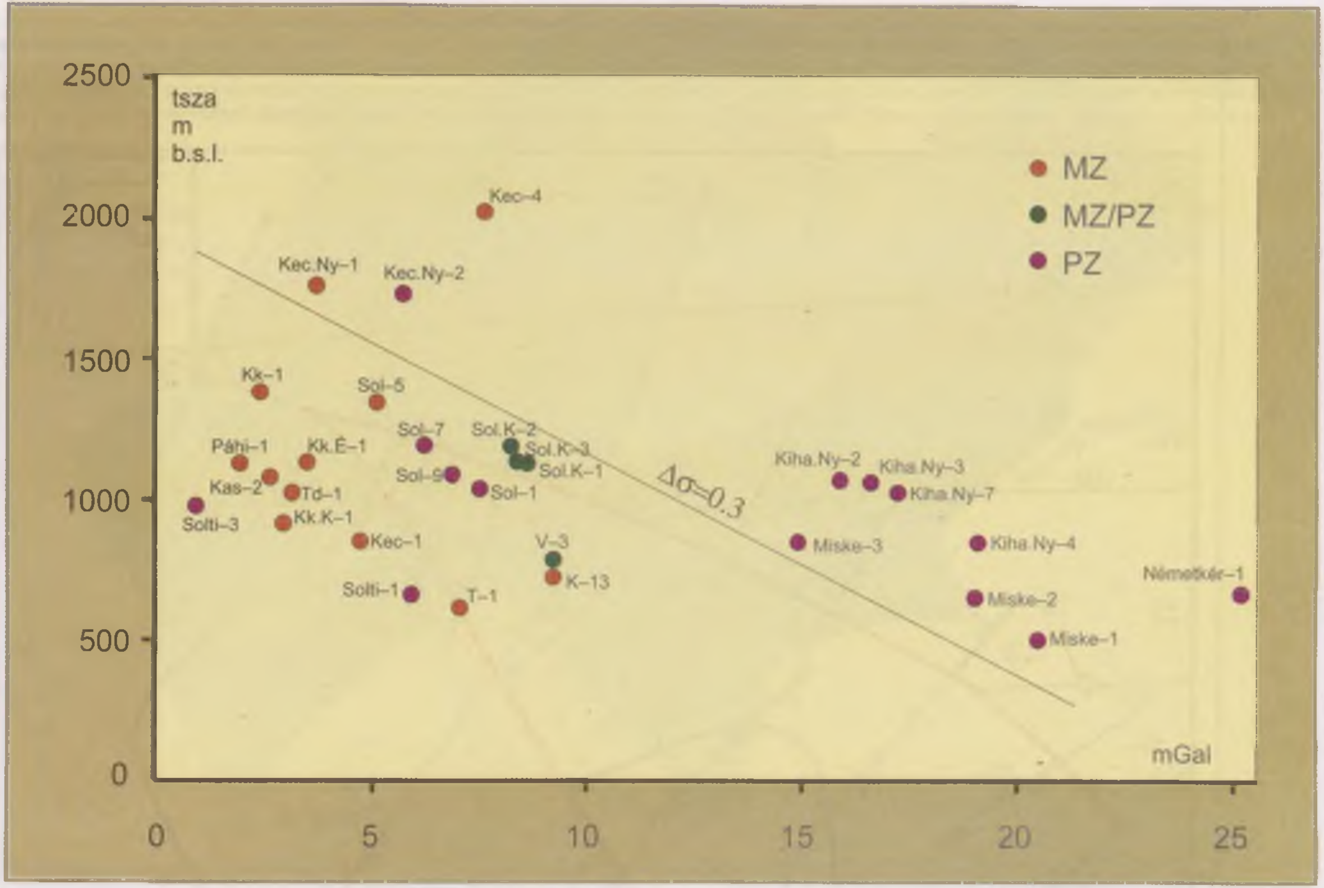

Fig. 4. The mGalm diagram for the boreholes with basement rocks in the Paks area. Compiled by A. Dudko 1995 (in Balla 1995b: *Figure 17*)

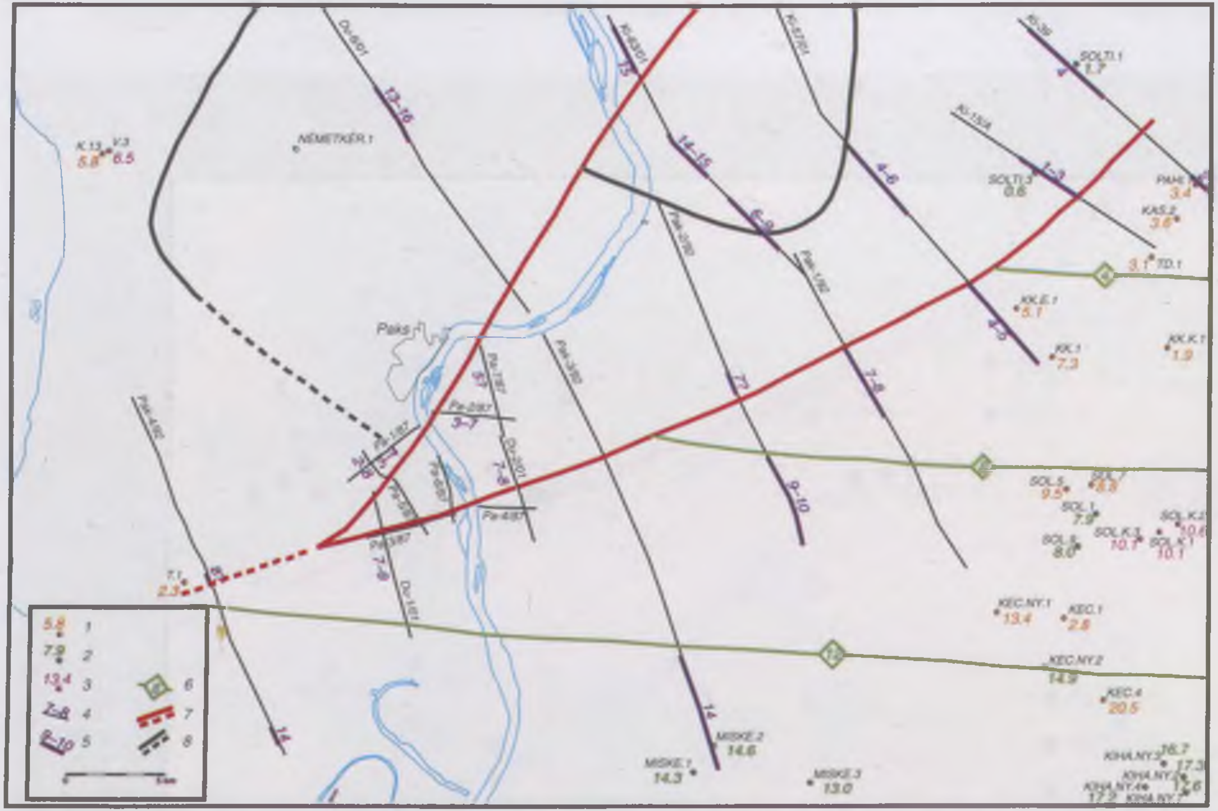

Fig. 5. The map of the basement gravity effect in the Paks area for the horizon about 1 km b.s.l. (Balla 1995b: *Figure 23*). For location, see insert in *Figure 9*. – 1-3 = type of the basement in a borehole and mGal value calculated for 1 km b.s.l.: 1 = Mesozoic, 2 = crystalline below Mesozoic, 3 = crystalline; 4 = section of a seismic profile with the mGal value calculated for 1 s; 5 = section of a seismic profile with well-expressed basement and with the mGal value calculated for 1 s; 6 = mGal value and contour line inferred for 1 km b.s.l.; 7 = fault within the basement; 8 = contour of the area with high mGal values, from the Bouguer anomaly map and magnetic anomaly pattern

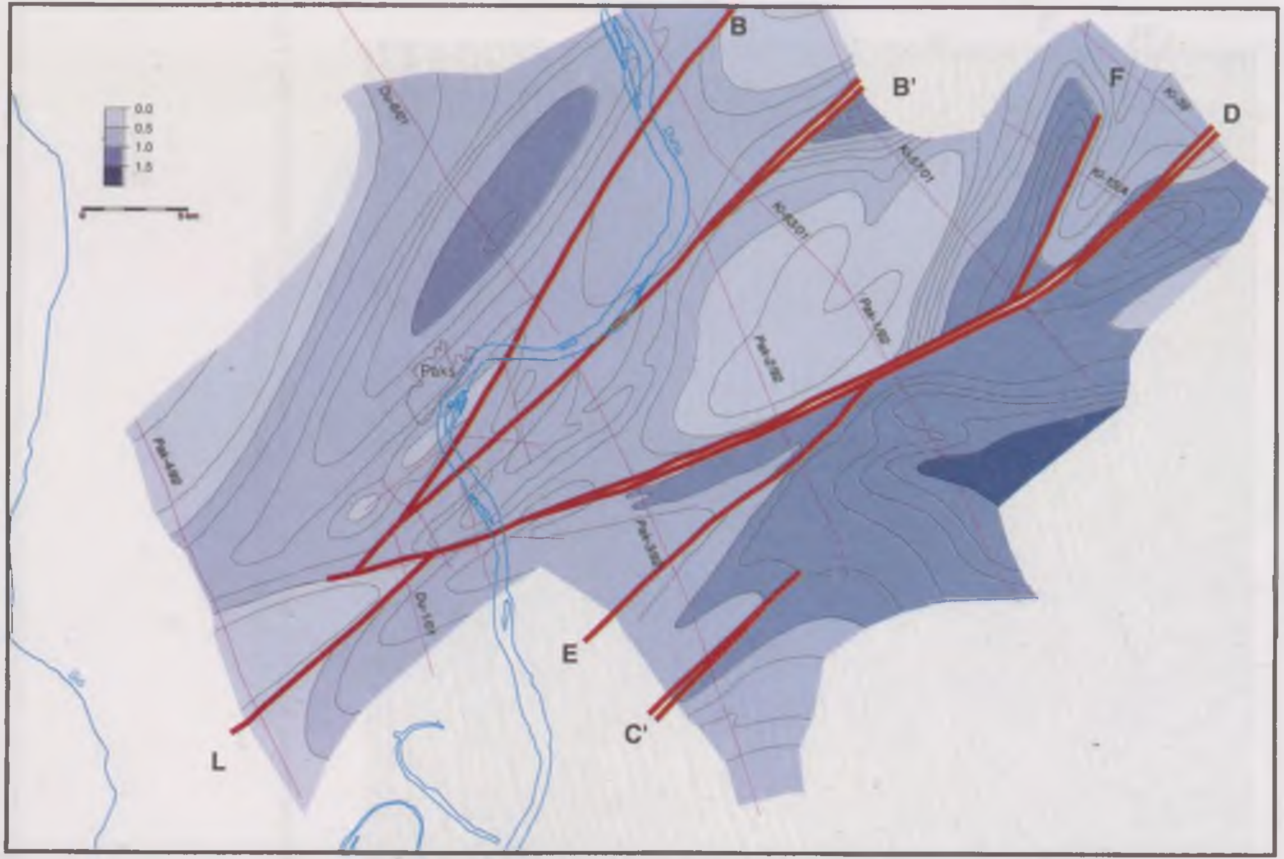

Fig. 6. Base Pannonian map for the Paks area. Compiled by A. Dudko 1995 (in Balla 1995b: *Figure 9*). For location, see insert in *Figure 5*. Contour line spacing = 0.1 s

Fig. 7. Horizon closing faults in the upper part of the Pannonian sequence (after Szabó-Kilényi 1994: *Figure 11*), fragment of the section Pak2 with the fault E

Fig. 8. Thickness map of the Upper Badenian to Sarmatian sediments in the Paks area. Compiled by Z. Balla, 1996, as a difference map from the maps for the bases of the Pannonian and Upper Badenian to Sarmatian sequences (Dudko 1995, in Balla 1995b: *Figures 9–10*). For location, see insert in *Figure 9.* Contour line spacing = 0.1 s

Fig. 9. Thickness map of the Karpathian to Lower Badenian sequence in the Paks area. Compiled by Z. Balla, 1996, as a difference map from the maps for the bases of the Upper Badenian to Sarmatian and Karpathian to Lower Badenian sequences (Dudko 1995, in Balla 1995b: *Figures 10-11*). For location, see insert. Contour line spacing = 0.1 s

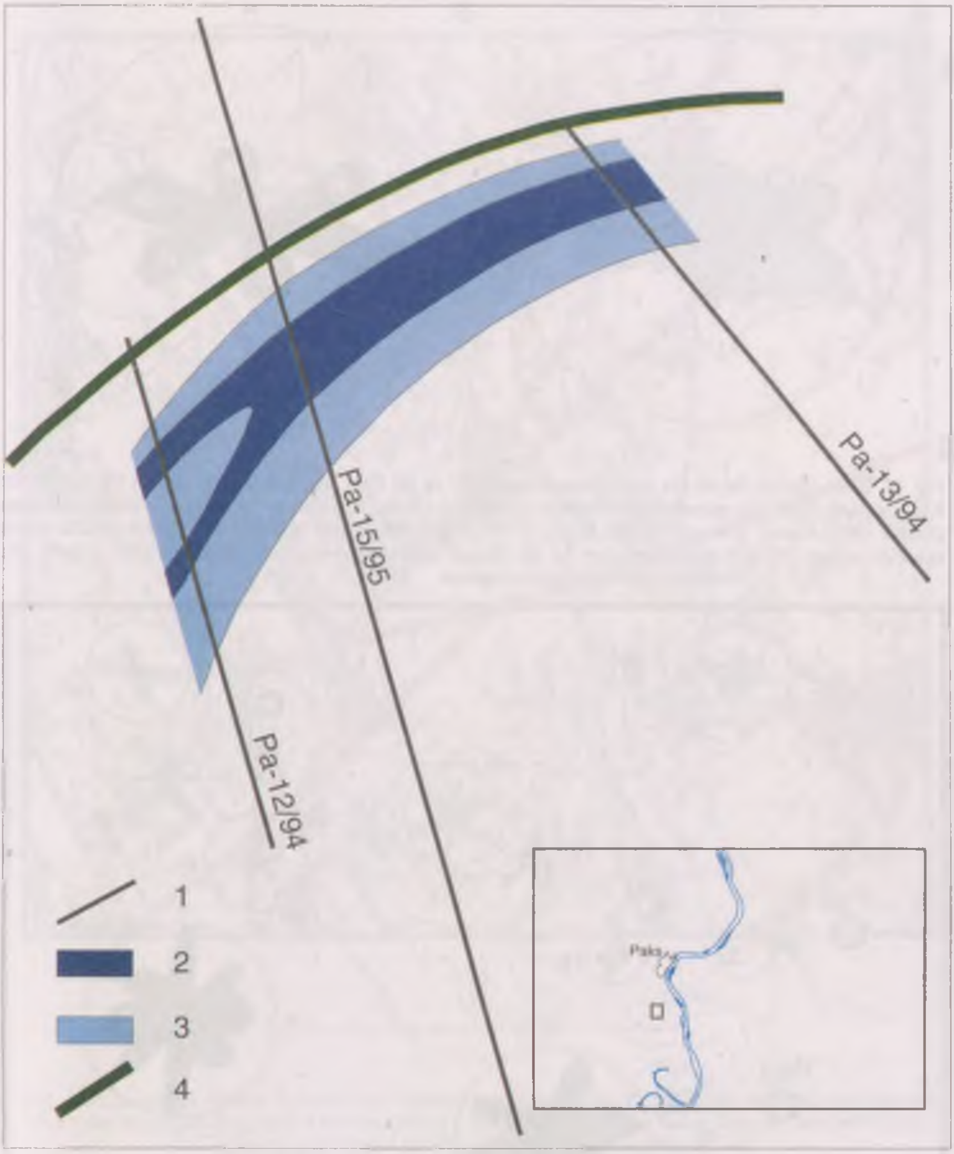

Fig. 10. Connection of the trough-like depression in the reflection pattern of the Quaternary sediments and of the zone poor in signals below it with a Danube ox-bow. For location, see insert. – 1 = high-resolution seismic profile; 2 = zone poor in signals; 3 = trough-like depression; 4 = outer edge of the Danube ox-bow

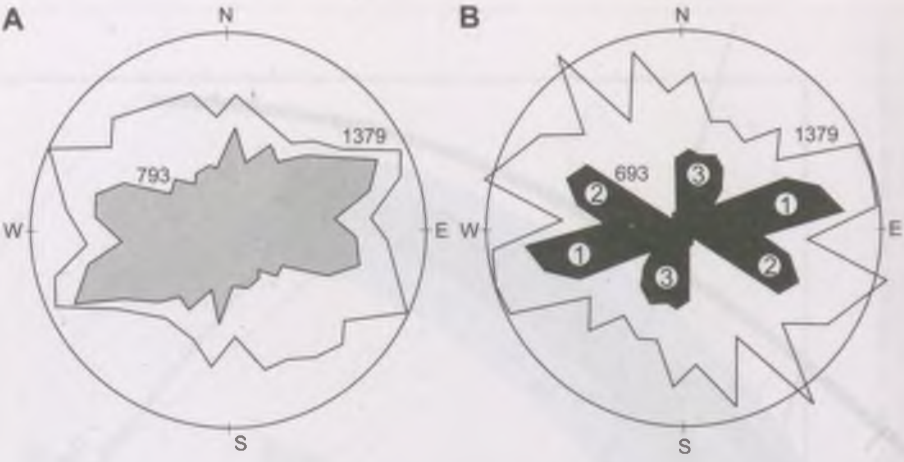

Fig. 11. Rose diagram for all the joints measured in 1992 in the Paks area (outer line) and for the joints after filtering (inner line). – A: smoothed distribution, radius = maximum, rest (grey) = "shear" (field definition) joints (Dudko 1992: *Figures 4.4.* and *4.5.*); B: radius = 100 measurements, rest (black) = after removing data which coincide within 20° with the orientation of the slopes and/or exposure walls (Gerner 1993: *Figure 18*), with serial numbers for the maxima

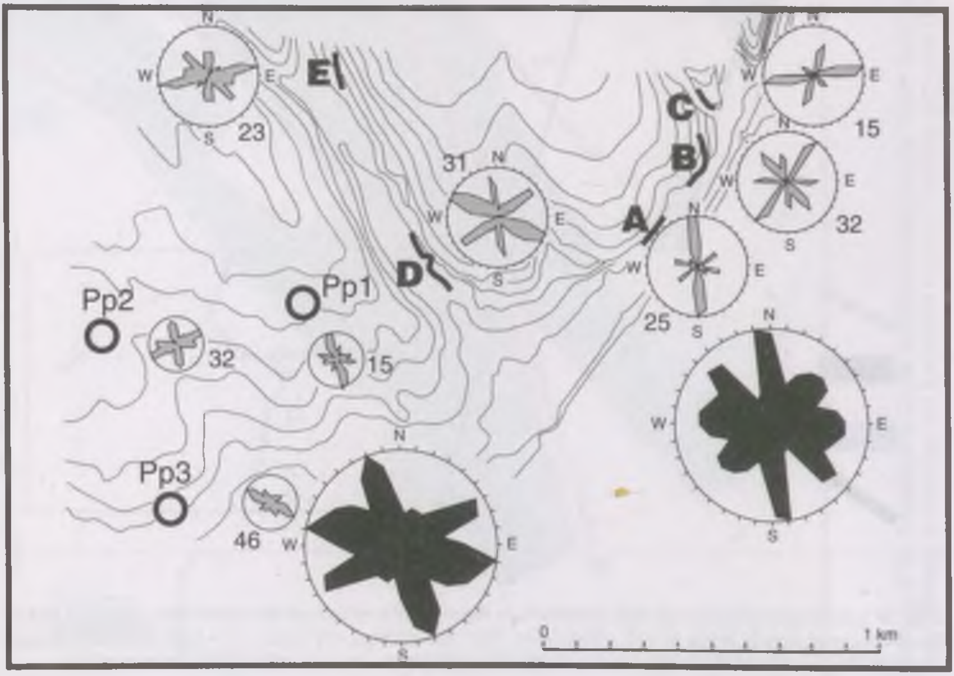

Fig. 12. Comparison of measurements of joints in 1992 and 1994 for the Paks area, after Dudko and Maros (1994: *Figure 39*). For location, see insert. Contour lines a.s.l. indicated. Empty circles with "Pp 1–3" = observation point; lines with "A–E" = outcrop sections measured; small rose diagrams = old measurements; medium-size rose diagrams = new measurements; large rose diagrams = total for the "Pp 1–3" and "A–E" sites

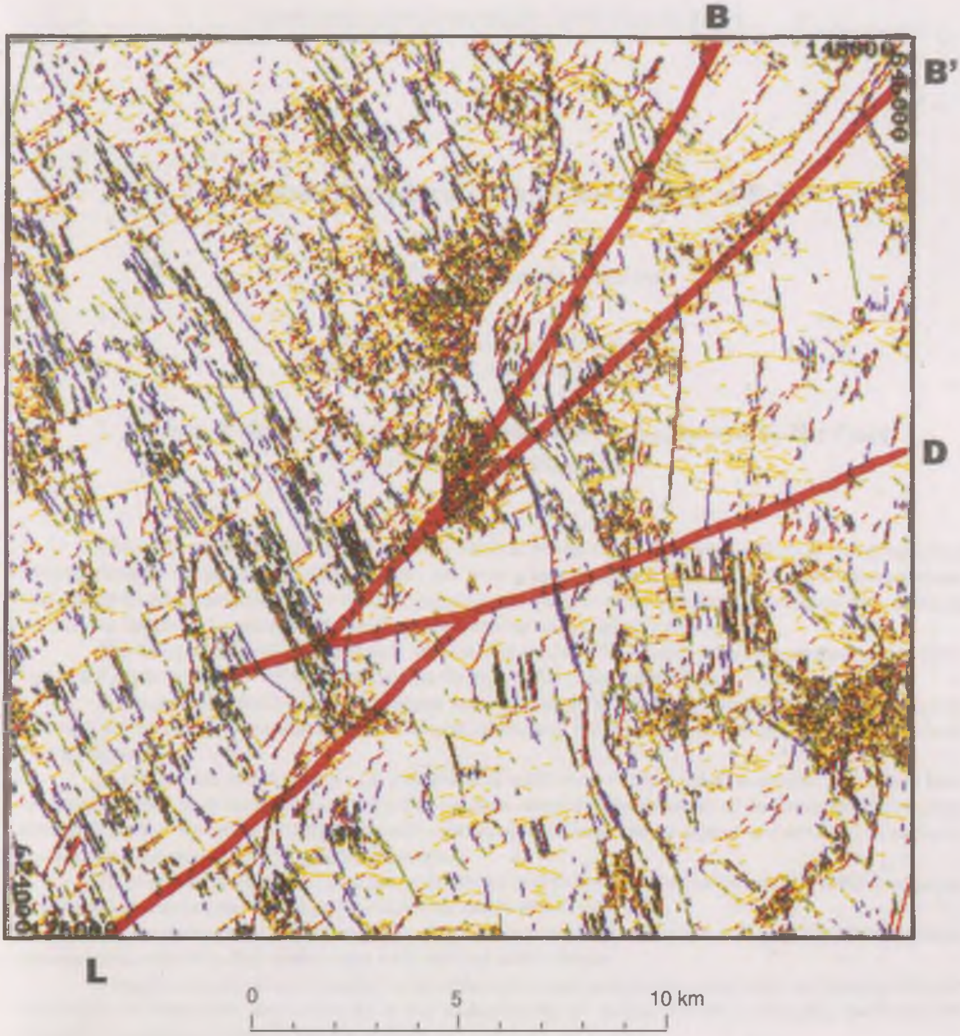

Fig. 13. Lineaments >100 m in a vectored, binary-transformed SPOT P image (line-oriented edge detection with Sobel filters, Bodrogi et al. 1994: Enclosure 6.e); faults from *Figure 6*. For location, see insert. Blue = Sobel E, red = Sobel SE, yellow = Sobel S, green = Sobel SW

Geophysical explorations in the region of Paks

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1. Review of the geophysical measurements commissioned by the Paks Nuclear Power Plant Co.

The study of the seismic risk of the Paks Nuclear Power Plant, including geological and geophysical investigations of the plant site and its vicinity has been a long procedure that started in 1972. Requirements concerning the necessary data have been continuously developing, in addition to the seismological data, demands on learning the geologic and hydrogeologic conditions have been gradually evolved.

The first geophysical measurements were carried out in 1979. Seismic refraction measurements determined the depth to the high velocity basement in the area of the Paks Nuclear Power Plant.

In this period teams of Soviet experts took part in planning, the task of the Hungarian party was to provide the adequate basic data according to the Soviet regulations and recommendations of the International Atomic Energy Agency.

Achievements in the geophysical methods and application of the up-to-date seismic techniques have rendered possible to develop the new scientific concepts about the development of the basin and the tectonic setting. From the viewpoint of seismotectonics separating of various tectonic phases and detection of regional-scale strike-slips proved to be of special importance.

These results and the associated uncertainties are well reflected in the evaluations of the different expert teams and some questions cannot be considered definitely settled even today.

In our opinion, more accurate imaging of the fracture zone detected in the vicinity of Paks and its precise seismotectonic classification remain issues for repeated safety checks.

It might be expected that it would be possible to describe the geology, geophysics and hydrogeology in the vicinity of Paks even more correctly as our understanding of seismic activity in Hungary grows and the available investigation methods becomes better.

Independently of the construction of the nuclear power plant it was discovered relatively early that a very complex geology might be expected around Paks. According to the study of Pintér et al. 1964, based on the spatial pattern of gravity and magnetic anomalies, four different units meet at Paks. The recent investigations have practically confirmed this geological complexity and the growing geomorphologic and hydrogeological knowledge also supports it.

Based on the distribution of the earthquakes, Paks lies in the middle of a relatively quiet area. Considering the difficulties of earthquake prediction, it is an important task however, to study this area of inhomogeneous geology and its vicinity in more detail and monitor its changes. Geological, geophysical, seismological, geomorphological, etc. studies of the nuclear power plant's site is a long procedure which should always be updated according to the scientific and technological level of the given period.

Paleoseismological reconstruction in the nuclear power plant's vicinity presents a great challenge to the Hungarian scientists who have not encountered a similar task earlier, therefore it is understandable that the work is being carried out with the involvement of international expert teams. Settled issues only rarely occur in research, new and new questions emerge in the course of understanding. This has also been experienced in the investigations about the seismic safety of the Paks Nuclear Power Plant. The engineering practice requires a different approach and it wants to close the investigations at a well defined phase.

Geological and geophysical prospecting faced the difficulty that the investigations had to be carried out in a relatively unexplored part of the country.

In spite of all difficulties the balance of the last decades can be considered extremely positive. Our understanding of the area's geology has significantly improved, revision and reinterpretation of the great structural units of Hungary have gained momentum. Intensive studies have been launched to reveal relationships between the tectonics and the earthquakes, in the neotectonics and in engineering seismology. Hopefully, the experience gained in this area will yield benefits for planning and construction of similar facilities of high value and high risk.

A majority of the domestic institutions took an active part in the investigations related to the Paks Nuclear Power Plant. This fact shows that Hungarian researchers felt the solution of the emerged questions of vital importance as well as a common task.

The following institutions took part in the geophysical investigations:
ELGI – Eötvös Loránd Geophysical Institute of Hungary
ELTE – Department of Geophysics Eötvös Loránd University
MTA GGKI – Geodetical and Geophysical Research Institute of the HAS
GEOPARD Ltd.
ELGOSCAR Ltd.
OFKFV – National Geological Prospecting and Drilling Co.
GES – Geophysical Services Ltd., earlier GKV – Geophysical Research Co.

A number of institutions and organizations coordinated the work technically, commissioned by the Paks Nuclear Power Plant. Co.; thus, the Seismological Department of the MTA GGKI led by Győző Szeidovitz, Department Head, ELGI, led by Zoltán Szabó, Department Head, the Scientific Coordinating Committee led by Attila Meskó, Member of the HAS and the Tectonic Project of the Hungarian Geological Institute, led by Zoltán Balla, Division Head.

National data sets of the MOL Hungarian Oil and Gas Co. and ELGI were used for the investigation of the regional zone (with a radius of 150 km) and the closer regional zone (with a radius of 25 km). To fulfill the demands concerning the geophysical coverage set by the "Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting" issued in 1991 by the International Atomic Energy Agency (Vienna) was feasible only in this way. The reliability of regional data sets is different. Coverage depends on the government-financed geological investigations and on the raw material potential of the given area. Improvement and updating of the requirements related to the regional information have been in progress in the international practice.

A wide variety of geophysical methods has been applied in the investigations. The work was primarily financed by the Paks Nuclear Power Plant Co., but results from other investigations were also integrated. The location map is presented in *Figure 1.*

2. Neotectonic investigations, determination of active or presumably active faults

One of the cardinal issues of safety studies is the determination of active or presumably active faults. Wide-ranging investigations with this objective were carried out in the vicinity of the plant and in its closer regional surrounding, commissioned by the Paks Nuclear Power Plant Co. In this article geological prospecting methods are not dealt with, only the possibilities of geophysical prospecting are discussed.

There are two possible approaches. One of these detects changes in physical parameters (density, magnetic susceptibility, seismic velocity, geoelectric resistivity, etc.) of surface and near-surface sequences and then it investigates places of sudden changes by direct geological methods (trenching, shafts, drilling, etc.). Analysis of satellite images, geoelectric profiling and soundings, ground penetrating radar measurements, engineering geophysical soundings and seismic velocity analysis of near-surface sequences were also applied with this objective in the vicinity of the Paks Nuclear Power Plant. Although practical experience and technical literature have supported application of each method we failed in correlating the lithostratigraphic changes with chronostratigraphic ones. Anomalous sites were too numerous to identify them by means of geological methods. (Changes in near-surface velocity was studied along the seismic profiles Pak-2 and Pak-3. Although decrease in velocity could be detected above the assumed neotectonic zones, similar values were obtained at many other points of the profile. According to published data magnetic ΔT, temperature and radiometric surveys might indicate active faults, these methods have not been tested yet.) In general, no information can be obtained about the uppermost few hundred meters from seismic profiles, used in routine hydrocarbon prospecting, due to the applied geophone and shotpoint distances. According to the surveys carried out by ELGI in the frame of its projects dealing with neotectonics and seismic risk the most expedient method is to follow the faults detected by the seismic reflection section upwards, using supplementary measurements. Investigations which started successfully at Szolnok and between the Danube and Tisza rivers have demonstrated the feasibility of this idea, but measurements cannot be considered finished. The high-accuracy imaging of the uppermost sequence is still missing, although the expected movements are in the order of few ten centimeters.

The shallow seismic measurements carried out in the vicinity of the nuclear power plant did not provide unambiguous result, due to the near-surface seismogeologic disturbances. It is advisable to continue these experiments in connection with the Quaternary movements in the areas of thicker sedimentary cover.

3. Connection between tectonics and the earthquakes

This problem has been one of the most controversial questions for the last period. The focal depth of earthquakes in Hungary varies between 5 and 15 km, i.e. the grade of inhomogeneity and rock physical properties should accurately be known down to this depth. It is, however, rather difficult to investigate this depth interval with conventional methods. Fractures within the sedimentary sequence and in the basement of the Tertiary basin can quite well be traced, their continuation downward is uncertain. An example for the successful investigation of the depth interval of earthquake source zones is the seismic profile PGT-4 which was measured in the southern part of the Great Plain with the objective of crust and upper mantle prospecting. We succeeded in detecting compressional zones extending down to the Mohorovicic discontinuity, or to the boundary between the upper and lower crust which could be brought into connection with the earthquakes generated in the Békés Basin and in the Makó–Hódmezővásárhely Graben. Studies about the latest Kobe earthquake suggest the increasing importance of studying such zones.

Deep seismic surveys require a great deal of experience and investment. Therefore, analysis of the existing national geophysical data sets (stripped gravity maps, classification of magnetic anomalies, analysis of seismic sections, telluric and magnetotelluric studies) is of special importance. In our opinion, new high accuracy data of the Microseismic Monitoring Network after a sufficiently long observation interval will allow to classify the activity of the individual tectonic units. Improving tectonic knowledge and monitoring of earthquakes then will contribute to resolving the apparent contradiction that certain zones are not at all or only partly active, and the orientation of the earthquake generating zones only partly coincides with the structural directions nowadays deemed to be the most important ones. Therefore, as a part of the geological investigation of the nuclear power plant's surrounding it will be important to study the earth crust and upper mantle.

4. Digital study of the remote sensing images (Gulyás, Ágnes)

Recommendations generally regard processing and interpretation of images obtained by remote sensing as starting point of tectonic studies. In the field of neotectonics analysis of satellite images is considered of primary importance. In addition, these images help, of course, in investigations of other geological purposes such as identification of formations or structural boundaries. The lineaments that can be revealed in the satellite images might be caused by changes in vegetation, rock type, network of rivers and texture of morphology.

The satellite images of Hungary show a definite trend of directions. In the western part of the country, e.g. a radial structure can be observed in the dominant directions of the river network, in the zone where Holocene sediments occur. Several authors dealt with the origin and explanation of the systems recognizable in the satellite images. Some of them tried to provide explanations related to tectonics, to changes in stress field, obviously due to the emphasized importance of neotectonics, others attribute the observed phenomena to the dominant wind direction, to differently moving blocks or to heterogeneous settlement in sedimentary basins. As a special question emerges: can the preforming tectonics be recognized in the generation of the system of fluvial-lacustrine sediments?

At first a research team of the ELTE Geophysical Department dealt with the vicinity of Paks, analyzing a Landsat image (Horváth et al. 1993). They attributed the dominant NW-SE orientation to the dominant wind direction and related the perpendicular, approximately S-W structures to geological structures.

ELGI (Airborne Geophysics and Remote Sensing Team) carried out the lineament and texture analysis of the available digital Landsat TM and very high spatial resolution SPOT P images of the 10 km radius vicinity of Paks in 1994 (*Figure* 2) (Bodrogi et al. 1994). Analyzing the images by digital processing methods it could be stated that the area could be divided into two fundamentally different subareas. In its central part a dense network of former river channels can be traced in the images, hiding older landforms. The question of the relation between the ancient river beds and tectonics has emerged. (According to some opinions deposition of fluvial Pleistocene–Holocene sequences was influenced by changes of tectonic origin having formed the paleotopography.)

The NW–W part of the survey area sharply differs from the above subarea; it is characterized by a definite NNW–SSE orientation which is mainly related to morphological elements. To decide about a possible tectonic relationship is the task of further investigations. In the E–SE part of the study area primarily lines of NE-SW direction and orientation could be identified.

According to the present evaluations we have failed to find adequate connection between the detected lineaments and the assumed neotectonic elements. We have not yet been able to finish processing of remote sensing data. Identification, classification of the detected elements require further investigations and integration with data from other sources.

5. Airborne geophysical investigations

Airborne geophysical measurements were carried out only along some experimental lines, in the surroundings of Tengelic. In the course of processing of these data we failed to detect unambiguously neotectonic elements.

Several survey proposals have been elaborated for airborne geophysical (airborne radiometric) monitoring of the vicinity of the Paks Nuclear Power Plant, similar to the Swiss example. Realization requires further preparation and analysis.

6. Gravity surveys (Szabó, Zoltán and Páncsics, Zoltán)

ELGI carried out gravity surveys in the vicinity of Paks between 1961 and 1970, as part of the national gravity measurements. The stations were located along the roads, with an average separation of 500 m which corresponds to a station density of about 1 station/km^2, i.e. to a coverage at a scale of 1:100 000.

The station density is by no means uniform, there are areas of 15–25 km^2 without data between the roads. In the frame of the regional survey supplementary measurements were carried out in 1994.

The anomaly map constructed from the extended data set is shown in *Figure 3*. The character of the Bouguer-anomaly map, the dimensions and magnitude of the anomalies as well as their distribution and pattern, the changes in the density of isogal lines demonstrate the compexity of the area.

The Bouguer-anomaly map reflects the integrated effect of the masses lying below the surface. Sources of the gravity anomalies can be grouped in the following way over the area:

a) density inhomogeneities within the sedimentary sequence;

b) density inhomogeneities within the basement of the pre-Tertiary basin and changes in the relief of the high-density basement;

c) density inhomogeneities in the volcanic sequence and changes in its relief.

If the lateral density changes are the results of tectonic processes, places in the map with high horizontal gradient might indicate boundaries of tectonic units.

Regional or local changes can be enhanced by means of different transformations from the map reflecting the integrated effect. Separation of regional and local sources was carried out using two-dimensional filtering. The map obtained by the filter parameter $\kappa=2$

and shown in *Figure 4* has a character of residual anomaly, the map calculated with the combination of filter parameters of κ=9 and κ=8 is of derivative character *(Figure 5)*. The problem of insufficent sampling can be recognized in the transformed maps as well. The largest station separation determines the resolution of the data set which might reach even 5 km in our case. This manifested itself especially seriously in the application of the highest horizontal gradient method when we did not get the expected result in the complex area reflecting the interference of several directions.

In the study of the seismic risk the idea came up to look for correlation between the earthquakes and the different geological and geophysical parameters (Szabó 1990). In an area of 10 km radius around the epicenter of 27 earthquakes with intensities $I_0 \geq 6°$ (MSK-64 scale) the following data sets were involved into these studies: horizontal gradient of the Bouguer-anomaly, horizontal gradient of the residual anomaly, depth to the basement, thickness of the Earth's crust, occurrence of magnetic anomaly, temperature at a depth of 1000 m, velocity of the recent vertical crust movement, Quaternary crust movements, thickness of the Upper and Lower Pannonian sediments. The study concluded that 18 of the 27 earthquakes fell on areas where the gradients were higher than a certain value (>2 mGal/km in the case of Bouguer-anomaly gradient, >0.5 mGal/km in the case of residual anomaly gradient). The studies were extended to the vicinity of Paks as well. According to this evaluation the probability of an earthquake with an $I_0 \geq 6°$ intensity (on the MSK-64 scale) is twice as large in the vicinity of Paks than the national average.

The results have emphasized the usefulness of the gravity data but a cluster analysis based on more accurate data sets expectedly would led to more convincing results. This study should use, of course, further data sets too. For preparing this advanced analysis we began the orientation and texture analysis of the gravity anomalies.

To obtain information about the depth interval of earthquake foci from the gravity map the effect of basin sediments should be eliminated. The gravity effect of the sedimentary layers, known from wells and other geophysical observations, could be calculated down to the basement and the Bouguer-anomaly values were corrected by the calculated values. This stripped gravity anomaly map shows better the density differences where different rocks form the basement as well as the changes in the thickness of the crust. Thus, we obtained information from the depth where the earthquakes occur. We should like to emphasize that the gravity data set is practically complete, covers the whole country and it might be considered homogeneous in a regional sense (Szabó 1993).

In *Figures 6* and *7* the stripped gravity anomaly map and the gradient map calculated from the stripped map are show with the distribution of the earthquake epicenters.

The source populations of different order can be very clearly discerned in the gradient map, together with their association with the major structural units, structural lines and their crossing. Due to the uncertain epicenter locations of the historical earthquakes, however, the conclusions have to be treated cautiously.

We expect that the use of new data from the microseismological monitoring system in the vicinity of Paks will significantly improve our understanding.

7. Magnetic surveys (Kovácsvölgyi, Sándor)

The ground magnetic coverage of the country is the result of efforts of several decades. The rare network of stations satisfies the requirements of a 1:200 000 scale survey only, therefore it would be advisable to have a more detailed coverage in the vicinity of Paks. According to the seismic sections several volcanic formations of smaller extent can be found which could be investigated more accurately with detailed magnetic measurements.

In *Figure 8* the ΔZmagnetic anomaly map of the area between Pécs and Kecskemét can be seen together with the earthquake epicenters.

The magnetic anomaly map indicates magmatic formations within the basement or within the sedimentary sequence in the vicinity of Paks that might suggest weaker parts, fractured zones in the crust. It is worth studying the connection between the distribution of magnetic anomalies and earthquake epicenters. The earthquakes around Pincehely and Tamási occurred at the northern edge of a magnetic body, similarly to the earthquakes in the surroundings of Kiskunfélegyháza, therefore they suggest an active zone. The magnetic source below Paks indicates the N–S shift of the two ranges which is the result of a later tectonic phase. This source was also studied with modeling. The structural zone below Paks can clearly be recognized in the magnetic anomaly map.

8. Tellurics and magnetotellurics

(Madarasi, András, Nemesi, László and Varga, Géza)

The MTA GGKI carried out telluric and magnetotelluric measurements in the vicinity of Paks in 1985–86 (Ádám et al. 1986). The investigations covered an area of about 600 km^2 with a station distance of 2.5–3 km (Ádám et al. 1986). With the help of a few magnetotelluric soundings from the pulsations with different frequencies could be chosen those penetrating down to the high resistivity basement.

In the frame of the Somogy-Baranya project between 1990 and 1993 the ELGI completed the measurements in the Transdanubian part except for the hilly areas (Madarasi 1997.) *Figure 9* provides information on the telluric coverage and the first preliminary results from an area of about 10 000 km^2 around Paks. Unfortunately, there are no measurements between the Danube and the Tisza, from the Danube approximately to the meridian of Kecskemét. Therefore, based on the telluric map we do not have even a qualitative reference to the connection between the structural lines detected in the course of investigations in Transdanubia and the Great Plain (Balaton line, Kapos line, Mecsekalja line, Rába line and the Mid-Plain structural zone).

There is an E–W oriented elevation in the basement south of Paks according to the telluric map from the vicinity of Paks and south of the Danube beyond the characteristic bend at Paks a bunch of isolines indicates an eastward deepening of the basin.

Completion of the telluric measurements are considered important because, together with the gravity and magnetic maps, telluric maps called the attention to many conspicuous features of the deep structure. Gravity, magnetics and telluric data taken together and by means of correct analyses could reveal new information. We consider continuing the magnetotelluric studies in the Paks area a very important task, too.

9. Seismic measurements

In 1979 the ELGI carried out the first seismic measurements in the Paks area. The relief of the high velocity basement was mapped with a refraction profile through the well Paks-2 (Rákóczy 1979a).

The reflection profiles Du-1 and Du-2 were measured by the GKV in 1986 to study the tectonic setting and they brought about a decisive change into the geological concepts. In the course of the interpretation of these seismic sections flower structures within the Miocene-Pliocene sedimentary sequence could be correlated with the structures in the underlying sequences of their basement and a lateral displacement along an E–W zone was assumed. The horizontal displacement could be linked to the zones of movement revealed during the investigations in the Great Plain (Lakatos 1987, Lakatos et al. 1988).

Because the zone of former lateral movement seemed to lie below the power plant, ELGI carried out vibroseis measurements along seven profiles in 1987 (Rákóczy et al. 1988). Detection of faults in the sedimentary sequence was considered of primary importance in choosing the parameters of data acquisition. According to the seismic sections faults of different age can be recognized within the Miocene-Pannonian sequence. The zone of E–W orientation assumed from the first studies could not be traced and a much more complicated system of fractures were outlined in the area. The explosion and vibroseis measurements were not of equal value below the sedimentary sequence, thus the interpretation of the changes associated with the Miocene volcanic sequence could be only limited. The network of seismic profiles should have taken into account the different facilities and the Danube, therefore requirements of proper coverage could not be fully met.

The objective of further seismic surveys was to follow the faults up to shallower depths on the one hand (Gúthy and Hegedűs 1990) and to understand the deep structure on the other hand (D. Lőrincz et al. 1992).

ELGI measured the seismic profiles Pak-1, Pak-2, Pak-3 and Pak-4 to map the assumed fracture zone between Kecskemét and Paks. The primary aim of these seismic profiles was to trace the displacements within the sedimentary sequence, therefore investigation of the Miocene volcanic sequence and the internal structure of the basement was pushed into the background.

The continuation of the fractures detected within the Miocene-Pannonian sequence was studied along the shallow seismic profiles. The Paks Nuclear Power Plant Co. financed these surveys (Gúthy and Kántor 1994), but ELGI performed additional methodological measurements as well, in the frame of its independent neotectonic and engineering geophysical studies (Tóth 1994). When the shallow seismic measurements were interpreted the effect of changes in near-surface seismogeological conditions became a much debated issue. The GEOPARD Ltd. carried out experimental measurements to study the Quaternary formations with the reflection method (Wittmann and Imre 1995). The shallow seismic measurements on the Danube organized by the Geophysical Department of ELTE should be mentioned particularly.

Processing and interpretation of the seismic profiles were carried out by several teams of experts, these are discussed in Tóth and Horváth (1997) in this volume.

Processing and interpretation of the profiles gave rise to quite a lot of debates. The deviations in results might be explained by the insufficiency of the available data sets. These should be continuously completed according to the requirements. The main problem of shallow seismic measurements is that the Pleistocene-Holocene fluvial sequence is thin (30–50 m). The seismogeologically disturbed zones occurring in some places require special data acquisition and processing methods.

9.1. Refraction measurements

The high velocity horizon obtained from refraction measurements follows the basement of the pre-Tertiary basement. It is likely that this horizon jumped to the surface of the Miocene volcanic sequence in the northern part of the N–S profile.

9.2. Reflection measurements (D. Lőrincz, Katalin and Redler-Tátrai, Marianna)

ELGI carried out reinterpretation of reflection profiles Pak-1, Pak-2, Pak-3 and Pak-4 in 1996, using the experiences gained in processing of measurements performed in other parts of the Great Plain (R. Tátrai I et al. 1996). Correlation of geological formations was carried out based on the reflection texture determined for the different sequences. From these sections Pak-2/92 and Pak-3/92 are shown in *Figures 10–12.*

The formations determined in the boreholes were identified on the seismic sections by using several reflection parameters (amplitude, frequency, pattern and continuity of reflections, interval velocity, etc.). Thus the point-like (1D) interpretation of boreholes has been extended along the plane of profiles (2D) based on the reflection pattern characteristic of the individual formations.

Interpretation of the seismic reflection sections caused a lot of debates in the past. To illustrate the problem three different interpretations of the same section: Pak-3/92 are shown in *Figures 13–15.*

Markings of the tectonic zones within the Miocene–Pannonian sequence is identical but marking of the displacements belonging to other phases is different.

The difference might be explained by the fact that the information content and reliability of seismic profiles depend on the applied measuring technique. Data acquisition parameters of profiles Pak-1, Pak-2, Pak-3 and Pak-4 have been chosen for studying the Miocene-Pannonian sedimentary sequence, therefore the results from them are unambiguous. Because of the applied law energy source and short geophone distances only unreliable information was obtained from the Miocene volcanic sequence and from below the surface of the pre-Tertiary basement. Therefore, the concepts and the experience of the interpreting geophysicist play here a greater role.

The following formations have been identified in the version prepared by ELGI:

Precambrian metamorphite

It appears with a chaotic image of weak reflections. Its surface rarely forms a continuously reflecting horizon, in spite of that it appears as a discontinuity horizon that can easily be picked. Its upper boundary can be identified most uncertainly where overlain by a Mesozoic carbonate formation. This can be explained by the low reflection coefficient and by the uniformly acting Alpine tectonics.

Triassic formations

It is characterized by short signal packages of high frequency. It has been marked on the basis of change in the seismic character.

Jurassic formations

Their appearance is not very characteristic, the main features being medium amplitude reflecting horizons, medium continuity and thin layers. Their surface is generally fractured.

The reflection image of the Mesozoic sequences shows the described features if they are not shielded by a Miocene volcanic sequence.

Miocene volcanic sequence

The volcanic cones appear with a relatively reflection-free chaotic image, their surface is generally a strongly reflecting horizon, in some places it is slightly stratified and characterized by hummocky reflections of medium energy.

Miocene sedimentary formations

The quality of the reflections from the Lower and Middle Miocene sequences is variable, they are generally stratified and can be characterized by reflections of medium energy.

Special problems in interpretation of the sections are classification of the basement penetrated with volcanic formations and the effect of the possible postvolcanic activity on the sedimentary sequence.

The tectonic phases systematized on the basis of the detailed tectonic studies performed in the central part of the Great Plain were applied in determination of the structural development.

Prerift tectonics

Mesozoic nappe formation – phase I
Early Miocene convergent strike-slip – phase II

Synrift tectonics

Middle Miocene extension – phase III

Postrift tectonics

Late Miocene (Early Pannonian) transpressional strike-slip – phase IV
Pliocene (Late Pannonian) extension – phase V
Strike-slips associated with Quaternary compression phase VI

The Quaternary strike-slip identified in the sections can be considered the renewal of earlier strike-slips. The flower structures of the Early Miocene transpression identified as phase II continue upwards to different levels, two branches, e.g. can be traced up to the top of the seismic sections.

The flower structure identified in the southern part of the seismic section Pak-3 falls in the strike direction of earthquakes around Kalocsa which can be marked in the gravity map as well, therefore it can be assumed as active.

9.3. Shallow seismic measurements (Gúthy, Tibor)

Flower structures suggesting horizontal displacement have been detected in the area at first in the sections marked Du, measured east and west to the Paks Nuclear Power Plant (Szilágyi 1986, Lakatos 1987). Profiles Pa-1–Pa-7 and Pak-1–Pak-4 studied the spatial spread of displacements, the shallow seismic profiles Pa-8–Pa-17 and Pak-2a, Pak-2b and

Pak-3a aimed at the extension of the interpretable data towards the surface. The primary objectives of interpretation were the classification of displacements as tectonic or non-tectonic and an exact dating of the movement (Rákóczy et al. 1988, Gúthy and Hegedűs 1990, Tóth 1994). The studies have made tracing of these structural elements unambiguous up to the Pannonian-Pleistocene boundary. Interpretation of sequences younger than these generated vehement debate among the different experts. Other geophysical and geological methods have been involved into the studies concerning the neotectonic elements. The task was to separate the effects of ground roll, lithological changes within the Pleistocene-Holocene sequence and structural elements.

Unambiguous solution of the problems associated with the structure of the Pleistocene-Holocene sequences is still to be waited for.

From the sections, prepared in ELGI the shallow seismic section Pa-15/94 is shown in *Figure 16.* The Pleistocene-Pannonian boundary is marked between 27 and 37 meters. The zone of movement which was identified earlier in sections Du-1 and Pa-8 can clearly be recognized in this section. Projecting the wells Pa-4a, Pa-4b and Pa-4c on the seismic section together with the data of well-logging the displacement between the wells Pa-4a and Pa-4c can clearly be seen.

9.4. Seismic measurements on the Danube (Tóth, Tamás)

The contribution entitled "Neotectonic investigations by high resolution seismic profiling" in the present volume deals with the seismic measurements carried out on the Danube. Thus, we do not discuss here the studies performed under the guidance of the Department of Geophysics (ELTE) in detail.

The waterborne measurements provided high resolution seismic sections starting from the bottom of the river bed along the reaches close to the Paks Nuclear Power Plant. According to the investigations of the ca 500 m thick sequence below the river bed the displacements identified within the Pannonian sequence could be detected up to the lower part of the Pleistocene-Holocene fluvial sequence. It can be regarded a great advantage of measurements on the Danube that the uncertainties caused by the seismogeological changes in the near-surface sequence have been eliminated and imaging of the fluvial sediments was also successful.

9.5. Further tasks of seismic measurements

It would significantly contribute to the understanding of the geology in the vicinity of the Paks Nuclear Power Plant if we had information, provided by the seismic and magnetotelluric data, down to the depth of Mohorovicic discontinuity. This could make certain the identification of really deep fractures and determination of main structural units. The task of further investigations is the study of basement rocks and the delineation the tectonic units. Special care should be devoted to the prospecting of the Miocene volcanic sequence.

Several studies, made in 1995, discussed suggestions for further shallow seismic investigations. According to the proposal detailed imaging of the Pleistocene-Holocene sequence should be achieved by additional measurements. It is advisable to carry out ground penetrating radar measurements and engineering geophysical soundings along the shallow seismic profiles.

Rock fissure studies and trenching should be connected to the neotectonic zones determined in this way. According to the experience gained from seismic profiles traces of neotectonic activity could be expected in a few zones only.

10. Geoelectric measurements (Nemesi, László and Stickel, János)

Geoelectric measurements have been carried out in the area several times. In 1992 the neotectonic units corresponding to the orientation of the Mór Graben, then in 1993–94 the seismologically disturbed zones west to the power plant were investigated by geoelectric measurements. Sites for ground penetrating radar measurements, then trenching were based on the results of geoelectric measurements performed on the loess ridges (Újszászi and Zalai 1992, Stickel and Zalai 1994).

According to the measurements carried out on the loess plateau the dry loess, the water-saturated loess, the clayey sequence and the surface of the Pannonian sequence can be effectively mapped by geoelectric methods.

The geoelectric structure of the Pleistocene–Holocene fluvial sequence is shown in *Figure 17*, along profiles measured west to the power plant. The changes within the Pleistocene-Holocene and Pannonian sequences have been classified of non-tectonic origin.

11. Engineering geophysical soundings (Fejes, Imre and Stickel, János)

The engineering geophysical sounding, applied in the investigations was an improved version of the static sounding or CPT (cone penetration test) sounding and it determined various geophysical parameters besides strength. Thus the evaluation, based on several more parameters than earlier soundings, provided better geological interpretation and allowed the calculation of geotechnical parameters.

ELGI has used this set of methods several times in the investigations carried out in the vicinity of the nuclear power plant. Soviet, Italian and Belgian companies also carried out similar investigations.

The loess, the sandy permeable formations and the impermeable clay could be reliably differentiated with high accuracy. The layers made up of the above mentioned formations, their geometry and some of their physical parameters can be traced reliably when the density of measuring points is high enough. The possible movements (landslips, landslides, faults) can be recognized, locations can be accurately determined by increasing the point density.

The levels with concretions can be recognized within the loess. Change in the state of loess with depth can be followed, based on the bulk density and water content, and the consolidation process can be evaluated. In some cases we also succeeded in getting information on the paleosol horizons.

The terrace formations of the Danube can also be divided reliably, based on the engineering geophysical soundings (sand, gravel and organic interbeddings). Due to the crossbedding lateral tracing of layers is feasible only in the case of very high point density.

In *Figure 18* an experimental profile measured in the vicinity of Csámpa is shown.

The engineering geophysical soundings performed along the seismic profile Pa-8 indicate changes in the physical parameters with an accuracy of 10 cm. The gravel benches can clearly be seen below the near-surface clayey, sandy formations. Tracing of characteristic changes is possible only over short distances and the reason for changes cannot be determined unambiguously (crossbedding or any other kind of movement).

12. Ground penetrating radar measurements (Pattantyús-Á., Miklós)

We deem the ground penetrating radar measurements the most cost-effective and most favorable means to investigate the near-surface formations in a continuous profiling manner. Simultaneous application of other geophysical methods might significantly help the interpretation, depending on the geological task and the environment. In ground penetrating radar measurements an electromagnetic signal of 25–200 MHz is transmitted and the geology is deduced from the reflected signal. Processing of measurements is similar to that of the reflection seismic measurements.

Ground penetrating radar has been applied twice during the investigations in the vicinity of Paks. In the frame of the neotectonic investigations ground penetrating radar measurements were carried out west to the Paks NPP, in the anomalous zones revealed by geoelectric measurements (Prónay and Gőgh 1992). The sections measured using the frequencies of 25 and 100 MHz (penetration depth about 10 and 5 m, respectively) were checked later by 2 m deep trenches at some places. In *Figure 19* the similarity between the geological and geophysical section can be seen clearly. No neotectonic elements were observed in the trenches. Determining the sources of the anomalies lying in the deeper parts of the section remains a task for the future.

In the frame of the neotectonic investigations ground penetrating radar measurements were also performed in the area covered with Pleistocene-Holocene fluvial sediments. If neotectonic investigations continue in the vicinity of Paks we deem advisable the application of this method is highly recommendable.

13. Sonic logging, P, S and Q measurements (Törös, Endre)

To model the probable effects of earthquakes the seismic compressional and shear wave velocities, denoted by P and S, the quality factor Q and the density should be known in the uppermost layers. These data can be obtained by seismic downhole and hole-surface transillumination measurements. In the wells drilled in the area of the Paks Nuclear Power Plant the P wave velocity was determined by sonic logging between 1979 and 1988 (Rákóczy 1979b, Rákóczy and Bagi 1987). Although experiments were also performed to determine the S wave velocity it was impossible to obtain continuous data. The researchers of the Seismological Department of the Geodetical and Geophysical Research Institute HAS used the basic data determined in this way to calculate the expected acceleration values.

Importance of the shear wave velocity measurement and the demand on the determination of dynamic elasticity constants triggered technological development in ELGI which, with the significant help of the OMFB (National Committee for Technical Development), led to the solution of the problem. The adequate energy source, data acquisition system and processing software have been developed. Using this sophisticated instrumentation P and S determinations were carried out in the area of the power plant for the Italian ISMES company. Similar studies were performed in Udvari and Üveghuta in the frame of site selection for radioactive waste disposal. In *Figure 20* the P, S and Q logs of the Udvari well can be seen.

According to the measurements in borenholes deepened by ISMES the shear wave velocity provides a better resolution of the Pleistocene–Holocene fluvial sequence than the compressional velocity.

14. Well-logging (Bucsi Szabó, László)

The required logging measurements in the wells were carried out by OFKFV (self-potential, resistivity, microlaterolog, natural gamma) and ELGI (sonic, induced polarization density, caliper, neutron porosity) in the course of investigations.

According to the correlation of logs measured in the wells Paks-4a, Paks-4c and Paks-4b a significant displacement can be assumed in the Miocene-Pannonian sequence *(Figure 21).*

ELGI carried out well-logging measurements in the boreholes drilled by ISMES in 1994. These clearly showed the structure of the Pleistocene-Holocene fluvial sequence.

15. Summary

The geophysical surveys commissioned by the Paks Nuclear Power Plant Co. together with the results of the hydrocarbon prospecting measurements of MOL Co. and surveys of ELGI provide basic data for geological, seismotectonic, engineering seismological and geotechnical evaluation. Based on this information the Ove-Arup team carried out a safety assessment of the power plant.

The geophysical investigations verified the strike-slips associated with the Quaternary compression, these are regarded as renewal of Early Miocene transpression. The geophysical investigations have failed to clarify the age of youngest movements.

The main elements of the tectonic system around Paks can be determined according to the investigations performed. To make this determination more accurate and to extend it spatially and downward are justified claims.

Classification of the activity of the fractures in the vicinity of Paks requires further carefully designed experiments. In this respect, significant contribution could be expected from the integrated interpretation of earthquake parameters recorded by the Microseismic Monitoring Network and that of the geophysical data.

Engineering geophysical and geotechnical studies could start from practically well founded data sets, here the SV and SH studies in accordance with the new trends of development are deemed useful.

It is very important that in the course of systematic safety checks the geological-geophysical information be reviewed, parallel with the increasing knowledge of the topic.

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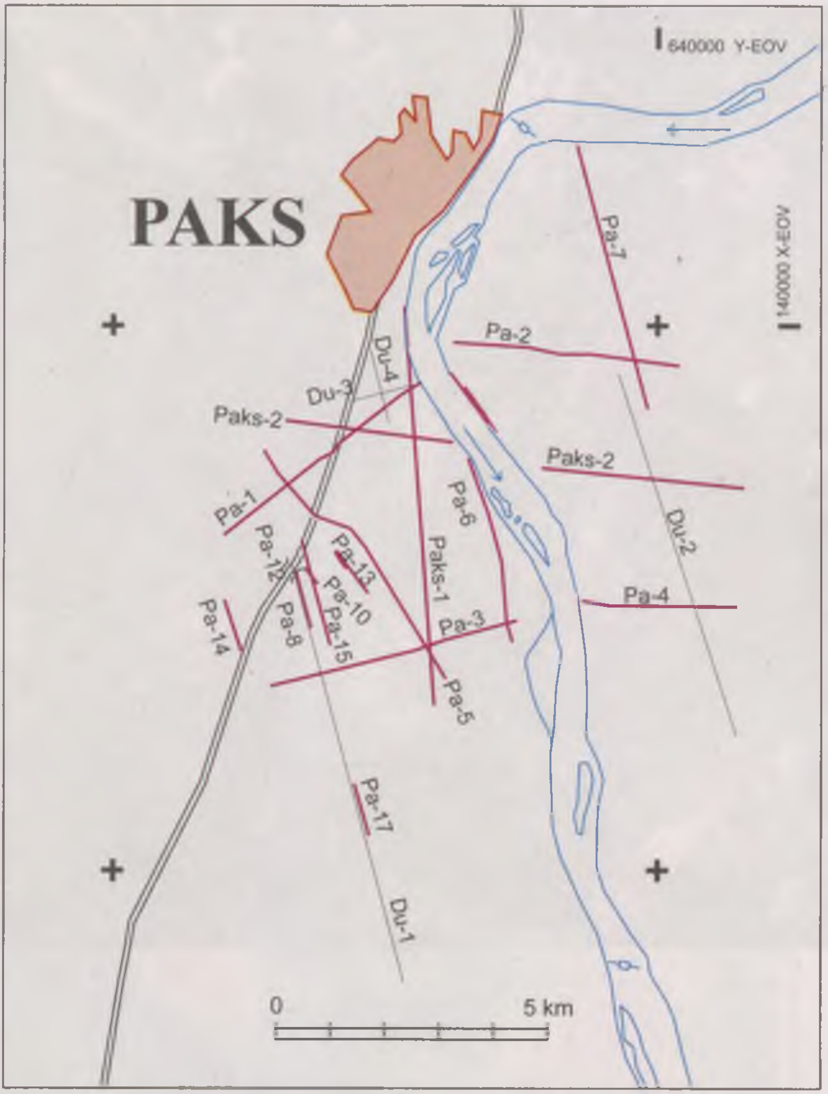

Fig. 1. Location map (Detzky 1997)

Fig. 2. Manual lineament detection, based on the Soebel-filtered SPOT P vector images (Gulyás 1994)

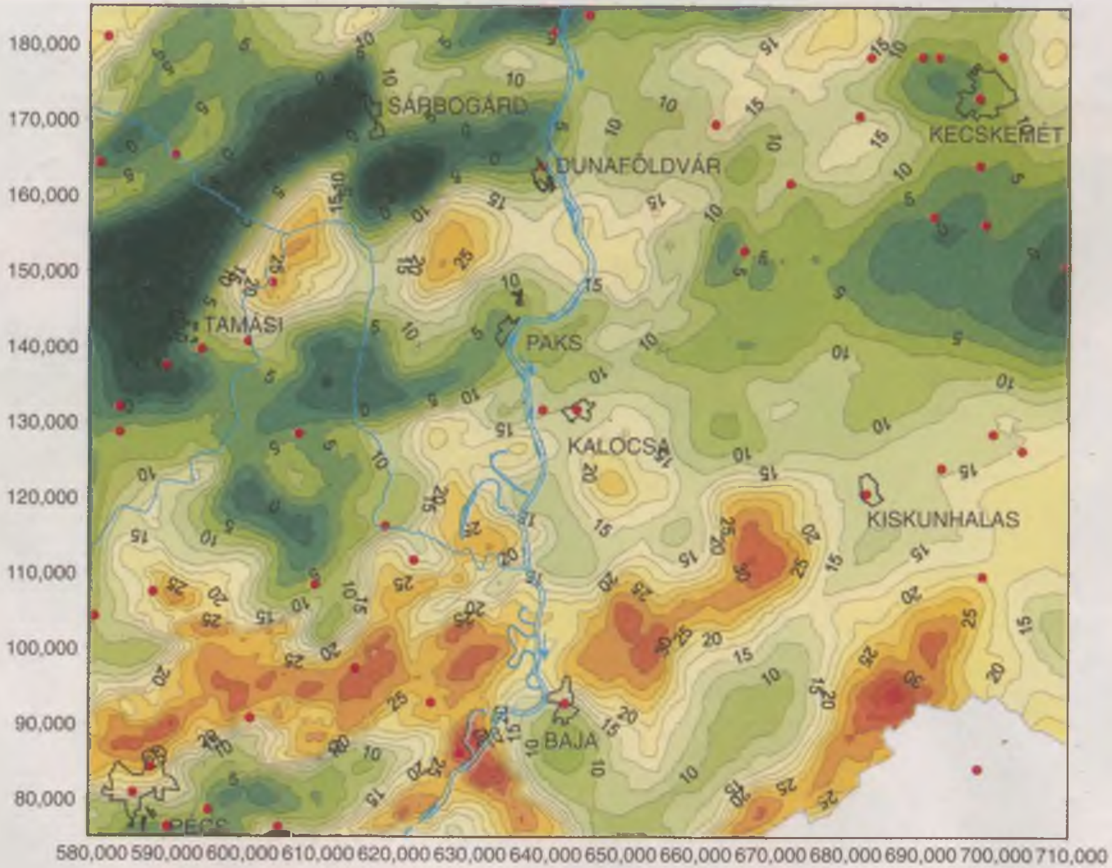

Fig. 3. Bouguer anomaly map (after Szabó and Páncsics 1996) with the earthquake epicenters (Earthquake Catalogue of the Carpathian Basin, GeoRisk, 1994)

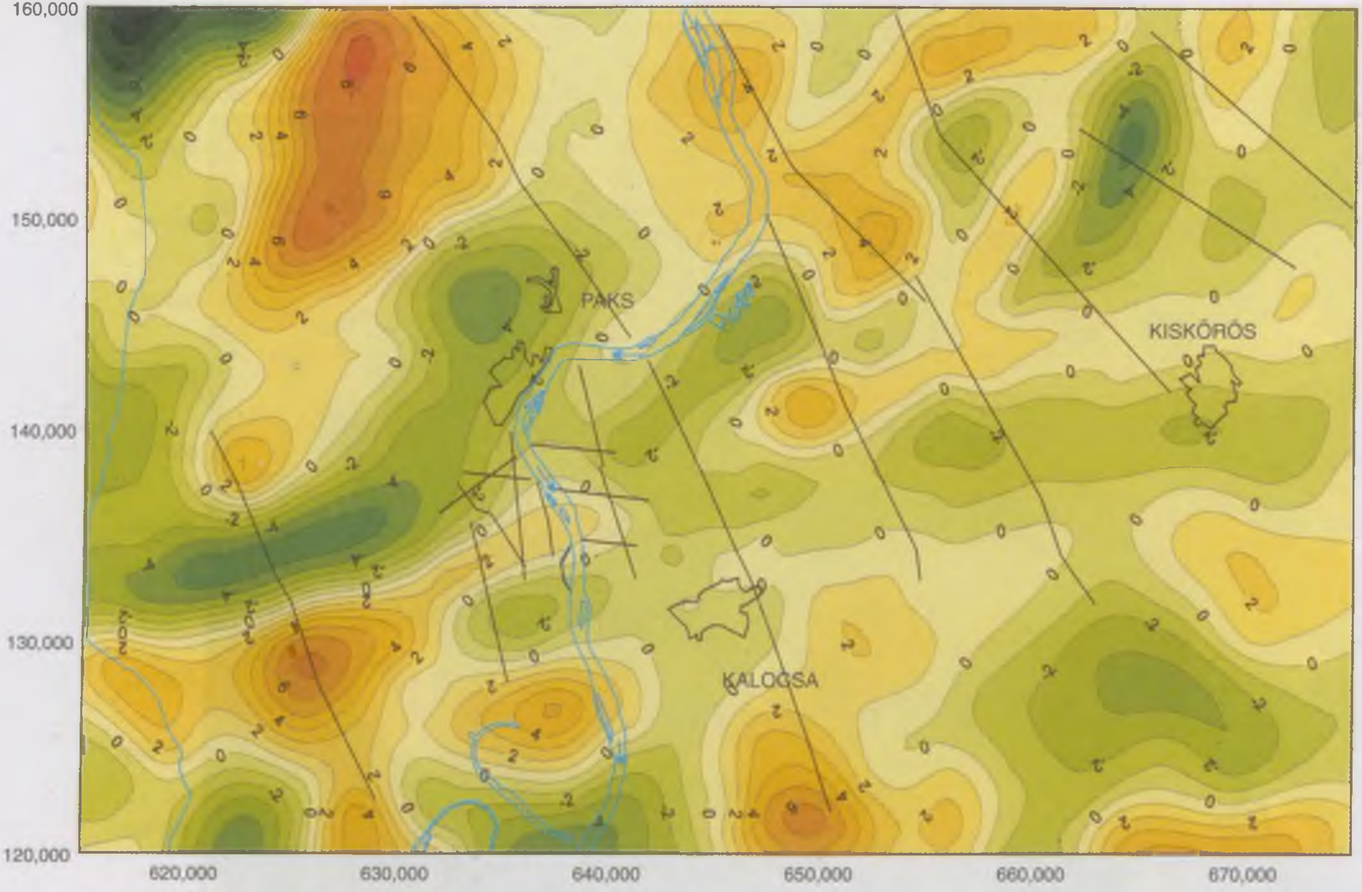

Fig. 4. Filtered (κ=2) gravity map in the vicinity of Paks with the lines of seismic measurements (Szabó and Páncsics 1994)

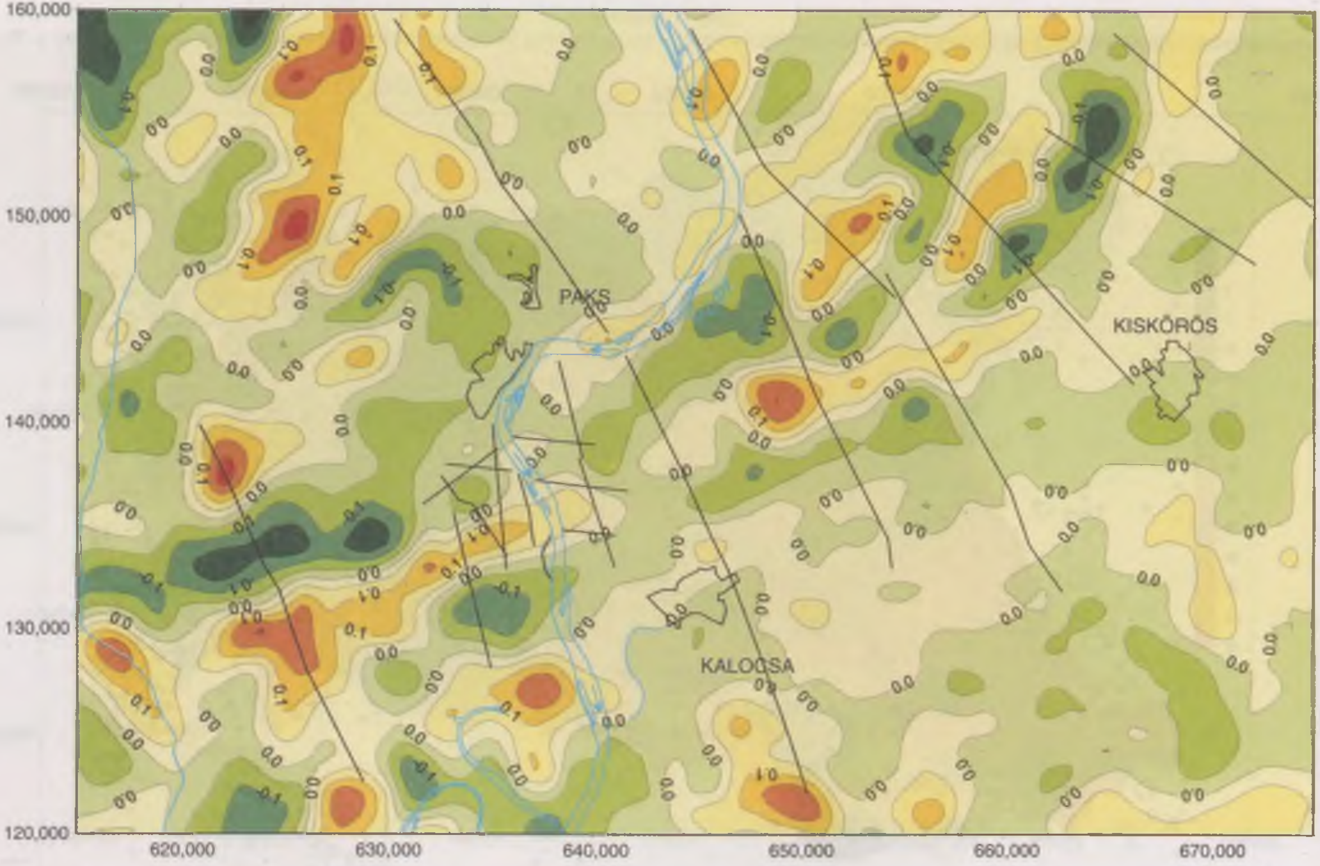

Fig. 5. Filtered (κ=9-8) gravity map in the vicinity of Paks with the lines of seismic measurements (Szabó and Páncsics 1994)

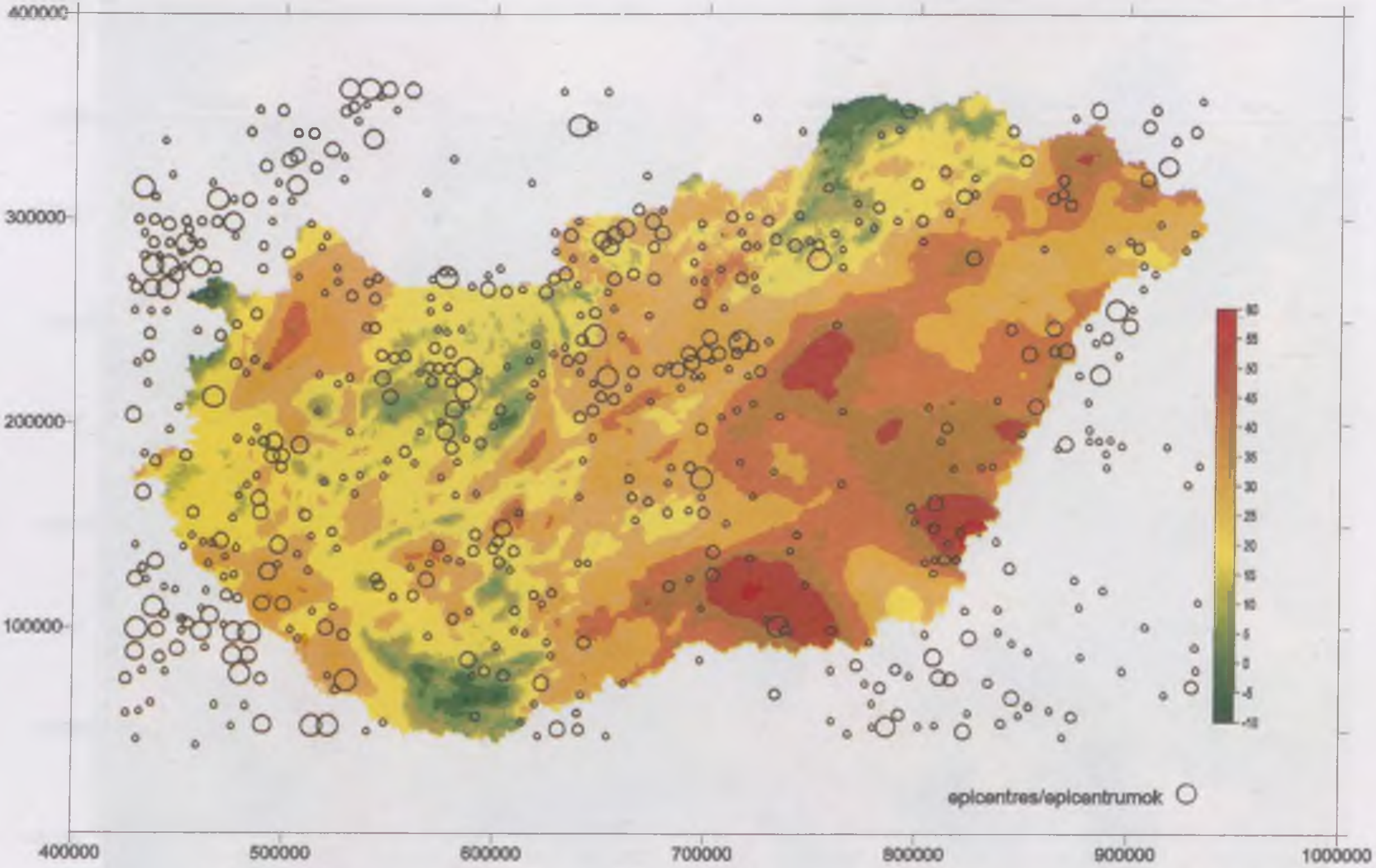

Fig. 6. Stripped gravity anomaly map of Hungary (Szabó and Páncsics 1996) with the earthquake epicenters (Earthquake Catalogue of the Carpathian Basin, GeoRisk, 1994)

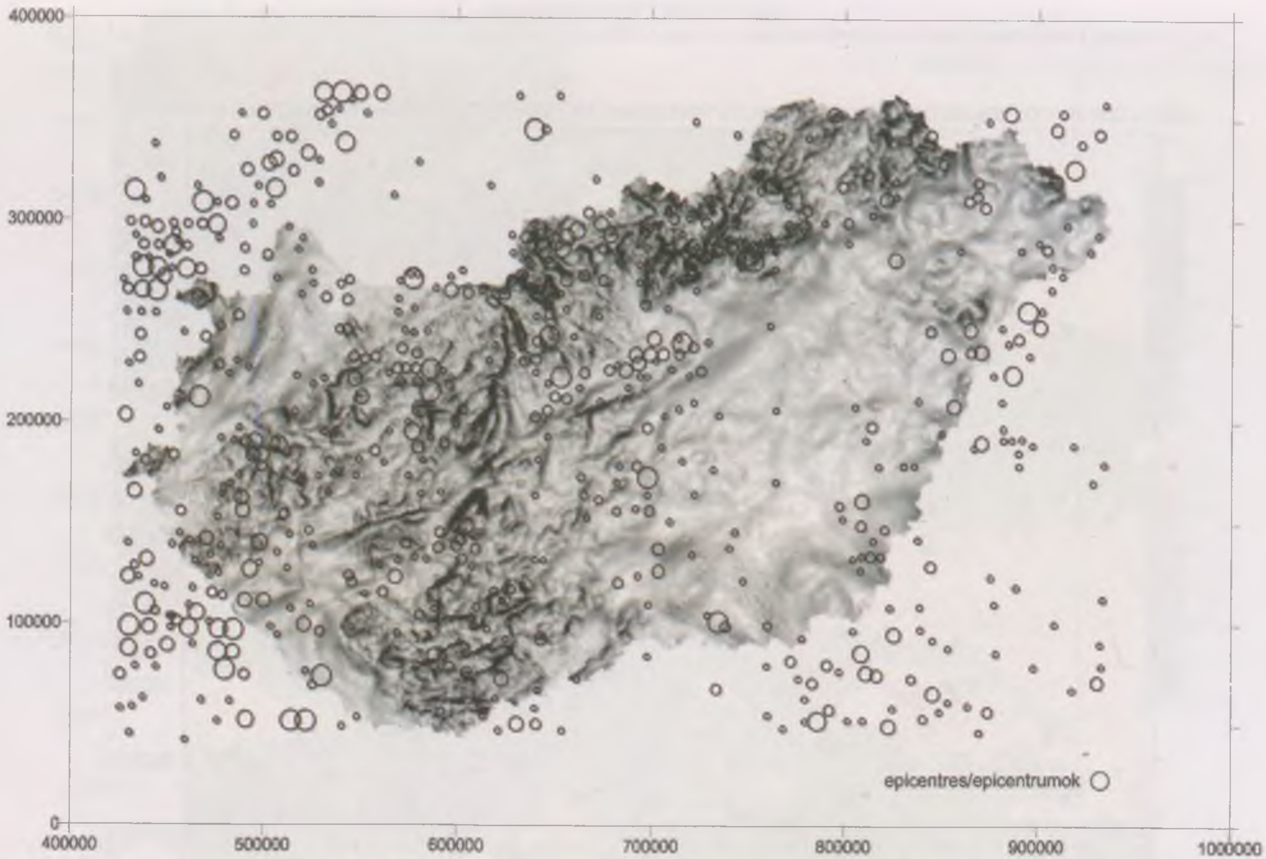

Fig. 7. Stripped gravity anomaly gradient map of Hungary (Szabó and Pancsics 1996) with the earthquake epicenters (Earthquake Catalogue of the Carpathian Basin, GeoRisk, 1994)

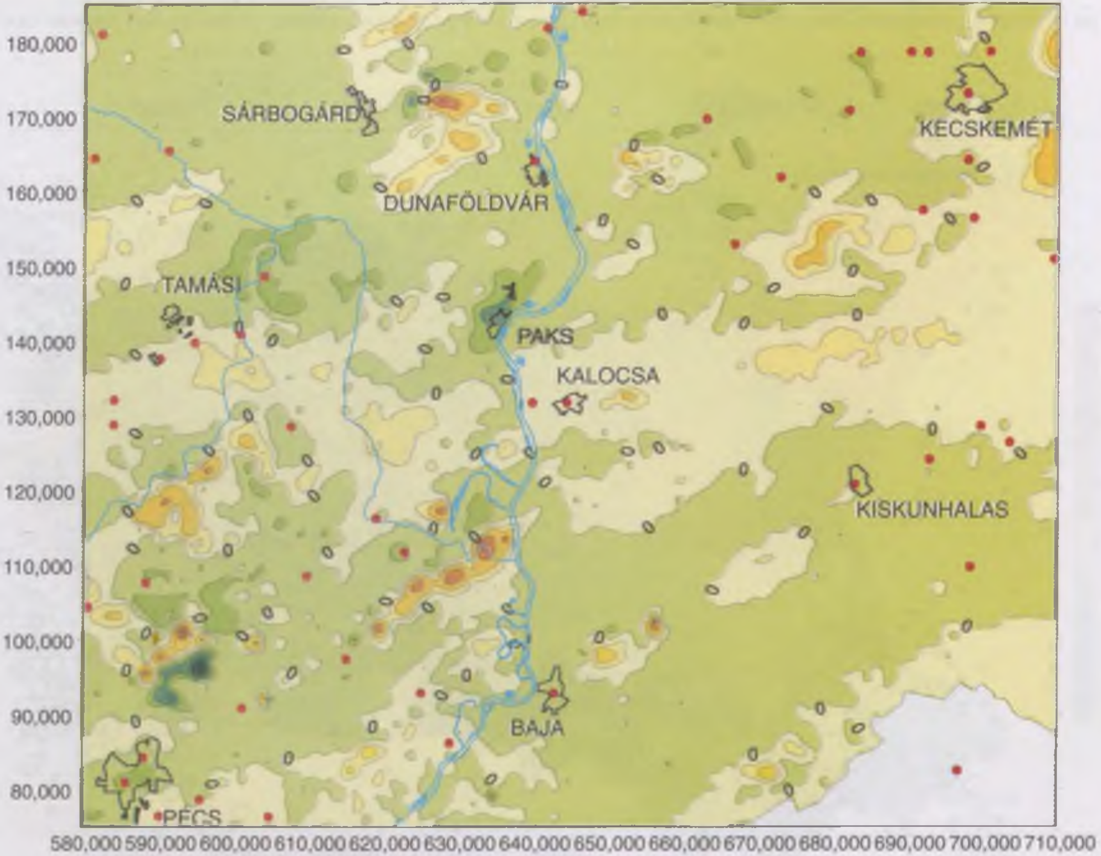

Fig. 8. Magnetic anomaly map in the vicinity of Paks (Kovácsvölgyi 1996) with the earthquake epicenters (Earthquake Catalogue of the Carpathian Basin, GeoRisk, 1994)

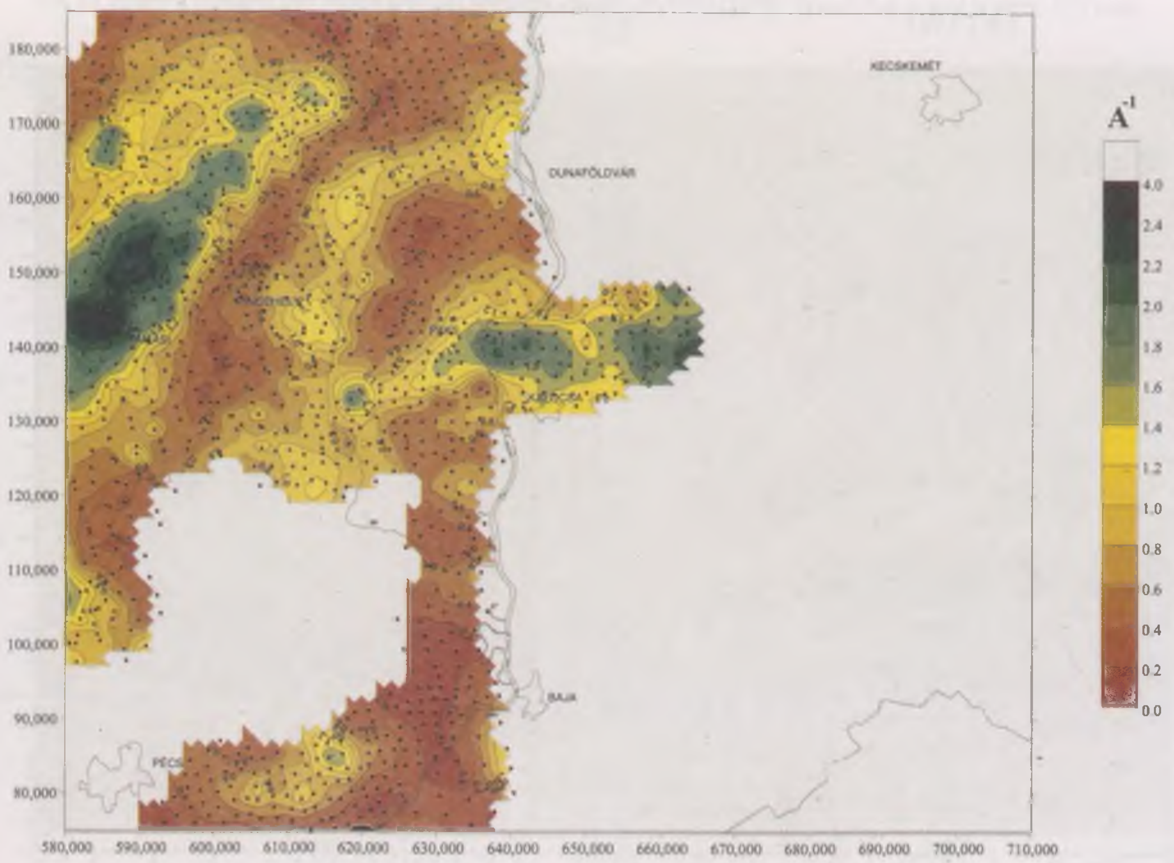

Fig. 9. Telluric isoarea map in the vicinity of Paks based on the data of the MTA GGKI and ELGI (Madarasi 1997)

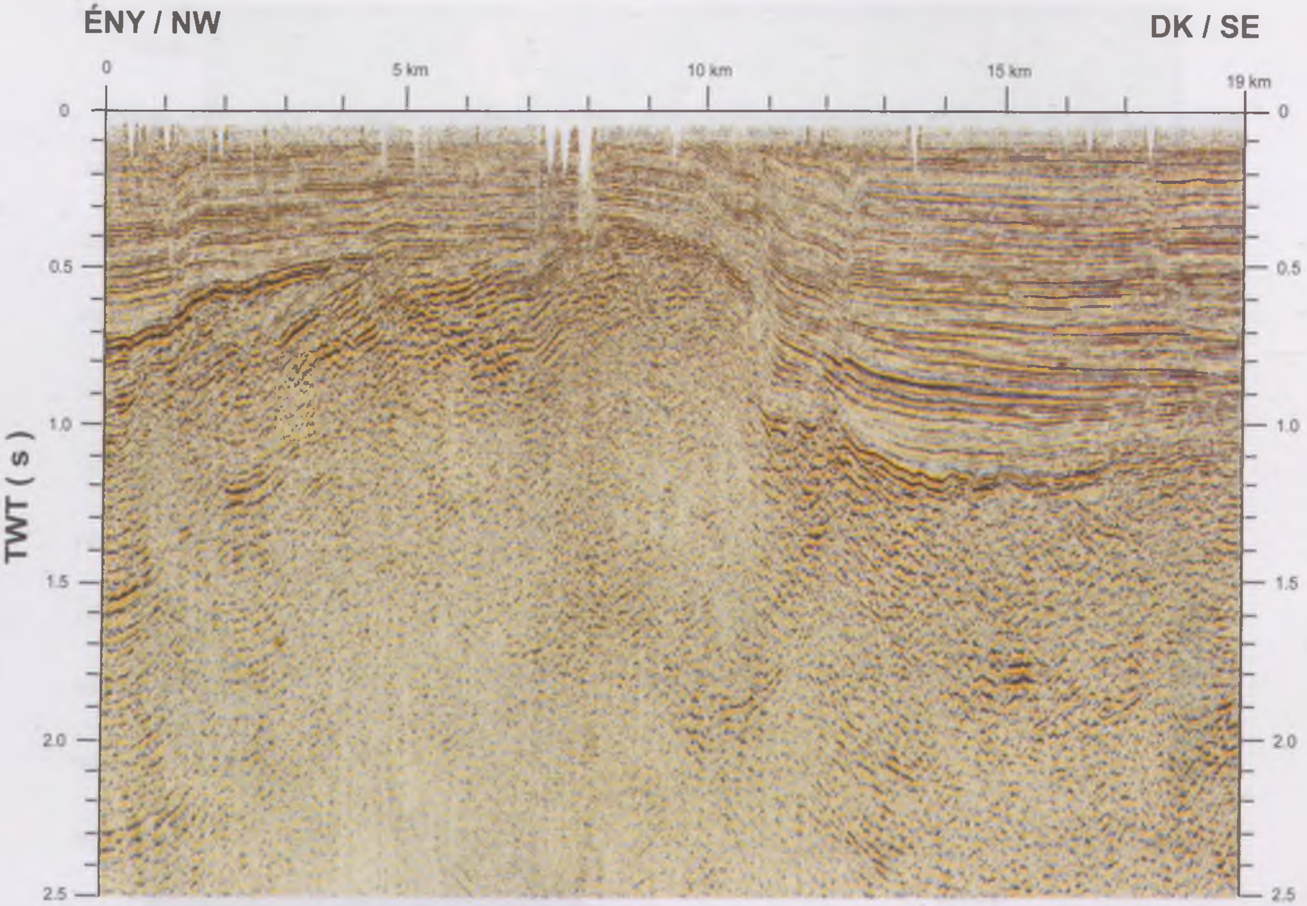

Fig. 10. Migrated reflection time section Pak-2/92 measured between the rivers Danube and Tisza, E of Paks (Lőrincz et al.1992)

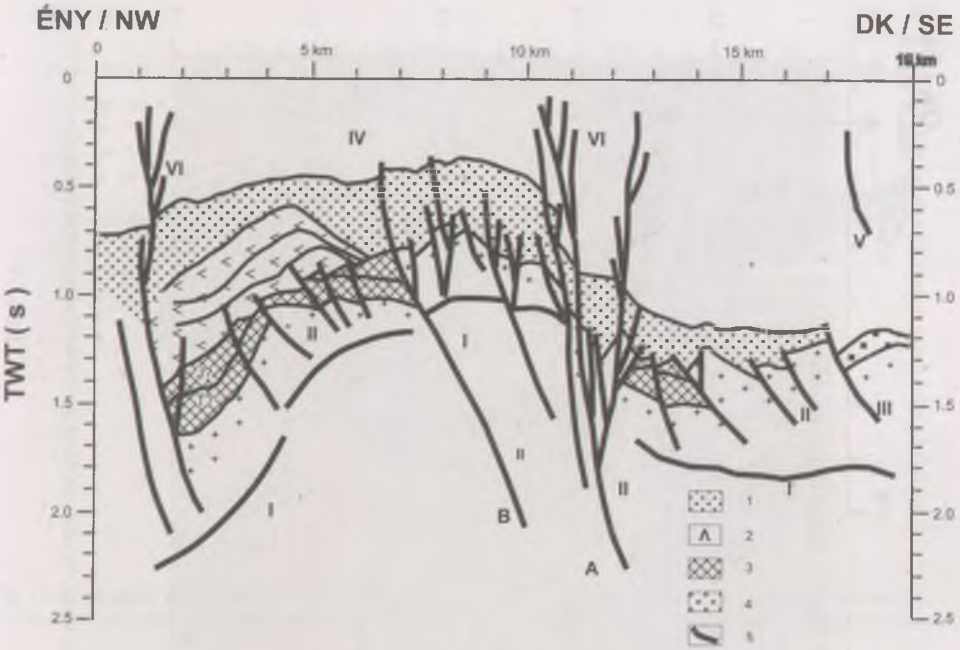

Fig. 11. Geological interpretation of the migrated reflection time section Pak-2/92 (Tátrai and Lőrincz 1996) 1 = Miocene sediments; 2 = Miocene volcanics; 3 = Mesozoic rocks; 4 = Precambrian meta-morphite; 5 = fault; I-VI = tectonic phases; A-B = overthrust

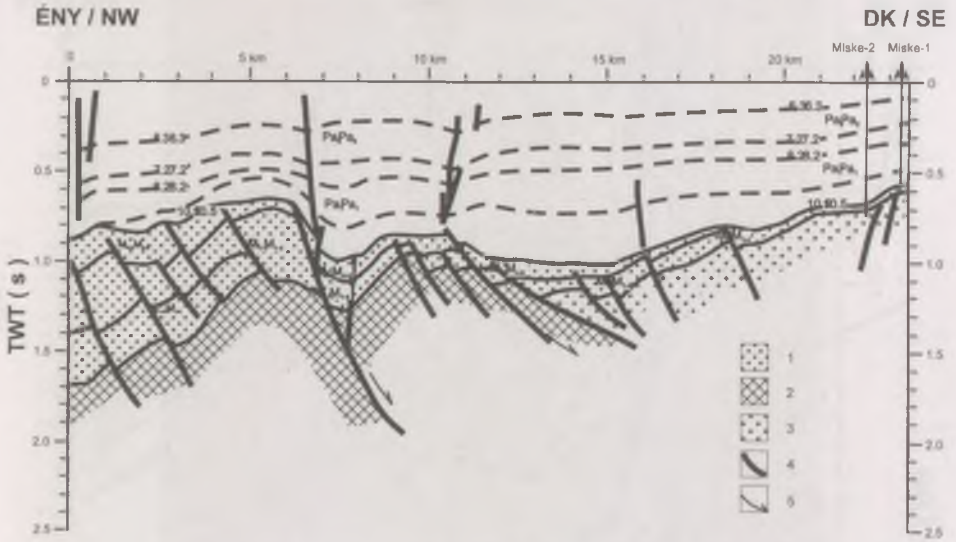

Fig. 13. Geological interpretation of the migrated reflection time section Pak-3/92 (Horváth et al. 1993) 1 = Miocene sediments; 2 = Mesozoic rocks; 3 = Precambrian metamorphite; 4 = fault; 5 = direction of movement

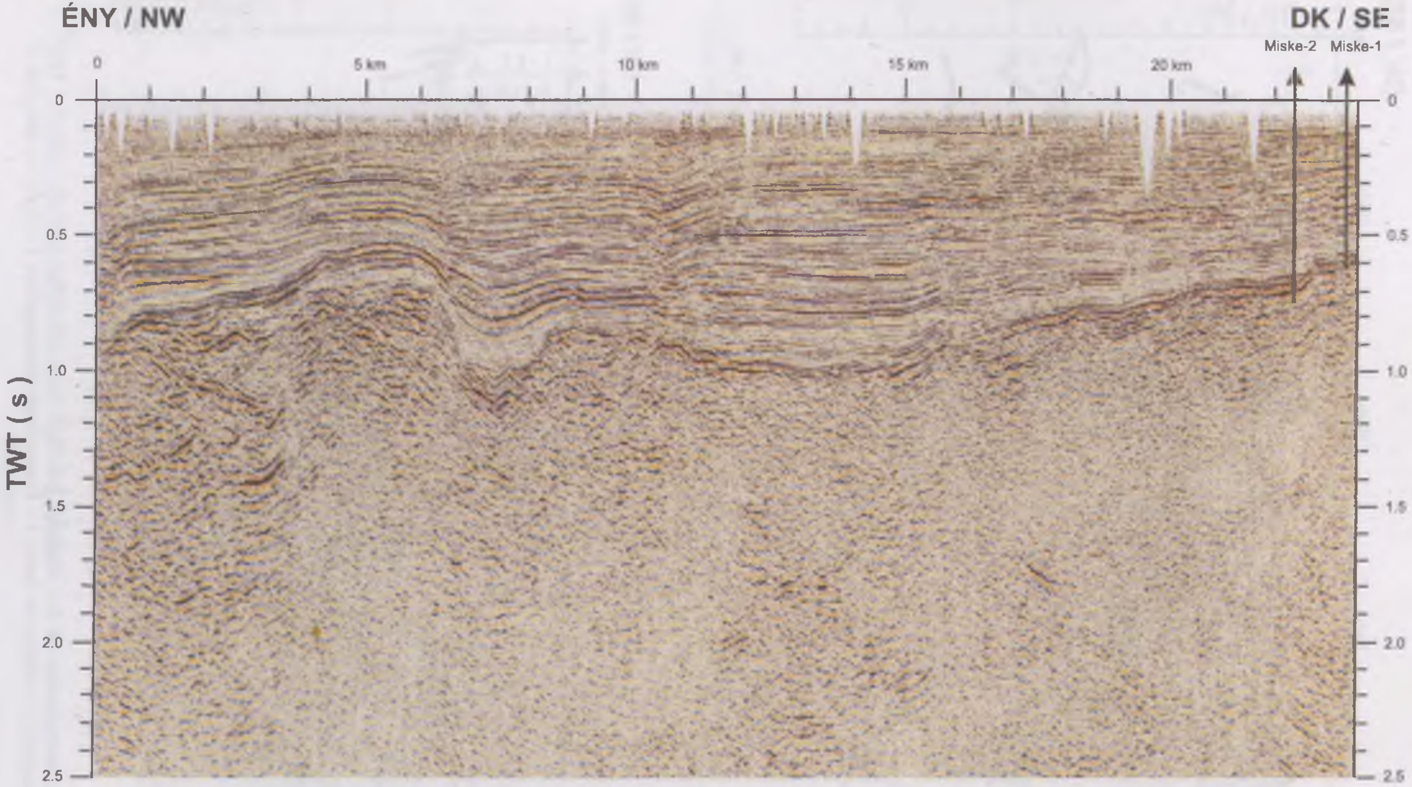

Fig. 12. Migrated reflection time section Pak-3/92 measured between the rivers Danube and Tisza, E of Paks (Lőrincz et al.1992)

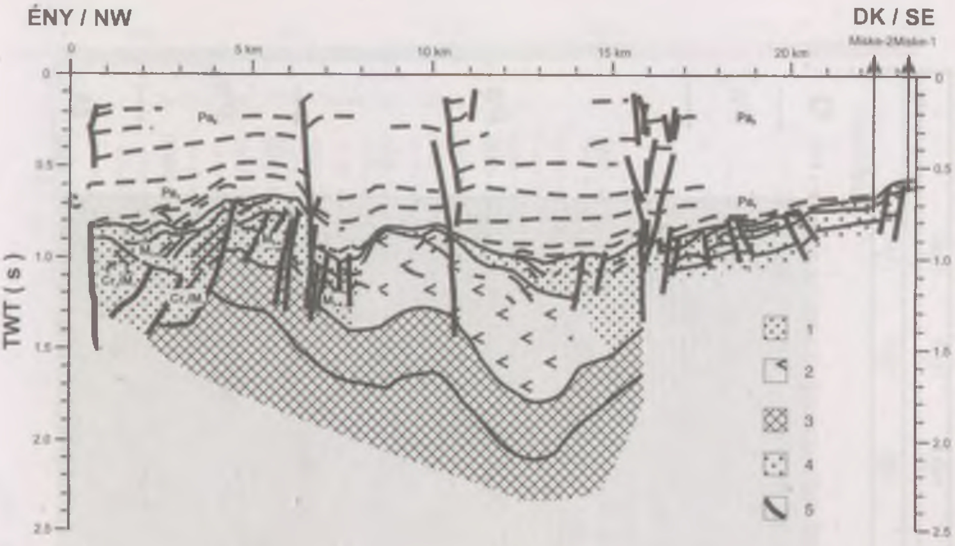

Fig. 14. Geological interpretation of the migrated reflection time section Pak-3/92 (Szabó-Kilényi 1994) – 1 = Miocene sediments; 2 = Miocene volcanics; 3 = Mesozoic rocks; 4 = Precambrian metamorphite; 5 = fault

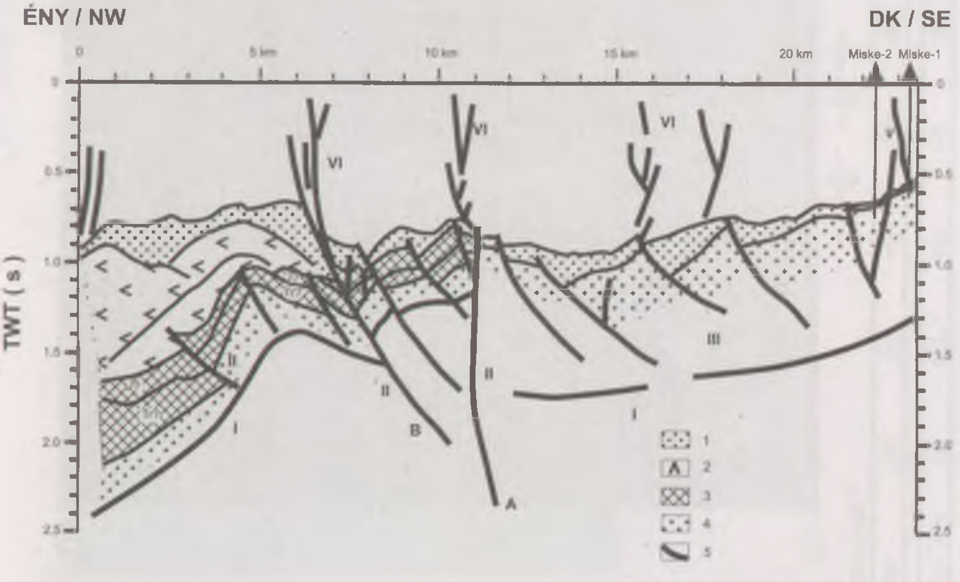

Fig. 15. Geological interpretation of the migrated reflection time section Pak-3/92 (Tátrai and Lőrincz 1996). – 1 = Miocene sediments; 2 = Miocene volcanics; 3 = Mesozoic rocks; 4 = Precambrian metamorphite; 5 = fault; I-VI = tectonic phases; A-B = overthrust

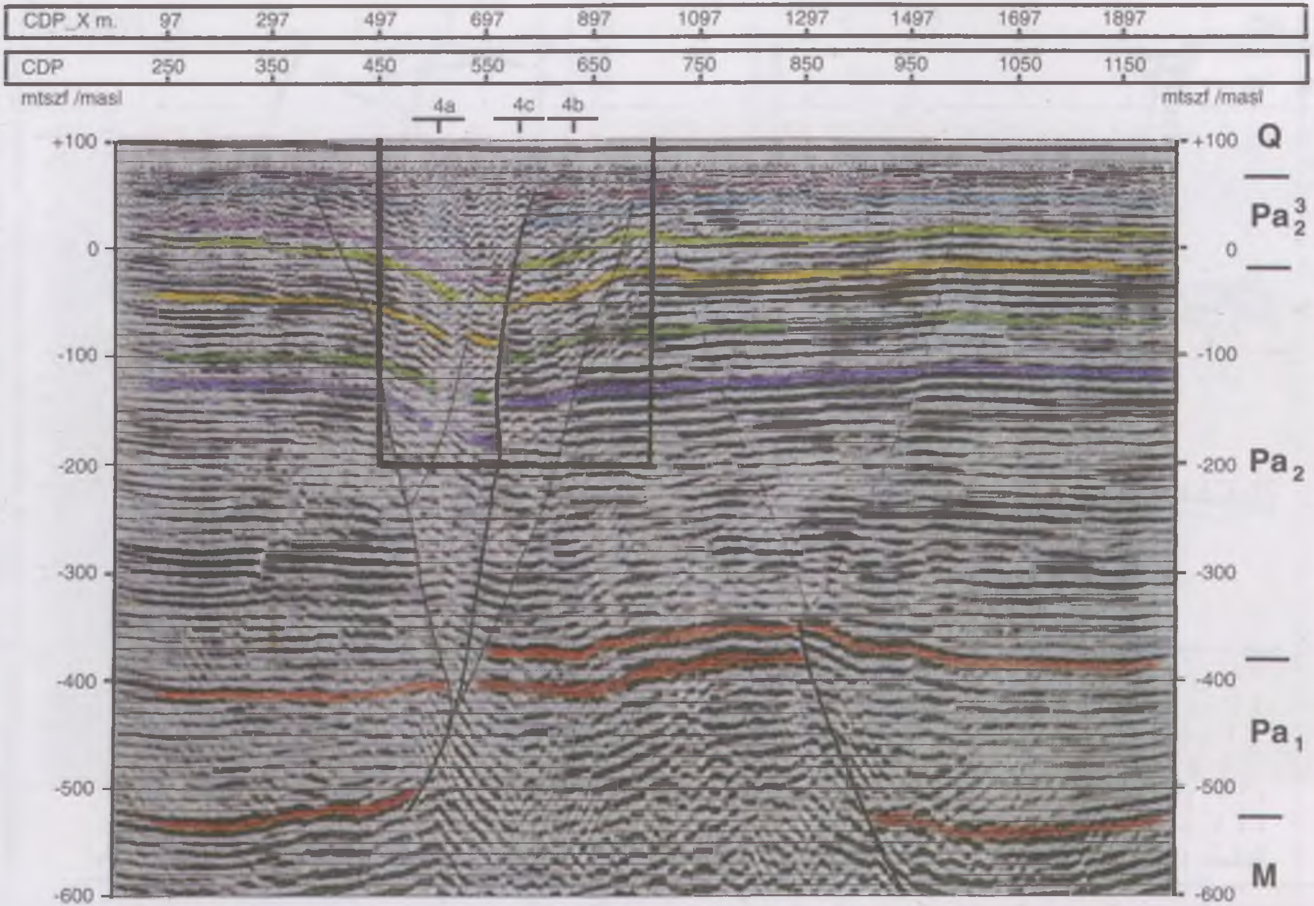

Fig. 16. Seismic depth section Pa-15 (Gúthy 1996)

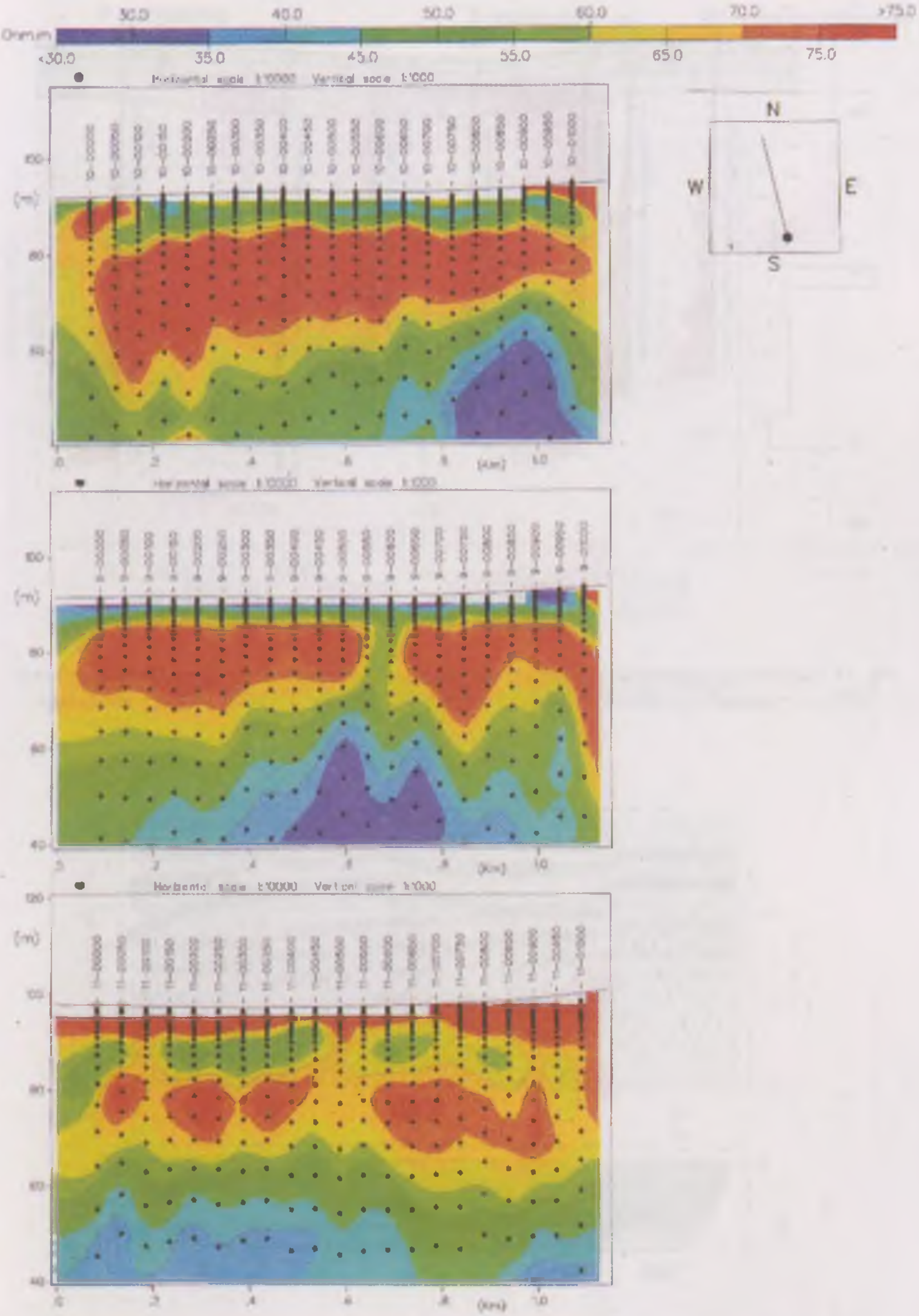

Fig. 17. Shallow DC geoelectric resistivity section W of the Paks Nuclear Power Plant (Stickel 1996)

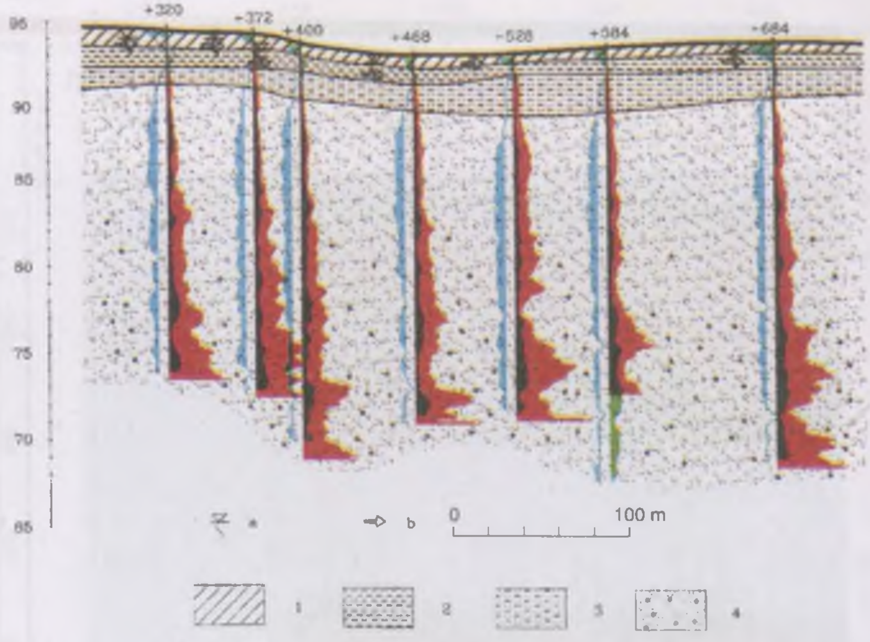

Fig. 18. Engineering geophysical sounding section W of the Paks Nuclear Power Plant (Fejes and Stickel 1996) – a = groundwater table; b = collapse level; 1 = soil; 2 = clay; 3 = sandy clay; 4 = gravel sand

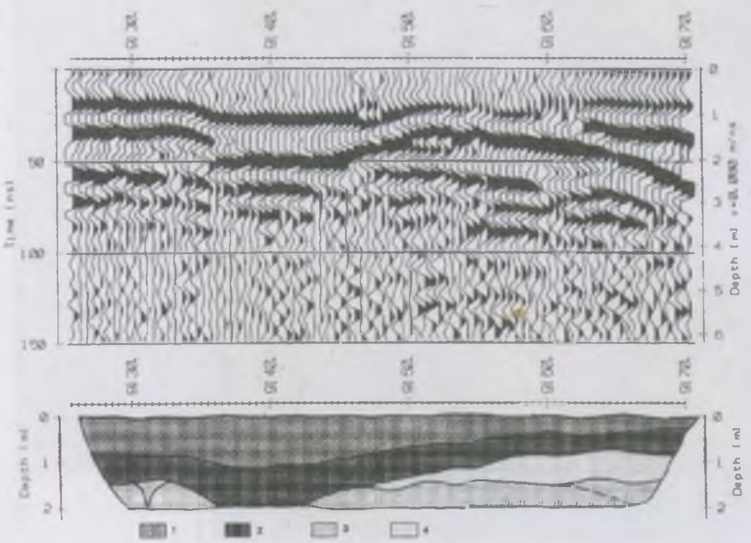

Fig. 19. Ground penetrating radar section with the geologic section obtained by trenching (Pattantyús-Á. 1997) 1 = soil horizon A; 2 = soil horizon B; 3 = sand; 4 = silty sand

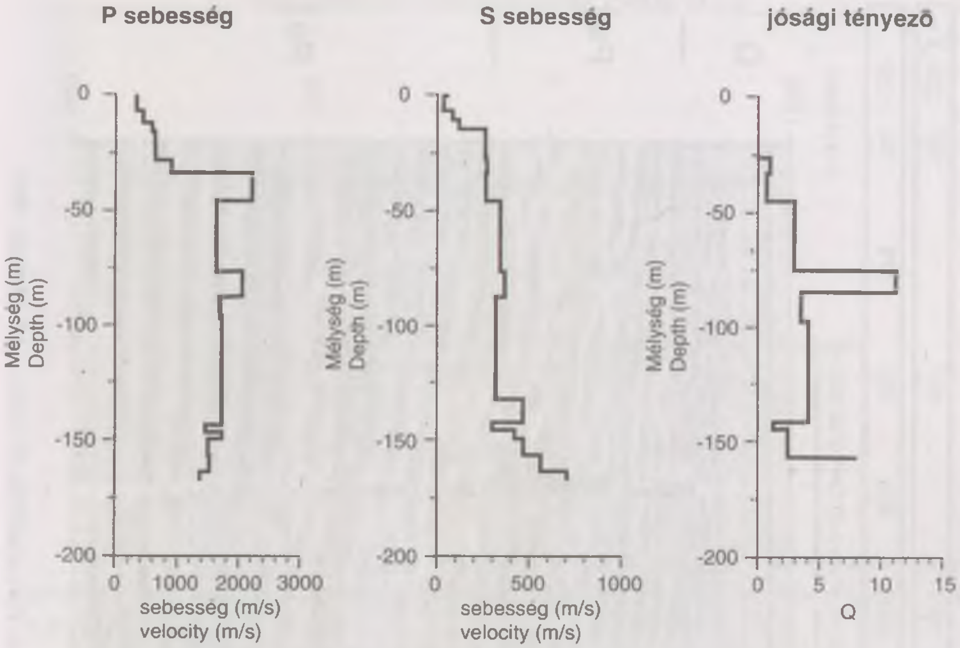

Fig. 20. P, S and Q logs from the well Udvari (Törös 1997)

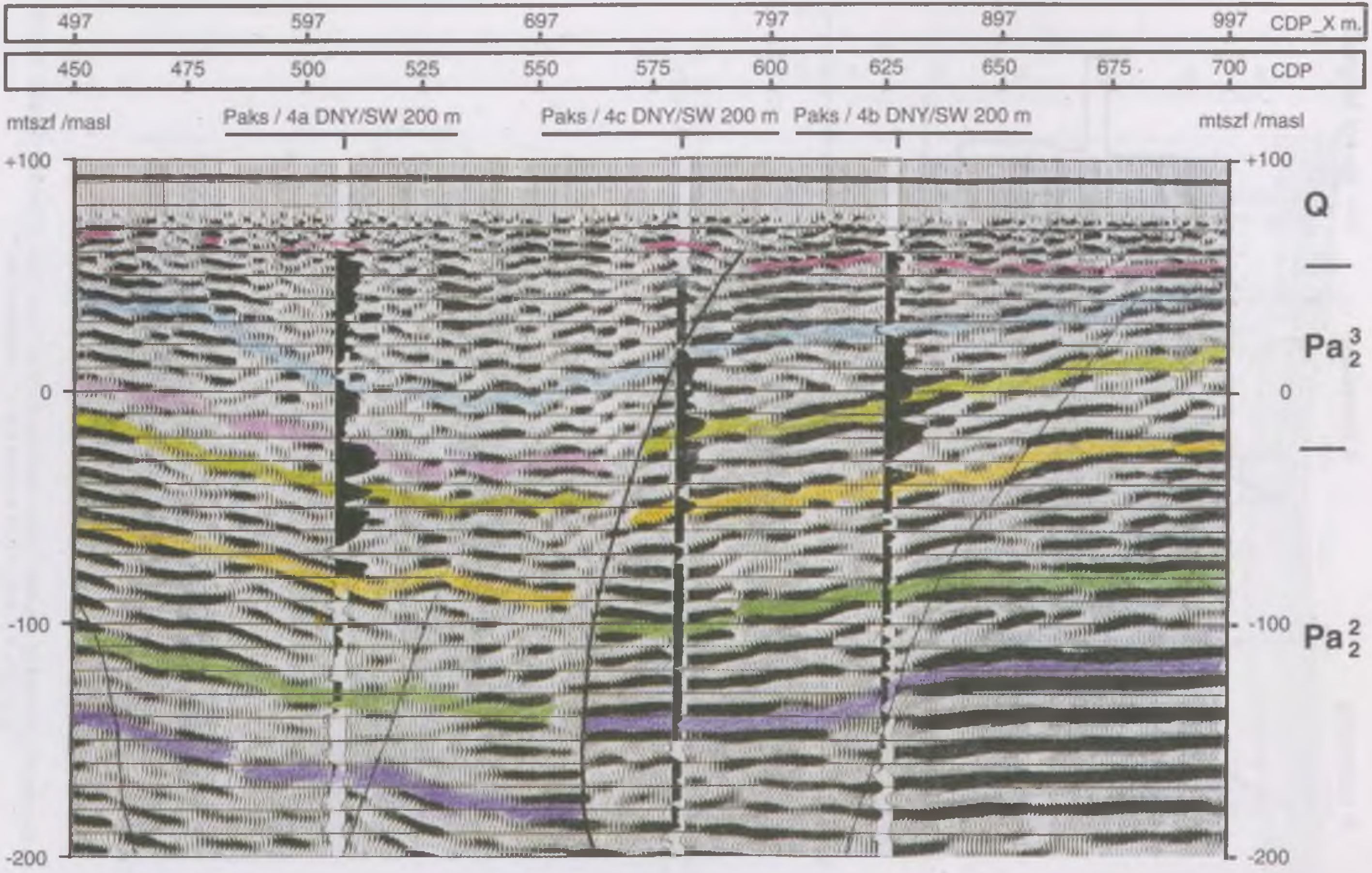

Fig. 21. Seismic depth section Pa-15 with the well logs of boreholes Paks-4a, Paks-4c and Paks-4b (Gúthy and Bucsi-Szabó 1996)

Earthquake hazard of the Paks NPP

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1. Introduction

For planning structures where earthquake safety is critical we have to know those parameters of expected earthquakes which during its operation will load the structure with a given probability.

The overwhelming part of the earthquakes has tectonic origin. Earthquakes occur by the release of stress accumulated during the movements of active faults. For the calculation of future effect of earthquakes those broken zones and active faults has to be investigated which can generate shocks with considerable effect on objects.

For estimation of earthquake hazard we have to know the length, spatial position and Pleistocene and Holocene movements of faults. It is necessary to know the recurrence of recent and paleoearthquakes generated by the given faults.

Attenuation of seismic waves and parameters of layers between earthquakes sources and Paks NPP have to be determined for calculation of earthquake hazard.

2. Review of studies on seismic hazard of the Paks NPP

Several researchers have been dealt with the earthquake hazard of the Pannonian Basin. Of them there have been studied only those which are in direct connection with the seismic hazard of the Paks NPP. One part of these investigations were carried out prior to the establishing of the 440 MW blocks of the Paks NPP. The chronological order of investigations can be found in Balla et al. 1993a.

In relation with the planned enlargement of the Paks NPP with two additional blocks of 1000 MW it was necessary to work out a new study in compliance with international requirements presented meanwhile. The task was done by the experts of the Institute of Earth Physics in Moscow (Bune et al. 1987b)

Hungarian experts took part mainly in the measurements. It turned out relatively soon that the site of Paks NPP, qualified as calm before the detailed investigation, was situated on a tectonically disturbed zone (Ádám 1985).

It became necessary to determine more precisely the tectonic structure by means of the measuring reflection seismic lines in a sufficiently dense network. Our suggestion for the detailed seismic survey was rejected, probably because of high expense, and a less expensive settling was chosen. Soviet experts did not argument against it and we did not persuade the client into financing a detailed survey.

A method was elaborated, based on the observation of large earthquakes that occurred in the Soviet Union, for the calculation of the expected largest magnitude (M_{max}) in a given area (Bune and Gitisz 1986). This method was applied for mapping of M_{max} in Hungary as well (Bune et al. 1987a).

For the calculations the following maps were used: four variations of recent vertical crustal movement (1973, 1979, 1985, 1986), seismic activity, Bouguer anomaly and its gradient, isostatic anomaly, areal distribution of heat flow and temperature at 1000 m depth, average height relief, thickness of the neogene sediment, density of lineaments and that of the water network.

It is relatively easier to determine the greatest earthquake to be expected on areas where seismic events often occur. In these high activity areas it is almost enough to use the statistics of earthquakes. On low to moderate areas the situation is quite different.

For the estimation of M_{max} the experts took into consideration the same geological, geophysical, geodetic and geomorphologic parameters, as described above, but they completed them by the data characterising the activity of the area. In the "Report" (Bune et al. 1987b) only the M_{max} value of the region of Paks was determined. In a later work they calculated the M_{max} value for the whole country (Bune et al. 1987a).

Characteristics of the M_{max} map of Hungary:

The map of the magnitudes constructed by the method of the extrapolation of the experts' estimations. The territory of the country was divided into a grid of 20x20 km. Earthquake was already observed in 20% of the squares. The experts gave for them the estimation of the M_{max} interval, further the geological and geophysical characteristics were also collected for each unit. If it is assumed that M_{max} is a periodically linear function of the geological-geophysical characteristics, the M_{max} value can be determined for each arbitrary square. According to their calculations an earthquake of magnitude $M_{max}=5$ is possible in the environment of Paks.

Without entering into details about this method we have to establish that large differences of M_{max} among neighbouring cells are impossible.

A very reasonable attempt aimed at making difference between active and inactive areas on the basis of geological structures. This effort has not achieved the expected result. The reason of this might have been as follows:

- insufficient investigation of active areas,
- improper knowledge of necessary data,
- inaccurate localisation of earthquake foci.

According to the contract the closing report was prepared by June 1987 (Report on the seismic hazard of the site of the Atomic Power Plant Paks. Moscow, 1987).

The Report consists of the following five chapters:

1) Present information on geodynamics and seismicity of the Pannonian basin.

2) The seismicity of Hungary. In this chapter the following three topics were dealt with:

a/ The earthquake catalogues of Hungary,

b/ Focal depths of earthquakes and the parameters of the equation of the macroseismic field,

c/ Evaluation of representativity of the earthquakes listed in the earthquake catalogue of Hungary, frequency diagrams, maps of seismic activity, evaluation of M_{max}.

3) Geological and geophysical characteristics of some strong earthquakes occurred in the Pannonian basin.

4) Evaluation of M_{max}, PZ, MRZ (assessment of "designed" and calculated maximum earthquakes). In this chapter the M_{max} map of the plant's environs, the evaluation of M_{max} based on geological and geophysical data are given, and the zones of seismic hazard are determined.

5) Seismic effects on the site of the nuclear power plant. The parameters of seismic effects and the modifying effect of the local geological conditions are computed. The calculated reaction spectra and the accelerograms are determined. The intensities of shake and deformations, the possibility of soil loosening are dealt with.

A list of references and a supplement are enclosed to the report. The latter contains the materials obtained from Hungary and a collection of artificial accelerograms.

The main results were summed up in six points in the conclusion of the report. Since these are the most important statements which caused a lot of discussion later, it seems to be important to list them here:

"It has been verified that the site of Paks NPP is situated on a geologically uniform block in a zone, where the occurrence of earthquakes of $M_{max} >= 5.0$ *maximum magnitude is possible. The most probable depth of an earthquake hypocentre is 10 km. For the proof of these results the deepening of 2–3 further boreholes would be advisable. These boreholes are required to solve geological problems which are connected with the clearing of the structure of the thin upper part of the earth's crust. In addition it is necessary to continue the reflection seismic surveys (additional two profiles with total length of 15 km).*

A zone of possible seismic hazard with potential earthquakes with magnitude $5.1 > M_{max} > 6.0$ *has been defined eastward and northward from the site of the plant. The focal depth is expected in the range of 5–20 km.*

In the south, along the border between Hungary and Yugoslavia, a zone of earthquake hazard with $M_{max}=5.8$ *was determined, but due to its distance of more than 100 km from the plant site it does not influence the PZ and MRZ values of NPP Paks.*

The parameters of the seismic regime of the zones were also estimated.

The intensity values of shake at the site of Paks NPP were determined as PZ=6 and MRZ=7 units for both the designed and the calculated maximum earthquakes.

The parameters of the seismic effects on the site were determined: the ball-unit values, the calculated accelerograms, and the spectra of reactions by taking into account the local soil conditions. As a result of the complex analysis of all the geological-geophysical and seismological data, it was possible to develop a method for the evaluation of the seismic hazard of areas with weak diffuse seismicity. The territory of Hungary in the Pannonian basin belongs to such areas.

In the course of the work a lot of problems arose, these are to be solved as soon as possible when new sites are selected for nuclear power plants. The most important tasks are as follows:

A comparative analysis of the strongly differing maps of the Carpatho-Balkan region showing recent vertical crustal movements.

Construction of a new map of recent vertical crustal movements during uniform time intervals (30–40 years) for the territory of Hungary.

Further research work for a more exact determination of the structural position of strong earthquakes. The research work should be organised specially for this purpose.

To organise radar-recording for finding the fractures of the sediment cover on certain parts of Hungary.

Another important task is to study further the geodynamics and seismicity of the Pannonian basin with the main goal to reveal the nature of the earthquakes occurring in this region. Earthquakes of small magnitude and of shallow focus may be dangerous for nearby engineering establishments, if the geological conditions are disadvantageous."

At the Soviet experts' request the study was discussed involving a large publicity of Hungarian specialists. During the discussion it turned out that there was a sharp contradiction between the Soviet and Hungarian experts regarding the character of faults in the vicinity of Paks NPP.

In the lack of space it is not possible to review the content of the report, submitted in 16 December, 1987. We have to point out only, that according to Soviet experts "Neither the disagreement of interpretation between the two parties nor the results of additional surveying or research work may have effect on seismological parameters calculated in the study for design considerations". Probably nobody of the experts at present believed in this statement, since by then it was clear that the Paks NPP was not on a large block but on a fault zone, which, obviously, is not the same thing.

Additional investigation, however, was suggested by the Soviet experts.

A. F. Gracsov and his co-authors in their work "Elucidation of the geological position and character of the fault in vicinity of the Paks NPP", published in January of 1989, tried to support their statement with further arguments.

It was expected that the results of Gracsov's collateral contract would not reach an agreement between Soviet and Hungarian experts. This became obvious after the Hungarian report was finished (Geological structure of Paks. Comprehensive report summarised by Z. Szabó in November of 1988).

Some critical remarks were created in the discussion of experts from ELGI (Loránd Eötvös Loránd Geophysical Institute), MÁFI (the Hungarian Geological Institute), GKV (Geophysical Research Company) and ELTE (the Geophysical Department of the Eötvös Loránd University) (Remarks on Gracsov's "Elucidation of the geological position and character of fault in vicinity of the Paks NPP"). The standpoint of the Hungarian experts can be summarised as follows:

"In our opinion the fault at Paks is only a small part of a first order structural line crossing the Carpathian region. The continuation of this line in SW and in NE direction is well known from the work of Rumanian and Yugoslavian specialists. Denying this fault means to deny not only our knowledge of structural geology of Hungary but denying the tectonical understanding of Carpathian and Dinarides."

For a new assessment of the seismic hazard of the Paks NPP it seemed advisable to consult the Hungarian experts (ELTE, ELGI, GGKI).

It was found that the M_{max} value to be expected in the area is higher than the Soviet estimate and, consequently, higher accelerations must be applied.

The main reason for the higher estimate arose from neotectonic investigations which established: *"In the investigated area important morphological changes took place during the Quaternary. Besides vertical movements there were dominantly strike-slip movements parallel to the Mór graben and along the main axis of the basement"*.

The Hungarian experts' viewpoints were summarised in nine points, as follows:

On the basis of geophysical and neotectonic investigations it can be concluded that in the vicinity of Paks the well know NE-SW main direction of basement is crossed by young fault structure of NW-SE strike which is parallel to the direction of the Mór graben. The young structure can be detected at some places in the soil layers as well.

On the basis of investigation of geological and geophysical parameters it can be concluded that in the vicinity of Paks the probality of the occurrence of an earthquake with an intensity of 6° MSK (corresponding to a magnitude $M = 4.4$) is twice as high as the Hungarian average.

Geophysical and geological investigations show that in spite of the low seismicity of the area in concern the occurrence of an earthquake with intensity of 8° MSK (magnitude of $M = 5.6$) similar to the earthquakes at Mór (1810), Kecskemét (1911), Dunaharaszti (1956) is not improbable.

The probability that an earthquake will occur with a intensity of 8° MSK during the lifetime (35 years) of Paks NPP is $8.4*10^{-4}$, that is one per thousand.

From the analysis of historical earthquake data it can be concluded that the probability of an earthquake occurrence with an intensity of 8° MSK during the lifetime (35 years) of Paks NPP is one order higher than the value received from geological investigations, that is one per ten thousand.

Maximum earthquake intensity with 95% probabilities of not being exceeded with 100 and 100,000 years are 6.2° and 7.8° MSK-64 (magnitudes $M = 4.5$ and 5.5).

According to synthetic accelerograms if an earthquake occurred with a magnitude of 5.6 in 10 km depth in the site vicinity the horizontal acceleration of the earthquake could reach 0.2 g on the surface in the area of the Paks NPP.

From the damage-analysis it can be concluded that the horizontal acceleration of seismic waves generated by the Kecskemét earthquake (July 8, 1911) was about 0.2 g.

The accelerograms of an earthquake with a magnitude equal to 5.9, registered on rock outcrop at a distance of 30 km from the source were used as input data for calculation the expected accelerations due to the frequency-dependent response of loose layers deposited in Paks. Results are for the horizontal amplitude of the radial component at the foundation of the Paks NPP 0.1 g, and at the surface 0.12 g. Similar computations gave for the transversal component 0.16 g and 0.19 g ., respectively

The tectonic situation was found more complicated than thought before. The Paks NPP is situated on the intersection of two faults.

A team consisting of a few experts: Balla, Z., Kilényi, É., Marosi, S., Scheuer, Gy. and Schweitzer, F. were asked to perform a more exact study on the fault structure of the given region. The authors came to the following conclusions concerning the earthquake hazard in the region:

"A major fault line in Hungary is striking in southwest-northeast direction through the Paks area but the joints surveyed in Pleistocene deposit are not associated with this lineament and their tectonic origin in most cases is ambiguous. Moreover, in the environments of Paks this direction is not endorsed by geomorphologic data for the majority of valleys in Mezőföld are oriented perpendicularly to it (i.e. northwest-southeast). Arguments for the tectonic origin of the latter are not convincing. Chloride anomalies also show Paks and its vicinity an area devoid of tectonic disturbances" (Balla et al. 1993a).

Considering that – in lack of data – the recent activity of fault zone had not been proved in Balla's study, proposals were made for additional investigations (Szeidovitz, 1991). The proposals were discussed and partly accepted by a team of experts (Ádám, A., Balla, Z., Chikán, G., Csontos, L., Horváth, F., Katona, T., Kilényi, É., Scheuer, Gy., Schweitzer, F., Szabó, Z., Szádeczky, Gy., Szeidovitz, Gy. and Tóth, L.) called together by the initiative of the Paks NPP.

The plan of a seismological network for observation of microearthquakes was accepted in this consultation as well. According to the evaluation of experts the observation of microearthquakes produced the most primary evidence of activity. As a counterargument for establishing the network the higher background noise, the signal processing and measurement-technical difficulties were mentioned. The implementation of the network needs about 8 months. The observation time is 2–3 years.

The British firm Ove Arup and Partners has also been asked to determine of earthquake hazard of the Paks NPP. The report: "Paks Nuclear Plant Seismic Hazard Assessment, 1991" used methods developed mainly for zones of large earthquakes. Arup worked according to the safety norms of IAEA: "How to Take into Account Earthquakes and Connected Phenomena at the Planning of Atomic Power Plants".

Four source models were calculated. The first model seems to be the most realistic, according to which the seismic activity is uniform in the Pannonian basin. The most disadvantageous is the fourth model in which the activity is concentrated to two fracture lines, one of them being directly under the Paks NPP.

In the first model the opinion of the authors is expressed according to which no characteristics indicate that Paks should be regarded as an area, where the seismic activity differs from that of the Pannonian basin.

The fourth model is the most conservative, since the seismic activity of the Pannonian basin is "concentrated" into a relatively narrow strip. In the Arup report 3.3 m/s is given as the most probable value of the horizontal acceleration with a period of 10,000 years.

In order to summarise various, sometimes contradictory, reports to define the further investigations and surveys and to prepare final recommendations a Committee was set up, composed from the best independent experts (Meskó et al, 1993). The Scientific Coordinating Committee worked for one and a half year commissioned and supervised geological, geophysical surveys and seismological research and summarised conclusions (Meskó et al. 1993) as follows:

The constructed 1:50 000 scale map of the surface geology and lithofacies gives a good start for further detailed research. In the outcrops and (shallow) grabens no signs of motions were found which were unambiguously of tectonic origin. On the shallow seismic profiles measured in 1989, however, the cut of the Pleistocene Danube alluvium by tectonic zones were unambiguously indicated. On this basis the satisfying conclusion can be drawn that in the region of Paks movements of the size producing tectonic near-surface structures (folded or fractured forms, faults, strike-slip faults, overlapping) did not occur during the last 420 000 years.

In spite of the lack of transverse profiles the new seismic measurements were in correlation with the previous ones, and helped to form a seismotectonic synthesis. The most important result of that was the mapping of a 1–2 km wide disturbed zone between Paks and Kecskemét, going over Pahi and Orgovány. It follows from the correlating structures that one has to count with potential occurrence of earthquakes of Kecskemét type and intensity in the area of Paks, too.

For the maximum intensity expectable in Paks the results varied within a wide range due to the fact that the final results are considerably modified by the choice of the source fields and damping. In spite of the uncertainties the Scientific Co-ordinating Committee agreed with the maximum acceleration values of 0.6 and 0.8 m/s^2 for the safety level SL-1 (at 50% and 84 % probability, respectively), and with 3.0 and 3.5 m/s^2 maximum acceleration for the safety level SL-2."

The maximum accelerations seem high for the first look, but it is well known that in case of earthquakes of magnitude M = 5.6 with shallow foci even greater maximum accelerations can occur.

Finally, the latest study was carried out by Ove Arup (1995–1996). Our remarks in connection with this study have been made thus we suffice here a summary of the main results of the Arup's report as follows:

A probabilistic seismic hazard assessment (PSHA) has been made for the Paks NPP. This combines a knowledge of source zones, rate of earthquake recurrence and attenuation relationships. Based on these three elements and using statistical techniques, the amplitude of ground motion was calculated that is associated with a given return period or annual probability of being exceeded. Uncertainties have been incorporated in a systematic and rational way, using the "logic tree" formulation. In this method various alternatives for the input parameters have been used, and each assigned different weights, based on expert judgement, and a weighted average of the results calculated to produce a best estimate hazard value.

The PSHA calculation show a consistent response spectral shape for the three return periods considered, namely 1,000 years, 10,000 years, and 100,000 years. The best estimate, or mean, peak horizontal ground (bedrock corresponds to the surface of Pannonian deposits in our case) acceleration varies from 10% g for 1,000 years to 25% g for 10,000 years and 55% g for 100,000 years.

The hard site spectra calculated in the site specific seismic hazard assessment has been modified to take account of the unconsolidated near-surface materials overlying the hard Pannonian deposits at the Paks site.

The spectral ratios scaled by the 10,000 year return period show a peak amplification of about 1.5 at a period of about 0.5 seconds.

In spite of the diversified investigation carried out in the last 10–15 years it can be said – with a little exaggeration – that we can neither confirm nor refute professor Medvegyev's forecast made 20 years ago and based only on the activity of the Carpathian basin: "*voszem ballov*" (8 degree on the MSK scale).

In spite of obvious insuffiencies the investigations can not be qualified as useless, of course. By taking part in this program Hungarian seismologists were provided possibilities never seen before.

In our opinion one reason of having modest results can be found in the fact that investigations have been concentrated mainly in the Paks area and other active structural regions in Carpathian Basin with their geo-characteristics have usually been neglected.

We have not yet examined satisfactorily the geophysical results obtained by hydrocarbon explorations. In the vicinity of Kecskemét seismic profiles with total length more than 900 km were shot and more than 1000 shallow and deep drillings were bored. A lot of exploration work were compiled in the active areas as well.

On the basis of more detailed data it could have been decided what kind of criteria could be used for the separation of active and aseismic areas. In the following – with no intention to be exhaustive – some criteria are suggested to identify active areas in Hungary in a more exact way.

3. On the detection of earthquakes sources

The following points were taken into considerations:

1. Stress accumulation is due to regional forces acting on the crust. Magnitude and direction of the forces change slowly.

2. The Pannonian basin consists of crustal fragments divided into smaller or larger plates (blocks) which are moving in a complicated way, similar to the movements of drift-ice.

3. The stress accumulation is a disturbed process. The main earthquakes are preceded by microearthquakes.

From these three obvious findings one can draw conclusions as follows:

– The areal distribution of the quakes must show some stability in some degree. (Here we do not think that the observation of earthquakes during the last few hundred years is representative of the seismicity of our territory, we say simply that the active regions remain active in the future as well.)

– In each focus several quakes occurred during the Pleistocene. These quakes might not cause noticeable changes on the surface one by one, but their cumulative effect perhaps can be reflected by geomorphologic and neotectonic investigations. In nearly horizontal level regions even little uplifting or subsiding have changed the network of rivers and the active areas can be designated by the analysis of ancient geographical picture.

– The earthquakes occur on the borders of plates moving at different velocities. In consequence of this the areal distribution of earthquakes can indicate the faults and perhaps the contours of the plates (blocks). From the size of these plates the magnitude of earthquake can be estimated.

Between brackets it is to be remarked that the assumption of plates has already appeared in Réthly's work (Réthly, 1952) where he spoke about "seismic lumps". One can refer to Gutdeutsch's work (Gutdeutsch, 1986) in which he writes: *"When we try to understand the seismicity of the Pannonian basin, we have to take into account the structure of the basement below the Neogene sedimentation. The basement is cut and disintegrated into a pattern of single blocks separated by more or less vertical faults."*

According to the statements above the geological environment of larger earthquakes occurred in Carpathian-basin can be characterised as follows:

1. There are fault zones in deep structures
2. Crustal movements took place during Pleistocene and Holocene.
3. In the vicinity of larger earthquakes the activity is higher than the average.
4. The contours of blocks or at least a part of them are indicated by the earthquake sources.

4. A review on larger earthquakes occurred in the Carpathian-Basin and their geological characteristics

We don't want to deal with the detailed description of earthquakes it is sufficient to refer to the paper of Szeidovitz and Mónus (1993). Our attention will be concentrated on space and time distribution, source mechanism and isoseismal maps of earthquakes that occurred in the vicinity of the source.

Efforts were made to identify the fault zones which generated the earthquakes and to establish the spatial position and measurement of the borders of blocks.

The main conclusions of the study are compiled in *Table 1.*

Table 1

N	Location Date	I_0 (MSK h M	Directions	Ae	Au	Geological structure in source zone
1	Békés 1978.06.22.	6° 12.5–15.8 4.5	N–S – NE–SW	10	20	The edge of the subsiding Békés basin
2	Berhida 1985.08.15.	6.5° 12 5	N–S – E–W	29	67	The boundary of the subsiding Berhida basin and Kungos-block
3	Dunaharaszti 1956.01.12.	8 4.8 5.6	N–S WNW–ESE NE–SW	8	37	The margin of the subsiding Alsónémedi basin
4	Eger–Ostoros 1925.01.31.	7.5 5.3 5.3	NE–SW NW–SE –	20	39	The edge of the Egerszalók-Ostoros-Noszvaj depression
5	Érmellék 1834.10.15.	8–9 – –	– – –	1	13	Gálospetri-graben
6	Gomba 1908.03.16.	6 2.8 –	NW–SE – –	15	22	The northern part of the uplifted Bugyi-block and the margin of the Alsónémedi depression
7	Jászberény 1968.06.21.	7.5 5.0–6.2 –	– – –	6	15	The sinking northern part of the Jászság depression
8	Kecskemét 1911.07.08.	8 20.0 5.6	NE–SW NW–SE –	13	27	Moving blocks in the triangle of Lajosmizse-Nagykőrös-Kecskemet
9	Komárom 1763.06.28.	8–9 7.0–9.0 6	E–W – –	2	40	Hurbanovo (Ógyalla)–Diósjenő fault zone
10	Mór 1810.01.14.	8 4.0 –	N–S – –	6	53	Mór graben
11	Pest–Buda 1561.02.012.	8 – –	– – –	0	0,9	The source of earthquake is uncertain
12	Pincehely 1892.06.22.	6.5 2.0 –	N–S – –	1	10	The boundary between the Tolna-ridge and the Kapos-line
13	Szeged 1444–08.04	8 – –	– – –	0	6	The source of earthquake is uncertain
14	Tápiósűly 1942.09.30.	6 8.0 4.2	E–W – –	20	6	The northern part of the uplifted Bugyi-block and the margin of Alsónémedi-depression
15	Teresje 1951.02.20.	6.5 10.0 4.7	E–W – –			Eastern part of the Hurbanovo (Ogyalla)–Diósjenő fault
16	Ukk 1953.09.13.	6.5 – –	E–W – –	4	139	Fault at Türje. Direction of the fault: NNW-SSE

Key to *Table 1*

N – *serial number*
h – focal depth in km
I_0 – epicentral intensity in MSK scale
M – local magnitude
Directions – 1st row: the main direction of isoseismal lines
2nd row: the direction of fissures generated by the earthquake
3rd row: the direction of rock-stress.
Ae– Number of earthquakes preceding the main shock per hundred years in the source region (in a radius of 30 km)
Au– Number of earthquakes per hundred years after the main earthquake in the source region (in a radius of 30 km). Aftershocks have not been taken into account (within two years after the main shock).

4.1. Fault zones affecting the Pannonian layers

A great number of faults lines can be seen in the Pannonian layers thus it was not difficult to bring some of them into connection with earthquake foci. It should be mentioned, however, that the localisation error of larger earthquakes is rather high therefore sometimes can not be decided which of the faults generated the earthquake.

The analysis of activity on a given area (fore– and aftershocks observed on a smaller area indicated in the last column of the table) gives a good estimate for the location of the occurrence.

In the few cases where detailed geological and geophysical investigations in the source region (Kecskemét) were available the direction and magnitude of the source could be determined even more exactly.

4.2. Traces referring to Pleistocene and Holocene movements

In the vicinity of a few earthquakes Pleistocene movements can be exactly detected: Berhida (Ádám 1959), Érmellék (Borsy 1961, Benedek 1960), Dunaharaszti, Ostoros, Pincehely, Gomba, Mór and Komárom (Schweitzer 1992, 1993 1993a).

Under the direction of Jámbor and Schweitzer two Pleistocene fault maps (in the scale 1:500 000) were compiled by the specialists of MÁFI (Hungarian Geological Survey, HGS) and FKI (Geographical Research Institute of HAS, GRI), independently from each other. The specialists of HGS were of the same opinion that the recent valley system is basically defined by the Pleistocene faults as dominating ones. On the maps many

Pleistocene faults were shown but only a few were accepted by the authors Balla, Z., Schweitzer, F. and Szabó, Z. (Balla et al. 1993b). They defined three classes for Pleistocene faults:

1. Faults that can be outlined by direct data,
2. Faults that can satisfactorily be identified by indirect data,
3. Faults that can be justified with some uncertainty.

The faults were practically identified on the basis of geomorphology and on the analyses of history of evolution.

East of the Danube in the North Hungarian Range only four faults were given the quality marks 2 or and 3, in the Great Hungarian Plain none. It may be added that there are very few Quaternary outcrops or exposures. The seismic reflection profiles generally do not show Pleistocene formations. Moreover, the traditional reflection seismic method as applied for oil prospecting can not indicate the Pleistocene faults, due to the upper limit of the resolving power (which is approximately 10 m).

It follows from previous discussion that according to Balla's report it is impossible to delineate the earthquake sources in the main part of Pannonian Basin on the basis of Pleistocene faults. There are no proof for Pleistocene faults at Berhida or at the Mór graben.

In spite of the difficulties a Quaternary kinematics map (1:500 000) was prepared by Jámbor et al., 1995. In compiling the map all results achieved in the last years were taken into account.

The following zones can be distinguished in the map compiled by Jámbor et al. (1995):

1. Paleogene and Mesozoic formation on the surface or covered by Quaternary formations.
2. Cainozoic (mostly Neogene) volcanic rocks on the surface or covered by Quaternary formations.
3. Deposits filling the Cainozoic basin.
4. Area of the largest Quaternary depression.
5. The main zones in Quaternary separating elevating and subsiding territories.
6. Main transversal faults being active in the Quaternary.
7. The boundary of a steep sided depression in the Cainozoic basement.

Comparing the kinematics map with the earthquake data the following comments can be made:

In 20% and 27% of epicentres and random points, respectively, within a radius of ten km of these points no geological structures, shown on the kinematics map could be found.

In 85% of all earthquakes with epicentral intensity of 5^0 or less some geological structures indicated on the map have not been found within a radius of 10 km.

In the case of the smaller earthquakes the better correlation can be explained by their better localisation.

Several earthquakes occurred between the Danube and Tisza rivers but Pleistocene geological structures were not found in that region, partly explaining the weak correlation. On the map, made by Schweitzer et al. (1993), however, there is a properly supported fault (Number 43) which was omitted later (Balla, 1993b). Nevertheless on the maps, made by Urbancsek (1979) and Rónai (1977) of the thickness of Quaternary deposits a distinctly visible Budapest-Cegléd direction (ancient river bed) can be identified.

In spite of the fact, that we are not fully satisfied with these results, the kinematics map may contribute to the indication of potential earthquake sources.

4.3. Stability of earthquake sources

A higher than average activity before main shocks is not characteristic to each source. It may be explained by our insufficient knowledge of smaller earthquakes before 1880.

After larger earthquakes the source activity gradually decreased but remained higher than the average.

The stability of sources is supported by the fact that all earthquakes observed by the seismological network set up around the Paks NPP did originated in the vicinity of well known sources. Assuming, as a few specialists suggested, that two faults: the Mór graben and the Zagreb-Kapos lineament cross each other below the power station, and supposing that every earthquakes occurred in the vicinity of Mór and Kecskemét was generated by the Mór graben and the Zagreb-Kapos fault zone, one could estimate the number of earthquakes which ought to have been detected in the vicinity of the Paks NPP. According to our calculation at least a few events should have been detected by the high sensitive (M>2) seismological network during the last two years.

4.4. Investigation of the contours of blocks

Looking at the map of earthquake epicentres one can recognise places in Hungary where earthquakes have not been observed (mainly in mountain regions and regions east of the river Tisza), and there are more active areas (piedmonts and edges of depression basins).

In a few cases the contours of blocks are outlined by the spatial distribution of earthquakes (Küngös plateau, Tolna ridge, Vértes, Bükk, Mátra).

It is remarkable that sometimes earthquakes far from each other happened practically simultaneously. These events can be explained by block movements. Good examples are the Küngös-plateau, Tolna-ridge and Bükk mountain.

The border of the Bükk-blocks was indicated by earthquakes which occurred in the west (Egerbakta, Egercsehi), in the north (Dédestapolcsány) and in the east (Miskolc).

Earthquakes occurred practically at the same time at Dédestapolcsány (December 5, 1896) and Mezőkövesd-Egerfarmos (November 30, 1896) and Miskolc (January 18, 1897).

Réthly, A. (1952) found the simultaneous occurrence of three events peculiar as well. He wrote: *"The earthquakes of these two days were the precursors of a larger earthquake in January 18, 1897. It is characteristic that the shocks occurred in the two days were far enough from each other: one (November 30) burst out at the edge of the Great Hungarian Plain and the other (December 5) occurred at the foot of Bükk, and they did not relate to each other from the tectonic point of view."*

The coincidence of earthquakes can be explained by an other way: the stress accumulation process in the sources was interrupted by the main earthquakes. Of course this explanation has supported our idea about the place of stress accumulation. Similar phenomenon was met at the edge of the Tolna-ridge, and in Küngös-plateau.

4.5. The largest earthquake in the vicinity of the Paks NPP

The largest earthquake about 60 km from Paks occurred in Kecskemét in 1911.

Earlier – till the end of the sixties – several authors supposed that the epicentral intensity of Kecskemét earthquake of July 8, 1911 was about 9^{o} on the MSK scale and it had a focal depth of h>20 km, a rather exceptional value for Hungary. The epicentre was obtained by Réthly at a distance from the centre of the city Kecskemét, in NW direction where a mud volcano (mole track) threw out sandy water. According to him, the intensity of the quake nearly reached the value of X on the Mercalli-Cancani scale. According to Réthly the epicentral area with intensity IX–X was 90 km^2 and the total area of the earthquake with intensity III–IV was 69 300 km^2

The isoseismal map prepared later by D. Csomor can hardly be interpreted as no values are given for isoseismal lines (Szeidovitz 1995). It can, however be supposed that the values are in increasing order IV, V, VI, VII, VIII and IX. A further difficulty is that in the areas between the isoseismal lines the intensity values are different. Thus inside the innermost isoseismal lines (IX) there are intensity values of IX, VIII, VII and VI too, then going outwards, there are intensities VI and VII between the isoseismals IX and VIII in addition to the intensities VIII expected there. The magnitude M = 5.3 and the maximum epicentral intensity IX are in agreement only if an unlikely shallow focal depth (about 3 km) is supposed. Nevertheless, the isoseimal in the map led to the determination of focal depth of h= 15–20 km or even more, being deep in the Hungarian tectonic setting.

According to an (unfinished) map in a manuscript by Z. Kiss an epicentral intensity I_0=VIII and a focal depth of h= 2 km could be estimated. But the magnitude value computed with the Gutenberg-Richter formula

$$M = 0.6\, I_0 + 1.8 \log h - 1 \qquad 1$$

with these values gives M = 6.2, a too high value.

The isoseismal map prepared by Kiss probably contains a contradiction too, as based on the areas of the isoseismal lines, a focal depth of $h = 13$ km should be computed and this depth yields together with $I_0 = \mathrm{VIII}$ a magnitude $M = 5.8$.

It seems to be necessary to re-evaluate the main parameters of this earthquake.

The uncertainty of the values I_0, M_S and h have been taken greater than that of recent earthquakes because parameters of historical earthquakes could be estimated less accurately. An acceptable basis for the determination of uncertainty of the 1911 Kecskemét earthquake is the Roermond earthquake on April 13, 1992 near to the German–Dutch boundary. Here a thick sedimentary cover lies on the basement rocks and no earthquakes of similar magnitude has been observed since 1756. The magnitude 5.9 and epicentral intensity of this German earthquake was determined with an accuracy of ± 0.1 and the focal depth as $h=14\pm 3$ km (Ahorner, 1992). It is important for the estimation of accuracy that this earthquake was also recorded with Wiechert-type instruments still being in operation in Germany.

The focal depth of the 1911 Kecskemét earthquake can be estimated by using various approximate methods. Assuming a spherical focal region, the formula

$$\log r = 0.51\,M + 2.73 \text{ (in cm)} \qquad 2$$

(Kasahara, 1981) an be applied and it yields with $M = 5.3$ and then the radius $r = 2.7$ km.

The maximum length L_{max} (in km) of the fault connected with the earthquake according to the formula (Kasahara 1981):

$$\log L_{max} = 3.2 + 0.5M \qquad 3$$

is 7.1 km, and the surface of the fault 22.9 km^2. The basement depth in the Kecskemét area is 2.5 km and the surface participating in the earthquake is minimum if the earthquake occurs along the whole length of of the fault. These assumptions give for the minimum focal depth of the earthquake 4.1 km.

Ten earthquakes, distributed in an area of 600 km^2 around Kecskemét gave an average depth 8.1 ± 2.9 km.

The empirical formula given by Kasahara (1981):

$$\log A = 1.02\,M + 6.00 \qquad 4$$

yields $M=6.5$, and even if the somewhat more distant earthquake of Fülöpjakab (with depth $h=7.8 \pm 3.0$ km) is excluded, the magnitude surpasses 6.

The question to be answered on the basis of all these assumptions and data is: whether an epicentral intensity and focal depth could be found for the Kecskemét earthquake in July 1911 which is in accordance with all the observed data?

The answer to the question was sought in the following way:

1. Isoseismal lines, based on survey of damages (Szeidovitz, 1995) were analyzed using Kövesligethy's formula.

2. The possible depth values determined by Kövesligethy's method were brought into accordance with the magnitude values known from instrumental observations using different empirical formulas such as the Gutenberg-Richter, the Kárník and the Szeidovitz formulas.

According to our experience, the Gutenberg-Richter formula and the Kárník fomula for European earthquakes are the most adequate for the present case. The two formulas are about identical.

As a summary of our investigation the following can be stated:

– the epicentral intensity of the Kecskemét earthquake of July 1, 1911 was less than supposed previously, and the most likely value is I_0= 7.5 to 8 MSK

– isoseismal lines have elliptic shapes

– the Kecskemét earthquakes originated north of the city, at a distance of about 20 km from the tectonic line connecting the Kapos-line with Maramures through the Great Plain and therefore they do not prove the recent activity of this important tectonic line.

5. Summary

Some part of the studies dealing with the seismic hazard of Paks NPP has been outlined.

Significant differences manifested in the results question the applicability of methods derived from the investigation of larger earthquakes.

The process leading to earthquakes can be imagined as follows: Under the influence of slowly changing forces acting on the crust the blocks are moving in a complicated way interacting with each other while stresses concentrate at their borders.

From the more or less independent movement of the blocks the conclusion can be drawn that faults separating the blocks are extended to the bottom of the crust.

At the borders of blocks moving with different velocity displacements had to happen during the Pleistocene and Holocene as well.

On the border areas where larger earthquakes were observed the activity remains higher than the Hungarian average.

Indications on active territories so far have not made possible to delineate the active zones in the Pannonian Basin with the required accuracy.

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The microseismic monitoring network of the Paks NPP

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1. Introduction

Seismicity gives the most direct evidence of tectonic activity. Several studies have shown (e.g. Evernden 1970) that the number of earthquakes is related to magnitude by the formula

$$\log N(m) = a - b\, m$$

where N(m) is the number of earthquakes with magnitude equal or greater than m and a and b are constants.

Both instrumentation and analysis techniques used in seismology have markedly improved in the last two–three decades. By now, only the background noise of natural and man–made sources set the minimum detection levels for seismic signals and the logarithmic magnitude frequency relationship could be extended for micro earthquakes down to magnitude –2. (Scholz 1968).

Even in Europe, where the number of seismograph stations in national networks are relatively high, it is hardly possible to go down with the overall detection capability below magnitude 3.0 (Tóth 1981). A local network of high quality seismographs should be used to locate earthquakes as small as magnitude 2.0 at a given area.

The wider area of Paks NPP site is geologically very complex. However, if the existing tectonic features are active in the present, or were active in the near past, this necessarily should be reflected in current local seismicity. To close this knowledge gap, installation of a local earthquake monitoring network was recommended by an IAEA expert team after their visit at the site in 1993. The purpose of this network should be to develop a database of well located earthquakes that can be used to resolve the tectonic framework in the vicinity of the Paks site as opposed to the more restrictive objective of determining whether seismicity can be associated with faulting in the vicinity of the site.

The Microseismic Monitoring Network (MMH) represents one of the most important elements of the study of the seismic hazard at the Paks NPP site. The longer is the monitoring time, the more data THE MMH gathers on current seismic activity, and the question of current tectonic activity can be answered with increasing reliability.

2. Scientific and technical concept

A study of the seismic hazard at the site requires input data from geology and tectonics of the area and, of course, the seismic activity. Research of historical earthquakes extends the time base and improves the statistical significance of the seismic database. While good information about larger historical earthquakes exists in Hungary for about the past 200 years, (Réthly 1952, Zsíros et al. 1988) the earthquakes are not located well enough to resolve which tectonic features are active. A microseismic monitoring network gathers data on current seismic activity down to quite small magnitudes and reveals details of possible active faults, local stress conditions, seismic activity rate and attenuation of seismic waves. Studying the historical seismicity at a wider area of Paks, 6–30 earthquakes with magnitude $ML \geq 2$ can be expected annually. According to the recommendations given by IAEA, a network of high quality digital seismographs should be installed capable of detecting and locating earthquakes as small as magnitude 2.0 within about 100 km, with an aceuracy at least ± 1 km of the Paks NPP site.

To approach the scientific goal defined above the followings are needed:

– Local network of 8–10 seismograph stations within a 50 km radius from Paks. The site selection of the stations should be based on well established seismological procedures which take into account the local geography, geology and soil conditions, seismic background noise and logistical problems relating to servicing the stations and retrieving data.

– The stations should be equipped with three component short period sensors with sensitivity at least ten times below the local noise level. The analogue output of the seismometers should be sampled by 16–20 bit dynamic range A/D converters and the sampling rate should be high enough to have 40 Hz signal frequency. The data acquisition system should perform automatic event detection and only detected events are recorded.

– The final event list should be compiled after extensive off–line analysis; other seismic stations from the national network and from neighboring countries should also make of use.

3. Site selection criteria for seismic stations

In planning the distribution of seismic stations, beside the geometry, it is very important to take into acconut:

– *Seismic background noise level* – it can be determined by noise measurements at the potential sites. The average noise level is the most important parameter which sets the detection threshold for the future stations. Low noise level and its small variation ensures the sensitivity of the station (Mónus and Szeidovitz 1991).

– *local geology* and soil conditions – the more consolidated is the basement of the seismometer the better is sensitivity. An outcrop is the ideal place for the station.

– *Logistical problems* – important relating to servicing the stations and retrieving data.

– *Distance from noise sources* – sites with known noise sources in the vicinity (e.g. railway, main roads, pipelines, mining activity, large lakes, settlements with industrial activity) should be avoided. Minimum distances from known noise sources are summarized in *Table 1.*

– Availability of and telephone power network for electric supply and communication channels respectively.

Table 1. Minimum distances from known noise sources

Noise source	Distance [km]
Main railway	10–15
Highway/main roads	5–10
Roads	1–3
Pipelines	3–5
Small roads	1–3
Mining activity	10–20
Large river	3–5
Large lakes	50–100
Deep drilling activity	5–10
Cities	10–15
Villages	1–3

4. Station description

The system comprises a network of ten seismometer stations located within a radius of about 50 km from the Power Plant at Paks (situated in the central part of Hungary) and a data center in Budapest where the data are collected and analyzed. Each field station consists of a three component short period seismometer located in a pit, with a digital recorder and time signal receiver housed nearby in a heat insulated steel container building. The seismometers used are the LE–3D three directional compact size high sensitivity 1 Hz geophones. The digital acquisition system is the MARS–88 recorder that uses 20 bit A/D converters sampling the data 125 times per second. The recorder also performs signal detection by its internal STA/LTA algorithm. Two of the stations are accessible over commercial telephone lines while the others store event and continuous monitor channel data on rewritable magneto–optical disks, which are collected and transferred to the data center on a weekly basis. Most of the stations are powered by solar panels, and absolute time is provided by DCF–77 time code receivers.

5. Data analysis and seismological interpretation

At the data center a SUN SPARC workstation with 3GB on–line disk capacity serves as a powerful tool for the routine data processing and analysis. Lennartz M88 database software is used for the data management and XPITSA for advanced seismogram analysis. HYPO71PC (Lee and Lahr 1975) has been used for the routine calculation of hypocentre parameters. The original program has been slightly modified in order to implement a routine for Richter local magnitude calculation for the instruments used. For the magnitude calculations the method published by Bakun and Joyner (1984) has been used.

A new genetic approach developed by Bondár (1994) for hypocentre determination of local earthquakes has also been tested.

The hypocentre parameters has been calculated using phase readings of seismological stations from Hungary and from the neighboring countries. However, a distance weighting is applied, phase data from stations with epicentral distance greater than 450 km have been assigned a weight of 0. In some cases, when enough P readings are available, S phase readings are not used in the calculations.

The three layer crustal velocity model used in the hypocentre calculations has been derived from crustal phase travel times of several hundreds of local earthquakes (Mónus, 1995).

Parameters of the model are summarized in *Table 2.*

Table 2. Parameters of the crustal model

Velocity (v_p) km/s	*Depth km*	*Thickness km*	v_p/v_s
5.60	0.0	20.0	1.78
6.57	20.0	11.0	
8.02	31.0	∞	

The Microseismic Monitoring Network is currently operated and its data processed analyzed and published by GeoRisk Ltd in the form of annual bulletins according to the international seismological practice (Tóth et al. 1996, 1997). The British Geological Survey have been supervising the network operation through the European Community's PHARE research program. Monthly Technical Reports, Semiannual Event Lists and Annual Bulletins are the products of the system.

Both waveform and bulletin data are available over INTERNET for authorized remote users. All row data, some 50–60 Gbyte annually, is archived at the data center on CD ROMs for future analysis and for quality assurance purposes.

6. Results

The Paks Microseismic Monitoring Network has been operating since April 1995. Although the given geological and background noise conditions are far from ideal at some stations, with average noise conditions the typical detection threshold of the network (supported by other existing stations) is around 1.5–2.0 ML, somewhat lower in the middle of the country and a little higher towards the border regions. This means that for the first time in the history of Hungarian earthquake seismology, in most part of the country, it is very unlikely that felt earthquakes go undetected.

During nearly two years of operation about thirty local earthquakes were detected and located within the Hungarian national boundary. Some others occurred in neighboring countries and were sometimes sufficiently large and near to be felt in Hungary and thus merit consideration in seismic hazard studies.

The magnitude of the detected Hungarian earthquakes range from 1.6 to 3.7 ML, typical of intraplate seismicity. Geographically the epicenters also show a near random distribution expected in an intraplate area with no dominant tectonically active features. Comparing historical seismicity with the recent events, it shows that the recent earthquakes, in general, lie near to clusters of historical activity. Three events at Szabadszállás are exceptions in the sense that they appear not to be associated with historical activity but lie near a cluster of historical events some 30 km to the east.

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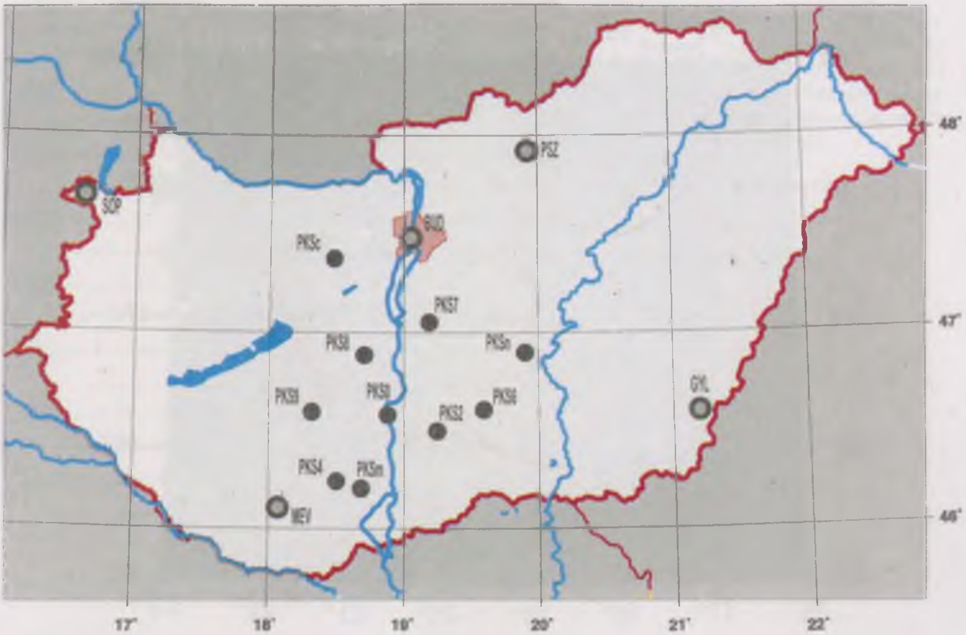

Fig. 1. Geographical distribution of seismic stations of the Microseismic Monitoring Network (black circles) and other supporting stations (grey circles) in Hungary

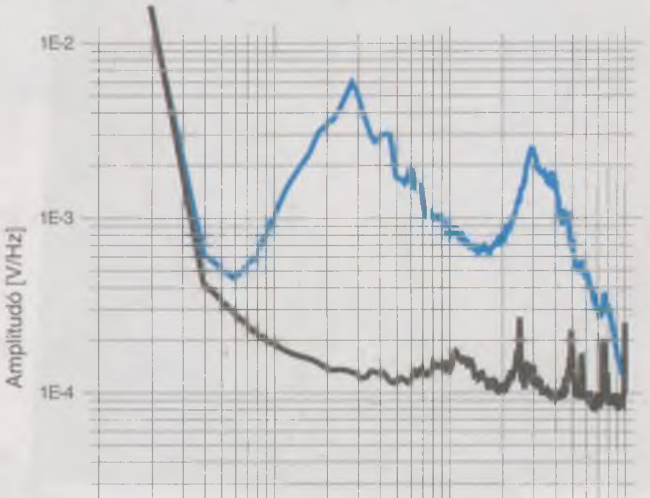

Fig. 2. Typical noise spectra recorded at a loose sediment and at an outcrop site, respectively

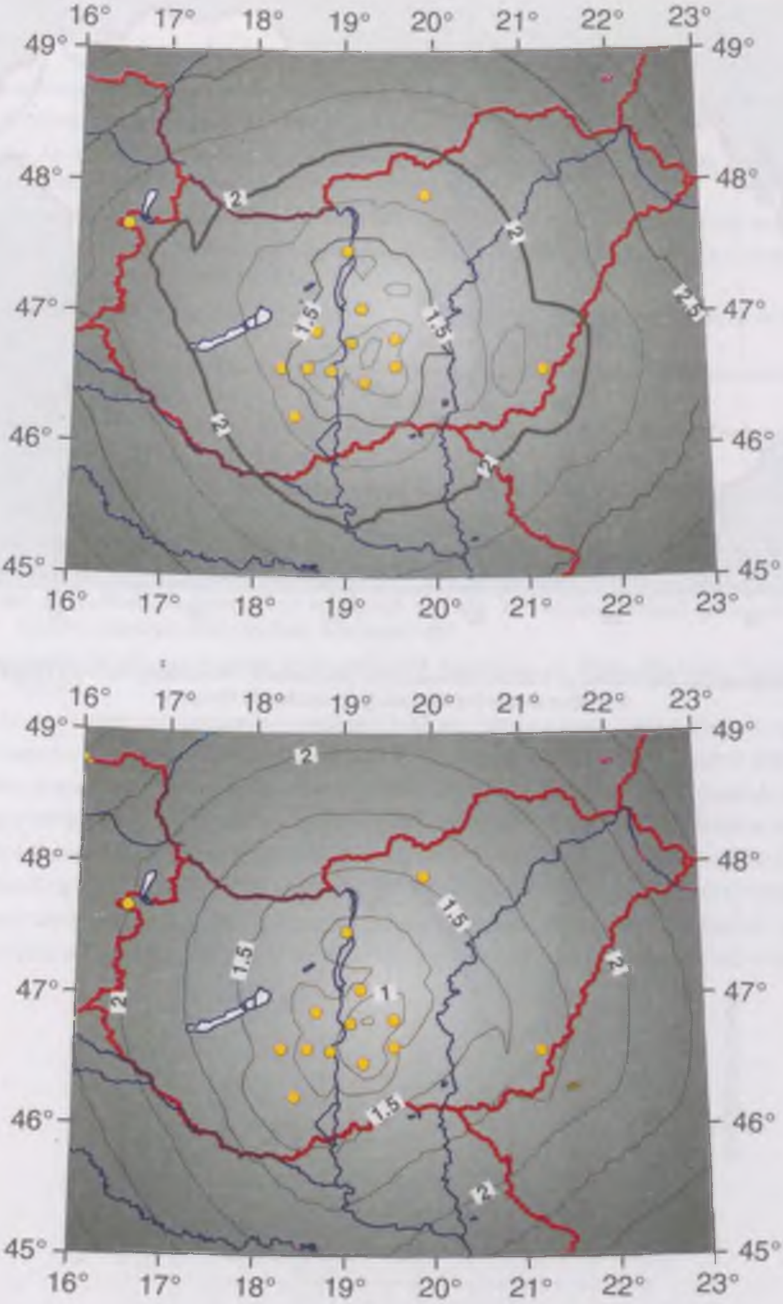

Fig. 3. Network detection capability with average noise conditions day (up) and night (down). Contour values are given in Richter local magnitudes (ML).

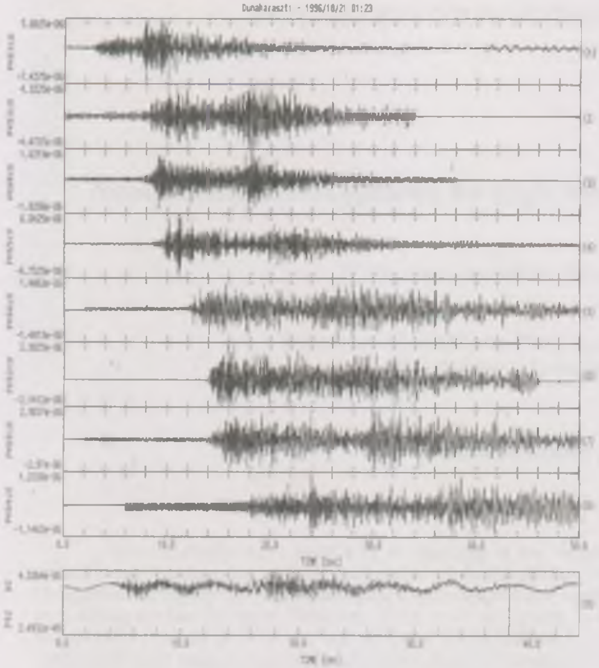

Fig. 4. Seismograms of the Dunaharaszti earthquake on 21st October 1996, 1:23:26 UTC (ML=2.5) shown by the Microseismic Monitoring Network. The vertical axis is ground velocity in m/s.

Fig. 5. Earthquakes in Hungary, 1995-96

Neotectonic investigations by high resolution seismic profiling

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1. Introduction

Several studies have dealt with the geology in the vicinity of the Paks Nuclear Power Plant. Special attention was paid to the age and correlation of faults cutting through Miocene and Pannonian strata. Most Hungarian and foreign geologists and geophysicists agree that some basement faults have been reactivated in the area during the late Neogene. However, debates are still going on if fault activity continued during Quaternary, and therefore recent activity and capability of faults can not be considered a closed subject. High resolution shallow-seismic measurements can contribute vital information for the clarification of the problem. The aim of this report is to present the results of the river Danube high resolution seismic survey carried out by the Geophysical Department of the Eötvös University (ELTE) and review the reprocessing of onland shallow-seismic lines measured by the Eotvos Lorand Geophysical Institute (ELGI). Joint interpretation of all of these seismic lines has been carried out and the results are presented.

The Geophysical Department carried out a seismic survey on the river Danube in October 1994 with the participation of foreign experts. This paper includes five multichannel seismic lines measured with a watergun source. These five profiles have been measured in the 15 km vicinity of Paks Nuclear Power Plant and provide information about the strata underneath the river from the riverbottom down to a depth of more than 500 meters. The aim of the survey was to obtain a detailed image of the faults crossing the Danube in order to carry out neotectonic and stratigraphic evaluation. The total length of the five profiles presented *(Danube-202, Danube-203, Danube-205, Danube-207* and *Danube-208)* is 16.1 km. In addition to these profiles further multi-channel lines from the Danube survey *(Danube-201, Danube-206* and *Danube-209)* and reprocessed versions of onland shallow-seismic lines *Pa-2a, Pa-2b, Pa-3b, Pa-12, Pa-13, Pa-14, Pa-15* and *Pa-17* were used for interpretation.

Chapter 2. is a brief summary of seismic profiling introducing both surveying and processing techniques to those who are not specialists in this field. Aim of this chapter is to provide the necessary background information for later chapters. In this short introduction we could not discuss all the details of the seismic surveying and the interested reader is referred to McQuillin et al. 1984 and Yilmaz 1987.

Chapter 3 discusses the field parameters and processing sequence of the multichannel Danube profiles, while Chapter 4. is a short description of the onland shallow-seismic sections.

In Chapter 5 the complex interpretation of the shallow-seismic profiles is discussed and a possible correlation of the observed faults is presented. Special attention has been paid to differentiate faulted structures from disturbances caused by shallow layer inhomogeneities. Conclusions are drawn in the final chapter (6).

2. Introduction to seismic profiling

2.1 Basics of seismic profiling

Seismic prospecting is a geophysical exploration method which investigates the subsurface with the help of elastic waves. The generated waves propagate into the subsurface strata and are reflected at every acoustic boundary. The surveyed depth interval can vary from the topmost few meters down to tens of kilometres. It must be noted, however, that penetration and resolution of the seismic section are strongly interrelated. If we wish to image the upper ten meter only, we can obtain even decimetre scale resolution, but imaging structures tens of kilometres deep can be achieved only with several hundreds of meter resolution. This is the consequence of frequency dependent attenuation of the acoustic waves.

Figure 1 shows a block diagram of the subsurface and its image on a seismic section. The seismic section used for the illustration is a migrated time section which can be considered the end product of seismic processing. Elastic waves generated by a source (e.g. small explosion) propagate into the subsurface and are partly reflected, partly transmitted at the layer boundaries. Observing the reflected energy on the surface we can image the subsurface structure. This imaging, if carried out along a section, is called seismic reflection profiling and the image obtained is the seismic reflection profile.

At the boundary of two strata, reflection is generated if the acoustic impedance of the two units differ. Acoustic impedance is the product of the density and the velocity of the acoustic waves in each strata. The amplitude of the reflected waves is proportional to the acoustic impedance contrast. The reflected energy is larger if the contrast is bigger between the two adjacent strata. The Pannonian basin can be characterised by strong impedance contrast between the basement and the basin fill in those areas where the basement is not too deep (i.e. a few kilometres). In these areas the basement is significantly denser and faster producing distinct and strong reflectors on seismic sections. Of smaller reflectivity, but usually well defined are the layers within the sedimentary strata.

The travel time of reflected waves depends on the depth of the reflector and the velocity of the overlying medium. Therefore the depth of the reflector can be characterised by the time elapsed between shooting at the source and arrival of the reflected waves back to the surface. This is called two-way travel time as the wave is propagating from the source down to the reflector and back to the surface. The sensors used for detecting seismic waves onland are called geophones, while the ones used off-shore are hydrophones. The geophone or hydrophone senses a seismic trace which is a time sequence of the waves reflected from the acoustic boundaries. The deeper the boundary is the later the reflection arrives back to the sensor. Seismic resolution is defined by the minimum distance between two boundaries which can give distinct reflection arrivals on the seismic trace.

The simplest method of measurement is called single-channel profiling. In this case the source and the sensor move together on the surface and at certain distances a measurement is made. The observed traces are displayed next to each other resulting in a seismic profile.

The more complex method, what we carried out on the river Danube is called multichannel and multifold profiling. In this case several sensors at different surface points register the waves generated by each shot. A sketch of a multichannel recording configuration is shown in *Figure 2.* In the figure different raypaths of the waves from the source to one reflector and back to the surface are displayed. Transmitted waves are also illustrated but, for simplicity, not the reflections generated by the first two boundaries. Of course, every boundary which is associated with an acoustic impedance contrast generates both reflected and transmitted waves. It is important to note that each sensor receives reflections from different portion of the same reflecting boundary. The location of the imaged part is given by the position of the source and the receiver. The imaged point is in the middle of the source and the receiver in the case of horizontal and constant velocity layers. This point is called the Common Depth Point (CDP), while the distance between the source and the receiver is the offset. CDPs are numbered and it can be found on the horizontal axis of seismic sections. CDP numbers can be used to refer to horizontal positions along seismic sections. On the vertical axis of sections the two-way travel time is displayed .

Using multichannel recording and moving the source and the receivers on the surface, one can gather reflections from the same boundary element with different source-receiver offsets. These traces are sorted to CDP order and traces belonging to the same CDPs are summed. This process is called stacking. During stacking coherent reflections are added together, thus increasing the signal-to-noise ratio of the section. This is a major advantage of multichannel seismic profiling over single channel profiling.

Another important advantage of the multichannel profiling is that we can estimate the velocity of the medium directly from the registered data. This is called velocity analysis. Knowing the velocity of wave propagation one can convert two-way travel time scale to depth scale.

There are several ways to generate acoustic waves during seismic profiling. Explosives are often used on-shore and the volume of the charge depends on the required penetration. For shallow-seismic profiling, when the interesting depth interval is the upper few hundred meters, small charges (i.e. few hundred grams) are suitable. Small charges were used for seismic sections *Pa-2a, Pa-2b, Pa-3b, Pa-15* and *Pa-17*. Alternative seismic sources have been developed for both onland and off-shore use. An on-shore alternative is using vibrator sources. These sources, in contrast to the impulsive sources, are less destructive and can be used in sensitive areas (e.g. densely inhabited areas). Vibroseis sources have been used for sections *Pa-12, Pa-13 and Pa-14.* Different types of sources have been developed for off-shore surveys. We have used a small watergun source during the Danube profiling. This gun generates pressure waves in the water by releasing high pressure (2000 PSI) air in a piston.

Resolution of the seismic section is determined by the frequency content of the signal generated by the source and the frequency dependent attenuation during wave propagation. The attenuation is most significant in the uppermost weathered layer. This layer is not so pronounced in water covered areas and the pressure waves propagate in water almost without loss of energy. That is why surveys carried out on water can provide better resolution.

Another advantage of the off-shore profiling is that imaging of the subsurface can be achieved right from the waterbottom. Unlike on the on-shore profiles the topmost part of the section is present as well. In this research it was of major importance as we had to be able to determine the shallowest horizons which is disrupted by the faulting. It is because the upward penetration of faults is a critical feature both in determining the age of faulting and the capability of faults.

2.2 Processing and interpretation

The acquisited data are processed on computers to produce a seismic section convenient for interpretation. Processing includes several corrections in order to diminish non-geological effects during wave propagation. Processing steps depend on the seismic acquisition itself, and the algorithms are refined as computing power increases. We cannot provide a full description of all the processing details, only summarise those steps which were applied during the processing of the presented seismic sections.

After recording has been finished the traces are grouped in shot gathers, geometry of the sources and receivers is described. This makes regrouping of the traces into CDP gathers. Then traces are edited, which includes removal of the noise dominated traces and those portions of the records which do not include reflections. This is mostly the first part of the seismic section where direct and refracted arrivals are recorded. This explains why the upper part of the on-shore sections is always missing.

However these first arrivals of the on-shore recorded seismic traces contain important information about the weathered layer and its lateral variations. As the wavefront travels through this layer these variations can cause artefacts in the seismic section. Analysing the first arrivals these artefacts can be removed during processing. This is called static correction.

It is also important to correct for the amplitude decay due to geometrical spreading of the wavefront. Without this correction reflections arriving from deeper reflectors would be too weak relative to reflections arriving from the shallower part.

Each record is contaminated by random and source-generated noises. Some of the noises can be removed based on their characteristic. Various algorithms have been developed to remove different noise contaminations. The simplest are frequency high-cut, low-cut or bandpass filtering. High-cut filtering can remove noises with frequency content above the signal bandwith, while low-cut filtering remove noises with frequency content below the signal bandwith. The bandpass filtering is a combination of the two.

Off-shore measurements are contaminated with the reverberation of the waves in the water layer. As the surface (water-air contact) is an almost perfect reflector the upgoing waves are reflected back to the subsurface again. This explains the appearance of "ghost" reflectors arriving at double, triple etc. times after the primary reflection. They are called multiples as they travel the surface-reflector-surface distance more than once. They can be suppressed by predictive deconvolution.

Before we can stack the traces corresponding to the same CDP location we have to correct for the differences in recording offsets. This is called the normal move-out (NMO) correction and it transfers the traces recorded with nonzero offsets into zero offset traces. After the NMO correction seismic traces belonging to the same CDP can be stacked, resulting one single trace. These traces make up the stack section. Noise and multiple suppressing filtering can be applied to the stack section as well. These are called post-stack processing steps.

Migration is usually applied to the stack section to move dipping reflectors to their true positions. Migration removes the so called diffraction hyperbolas as well which appear on the stack sections at abrupt terminations of layers. This makes faults better defined and hence easier to interpret. The seismic sections presented in this report are migrated time sections.

3. Multichannel high-resolution seismic survey carried out on the river Danube

3.1 Surveying technique and field parameters

A 15 cm^3 Sodera watergun was the source for the multichannel survey and a 93.75 m long, 16 channel hydrophone array was used as detector. The watergun was run from a 2000 PSI compressor and fired every other second. At firing the compressed air expels the water from the chamber of the watergun which creates a compressional wave radiating from the source. These waves are reflected from the subsurface impedance boundaries and are detected by the hydrophones.

The source and the hydrophone array were towed behind the ship, as shown in *Figure 4.* As the source and the hydrophone cable were towed behind the laboratory boat the tug boat was far away even from the small offset traces. This together with the quiet weather conditions resulted in improved signal-to-noise ratio compared to marine surveys.

The speed of the ship relative to the ground was maintained between 3–4 km/h. Using two seconds firing rate resulted approximately 2 m shotpoint distance. Positioning has been carried out using a differential GPS (DGPS) system. Position readings were made every 10 second and interpolated in-between. Estimated accuracy of the positioning is 1 to 2 m.

Recording has been done with an OYO DAS-1 system on DAT tapes in SEG-D format. Sampling frequency was set to 4 kHz, recording length to 500 ms. High frequency content of the source resulted 1 m resolution in the upper part of the sections (first 100 ms) and 2–3 m resolution in the deeper part of the sections (down to 500 ms). This makes sure that a fault displacement of 2–3 m can be observed with confidence on the sections. *Table 1* shows the most important parameters of acquisition.

Table 1: Field parameters for the multichannel survey

Source type	Sodera 15 watergun run at 2000 PSI
Average source depth	0.5 m
Firing rate	2 s
Sensors	16 channel hydrophone-cable, 5 hydrophones serially connected for each channel
Group sensitivity	4 mV/mBar
Hydrophone spacing	6.25 m
Hydrophone depth control	2 DIGICOURSE 510
Recording instrument	OYO DAS-1
Recording format	SEG-D on DAT tapes
Sampling frequency	4 kHz
Recording length	512 ms
Low cut filter	3 Hz 6 dB/o
High cut filter	1 kHz 6 dB/o
Notch filter	off
Source position	Between channel 1 and 2

3.2 Processing

Special codes were written for geometry installation. The following processing steps were applied to the data.

1. Data input, sorting and editing:

Field data was loaded from magnetic tape.

2. Geometry installation:

Geometry was installed for each trace based on the time information stored in the trace header and the DGPS position files. 5 m CDP bin size was chosen and CDP sorting was based on this CDP binning.

3. Geometry verification:

The installed geometry was verified.

4. True amplitude recovery:

Spherical spreading correction was applied to the data.

5. Frequency filtering:

Time variant zero phase Butterworth bandpass filter was applied to remove high frequency noise and to suppress low frequency coherent noise present in the field data. Zero phase Butterworth filter was applied with 80 Hz low cut frequency and 20 dB/o slope to suppress low frequency noise, while for suppressing the high frequency noise time varying filter was applied with two time gates. At shallow depths (between 0 and 150 ms) zero phase Butterworth high cut filter was applied with 700 Hz high cut frequency and 24 dB/o slope, while in the lower part of the section (between 200 and 500 ms) 500 Hz high cut frequency and 24 dB/o slope was chosen after filter tests. Between the two time gates linear combination of the two filters was applied. Noticeable absorption of the high frequency content of the seismic signal in the deeper part of the section made it worthwhile to apply the time variant high cut filter.

6. Predictive deconvolution:

Minimum phase predictive deconvolution was applied to suppress the waterbottom multiples in the section. Similar to the bandpass filtering, deconvolution was applied in a time varying manner. The two time gates were the same as the ones selected for bandpass filtering and deconvolution parameters were chosen after parameter testing.

In the upper time gate 9 ms operator length and 2 ms prediction distance was applied, while in the lower gate 20 ms operator length and 3 ms prediction distance have been chosen. Prewhitening was 0.1% in both time gates.

7. Frequency filtering:

Time variant zero phase Butterworth bandpass filtering was repeated after deconvolution with the following frequency bands and slopes: in the upper time gate 60 Hz 18 dB/o low cut and 700 Hz 24 dB/o high cut, while in the lower time window 60 Hz 18 dB/o low cut and 500 Hz 24 dB/o high cut.

8. Interactive velocity analysis:

RMS velocities were derived from the CDP gathers using constant velocity stack and semblance analysis. Velocity analysis was carried out at least every 500 m and where abrupt change in the velocity field could be expected more densely spaced velocity analysis was carried out.

9. NMO application:

Normal moveout correction was applied using the estimated RMS velocities with 30% stretch mute allowed.

10. Trace Muting

Top muting of the NMO corrected gathers was performed in channel domain. Reflections from the waterbottom could be observed only on the first two traces, on all the other traces the first reflections were masked by the direct arrival. This direct arrival was progressively muted out from the traces. However, on the first two traces the substrata can be examined for the waterbottom down to more than 500 m depth

11. Predictive deconvolution

Minimum phase predictive deconvolution was applied in two steps to remove peg-leg multiples in the record. The removal was focused on the lower part of the section, where peg-leg multiples were stronger. The upper part of the traces was virtually left untouched by this deconvolution due to the applied parameters. The same time gates were used as mentioned before. In the first step waterbottom peg-legs were attacked (relatively small prediction distance) with 100 ms operator length and 7 ms prediction distance, while in the second step longer prediction distance was applied to suppress intrabed peg-legs. In this step 150 ms operator length and 25 ms prediction distance was used. Prewhitening was 0.1% in both cases.

12. CDP stack:

Due to the slow velocity of the ship (3–4 km/h) and the relatively high firing rate (2 seconds) high fold sections were measured even with only 16 channels and the chosen 5 m CDP bin size. The fold of the stack sections is usually above 40 and at some places, where the velocity of the ship was even less above 50. This is true only for the lower part (below 130–140 ms) of the sections as the top mute reduced the fold in the very top part of the sections down to 4–6.

After testing several stacking algorithms (mean, diversity power, diversity amplitude, median, alpha trim) diversity power stack was applied using 150 ms long diversity scalar operator.

13. Trace mixing:

Weighted trace mixing was applied to enhance the coherency of the stacked section. Three adjacent traces were mixed using 1.0, 3.0, 1.0 weights.

14. Trace equalisation:

Trace equalisation was carried out based on the rms scalar value calculated in the 100–500 ms time window for each trace.

15. Hand statics:

A static shift of –24 ms (negative sign means upshift) was applied to every trace to compensate for the mechanical delay of the watergun. The delay was estimated from the recorded source signature. After the static shift applied the water depth estimated from the single channel measurements was in good agreement with the water depth observed on the multichannel lines.

16. Migration:

Steep dip explicit finite difference time migration was performed using spatially varying interval velocities derived from the RMS velocities.

17. Presentation of the seismic sections:

CDP values plotted on the top of the sections are increasing upstream, from South to North. CDP interval is 5 m. CDP values of different sections are not independent, the gap between two sections can be calculated from the gap in CDP numbers.

Figures 5–9 show the migrated and interpreted time sections of seismic profiles *Danube-202, Danube-203, Danube-205, Danube-207* and *Danube-208.* The vertical scale of the sections corresponds to that of the standard onland sections, and the horizontal scale is 1:20 000.

4. Reprocessing of onland high-resolution seismic sections measured by ELGI

Reprocessing and interpretation of shallow-seismic sections *Pa-2a, Pa-2b, Pa-3b, Pa-12, Pa-13, Pa-14, Pa-15* and *Pa-17* measured by ELGI in 1993, 1994 and 1995 was also carried out. Seismic sections *Pa-2a, Pa-2b, Pa-3b, Pa-15* and *Pa-17* were measured using explosive sources, while the source for sections *Pa-12, Pa-13* and *Pa-14* was a small IVI vibrator. Detailed description of the sections can be found in Ráner and Szabó 1997, in the present volume.

Estimation and elimination of the static shifts due to shallow layer velocity variations, and optimal top muting were the prime goals during the reprocessing. Estimation of the static shifts was based on the picked first arrival times. Average elevation of the line, or the average elevation of two adjacent lines (e.g. *Pa-2a and Pa-2b*) were chosen for final datum and 1600 m/s was applied as replacement velocity. This value is a good estimate of the refractor velocity in this area. During reprocessing of *Pa-2a, Pa-2b* and *Pa-3b* seismic profiles several shallow layer inhomogeneities, some of them probably caused by former river channels, were corrected for. Elimination of the static shifts caused by these inhomogeneities improved the coherency of the sections considerably, and removed the fault like structures caused by these static errors. These static corrections resulted in significant improvement for lines *Pa-12, Pa-13, Pa-14, Pa-15* and *Pa-17* as well.

Detailed description of the reprocessing of profiles *Pa-3b* and *Pa-14* can be found in a report prepared for Paks NPP and Ove Arup Ltd. (Tóth et al. 1995, Tóth and Horváth 1995). Reprocessing of profiles *Pa-2a* and *Pa-2b* was carried out with the same processing steps as for *Pa-3b*, while profiles *Pa-12* and *Pa-13* were processed as profile *Pa-14*. Profiles *Pa-15* and *Pa-17* were processed similar to profile *Pa-3b*.

Oil industry type seismic sections *Pak-2* and *Pak-3*, measured by ELGI in 1992, indicated faults at several places along the sections. Some of these faults could be traced up to the very top of the sections (100–150 ms). Shallow-seismic sections *Pa-2a, Pa-2b* and *Pa-3b* were measured along these lines at faulted areas to image the top layers with high resolution, and examine the upper termination of the observed faults. *Figure 10* shows the migrated and interpreted time section of *Pa-2a*, while *Figures 11* and *12* show the migrated and interpreted time sections of profiles *Pa-2b* and *Pa-3b,* respectively. All the three sections give good penetration down to 500 ms, and their signal-to-noise ratio is good or very good along the lines.

Shallow-seismic vibroseis profiles were measured by ELGI in 1994 along and parallel with standard industry type section *Du-1. Pa-12* is situated along the *Du-1* section, while *Pa-13* and *Pa-14* are running parallel with *Du-1*, approximately 1 km to the east and west, respectively. These sections were shot to determine the direction of the fault zone detected on profile Du-1, and to clarify the much debated disturbance zone observed on profile *Pa-8*. Quality of the shot records was strongly degraded by high amplitude ground roll, which, at some places decreased the signal-to-noise ratio of the sections below the critical level (see for example the northern end of section *Pa-12*). Average penetration of the section is 200–250 ms, varying along the individual sections as well. However, the investigated fault zone can be clearly identified in all the three sections. Due to the large minimal offset (24 m) imaging of the very shallow layers (below 15–20 m) was not possible. The sections give valuable information about the 40–200 m depth interval. Migrated and interpreted time sections of profile *Pa-12, Pa-13* and *Pa-14* can be seen in *Figures 13, 14* and *15.*

In 1995 two shallow-seismic lines were measured for Paks NPP by ELGI. Both profiles are located along line *Du-1. Pa-15* passes parallel to the northern end of *Du-1,* approximately 100 meters to the east. This section is crossing the fault zone already imaged by *Du-1, Pa-12, Pa-13* and *Pa-14*. Profile *Pa-17* was measured as a reference section along the southern part of *Du-1*, characterised by unfaulted strata.

In spite of the small amount of explosives used, at some places the sections image the whole Pannonian strata with high resolution down to the top of the Miocene. The signal-to-noise ratio is decreasing at some places along the lines, but this is due to near surface variations.

Migrated and interpreted time sections of profiles *Pa-15* and *Pa-17* can be seen in *Figures 16 and 17* respectively.

5. Interpretation

In the course of interpreting the shallow-seismic sections we paid special attention that all available data be interpreted in a coherent way. As a first step we indicated the Quaternary/Pannonian boundary on the seismic sections using an up-to-date borehole database (Chikán, 1992).

Then, we assigned the faults observed on the seismic sections and attempted to determine their upper termination. We have already mentioned before, that there are differences between the shallow-seismic sections in their depth of penetration. This is a fact that comes from the conditions and geometry of data acquisition. On land the least penetration (a few hundred ms) was achieved by the vibroseis sections. The sections using explosive sources, however, offered a deeper penetration, often reaching the Pannonian/Miocene boundary (*Pa-15* and *Pa-17*). The unique feature of the sections measured on the river *(Danube-202, Danube-203, Danube-205, Danube-207* and *Danube-208)* is that they offer a complete image of the subsurface from the very bottom of the river Danube including the recent river sediments down to 500 ms. This feature is of critical importance to determine reliably the actual upper termination of the faults and, hence, to asses their activity and capability.

Finally, we have attempted to correlate the faults identified on the individual sections. In some cases it was quite straightforward on the basis of the shallow-seismic sections only. In other cases, however, the standard industry type sections had to be taken also into consideration. We arrived at the conclusion that the uneven space distribution of the sections, particularly the limited number of west–east oriented cross-sections can not guarantee an unquestionable correlation and different alternatives could be put forward.

5.1 Identification of stratigraphic and structural features

5.1.1 Identification of the Quaternary/Pannonian unconformity

Identification of the unconformity between Quaternary and Pannonian strata was helped by information from several boreholes. We used this information in accordance with the seismic axiom stating that true time horizons do not cross seismic reflectors. During depth conversion we used two different velocity profiles for the onland and river sections. The velocity of the uppermost strata in case of the river data was taken equal to the velocity of pressure waves in the water (1450 m/s), while for the onland sections the 1600 m/s replacement velocity was chosen. The location of the Quaternary/Pannonian unconformity is indicated with green colour in *Figures 5–17.*

5.1.2 Identification and correlation of faults

It is easy to identify the faults by termination of reflectors and sudden change of their dip when the section is characterised by a good the signal-to-noise ratio. However, near surface disturbances resulted in such a decrease of signal-to-noise (S/N) ratio at some places that faults cannot be identified in the corresponding vertical strips of low signal areas. In such cases our working method of interpretation was the following: if individual reflectors on the two sides of the low signal strip can be correlated and tied together with a straight line then we assumed lack of any fault within the strip. A typical example can be seen on the southern half of section *Pa-17.* We note the refractor depth exhibited remarkable change that always at the top of the low signal strip. In most cases this deepening of the refractor was due to the appearance of an old river channel. Such a channel can be seen on the section *Pa-13* on the top of the section between CDP 525–575.

There are cases when individual reflectors at the two sides of the low signal strip can be correlated but their depth and/or dip was obviously different. We considered such cases as an evidence of fault inside the low signal zone. Of course, the geometry of the fault and its upper termination can not be determined.

Similarly to the onland sections, the S/N ratio of the Danube sections can locally be low. This is caused by a sudden increase of the reflectivity of the river bottom. Locally the river bottom was so hard, that practically all the energy was reflected back and created strong multiples of the river bottom. At these places imaging of the deeper layers is very poor, and the interpretation is, of course, very difficult or impossible. These low signal strips were interpreted the same way as onland.

Interpretation of the sections can be seen in *Figures 5–17*. Green colour indicates Quaternary strata, red shows the faults and uncertainty is expressed by dashed red lines. Yellow indicates remarkable and correlatable stratigraphic horizons in the Pannonian strata. In *Figures 16* and *17* orange indicates the base of Pannonian. Structures seen on the sections can be summarised as follow.

Danube-202: The section is characterised by a good S/N ratio and faults can not be observed. However, on the southern end of the section (1450–1550 CDP) the S/N ratio is much lower due to the presence of a strong topmost reflector. Correlation of reflectors on the two sides of the low signal strip suggests a folded or faulted zone in this strip. The bottom of Quaternary is thought to be located at 50 ms, and it is fairly horizontal and continuous showing no offset by faults.

Danube–203: The main structure on the section is the fault zone in the 2675–2725 CDP interval. Strata are offset up to 90 ms two-way-travel (twt) time, and further up layers are continuous but deformed. The deformation can be followed right up to the bottom of the river. There is a low signal-to-noise strip in the 2500–2550 CDP interval. Reflectors can be correlated across without assuming a fault zone. The bottom of Quaternary can be found at about 70 ms twt time at the northwestern and rises to 25 ms twt time at the south eastern end of the profile. The unconformity is apparently not influenced by faulting.

Danube-205: The section is characterised by good S/N ratio all along, but locally side diffractions from the riverbank are interfering with reflections. These interference zones are very characteristic and can not be misinterpreted. The most important structure on the section is a fault zone in the 3500–3550 CDP interval. The fault terminates upward at about 100 ms and folding can be seen further up. The fault is quite complex in the lower part of the section and a few branches are terminating even below 200 ms. The bottom of the Quaternary can be identified at about 70 ms.

Danube-207: This section images distinct structural features with good signal-to-noise ratio. The main structural elements are two fault zones around CDP 4525 and CDP 4800. The later separates two completely different units. Western half of the profile can not be correlated to the eastern part. This observation suggests strike-slip displacement along this fault. The fault does not disturb the topmost 30 ms of the section. The bottom of the Quaternary is well defined, almost horizontal at about 20 ms twt time on the western part of the profile (CDP 4600–4700). However on the eastern half of the section Pannonian strata are tilted and likely to crop out at the waterbottom.

Danube-208: The section images the continuation of the fault zone already observed on section Danube-207. The main fault located at CDP 5680 and the other faults imaged on the section supports the strike-slip displacement suggested before. Pannonian strata are both faulted and folded but this deformation ceases below 35 ms twt time. The Quaternary/Pannonian unconformity is distinct above the remarkable fault zone.

Pa-2a: The section shows clearly the top part of the fault zone which is visible on the Pak-2 standard section. The fault zone can be recognised in the 225–250 CDP interval and it terminates at about 80 ms, below the Quaternary/Pannonian unconformity. There are faults also to the north and south of this CDP interval and they are certainly associated with the main fault zone, but terminate deeper. The Quaternary/Pannonian unconformity can be found at 70 ms at the northern end of the section, and around 80 ms at the southern end. The dip is seemingly constant and the faults offsetting the Pannonian strata do not reach this horizon. Note, a marked intra-Pannonian unconformity characterised by onlaps on the southern part of the section.

Pa-2b: On the lower part of the section termination of reflectors and change of their dips indicate a fault zone in the 275–300 CDP interval. The fault penetrates up to 150 ms. A marked intra-Pannonian unconformity can be seen at 250 ms which is also offset. Strata above 150 ms twt time are seemingly continuous. The Quaternary/Pannonian unconformity can be found at about 100 ms and it is seemingly not faulted.

Pa-3b: A clear fault can be seen in the 300–350 CDP interval in the middle of the section. A comparison of the stratification shows that strata can not be correlated across the fault, which suggests strike-slip character. The fault clearly offsets an intra-Pannonian unconformity which is located at about 180 ms on the southern part of the section, and rises towards the north. The fault is well defined up to 100 ms twt time. Quaternary/Pannonian unconformity is most probable between 60 and 70 ms and the base of Quaternary can be faulted.

Pa-12: The northern end of the seismic section is characterised by very low S/N ratio up to CDP 350. A southern dip of the strata can be guessed from the noisy image. At CDP 360, however, the dip of reflectors remarkably changes and reflection termination can be seen above 100 ms. This suggests a fault between CDP 350 and 370 which is also present on the nearby parallel lines. The upper termination of fault can not be determined precisely due to bad quality of the section above 40 ms, but the reflection at 60 ms is probably faulted. Another, deeper fault can be seen between CDP 520–570. Due to poor imaging of the upper part of the section it is just a guess that the Quaternary/Pannonian unconformity can be at about 40 ms.

Pa-13: This is the best quality section from the three vibroseis profiles. There are two characteristic features on the northern part of the section. A fault between CDP 270 and 300, and a zone of disturbance between CDP 500–570. Correlation suggests that this zone of disturbance is associated with a fault with 50 ms offset. The northern fault is well defined and most probably it reaches the bottom of the Quaternary strata. On the southern end of the section the Quaternary/Pannonian unconformity is identified as the strong reflector at 45 ms twt time.

Pa-14: The section only images the 50–250 ms twt interval and the signal-to-noise ratio is quite variable along this profile. Still, a fault between CDP 475–500 is obvious which is reaching the reliably imaged topmost layers at about 45 ms. Remarkable change of dip of strata at the southern end of the section suggests another possible fault here. Due to poor imaging of the upper part of the section it is just a guess that the Quaternary/Pannonian unconformity can be at about 40 ms.

Pa-15: The signal-to-noise ratio varies along the line but can be described as very good all along the profile in the 50–600 ms twt time interval. The CDP 525–625 interval of the section clearly shows the fault which has been documented earlier on the *Du-1* oil company line (Horvath et al. 1993). It is clear that the fault is a flower-structure with roots in the pre-Pannonian strata. The fault zone in the 525–625 CDP interval disturbs the shallowest imaged layers as well. In this strongly faulted zone base of Quaternary can not be identified, but on the two flanks of the section it can be assumed at 40 ms (northern end) and 50 ms (southern end) twt times.

Pa-17: It has been a reference section to test shallow-seismic profiling along a part of *Du-1* section, which was clearly not faulted. The first processing indicated a zone of disturbance of unknown origin at the southern end of the line. Reprocessing however has shown, that the disturbance is of very shallow origin. All the reflectors can be correlated across the low S/N strips without assuming any faulting. The Quaternary/Pannonian unconformity can be located at about 50 ms.

In *Figure 18* the identified faults are assigned by circles in order to avoid any misleading directivity of the used symbol. Correlation of the observed faults can be seen in *Figure 18* as well.

5.2 Age of faulting and the problem of fault capability and present activity

In the course of seismic hazard evaluation of nuclear power plants special attention is to be paid to the *faults* in the site vicinity. If mapping of these faults and/or reliable detection of these faults in the subsurface realm are solved then two basic questions are to be answered.

The first question is the age of the faulting and, if it is not too old, we have to assess the possibility if the faults are still active. In other words, is there any reasonable probability that the faults can be reactivated in the present or near future. Because faulting is brittle fracture in the rigid crust this event is usually associated with an earthquake.

If the answer for the question of present activity is yes, than the second question is to be answered: is the extent of the fault zone such, that it can produce a detectable displacement at or near the surface. In other words the releasing energy is enough to produce a fracture up to or very near the surface. This potential of a fault is called "capability" (IAEA, 1991).

It follows that capable faults represent a subgroup of active faults. Obviously, only an active fault can be a capable fault which implies that an inactive fault cannot be capable. It also follows that *there is a second subgroup of the active faults, which are those active but not capable to produce a surface reaching fault system.*

We call the attention for the fact, that age determination of a fault is a very difficult and responsible job. Namely, the widely hold view that a top layer which is sealing a fault system is giving an age limit for the termination of fault activity is not necessarily true. An observation like that needs a careful evaluation with special attention to the thickness and the time interval represented by the fault sealing strata. We are discussing the activity and capability of the faults derived from seismic data in the light of these considerations in the vicinity of Paks NPP.

The good quality seismic data makes possible a reliable correlation of the observed structures *(Figure 18).* The young fault zone in the immediate vicinity of the power plant (Horváth et al. 1993) is supported by the new seismic lines of *Pa-12, Pa-13, Pa -14* and *Pa-15.* The fault zone appears on section *Danube-203* as it was expected, then crossing *Pa-2* and *Pa-7,* reaching the northwestern end of the sections *Pak-3* and *Pak-2.* The main fault which was found right at the well *Paks-3* has received further credit from the sections *Pa-3b, Pa-2a* and *Pa-2b.* Unfortunately, its trace below the Danube was not registered due to data acquisition difficulties during the survey. The fault seen on section *Danube-205* can be considered the continuation of the fault observed earlier on sections *Pa-7* and *Pa-3* but was not considered earlier as an important fault.

The new special seismic lines, recorded on-land and on the river, have brought a remarkable progress in the assessment of the activity and capability of the faults. It can be concluded that the much debated zone of noise on the section *Pa-8* located at the northern end of section *Du-1* in the area of wells *Paks-4a, 4c,* and *4b,* is indeed associated with a fault zone, however the continuation of the noise zone up to the surface can not be taken as an evidence for the Quaternary age of the fault (Horváth et al. 1993). The question of faulting of Quaternary strata can be reliably answered on the base of the new sections *Pa-13, Pa-15* and *Danube-203, Danube-205, Danube-208.*

Among the onland sections *Pa-2a* and *Pa-2b* are those, which document obviously the termination of fault in Pannonian strata, and also the angular discordance at the Quaternary/Pannonian boundary. Special importance is of section *Pa-3b,* because here the fault zone reaches the Quaternary/Pannonian unconformity. Seismic sections Pa-13 and Pa-15 show similar faulting, but in these cases it is even more likely that the faults propagate up to the Quaternary/Pannonian unconformity. The Danube sections support the view that Quaternary strata can not be considered post-tectonic.

The Danube river deposits (alluvium) are blanketing the Pannonian strata. The age of these river deposits is unlikely to exceed 45 000 years (Chikán, 1992). *Danube-203* and *Danube -205* profiles show that these young sediments are slightly deformed. The tectonic origin of this deformation and genetic relationship to the faults observed in the Pannonian strata becomes evident on profile *Danube-208.*

All these observations led us to the conclusion that evolution of the observed fault zones has been going on during the late Pleistocene time as well, that is 40 000–50 000 years ago. This is so near in time to the present that future activity of the fault cannot be excluded. A most conservative conclusion is, therefore, that the fault is to be considered active. However, no displacement can be observed at or near the surface, therefore capability of the fault can be excluded.

6. Conclusions

In order to arrive at a better understanding of the seismic risk at the site of Paks NPP multi-channel and high-resolution seismic profiling has been carried out on the river Danube. The multichannel survey offer a penetration of more than 500 m and a resolution of 1 m and 3 to 5 m at the top and the bottom of the imaged interval, respectively. In order to arrive at a joint interpretation, the special seismic profiles measured onland have been also reprocessed and they allow to arrive at the following main conclusions:

1. Seismic sections *Danube-202, -203, -205, -207, -208* and *Pa-2a, -2b, -3b, -12, -13, -14, -15* and *-17* after reprocessing represent top quality data and offer the most credible source of information to delineate subsurface structures.
2. These sections confirm the main fault zone to the south of the power plant passing towards ENE, and also the existence of its branch going towards NE and located in the immediate surrounding of the power plant.
3. The activity of the young fault zone can be bracketed between the youngest Pannonian and the oldest river deposits in the area, which is the 5–0.045 Ma time interval. However, because of the small value of the upper time limit, a most conservative approach suggests that the fault must be considered active at the present time.
4. It can be excluded, but at least it is highly improbable that the fault can create an offset of strata at or near the surface. The fault system therefore in the vicinity of Paks NPP is not capable.

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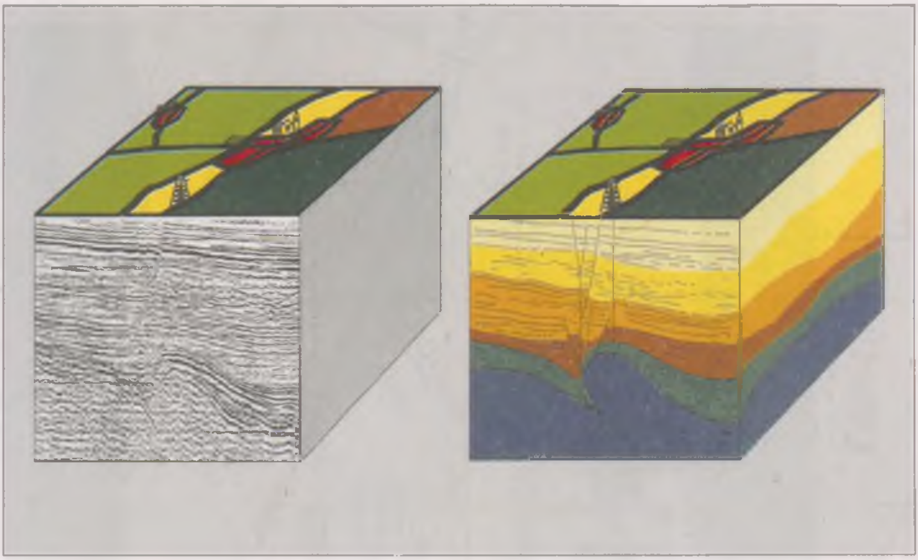


Fig. 1. Block diagram explaining the use of seismic sections to understand the stratigraphic and stuctural conditions below the surface

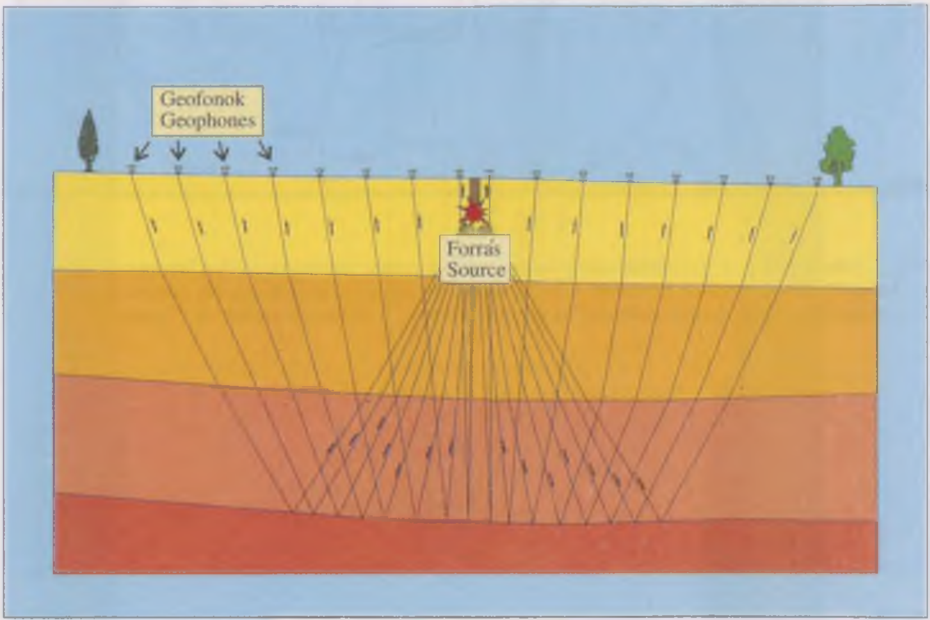


Fig. 2. Multichannel reflection seismic profiling

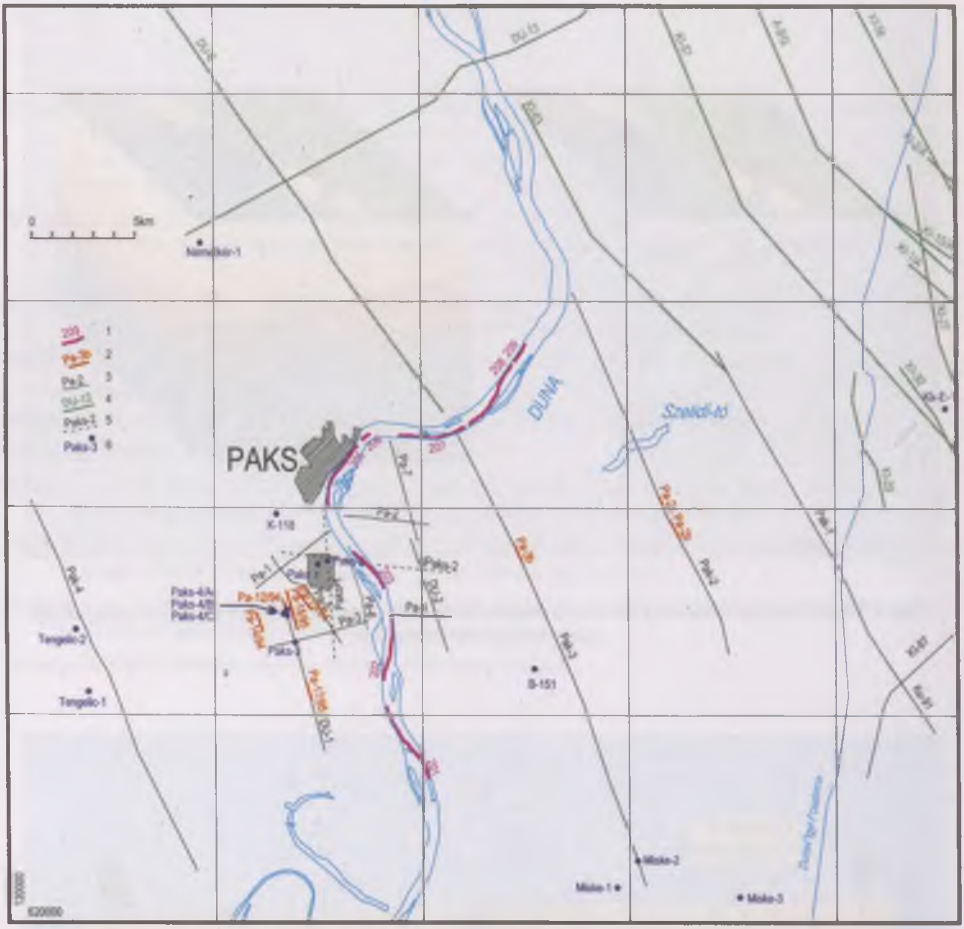


Fig. 3. Location map. 1 = multichannel reflection seismic section measured on river Danube; 2 = high-resolution reflection seismic section measured by ELGI; 3 = reflection seismic section measured by ELGI; ; 4 = reflection seismic section measured for the oil industry; 5 = refraction section ; 6 = location of the well

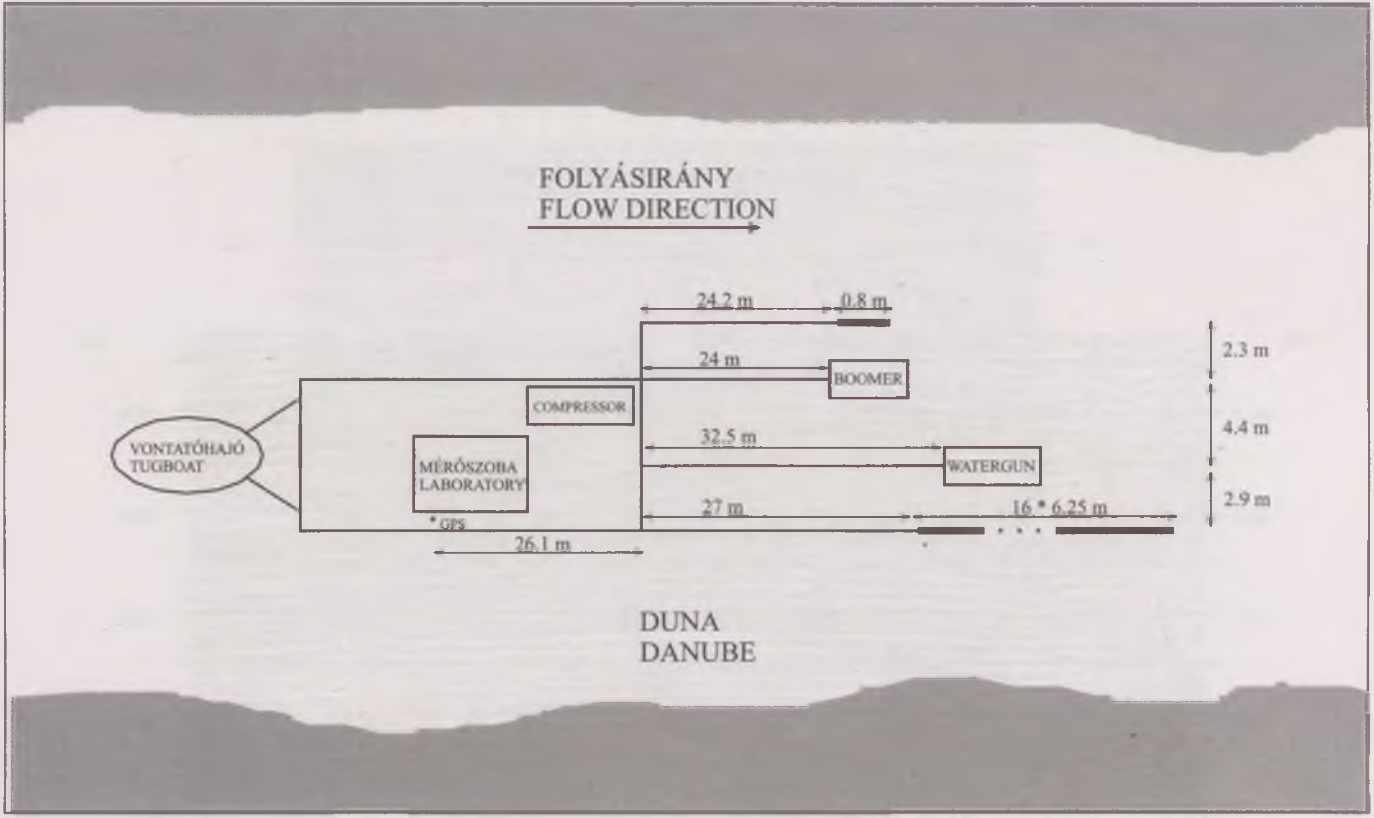


Fig. 4. Survey configuration

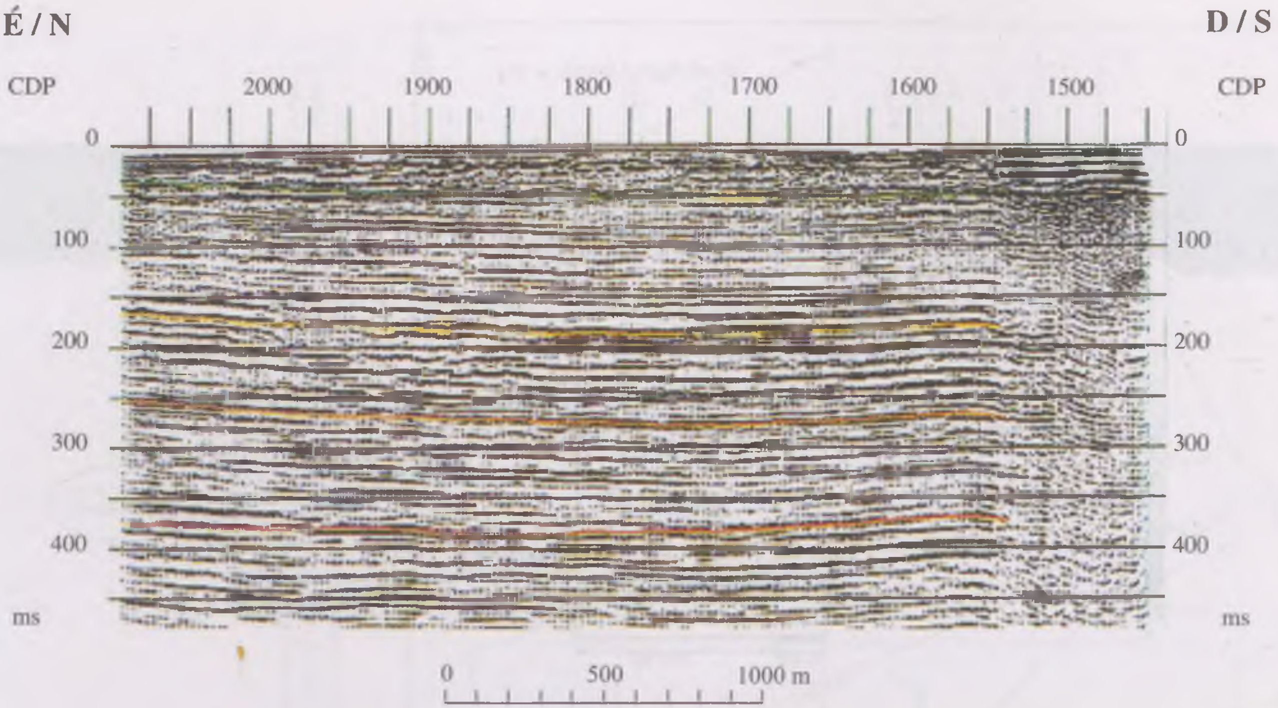


Fig. 5. Danube-202 interpreted time section

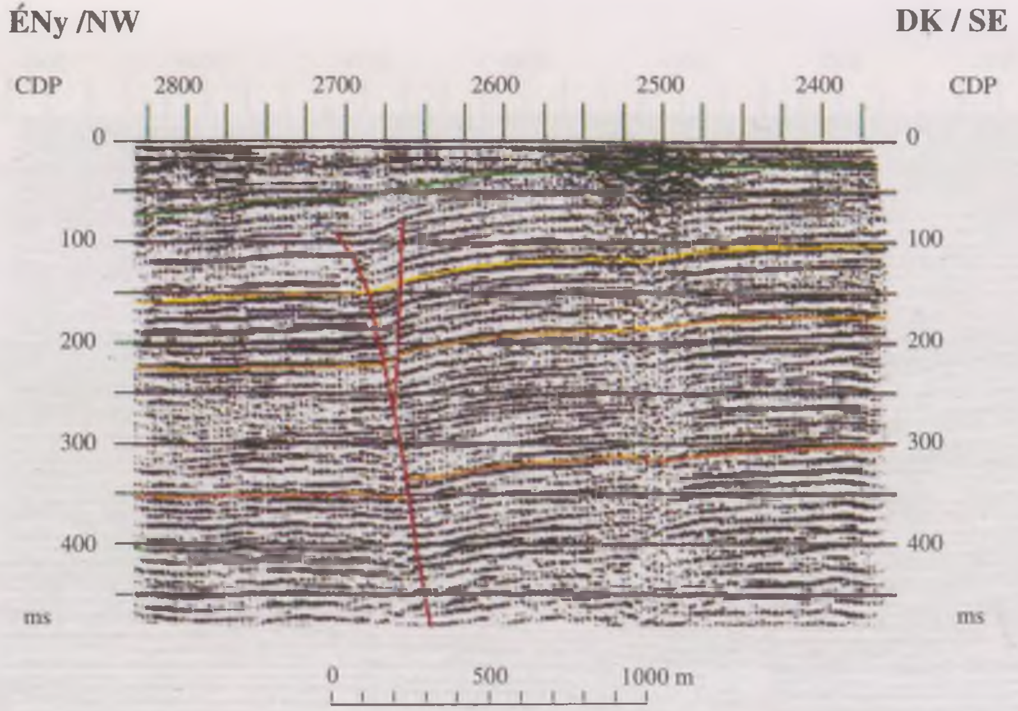


Fig. 6. Danube-203 interpreted time section

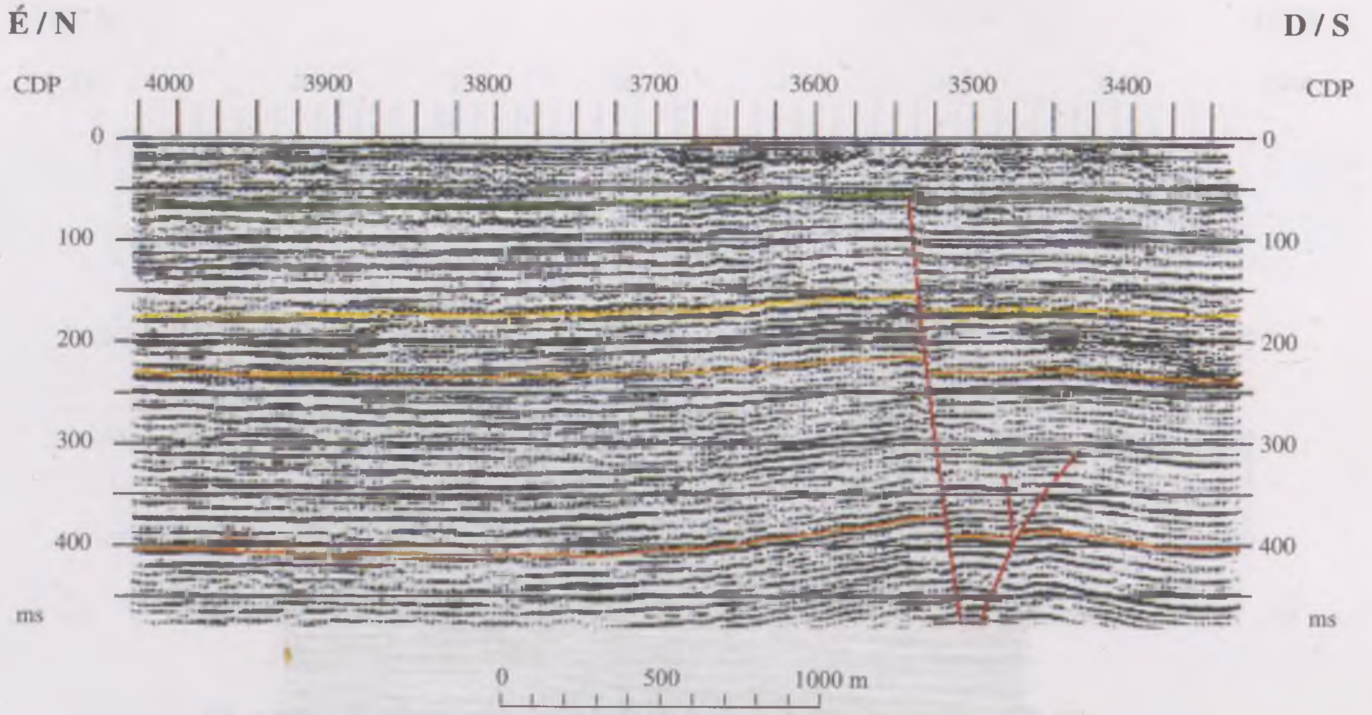


Fig. 7. Danube-205 interpreted time section

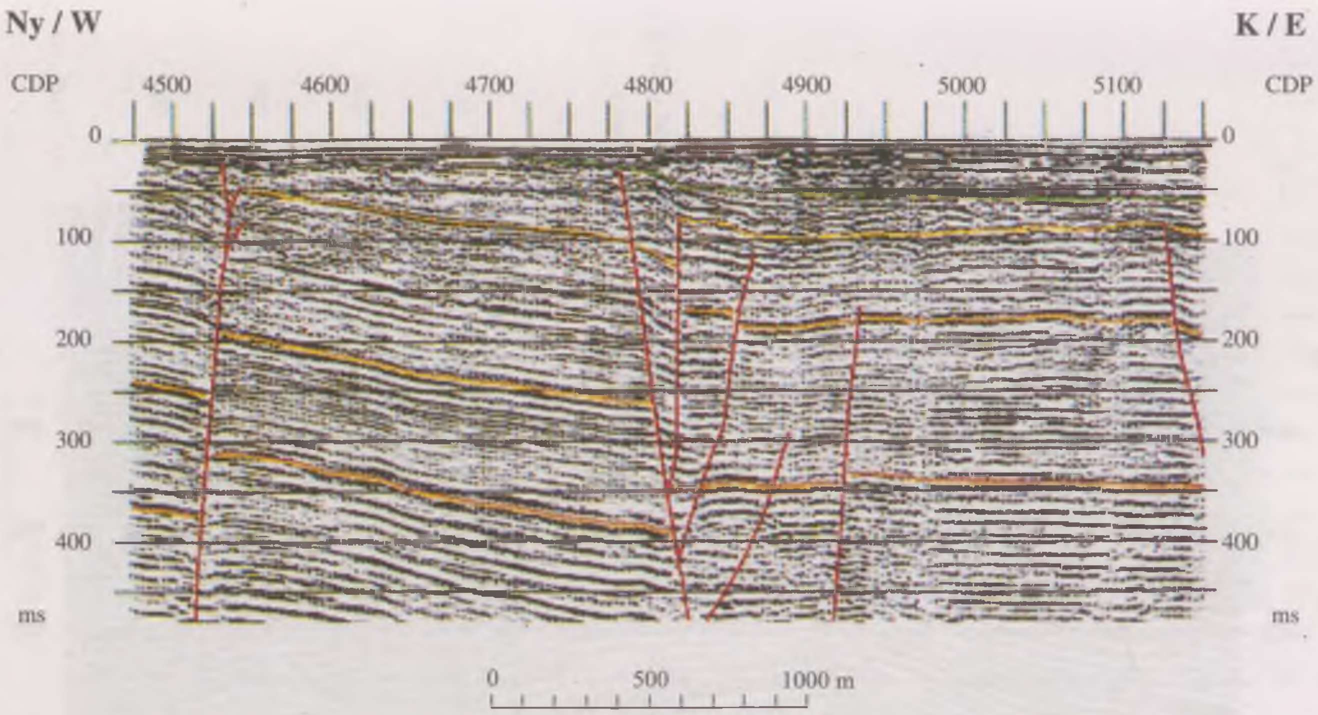


Fig. 8. Danube-207 interpreted time section

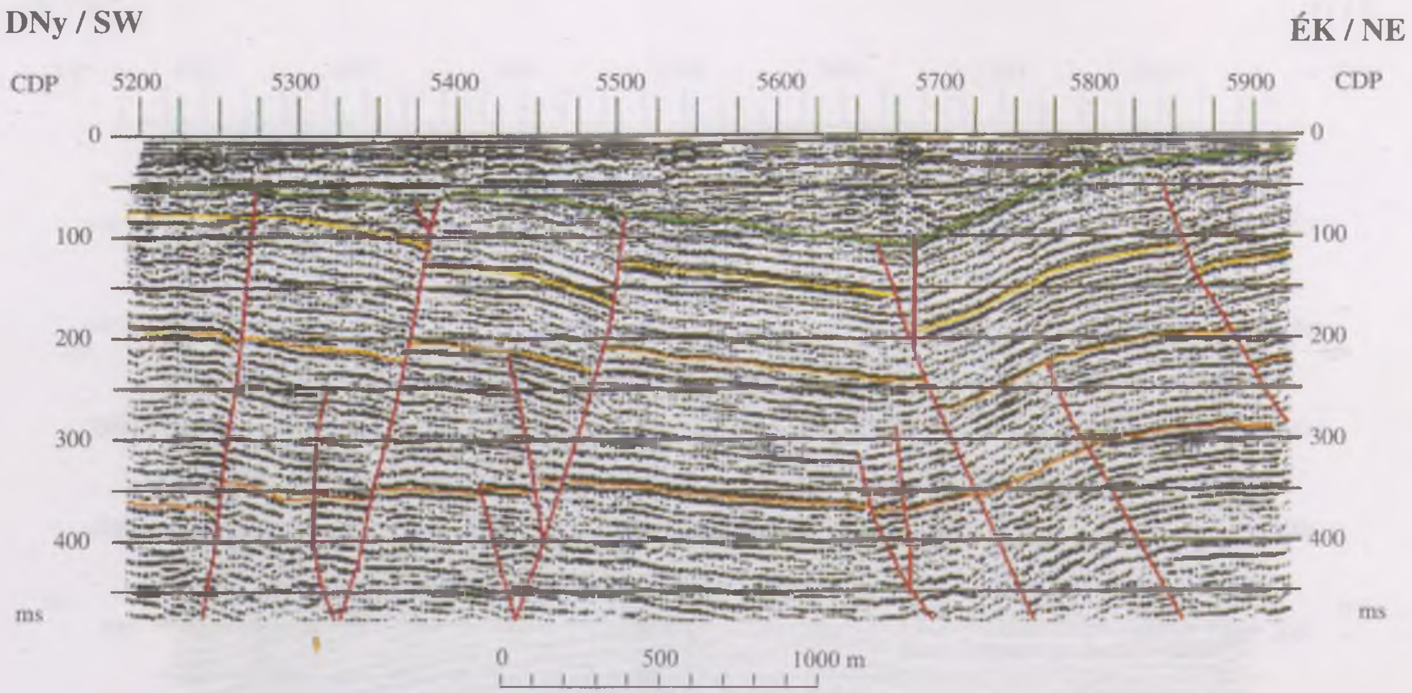
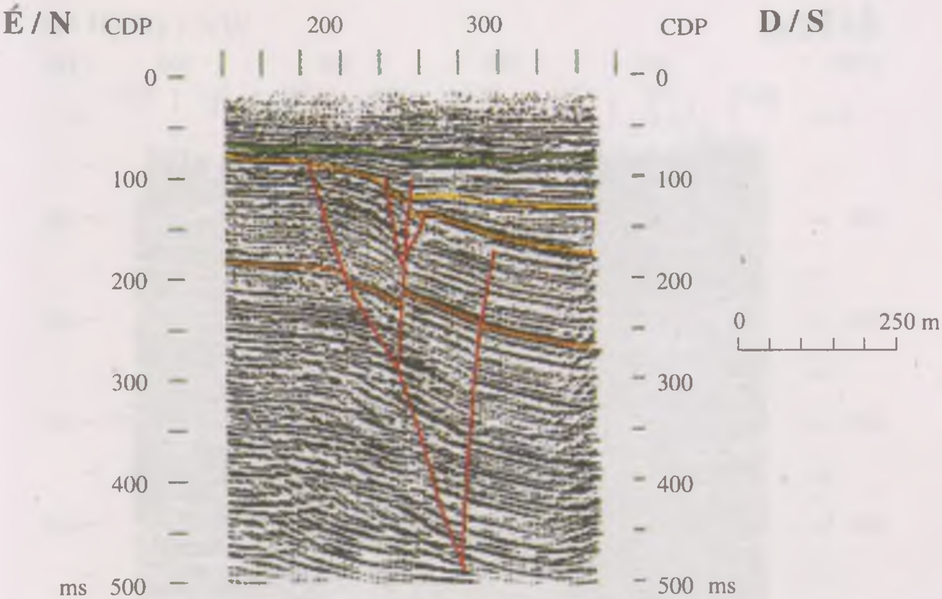


Fig. 9. Danube-208 interpreted time section



10. ábra. Pa-2a értelmezett időszelvény
Fig. 10. Pa-2a interpreted time section

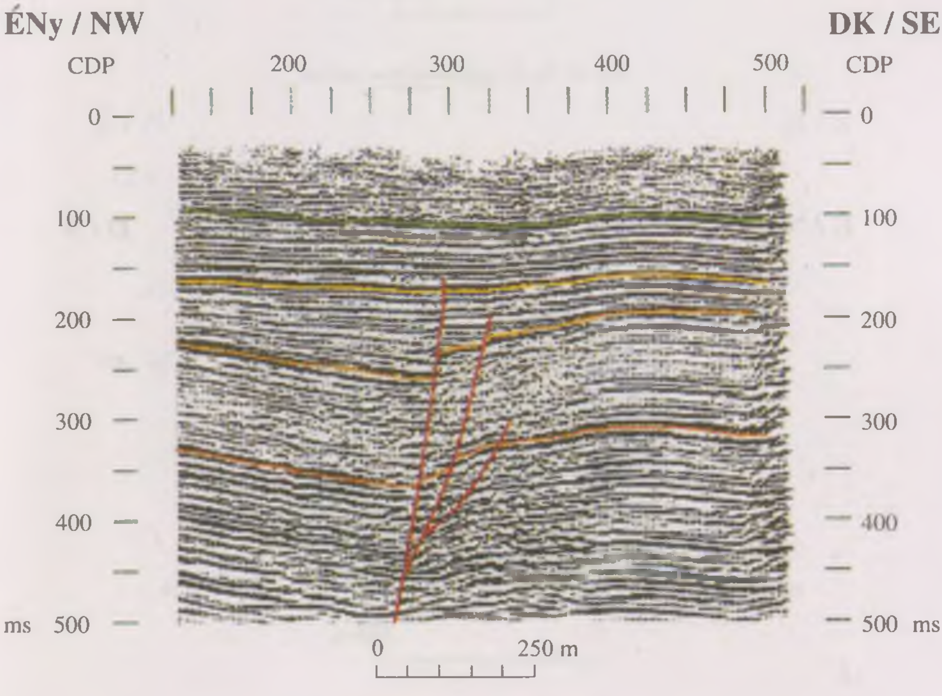


Fig. 11. Pa-2b interpreted time section

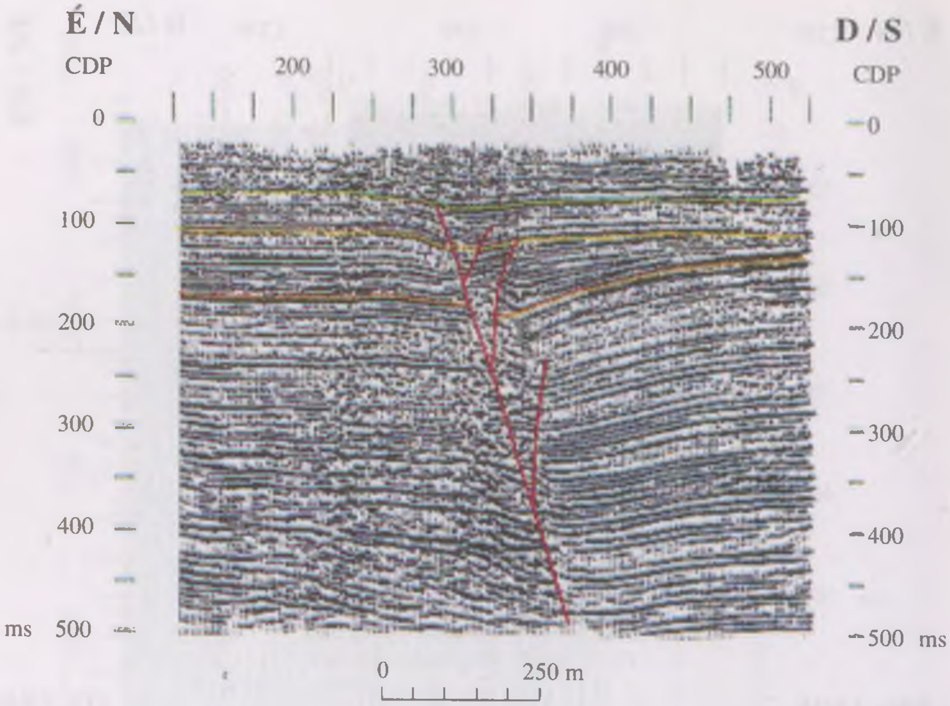


Fig. 12. Pa-3b interpreted time section

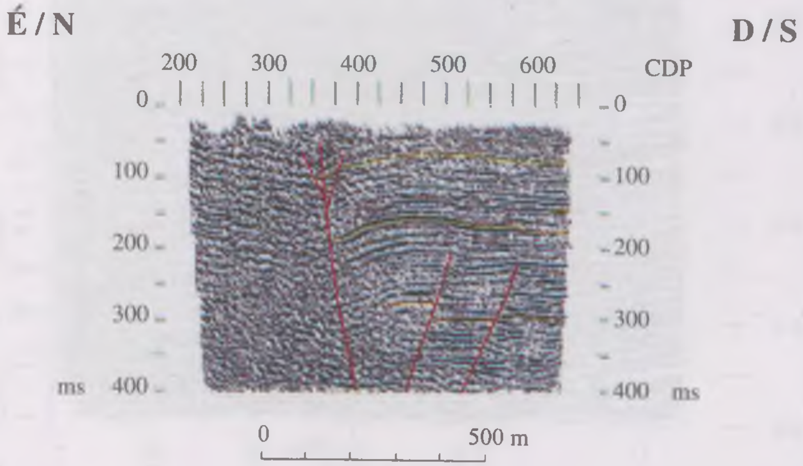


Fig. 13. Pa-12 interpreted time section

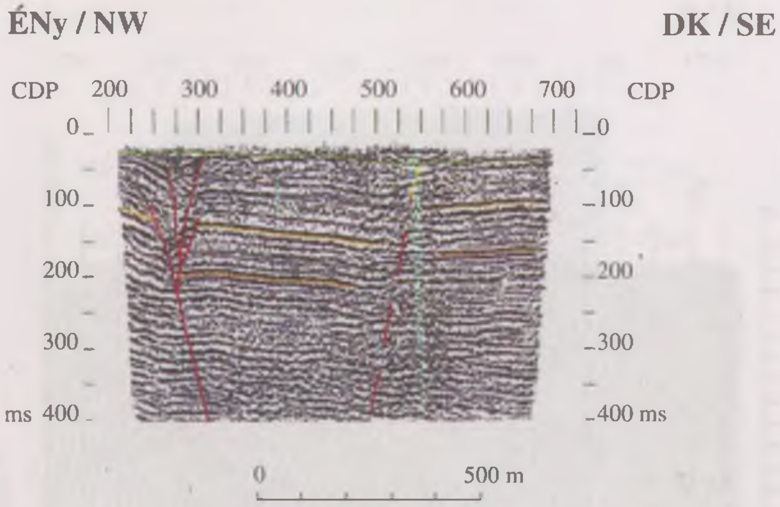


Fig. 14. Pa-13 interpreted time section

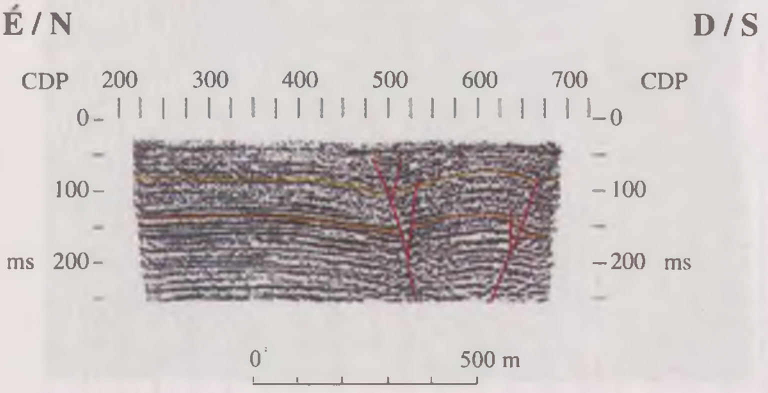


Fig. 15. Pa-14 interpreted time section

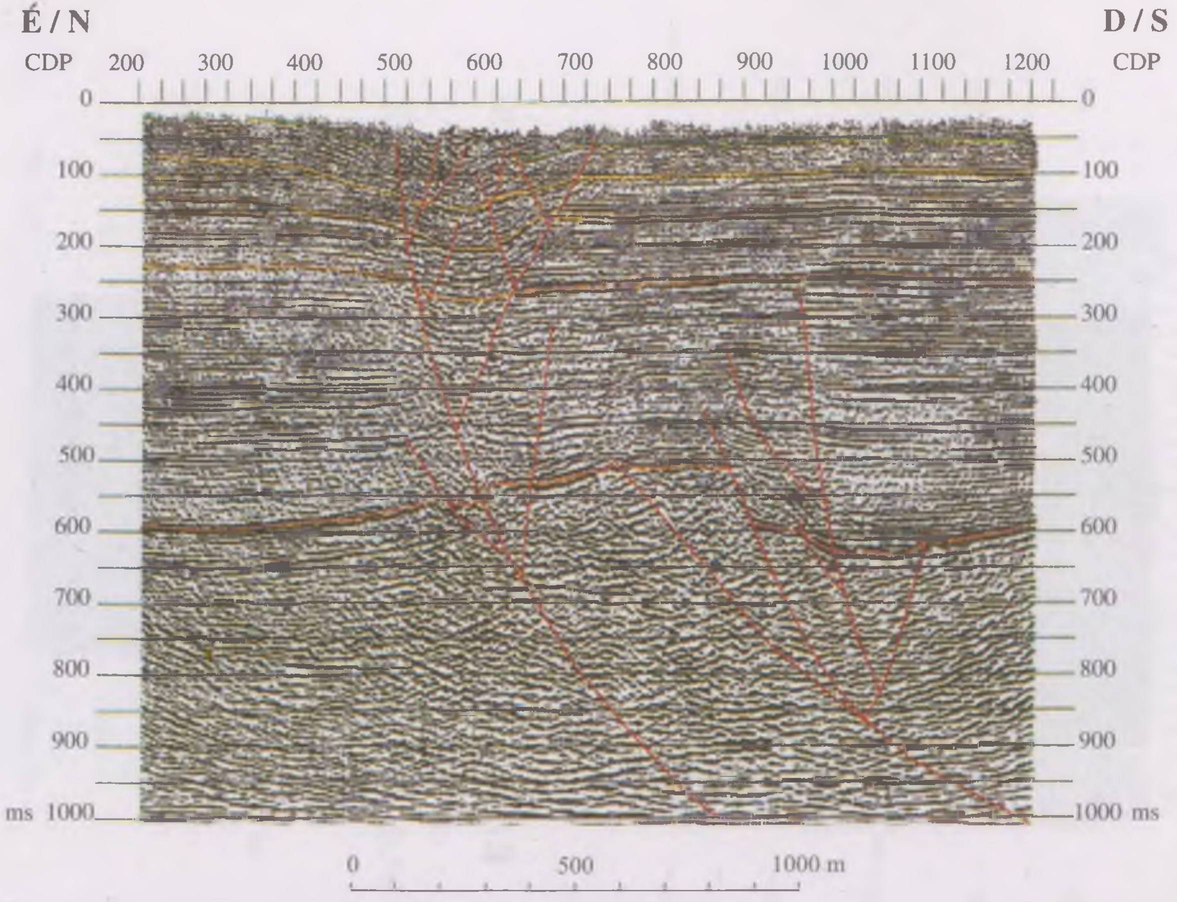


Fig. 16. Fa-15 interpreted time section

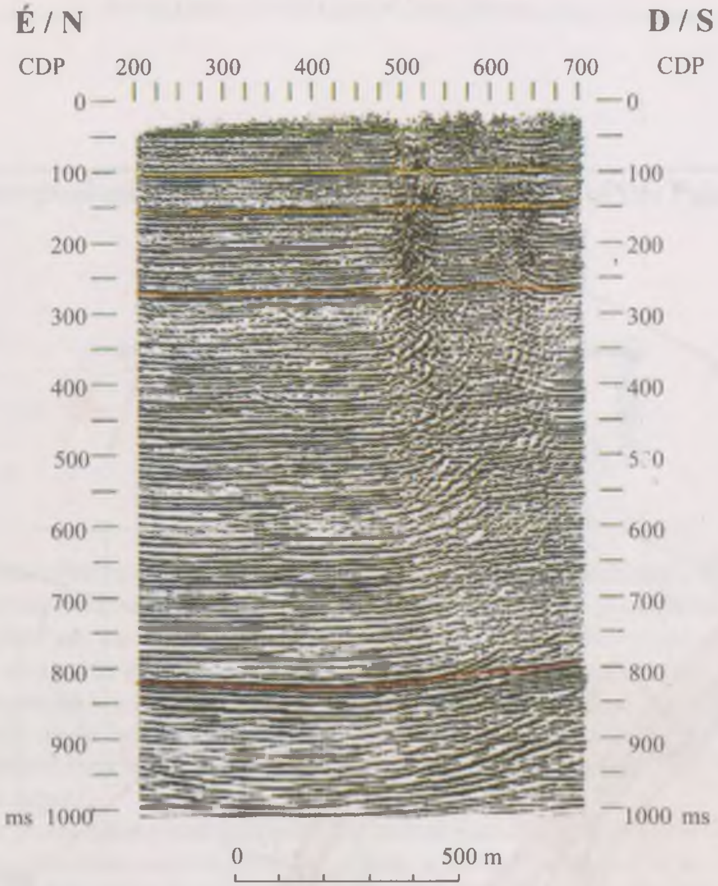


Fig. 17. Pa-17 interpreted time section

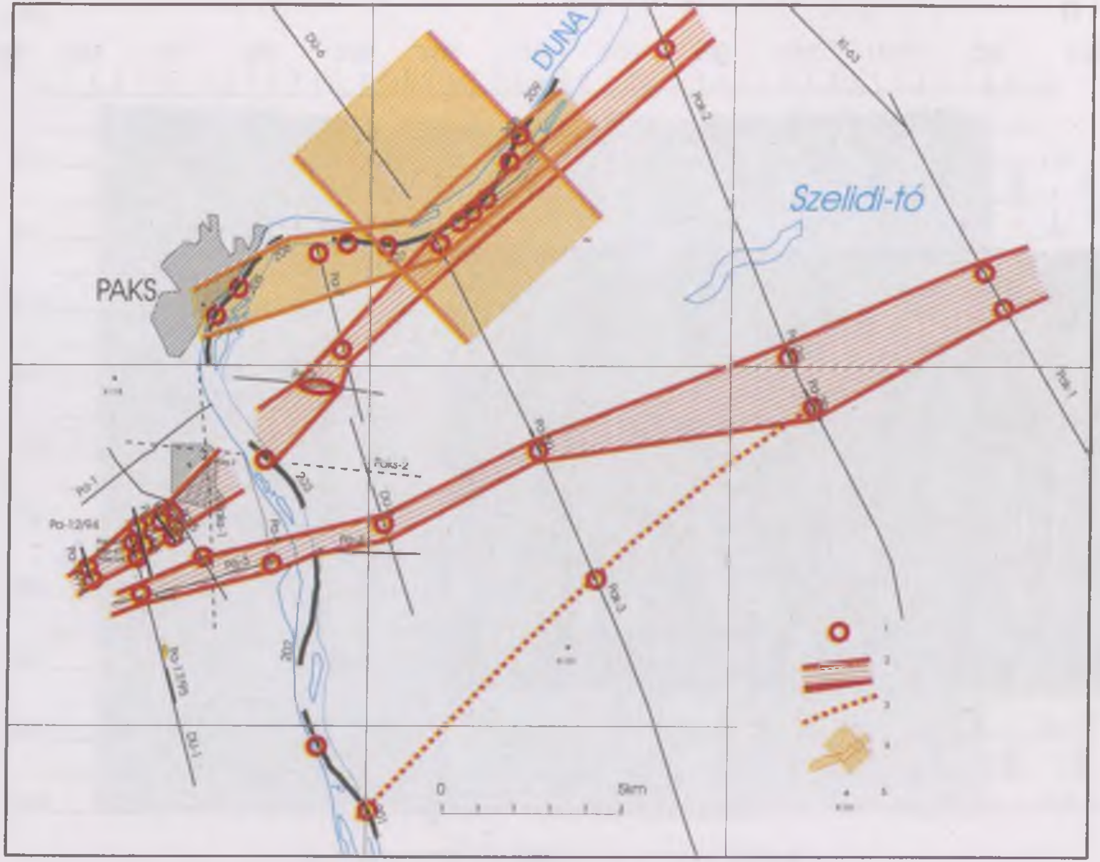


Fig. 18. Correlation of faults observed on seismic sections in the vicinity of the Paks NPP. – 1 = young faulting observed on seismic sections; 2 = known fault zone confirmed by the new seismic sections; 3 = presumed branch of the known fault zone; 4 = alternative correlation of the faults observed on seismic sections Danube 205–208; 5 = location of the well

Geomorphological investigations in the environs of the Paks NPP

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1. Introduction

Geomorphological analyses and mapping to estimate the earthquake hazard in the environs of the Paks Nuclear Power Plant are substantiated by the geomorphic evolution, its actual state and the ensemble of landforms in a given region being a result of a joint effect and alternation of endogenic and exogenic processes in time and space. Recent and actual topography is a tool for reconstructing past processes and their causal relationship while trends might be useful in building scenarios for the future. Especially tectonic movements and their subsurface and surface effects might be relevant for judging about earthquake hazard.

The geomorphological and geological literature are chiefly engaged in analyses and evaluations within *two major topics*. One of them is tracing the origin of subsurface *joints* emerging through *mass movements* in a broader sense, such as landslides, tectonic movements and for other reasons, while the other deals with the relationship between *base levels and stream channel modifications* and characteristics of the contemporary drainage network orientation and valley development as a consequence of the activity of the structural-tectonic factor.

To complement the chapters on geology and neotectonics of the present volume of studies some examples are drawn in the following when actually atectonic joints had been claimed earlier as structural ones and were used as arguments for the tectonic origin of valley orientation.

2. Atectonic joints

Upper Pannonian and Quaternary sediments of the high bluff of the Danube are rich in *atectonic movements* and phenomena. Fractures of tectonic origin do occur, too, but what is really typical is an abundance of joints with lithophysical and engineering-geological (landslide) origin. $CaCO_3$ infillings, limonite coatings and mollusc remnants observed and described in several places might be a useful contribution to determining the age and genesis of joints in concern.

The atectonic origin of joints might be argumented by several examples; of them the most instructing one is *the loess exposure at Alsószentiván*. At the western margin of a loess ridge there is a wall of 100–120 m width at both ends of which a dense set of parallel joints can be observed. In both cases there is a dip of fissures toward the slopes, i.e. in an *opposite direction*. In the middle part of the exposure, along the ridge no joints could be found however. Joints as a rule appear at a place where the slope of the inter-valley ridge has a minimum resistance in a soil mechanical sense, where the active tension originating from vertical loading exceeds the passive pressure of the mass of the loess ridge. The eastern joint set even follows the bending of the slope. Dominant strike directions are between 140 to 320° and 165 to 315° and closely associated with the surface of the loess ridge and and trend along the marginal valley sides. All this refers to the atectonic origin of joints as a consequence of previous sliding–slumping processes having provoked by an even earlier valley formation. In the middle, southern part of the ridge, below the chapel, no similar joint sets can be observed due to the lack of soil mechanical conditions (i.e. instability) calling for their emergence and displacement.

The above case means that along the slope margins the *initial relief* and *plasticity* of the active layers due to their high moisture content played a prominent role in emerging deformations. These strata – under the weight of rocks towering above them – slipped and slid toward the marginal valleys. Such a process, consequently, means not only deformation of layers, but, because of an uneven support of the latter, the emergence of cracks and fissures and of the rock mass broken into blocks. Subsequently the fissures were filled, and the surface was covered and conserved by the superimposing sediments.

The loess section at Alsószentiván provides a convincing example that the presence of joints running parallel to main valleys might be controlled not only by fractures having formed these fissures. An opposite trend is possible when joints come about under the impact of landslides triggered by valley downcutting and are not associated with structural evolution. This is our basic assumption for studying the origin and orientation of the valley network of the Mezőföld.

3. A sketch of geomorphic evolution and reconstructed paleogeography

It has long been agreed upon (Ádám et al. 1969) that streams running from the Transdanubian Mountains through the Mezőföld toward the Great Plain (northwest to southeast) had cut into the surface of the Pannonian sediments following the upfilling and desiccation of that lake.These valleys were subsequently filled up by Pliocene red clays and, to a lesser extent, by sand and sand silt *(Figure 1)*.

3.1. Paleogeography of sediments underlying fluvial deposits in the environs of the power plant

Until the end of the middle Pleistocene (ca 120 ka BP) the area belonged to the loess region of Paks-Dunaszentgyörgy-Tengelic characterised by erosional valleys and remnants of alluvial fans running from the Mezőföld toward the Great Plain (NW to SE) that had lowered the loess surface between Tengelic and Paks.

Figure 2 showing paleogeographical conditions with the contemporary relief underlying fluvial deposits was compiled using borehole data of the Company of Land Surveying and Soil Prospecting (FTV) basically. These drillings penetrated the Upper Pannonian formation and reached down the deepest point of the gravel sequence. After having studied material of more than 800 boreholes it should be stated that in most cases identification of Pliocene and Quaternary sediments was ambiguous. Another problem was that in several cases typical terrestrial deposits like red clays and old loess or loess-like sediments were labelled as "silt" of Upper Pannonian origin. That is why the map only presents a paleogeographic sketch of the Upper Pannonian (Upper Miocene); it rather represents the topography of Upper Pannonian lacustrine deposits partly eroded during the Pliocene (5.3 to 2.4 Ma *(Figure 2).*

According to the borehole data the alluvial sequence of the Danube is situated at 66–71 m a.s.l., below the Holocene and late Würm blown sand sequences of 3–5 m thickness. The minimum age of the gravelly sequence (based on the floated timber found in it) is 40 Ka (This is the lower limit of ^{14}C dating) *(Figure 3).*

Figure 2 shows that strata underlying the fluvial sequence at 66–73 m a.s.l. are constituted partly by Upper Pannonian formation, partly by red clays of 3–4 Ma yr age, and partly by old loess and loess-like sediments (silt) accumulated in wide, 2–6 m deep erosional valleys cut into the Upper Pannonian layers.

In the area of the power plant and in its immediate surroundings the buried Upper Pannonian surface is represented by two distinct geomorphological levels. One of them is the so called lower level with islands and valleys of various width and N–S orientation. The other geomorphic level is related to the first one through a slope. Its surface lies at 70–72 m a.s.l. divided into two parts by a marked erosional valley running NW to SE. The wide and shallow (3–4 m deep) valley has red clay infilling sometimes covered by old loess eroded after the Danube had appeared in the area.

This reconstructed underlying topography has a low energy of relief with the highest point being at 73 m and the lowest one at 66 m a.s.l. *(Figure 2).*

Islands situated between 66–68 m a.s.l. also belong to the low landforms. The channels, based on the age of the red clay infilling might be older than 3.5–4.0 Ma. Old loess (1.3 to 0.4 Ma) and loess-like deposits superimposing red clays are also important geochronologial markers. In the wider channels some drillings reached the Upper Pannonian surface even deeper, under the red clays.

Higher situated surfaces are parralel to the N–S oriented river channel and have altitudes of 70–72 m a.s.l. They are linked to the surfaces of 66-70 m and 73 m by slopes.

An erosional valley running WNW-ESE and NNW-SSE has cut into these surfaces having a base level of an other erosional valley stretching N-S with an altitude of 66–69 m a.s.l. (low lying level) A few boreholes deepened here gave evidence of the presence of red clays in this valley.

The sediments and surfaces formed during a transitional period of the Plio–Pleistocene and witnessing on an ongoing fluvial activity are covered by strips of loessy deposits with a thickness of 20–100 m. For these sequences, which are typical of the Mezőföld region, paleomagnetic datings provided ages less than 1 Ma *(Figures 1, 4* and *5).* The loess sequences clearly observable at high bluffs along the Danube are dissected by valleys inside the Mezőföld region, similar to the blown sand surfaces. The orientation of these valleys also suggests tectonic control.

3.2. Orientation of the valley network on the Mezőföld

The valleys of the Mezőföld fit into a system of a radial pattern. Orientation of the valleys in West Transdanubia (Zala region) is showing N-S, in Somogy it tends to be NNW-SSE, on the Mezőföld it turns NW-SE, while in the north of the Danube-Tisza Interfluve WNW-ESE is the dominant direction in several places crossed by the main tectonic strike parallel to the Transdanubian Mountains. A specific feature is a similar configuration of the rose of the prevailing winds that had created deflation landforms of a corresponding pattern. The above conditions have made it quite problematic to evaluate the role and weight of the structural factor in shaping geomorphic features.

In the special literature there is a widely accepted viewpoint (e.g. Egyed 1957, Gábris 1986) also applied to the region in concern (Ádám et al. 1969, Horváth et al. 1990) that a close relationship can be established between the drainage network and structural characteristics. This statement might be correct in many cases, however as an argument for the tectonic control it is not sufficient by itself.

The orientation of valleys, as it was indicated above, need not to be of tectonic origin necessarily, even if the joints show parallel pattern (Marosi and Schweitzer 1991, Balla et al. 1993). Therefore causal relationship between the valley system of the Mezőföld and the fractures, in spite of the definite orientation of the former, cannot be considered a proven fact. Nevertheless, even though water courses do not follow tectonic fractures, their orientation might have been influenced by structural movements, e.g. by attracting the Transdanubian (Mezőföld) streams toward base levels as it happened in the course of the subsidence of the Great Plain in general and of its minor marginal basins in particular.

3.3. Base levels along the margin of the Great Plain and shifts of the channel of the Danube

Until the end of the middle Pleistocene (ca 120 ka BP) the area in concern was part of the Paks-Dunaszentgyörgy-Tengelic loess region. This was the period of formation of valleys running from the Mezőföld toward the Great Plain (NW-SE). Transversal profiles of erosional valleys, torrents cut into the Upper Pannonian surface can be identified in boreholes deepened at the Öreg Hill (Dunaföldvár) and Sánc Hill (Dunakömlőd) or in those drilled under the power plant. These valleys are filled partly by red clays redeposited or those with $CACO_3$ horizons *(Figures 1* and *6).*

Erosional valleys recognised in boreholes are 50–70 m wide and 3–10 m deep *(Figure 1).* Similar depressions and valleys with slope angles of some degrees are frequent phenomena and in some cases (environs of Dunaújváros, Dunaföldvár or Dunakömlőd) the boreholes have given evidence of their eastward continuation as they are discernible on the gently sloping Upper Pannonian surface.

Pávai Vajna (1941, 1951), who was an adherent of the tectonic theory, conceived these valleys gently sloping eastward as synclines. He described two synclines and a narrow fold in the vicinity of Dunaföldvár, and in his opinion this settlement was also located in such a trough.

According to geologial-geomorphological investigations the Danube appeared in this area in the wake of the late Pleistocene as no older material of Danubian origin could be identified (Rónai 1964, Pécsi 1959, Erdélyi 1960, Marosi 1953). Separation of this area from the rest of the loess region was caused by a process of subsidence (the emergence of the Kalocsa basin, *(Figures 7* and *8)* having attracted the western branches of the Danube, which is manifested by a sandy-gravelly sequence.

Structural movements in the Kalocsa basin during the late Pleistocene has long been known about through stratigraphic and sedimentological data. The depression soon became filled up by the alluvium of the Danube and then in the western part of the area (between Dunakömlőd, Paks and Tengelic) the river, cut down deeply into the Upper Pannonian surface and eroding it laterally, eliminated the slope constituted by red clays and old loess, and has shaped a broad plain. This subsidence took place in 2–3 phases as evidenced by 2–3 levels of gravelly horizons with a thickness of 6–10 m each within the 30–60 m thick fluvial sequence of the basin *(Figure 7).*

In the initial phase (last interglacial) the area sank 20–25 m, then in the middle of the late Pleistocene (40–50 ^{14}C ka BP) a subsidence of 20–25 m (an in some places even more intense) occurred between Paks and Tengelic *(Figures 9* and *10a).* This way a 15–20 m thick alluvium was deposited upon the sediments having been accumulated by the river.

At the end of the middle Würm (32–26 ka BP) the terrace surface IIa formed. This data is corroborated by the presence of cryogenic pseudomorphoses (sand wedges, cryoturbations) observed in flood plain deposits originated from the period 26–13 ka BP. Above them fossil sand dunes of considerable thickness developed (Schweitzer and Tarnóczay 1996).

Geological and geomorphological conditions in the area of the power plant and in its immediate surroundings suggest that no major structural movements are likely to have occurred since the final stage of the late Pleistocene. Investigations conducted prior to the construction of the plant seem to endorse this assumption. Exposures studied in 1967–68 contain blown sand of 3–7 m thickness subdivided by 2–3 fossil soils. The lowermost one of them was the best developed showing similar features with the lowermost fossil soil of the sand pit located west of the power plant.

These data support the idea about the Danube having left the area by the final phase of the late Pleistocene with its main channel and branches shifting eastward, due to a steady subsidence in those areas. It is very likely that by this time the place where the power plant is actually located had become land and blown sand accumulated in several phases upon the Danubian alluvium.

Based on ^{14}C analyses a period of stadial but intense subsidence was probable, then the movement slowed down and stopped. This is supported by data provided by boreholes deepened along the Danube bank between Paks and the confluence of the Sió canal. In these boreholes coarse grained and gravelly layers are recurring in 2–3 horizons with the sediments becoming finer upward the profile as these periods of upfilling were closed by silt or sand silt deposition *(Figures 6, 7, 8* and *10b)*.

The latest result of the subsidence process is the Sárköz basin. Based on ^{14}C data the westernmost branches of the Danube and the main channel itself were diverted to their present location by a subsidence occurring 11 ka BP. This area has experienced an intense, 20 m subsidence since the end of the late Würm through the Holocene *(Figures 10a, b)*.

3.4. Channel modifications of the Danube

North of Paks gravelly sediments of the river bed present a hindrance to the incision of the *Danube* and to the formation of *free meanders*. South of Paks, however, no similar obstacles exist since the gravel layer lies at 5–10 m depth below the actual channel, so free meanders of the Danube could develop. The evolution and natural cut-off of large meanders based on the investigations by Somogyi (1974) took 150–200 years *(Figures 11, 12)*.

To study structural orientation of the Danube meanders maps by Mikoviny published between 1735–1750 have been involved. Typical channel orientations of the (already abandoned) meanders were NW-SE and perpendicular to it, though N-S and W-E were rather common, too. On the map showing the section between Paks and Szekszárd former channels made up a dense network with the highest density in the vicinity of Kalocsa. Based on the above data a statement can be made that if meanders followed structural directions and lines, Kalocsa and surroundings might be evaluated as the most active area tectonically.

Summarising our knowledge about the natural evolution, geomorphic development as well as the social interference, man-made impact, it can be stated that joints studied in the Pleistocene sequence are of atectonic origin and valley orientation even in the case of parallel joint pattern fails to prove tectonic control. Along the Danube channel before flood protection, in the Dunaföldvár-Dunakömlőd-Paks area no unambiguous evidence was found which would support the assumption that the Danube channel has followed fault line(s). The river flow rather has always been directed toward basins of subsidence *(Figure 13).*

In the structural analyses, apart from the geomorphological data, an indirect method of studying chloride content of the subsurface waters can produce useful contribution.

3.5. Interfluvial valleys between loess ridges and the ancient Sárvíz stream

Surface characteristics of the Mezőföld loess plateau are determined by valleys of various genesis having dissected the surface heavily. Of relief forming processes sheet wash, landslides, linear erosion and deflation have played a prominent role.

Along the margin of the narrowed and lowered loess plateau sometimes appearing in islets, generations of the alluvial fans of the ancient Sárvíz have been adjoined since the early Pleistocene. Later these surfaces became completed by the young fan material of the same water course from the late Würm. Sometimes these landforms were covered by loess and loess sand. The Sárvíz alluvium and sandy-gravelly terraces provided abundant material for a large amount of blown sand. This cover sequence is often hard to separate from fluvial deposits due to the short distance of transport.

Most important landforms include blown sand dunes and long and wide depressions between them, deflation flats etc.

4. Landforms occurring in the area (geomorphological map)

The geomorphological map of the wider surroundings of the power plant *(Figure 14)* presents the genetic types of landforms also as a synthesis of relief evolution and lithological endowments, their groups and microforms which might serve as a basis for any kind of land use (Balogh et.al. 1994, Schweitzer et al. 1994a, Kanyár and Schweitzer 1996).

Geomorphological features of the studied area are shaped basically by the landforms of two relief types.

The *Mezőföld* is characterised by loess plateaus, alluvial ridges and high bluffs with steep slopes stretching toward the Danube. Erosional valleys, derasional and erosional-derasional valley systems, derasional niches and valley heads in intense change. Ridges of alluvial fans covered by wind blown sand are rich in microforms created by processes of deflation.

The *Danube Plain* is a tripartite landscape. The main channel of the river and its branches are flanked by a narrower or wider flood bed while the low and high flood plain surfaces are to be found farther.The most typical landforms are the meanders in different stages of evolution, the point-bars situated between them, the ox-bows (former meanders) and the salty depressions. Isolated flood-free surfaces of the high flood plain emerge from the low flood plain.

The *parent material for both of the relief types* are loose deposits exclusively. Loess plateaus constitute typical loess, sand loess and sandy slope loess. Ridges of the alluvial fans are surfaces covered by wind blown sand.

On the surface of the high flood plain of the Danube fluvial sand, loess silt and wind blown sand serve as the main parent material for soils. Surfaces of the low flood plains with high table of ground waters are formed by meadow clays and variations of mud mixed with sand.

4.1. Fluvial erosional and accumulational landforms

Of the landforms shown in the map *(Figure 14)* this category comprises *erosional valleys, alluvial fans, fluvial terraces* and *flood plains*.

4.1.1. The *low flood-plain level* of the Danube valley. The area is a perfect plain of the river.

The early Holocene terrace of the Danube represents a level of 93–97 m a.s.l. on the flood plain. A complex network of abandoned river channels and the surface of eroded flats is situated by 2–3 m lower, at 91–94 m a.s.l.

4.1.2. The *high flood-plain level* is represented by isolated elevations on the left bank of the Danube with settlements built on them. This surface is constitued by alluvial mud, loess silt. The area is largely covered by wind blown sand. The boundary of the high flood plain on the right bank coincides with the margin of the II terrace of the Danube.

4.1.3. *Flood-plain terrace islands.* They are isolated surface forms situated on the broader talwegs (valleys of the Sárvíz, Kapos, Völgységi-patak) and larger flood plains (Sárköz) as a result of lateral erosion of the above tributaries of the Danube. Their material is alluvial sand, alluvial mud and loess reworked by water. Terrace islands elevating 2–4 m above their environs are flanked by the remnants of abandoned branches of the river (Marosi 1953).

4.1.4. *River terrace.* Along the Danube between Dunaföldvár–Paks–Szekszárd there is a 1–6 km wide flood-free Pleistocene (IIa) terrace adjoining to the margin of the loess plateau of the Mezőföld. From the east the edge of the Danube-Tisza Interfluve elevated by wind blown sand is stretching made irregular by flat depressions.

4.1.5. *Flat alluvial fans.* The largest of them is the Lower and Middle Pleistocene alluvial fan of the ancient Sárvíz of northwest–southeast orientation built along a series of depressions. The contemporary channel of the Sárvíz was stretching 4–6 km east of the present-day one as a continuation of the Mór Trench. The stream was filling the rapidly subsiding southern part of the Mezőföld with sediments (gravel, gravelly sand). Along its sloping the thickness varies considerably widening into a 50 m thick vast alluvial fan in the South Mezőföld; south of Szedres its material is mixed with the Late Holocene channel infilling of the Danube (Marosi 1953).

A substantial part of the alluvial fan in the South Mezőföld turned into windblown sand surfaces (longitudinal ridges of accumulation and furrows of erosion dunes, deflation hollows and blow-outs) at the end of the Late Pleistocene and during the Holocene.

4.1.6. *Valleys.* They are the most frequent landforms of the hill region and of the Dunaföldvár–Paks loess plateau.

Figure 14 shows the erosional valleys by their depths even if these valleys cut down to a different extent belong to various types according to their history of evolution morphological features.

Evolution of the *major erosional valleys* has been determined by the intensity of valley formation.

A typical example of the remains of a valley bottom filled up during the warm and dry *Corylus* phase of the Holocene (terrace I, Early Holocene) is to be found in the Sárvíz Valley. Its elevation above the flood plain is 2–3 m in the northern reaches of the valley and 3–4 m in its southern part. The infilling is predominantly sand, silt sand and lime mud.

– *Erosional valleys of 20–50 m depth* belong to the short asymmetric erosional valleys (valley basins). Their typical representative are the short erosional valleys of the Dunakömlőd–Paks loess plateau opening to the Danube Valley.

Their characteristic feature is a W-E or WSW-ESE orientation.

– *Erosional valleys with a depth less than 20 m* are those of the large intermittent streams (tributary valleys).

– *Broad and flat erosional valleys* are represented by the minor erosional valleys of the Mezőföld.

4.2. Landforms of complex genesis

Generally these are landforms shaped by a joint effect of different kinds of impacts (structural movements, linear erosion, sheet wash, eolian sedimentation etc., Ádám 1964, Pécsi 1967).

4.2.1. *Loess plateaus.* They are the most typical macroforms of the Mezőföld.They are situated along NW–SE strike, with a significant elevation (160–180 m) above the environment and a 5–6% sloping toward SSE due to their one-sided uplift.

Another geomorphological property is a relatively poor dissection of their surface (Ádám et al. 1969).

Plateaus are covered with a thick (in some places 50 m) loess.

Along with the typical loess they are constituted by different kinds of deluvial loess-like sediments.

4.2.2. *Low interfluvial ridges*. They are built of loose deposits: loess, sand and sedimentary rocks emerging from between deeply incised erosional and erosional–deflational valleys. They are gradually narrowing landforms of erosional-derasional origin genetically. Altitude a.s.l. as a rule is less than that of the surrounding loess plateaus in summit position.

4.2.3. *Dry (derasional) valleys*. They are the most frequently encountered landforms the Mezőföld.

The dry derasional valleys are in most cases through-like or pan-shaped elongated depressions enclosed by convex and concave slopes, without valley bottoms. Both shape and size might be different. They are void of bed and permanent stream and considerably widen toward the valley head. Water is to be found in them only during intense rainfall and showers.

4.2.4. *Derasional niches*. Round-shaped and oval microforms shown in the map are to be found mainly on the valley slopes covered by loess, along the margins of loess ridges and in heads of derasional valleys.

4.2.5. *Erosional–derasional valleys*. This type comprises all the dry valleys of the area which were derasional valleys originally and even today remind them by morphological properties but have permanent or intermittent watercourses.The apperance of streams refers to the transformation of dry valleys.

4.2.6. *Derasional saddles*. These are landforms of the narrow crests of watersheds. They are most common between neighbouring valley heads, residual hills and loess ridges.

4.2.7. *Slopes undistinguished* appear on the map where slopes steeper than 2.5° occur that have not been evaluated according to their dynamics.

4.2.8. *Stabilized fossil slumps*. Slopes those having affected by old slumps were classified here, hydrogeological properties of and man-made impacts on which are creating possibilities for the reactivation of landslides.

4.2.9. *Unstable bluffs*. Unstable high bluffs underwashed by the Danube, with slips and slumps belong to this category. Their degradation is a consequence of both natural factors and man-induced changes *(Figure 13)*.

4.3. Wind erosion (deflational) landforms

4.3.1. *Sand cover*. The largest contiguous area of wind blown sand cover occurs in the southern part of the Mezőföld which is associated with the wide distribution of alluvial fans and fluvial terraces over the region. The alluvial fan of the ancient Sárvíz and the surface of its late Pleistocene terrace had turned into a region of wind blown sands because thick and uncovered sands were exposed to the prevailing northwestern winds in a period promoting deflation.The material of the sand cover is coarse, poorly sorted and rounded, i.e. of local origin. The above area to the south adjoins the wind blown sand surface formed on the joint late Pleistocene terraces of the Danube and Sárvíz.

4.3.2. *Sand forms undistinguished.* The sand forms shown on the geomorphological map *(Figure 14)* are not individual "in situ" forms but generally they indicate semi-fixed sand configurations instead (longitudinal dunes, deflation furrows and hollows, blow-outs, residual ridges. *The most frequent forms are deflation hollows and residual ridges* and the longitudinal dunes separated from the hollows.

4.3.3. *Sand blankets.* These are sand covers of several dm thickness blown out from abandoned stream beds, deflation furrows and low flood plains and accumulated in the vicinity.

4.4. Man-made landforms

Sunken roads. Dirt roads leading to the fields from villages are liable to be turned into sunken roads. Their depth is highly variable (3–15 m). In a mature state of evolution they fold up and turn into loess gorges.

The network of *drainage canals* leading off excess waters along the channelised and filled meanders should also be classified as man-made landforms.

5. Conclusions

The geomorphological analyses attest to the typically atectonic origin of joints encountered in Pleistocene and Holocene sediments. They are associated with mass movements, and partly with desiccation cracks. Even in the case of parallel jointing, the oriention of valleys cannot be an unambiguous evidence of tectonic origin.

Along the Dunaföldvár-Dunakömlőd-Paks Danube section before regulation the channel cannot be regarded to follow one or more fault lines. Rather, it seems to have headed for areas of subsidence.

A hyphothesis of tectonic origin of northwest–southeast erosional, partly (especially the more recent ones) derasional or erosional-derasional valleys of the Mezőföld is questioned by the fact that prevailing winds are also northwestern. As the geomorphological map clearly shows, landforms of various origin are aligned in this direction and control the present face of the landscape.

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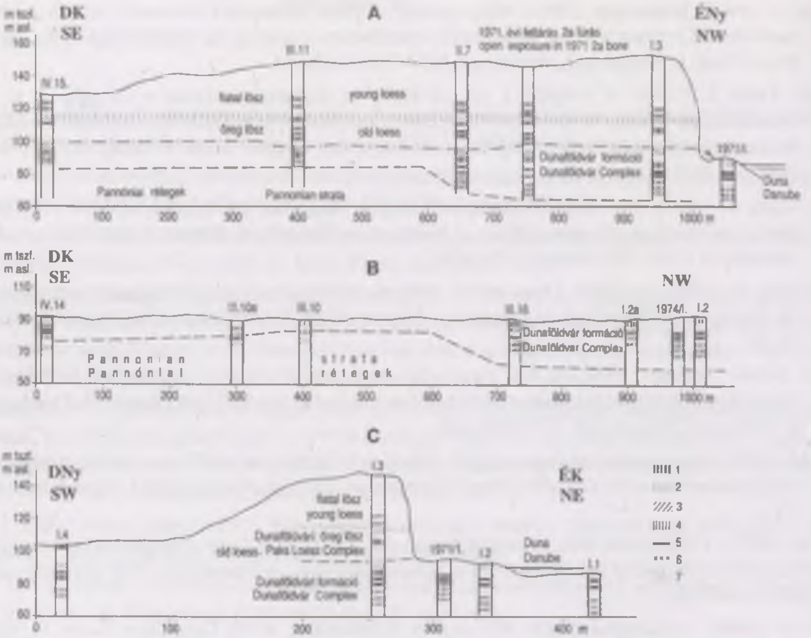


Figure 1. Red clay infillings of erosional valleys incised into the Upper Pannonian surface turned into land (Schweitzer 1971). Sections of the loess bluff at Dunaföldvár. – A = profiles of top boreholes; B = profiles of bank boreholes; C = transversal profile. 1 = meadow soil; 2 = fluvial sand; 3 = soil sediment; 4 = chernozem like soils; 5 = red forest soils, brown forest soils; 6 = red clay; 7 = pink sand loess; I. 1–IV. 15 = borehole numbers

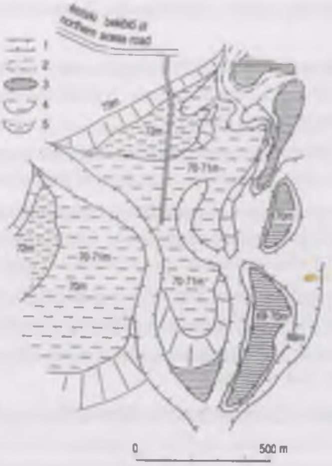


Figure 2 . Paleogeography of sediments underlying fluvial deposits in the surroundings of the power plant (comp. by Schweitzer 1995). – 1 = erosional valley; 2 = presumed erosional valley; 3 = island (69–70 m a. s. l.); 4 = eroded surfaces (70–71 m a. s. l.); 5 = eroded surfaces (72–73 m a. s. l.)

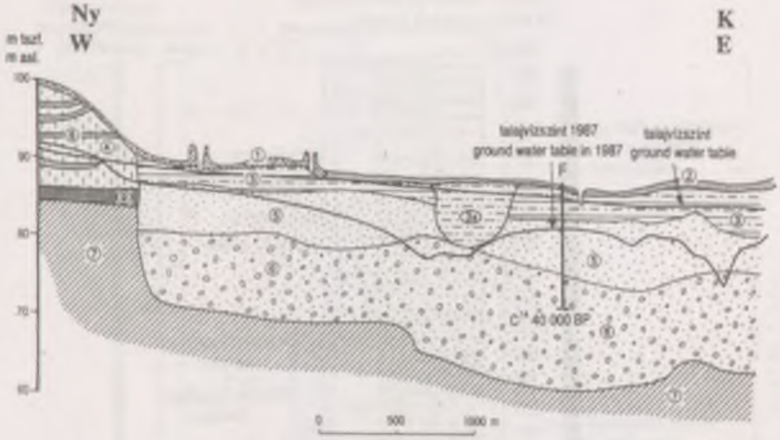
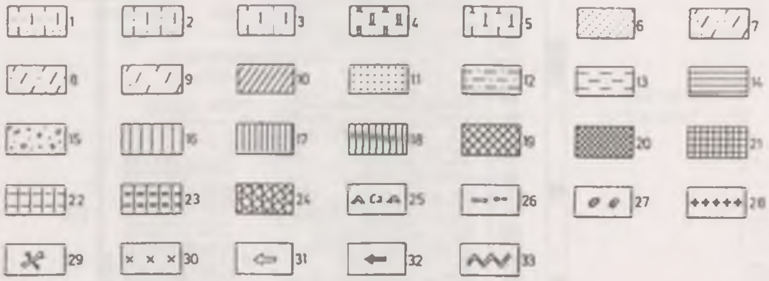


Figure 3. Infilling of the depression formed during the last interglacial and early Würm. – 1 = filling material; 2 = recent soil; 3 = Holocene sediments (meadow clay, silty sand, peat); 3a = upfilled river channel remnant; 4 = Pleistocene loess series with intercalated paleosols; 5 = Holocene fluvial sand of high organic content; 6 = predominantly sandy–gravelly fluvial series of late Wurm–early Holocene origin; 7 = Upper Pannonian sediments; 8 = paleosols; 9 = red clays; F = borehole south-southeast of Paks (Scheuer and Schweitzer 1989)



Generalized key to the loess profiles of Hungary *(Figures 4* and *5)* – 1 = very sandy loess; 2 = sandy loess; 3 = unstratified loess; 4 = old loess; 5 = infusion loess; 6 = slope sand; 7 = loessic sand; 8 = sandy slope loess; 9 = slope loess (6–9 = stratified slope deposits); 10 = soil deposit; 11 = fluvial sand; 12 = silty sand; 13 = silt, gleyic silt; 14 = clay; 15 = sandy gravel; 16 = slightly humic horizon; 17 = steppe paleosol; chernozem, chestnut paleosol; 18 = forest soil transformed under steppe vegetation; 19 = brown forest soil; 20 = lessivée brown forest soil; 21 = red clay; 22 = hydromorphous soil; 23 = alluvial and meadow soil; 24 = flood-plain forest soil; 25 = CaCO3 accumulation; 26 = loess doll; 27 = krotovina; 28 = charcoal; 29 = microfauna; 30 = volcanic ash; 31 = slight erosion or derasion; 32 = erosion gap; 33 = interruption in the profile; l_1–l_6 = young loess series; L_1–L... = old loess series; s_1–s_3 = fluvial sand; n_1–n_8 = clay with fine sand, c layey sand; a_1–a_4 = clay; h_1–h_2 = humic loess horizon; MF = forest steppe paleosol complex 'Mende Upper'; BD = forest paleosol complex 'Basaharc Double'; BA = chernozem paleosol 'Basaharc Lower'; MB = 'Mende Base' paleosol complex (brown forest soil + forest steppe soil); Phe = Paks sandy forest soil; PD = paleosol complex 'Paks Lower Double' (brownish–reddish mediterranean forest soil); PDk = Paks–Dunakömlöd paleosol; Pv_1, Pv_2 and Pv_3 = Paks red paleosols; Dv_1–Dv_6 = red paleosols of the Dunaföldvár formation; F_1–F... = earlier numbering of paleosols without indicating pedological type

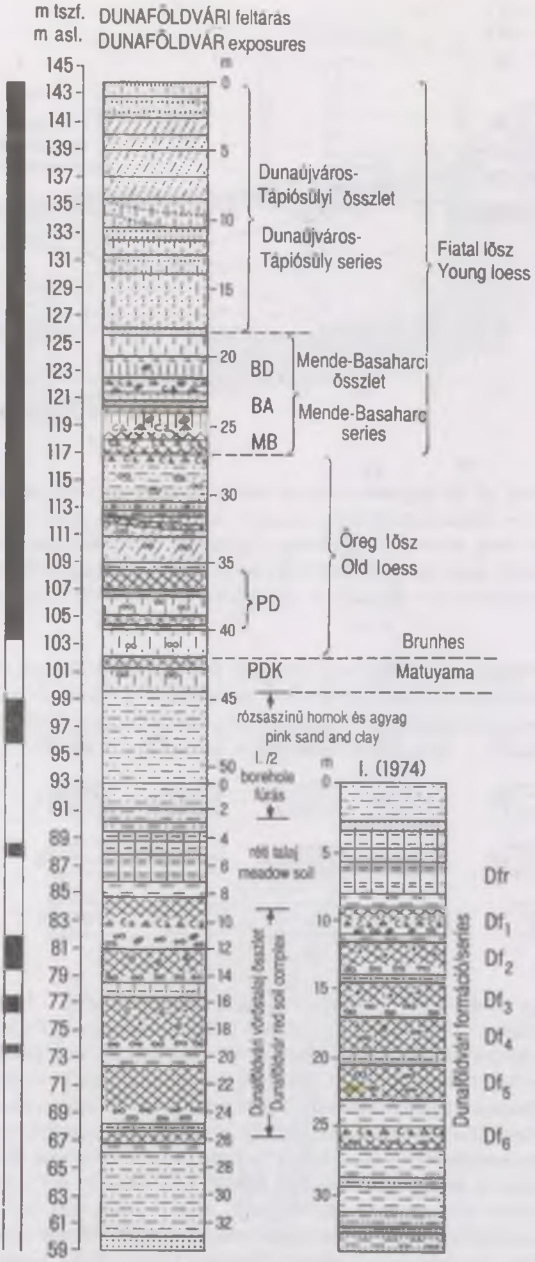


Figure 4. Subdivision of the Dunaföldvár section based on paleopedological and paleomagnetic investigations (Pécsi et al. 1974). – BD = Basaharc Double Soil Complex; BA = Basaharc Lower Soil; MB = Mende Base Soil; PD = Paks Double Soil Complex; PDk = Paks–Dunakömlőd Soil; Dfr = Dunaföldvár Meadow Soil; Df_1–Df_2 = Dunaföldvár Red Soil Complex. For datings see *Figure 5*.

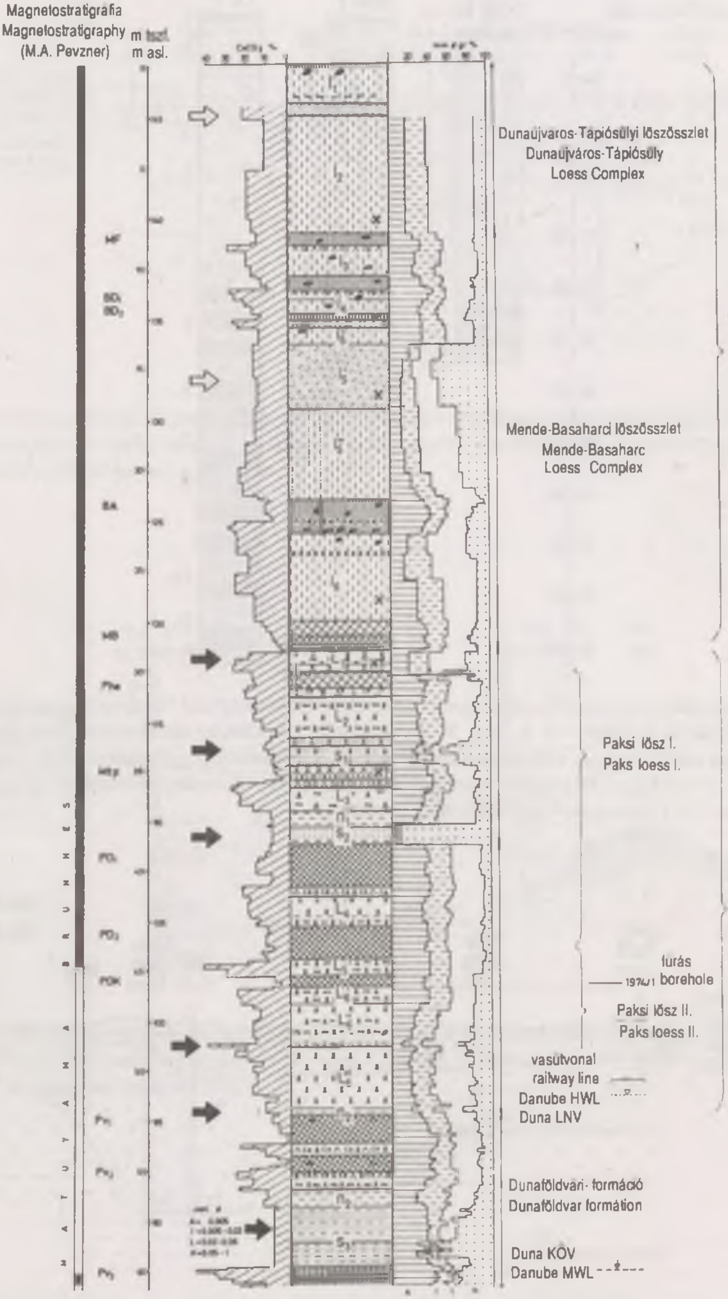


Figure 5. $CaCO_3$ content and paleosols in the Paks North loess section (Pécsi 1982; paleomagnetism by Pevzner)

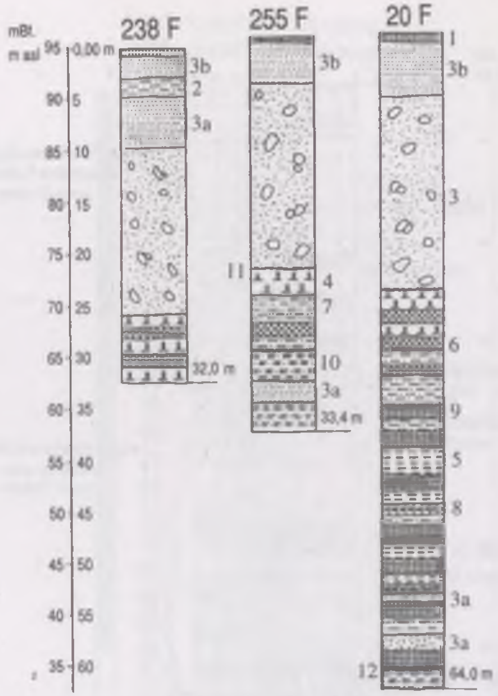


Figure 6. Stratigraphic columns of boreholes penetrating older Pleistocene and Pliocene deposits south of Paks (Scheuer and Schweitzer 1989). – 1 = soil; 2 = alluvial mud; 3 = Danube sandy gravel; 3/a = alluvial sand; 3/b = windblown sand; 4 = loess with concretions; 5 = mud; 6 = paleosol; 7 = muddy sand; 8 = boggy clay; 9 = sand mud; 10 = red clay; 11 = Upper Pannonian muddy clay; 12 = boundary of extension of the Danube's fluvial deposits; 13 = Pleistocene–Upper Pannonian boundary

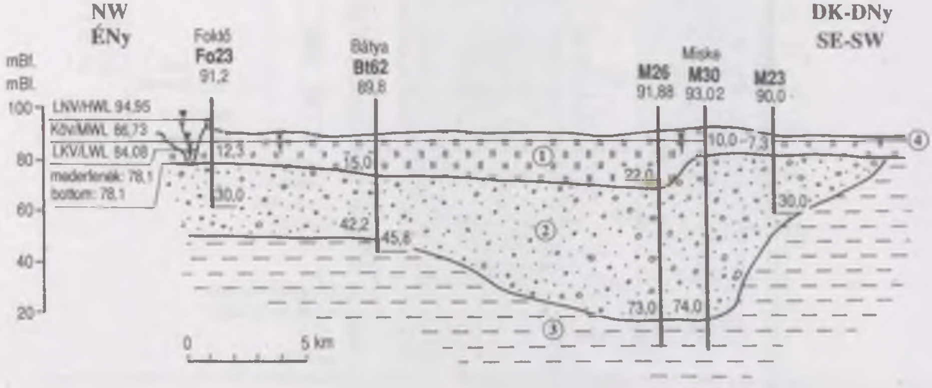


Figure 7. Hydrogeological cross section showing filling up of the Kalocsa Depression (Petz and Scheuer 1990). – 1 = overlying bed (mud, sand); 2 = aquifer (sandy gravel, gravelly sand); 3 = underlying bed; 4 = medium depth of ground-water table

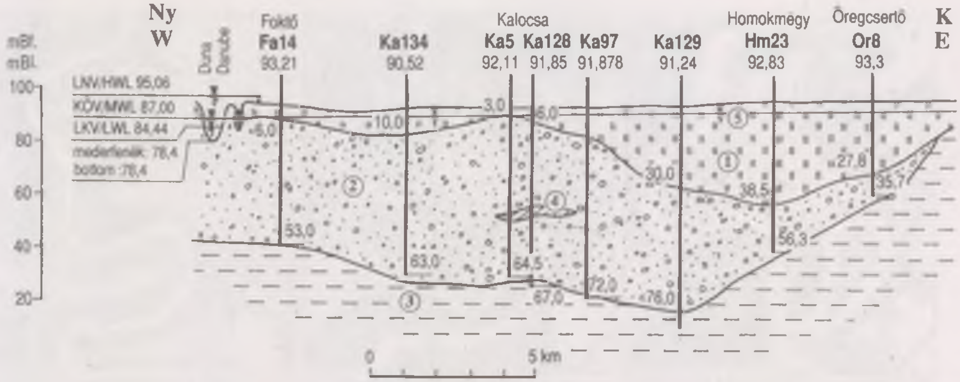


Figure 8. Hydrogeological cross section showing filling up of the Kalocsa Depression (Petz and Scheuer 1990). – 1 = overlying bed (mud, sand); 2 = aquifer (sandy gravle, gravelly sand); 3 = underlaying bed; 4 = clay; 5 = medium depth of ground-water table

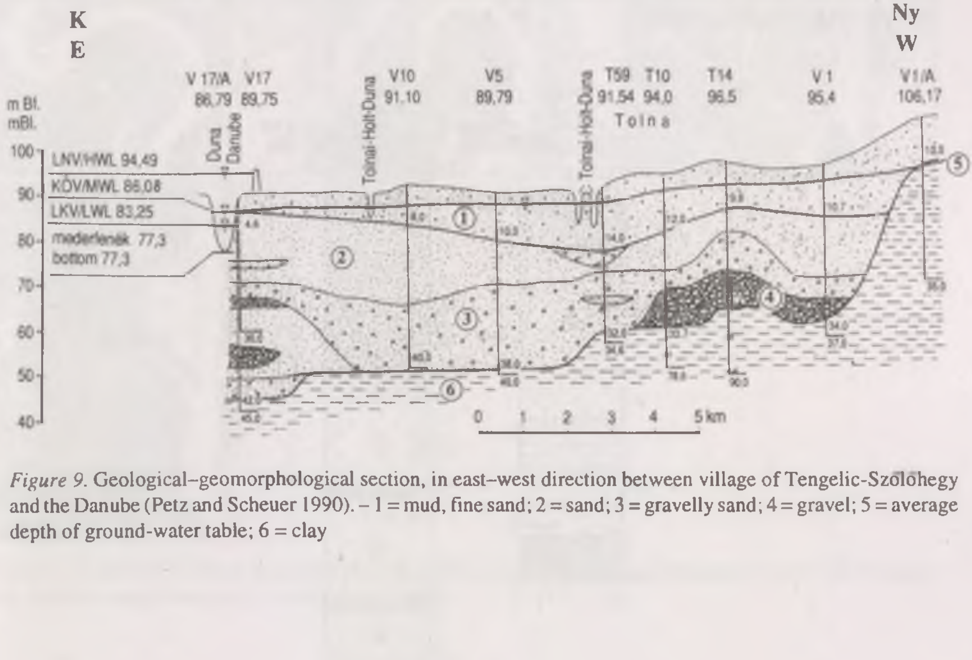


Figure 9. Geological–geomorphological section, in east–west direction between village of Tengelic-Szőlőhegy and the Danube (Petz and Scheuer 1990). – 1 = mud, fine sand; 2 = sand; 3 = gravelly sand; 4 = gravel; 5 = average depth of ground-water table; 6 = clay

Figure 10a. Generalized sketch of the right bank of the Danube indicating boreholes with floated timber (Scheuer and Schweitzer 1989). – 1 = Paks–Szekszárd depression; 2 = bluff type margin of the depression; 3–4 = sites of the Szekszárd and Paks boreholes

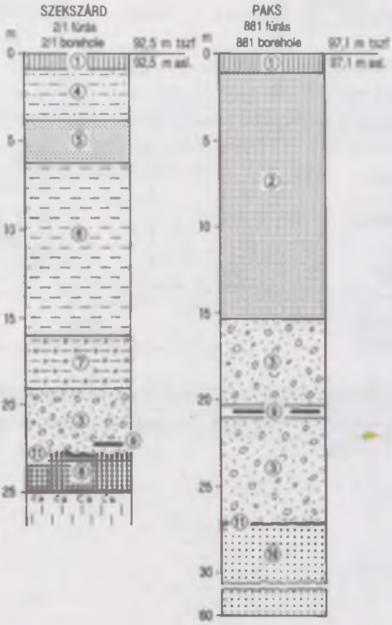


Figure 10b. Stratigraphic profile of boreholes (Scheuer and Schweitzer 1989). – 1 = soil; 2 = sand; 3 = sandy gravel; 4 = sandy mud; 5 = fine grained sand; 6 = mud; 7 = gravelly mud; 8 = red clay; 9 = site with floated timber; 10 = Upper Pannonian sand; 11 = erosional unconformity

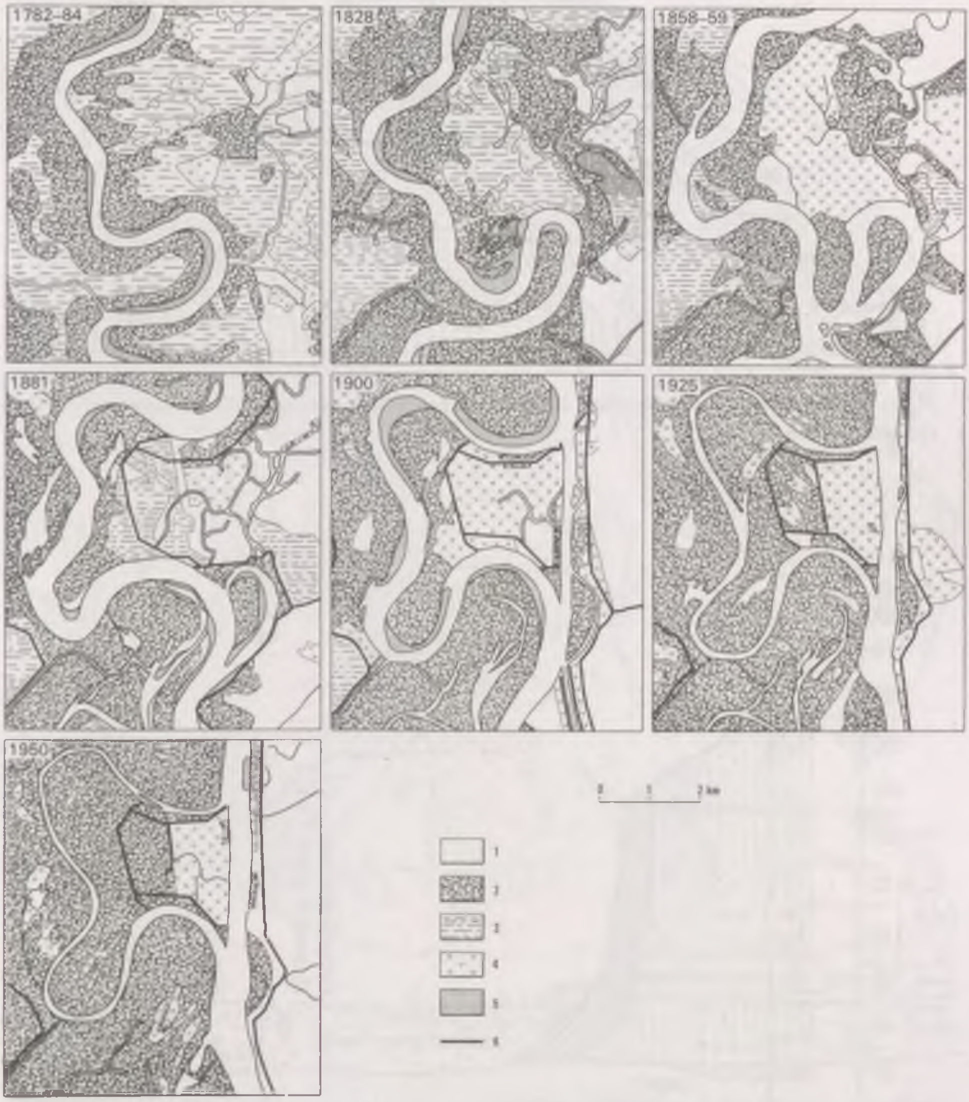


Figure 11. Topographic survey fragments from the past (Somogyi 1974). – 1 = arable land; 2 = forest; 3 = swamp, bog; 4 = waterlogged meadow; 5 = point-bar; 6 = dyke

Figure 12. Block-diagram of the Kiskoros–Dunapataj area with Early and Late Holocene surfaces and ox-bows (Szilárd 1955).

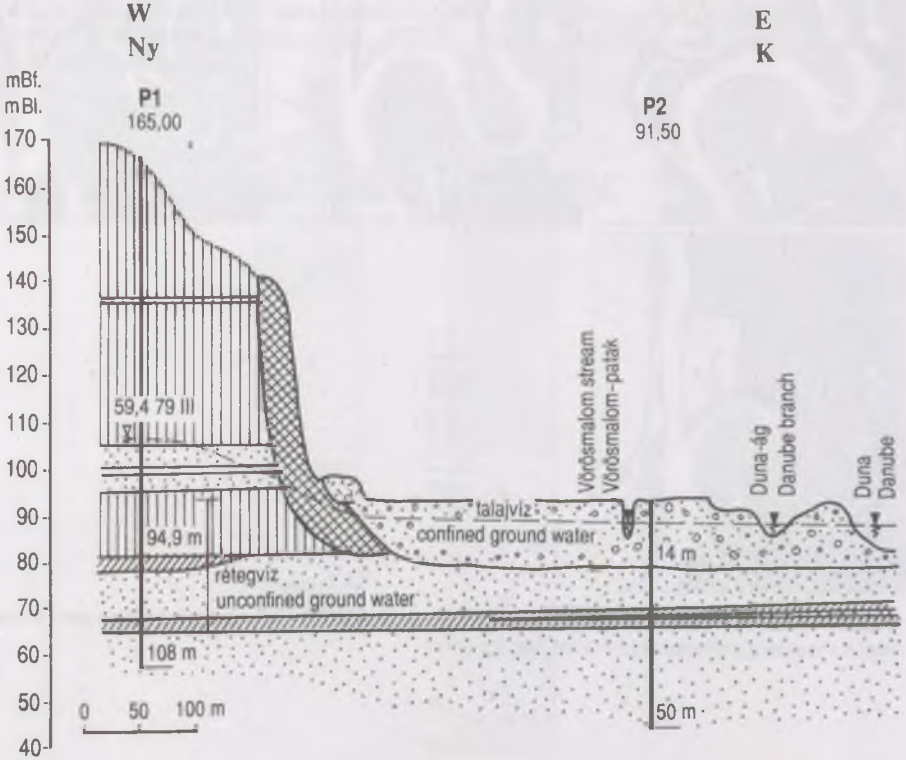


Figure 13. Generalized geological profile south of Dunakomlód (Fodor et al. 1981). – 1 = Pleistocene loess sequence; 1/a = interbedded sand layers; 1/b = intercalated paleosols; 2 = Danube alluvium; 3 = Upper Pannonian sand; 3/a = Upper Pannonian clays; T = unconfined groundwater; R = confined groundwater

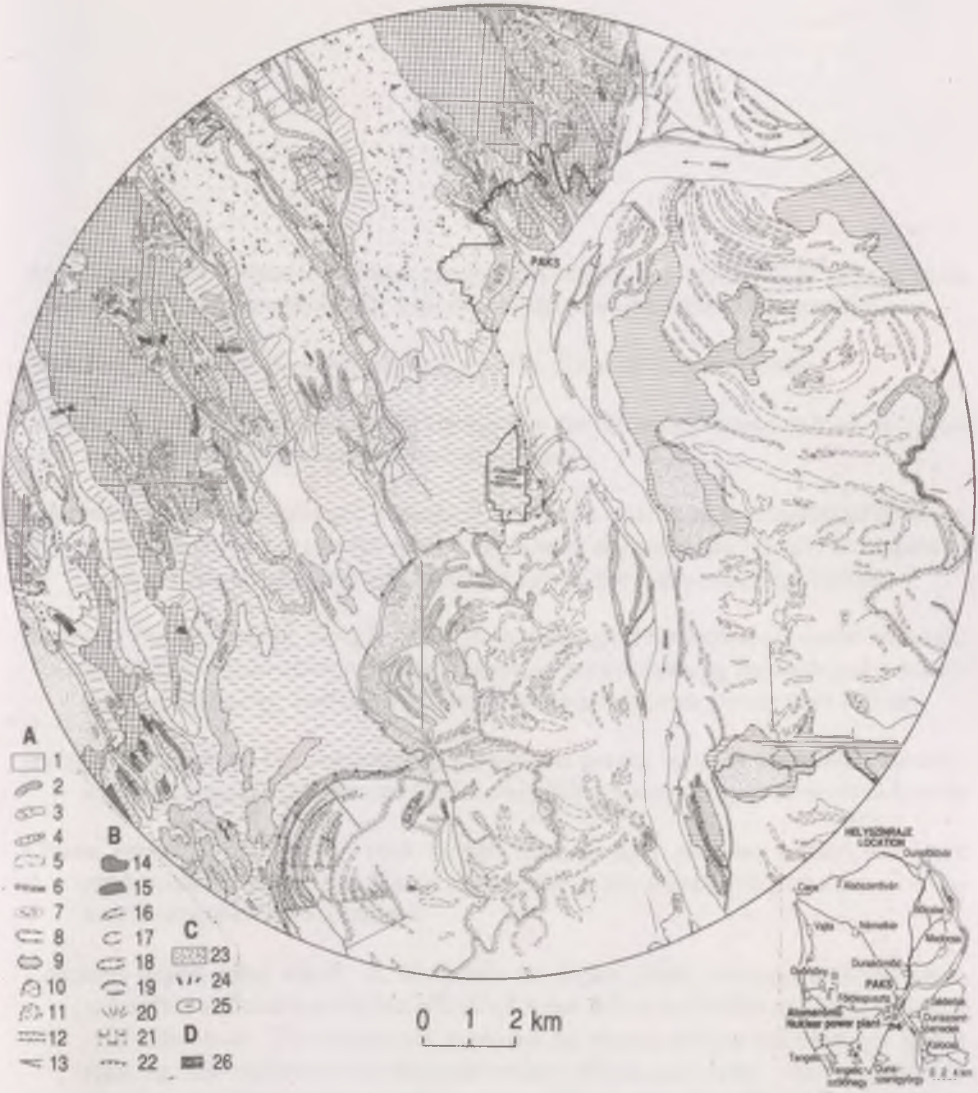


Figure 14. Geomorphological map of the environs of the Paks Nuclear Power Plant (Balogh, et al. 1994) – A = Fluvial erosional and accumulational landforms: 1 = low flood plain level; 2 = former, cut off or abandoned meanders; 3 = former upfilled meanders, intermittently inudated, with water vegetation; 4 = former, cut-off or abandoned meander, in flood-plain forest; 5 = former, upfilled meander, cultivated; 6 = former, upfilled meander, channelized; 7 = alkali flats, frequently covered by water; 8 = high flood plain; 9 = former terrace island on the flood plain; 10 = fluvial terrace; 11 = flat alluvial fan; 12 = broad and flat erosional valley; 13 = gully. B = Landforms of complex genesis; 14 = loess plateau; 15 = low interfluvial ridge; 16 = derasional dry valley; 17 = derasional niche; 18 = erosional-derasional valley; 19 = derasional col; 20 = slope, undistinguished; 21 = slope with stabilized fossil slump; 22 = unstable bluff. D = Landforms of deflation: 23 = sand blanket; 24 = sand forms (longitudinal dunes, blowout, residual ridges); 25 = deflation hollows, D = Man-made landforms: 26 = sunken road

Glossary

Anisotropic Any material in which physical properties (e.g. resistivity or seismic wave velocity) vary quantitatively with the direction in which they are measured.

Anticline A fold that is convex upward with the oldest strata at the centre.

Asthenosphere Partially molten soft layer below the lithosphere which is marked by low seismic velocities and high seismic attenuation.

Basement A well consolidated geological formation which can be considered homogenous with respect to seismic wave transmission and response. Usually a complex of metamorphic or igneous rocks that underlies all the sedimentary formations.

Bedrock The uppermost, strongly consolidated geological formation, above the baserock, which exhibits contrast in mechanical properties to overlying deposits and is homogenous. Generally, bedrock exhibits shear wave velocities greater than 700 m/s.

Bouguer correction The correction of a measured gravity value by an amount theoretically calculated to compensate for the mass of known topography around the station.

Clastic rock A sedimentary rock formed from mineral particles (clasts) that were mechanically transported. Clastic sedimentary rocks include conglomerates, sandstone's siltstones and mudstones.

Common-depth-point stack A composite of traces which correspond to the same subsurface reflection point but which are from different profiles and have different offset distances. The records are corrected for statics and normal moveout before stacking. The objective is to attenuate random effects and events whose dependence on offset is different from normal moveout. Hence multiple reflections which have a different apparent average velocity from primaries, surface waves, refractions, diffractions, etc. will be attenuated relatively to primary reflection events.

Compressional wave, P wave, dilatational wave, longitudinal wave An elastic body wave in which particle motion is in the direction of propagation. The type of seismic wave assumed in conventional seismic exploration.

Conglomerate A sedimentary rock, a significant fraction of which is composed of rounded pebbles and boulders.

Continuous profiling A seismic method in which geophone groups are placed uniformly along the length of the line and shot from holes so spaced that continuous (or 100%) subsurface coverage is obtained.

Contour Line connecting points of equal value, or representing the locus of a constant value of a quantity, on a map or diagram.

Contour interval The difference in value between two adjacent contour lines.

Correlation Identifying a phase of a seismic record as representing the same phase on another record. Indicating that events on two seismic records are reflections from the same stratigraphic sequence, or refractions from the same marker.

Cross section A drawing showing the features that would be exposed by a vertical cut.

Datum plane An artificially established, well-surveyed horizontal plane against which elevations, depth etc. are measured.

db/octave Unit for expressing the slopes of curves in which parameters such as filter curves are plotted vs. frequency.

Deconvolution (1) The process of undoing the effect of another filter. An inverse filter is designed and convolved with the signal, the objective being to remove an objectionable effect of some earlier filter action. **(2)** More specifically, deconvolution may mean:

(a) Dereverberation or designing, removing the filtering action of a water layer
(b) Removing the filtering action of a more complex near-surface
(c) Deghosting
(d) Whitening or equalising all frequency components within a bandpass in order to shorten the reflection pulse length.

Capable fault A fault which has a significant potential for relative displacement at or near the ground surface.

Crust The outermost shell of the earth, varying in thickness from 5 km under the oceans to 60 km under mountain ranges.

Diffraction Scattered energy which emanates from an abrupt irregularity of rock type, particularly common where faults cut reflecting interfaces. The diffracted energy shows greater curvature than a reflection.

Dip-slip fault A fault in which the relative displacement is along the direction of dip of the fault plane, either a normal or a reverse fault.

Discontinuity A boundary within the Earth between zones of different seismic characteristics.

Dome An anticlinal fold structure that plunges radially. The term is also used for any dome-shaped feature or rock formation.

Ductile rock A rock that can withstand 5 to 10 percent strain without fracturing.

Dyke A roughly planar body of intrusive igneous rock that cuts discordantly through the surrounding rocks.

Dynamic range The ratio of maximum recoverable signal (for a given distortion level) to the noise level of the system. The maximum range of standard magnetic tape is about 50 db, of high output tape about 60 db. In digital recording the dynamic range is limited by word length, a 13-bit word represents about 84 db.

Earthquake A series of shocks subdivided into foreshocks, principal shocks, and aftershocks, which generate seismic waves within the earth, as a result of fracturing of brittle rocks within the lithosphere. They result from the accumulation of stresses within the rocks until they are strained to a point beyond which they fracture.

Earthquake behaviour Earthquakes produce random ground motions which are characterised by simultaneous but statistically independent horizontal and vertical components. A moderate earthquake may persist for 15 s to 30 s; a severe earthquake for 61 s to 1200 s. The typical broad band random motion has its maximum energy over a frequency range from 1 Hz to 10 Hz. Usually the vertical component of the ground motion is assumed to be between 67% and 100% of the horizontal below 3,5 Hz and equal to the horizontal above 3,5 Hz.

Elevation correction The correction applied to reflection time values to reduce observations to a common reference datum.

Evaporite Any sedimentary rock formed by precipitation from saline water, e.g. rock salt.

Extrusive rock Igneous rock formed from magma that has flowed out at the Earth's surface as lava. It usually has small crystals or a glassy texture.

Facies (sedimentary) The sum of the lithological and paleontological characteristics of sedimentary strata, with their implications for the environment of deposition.

Fault A fracture in the earth's crust along the plane of which there has been displacement of rock on one side relative to the other, either in horizontal, vertical or oblique sense.

Fault scarp A steep topographic slope caused by faulting.

Flysch Thick sequences of interbedded shales and greywacke sandstones, deposited by turbidity current from rapidly uplifted and eroded mountains.

Filter Part of a system which discriminates against some of the information entering it. The discrimination is usually on the basis of frequency, although other bases such as wavelength or moveout may be used. Filters may be characterised by their impulse response or more usually by their amplitude and phase response as a function of frequency. Filter characteristics are often designated by specifying the frequencies at which their amplitude is down by a given amount, often 3 db (70% or half power), and by the slope of their cut-off.

Fold A flexure in rocks resulting from compressional or gravitational forces.

Fracture A crack (fault or joint) in rocks resulting from deformation.

Free Field Ground Motion The motion which appears at a given point of the ground due to an earthquake when vibratory characteristics are not affected by structures and facilities.

Graben A generally elongated block of rock that has been downthrown between two parallel faults relative to the surrounding area.

Ground Motion Intensity A general expression characterising the level of ground motion at a given point. It may refer to acceleration, velocity, displacement, macroseismic intensity or spectral intensity.

Ground Response The behaviour of a rock or soil column at a site under a given ground motion load.

Holocene The present epoch, covering ca the last 10,000 years of geological time from the end of the Pleistocene.

Horst An elongate body of rock between parallel normal fault, uplifted relative to surrounding rock.

Hydrophone pressure detector A detector sensitive to variations in pressure, as opposed to a geophone which is sensitive to motion. Used when the detector can be placed below a few feet of water as in marine or marsh work or as a well seismometer. The frequency response of the hydrophone plant depends on its depth beneath the surface because of a standing wave pattern subject to the boundary condition that pressure be zero at the surface and a maximum at a quarter wave length.

Igneous Denoting rocks formed by solidification from a molten state, either intrusively below the Earth's surface or extrusively as lava or pyroclastic segments.

Intensity A set of numerical indices describing the physical effects of an earthquake on man, or structures built by man, and on the Earth's surface. The indices are based on subjective judgements, not instrumental records (continuation see over).

Intensity scale by Medvedev, Sponheuer and Kárnik (MSK) version, 1964

Classification of the scale

Types of structures (buildings not antiseismic)

A: Buildings in field-stone, rural structures, adobe houses, clay houses.

B: Ordinary brick buildings, buildings of large block and prefabricated type, half-timbered structures, buildings in natural hewn stone.

C: Reinforced buildings, well-built wooden structures.

Definition of quantity

Single, a few: about 5%

Many: about 50%

Most: about 75%

Classification of damage to buildings

Grade 1: Slight damage. Minor cracks in plaster, fall of small pieces of plaster.

Grade 2: Moderate damage. Small cracks in walls; fall of fairly large pieces of plaster; tiles slip off; cracks in chimneys; parts of chimneys fall down.

Grade 3: Heavy damage. Large and deep cracks in walls; fall of chimneys.

Grade 4: Destruction gaps in walls; parts of buildings may collapse: separate parts of the building lose their cohesion; inner walls and filled-in walls of the frame collapse.

Grade 5: Total damage. Total collapse of buildings.

Intensity grades from I. (not noticeable) to XII. (catastrophe)

Description of three grades often occurring in the present volume:

VII. Damage to buildings

In many buildings of type C damage of grade 1 is caused; in many buildings of type B damage is of grade 2. Many buildings of type A suffer damage of grade 3, a few of grade 4. In single instances landslide of roadway on steep slopes; cracks in roads; seams of pipelines damaged; cracks in stone walls.

VIII. Destruction of buildings

Many buildings of type C suffer damage of grade 2; a few of grade 3. Many buildings of type B suffer damage of grade 3; a few of grade 4. Many buildings of type A suffer damage of grade 4; a few of grade 5. Occasional breakage of pipe seams. Memorial and monuments move and twist. Tombstones overturn. Stone walls collapse.

IX. General damage to buildings

Many buildings of type C suffer damage of grade 3; a few of grade 4. Many buildings of type B show damage of grade 4; a few of grade 5. Many buildings of type A suffer damage of grade 5. Considerable damage to reservoirs; underground pipes partly broken. In individual cases railway lines are bent and roadways damaged.

IAEA International Atomic Energy Authority.

Interval velocity Seismic wave velocity measured over a depth interval. Usually refers to compressional velocity and usually implies measurements across the bedding.

Intrusive rock Igneous rock formed from magma that has forced its way among pre-existing rocks. Types of igneous intrusions include batholiths, dykes, sills etc. Crystals are large relative to extrusive rocks.

Isoseismal line A line on a map joining points on the earth's surface of equal earthquake intensity.

Isoseismal map A contour map showing geographic areas that experienced the same level of intensity during an earthquake.

Isostasy A condition of equilibrium in the Earth's crust. Since the lighter continental masses flout on a denser medium, changes in elevation must be compensated in some way at depth.

Karstic phenomena Formation of sinks or caverns in soluble rocks by the action of water.

Lignite A brown coal with a high moisture content, representing a low grade of coalification.

Limestone A sedimentary rock formed principally of calcium carbonate, usually as calcite.

Lineament An extensive linear topographic feature which may reflect the trend of some underlying structure, often detectable only from aerial photography or satellite imagery

Lithification The formation of solid rock from louse sediments by compaction, cementation and diagenesis.

Lithosphere The outer rigid shell of the Earth situated above the asthenosphere and containing the crust (both oceanic and continental) and the upper rigid part of the mantle (the lithospheric mantle).

Liquefaction Sudden loss of shear strength and rigidity of saturated, cohesionless soils, due to vibratory ground motion.

Love wave A type of seismic wave travelling along the ground surface, in which particles move in a horizontal direction at right angles to the direction of propagation.

Macroseismicity Seismicity of a level such that it implies significant, coherent, sustained tectonic activity.

Magnetic field strength H = magnetic field intensity: the force exerted on a unit pole at any point is numerically equal to the field strength at that point.

Magnetic permeability The ratio of the magnetic induction, B, to the inducing field strength, H.

Magnetic susceptibility A measure of the degree to which a substance may be magnetised, the ratio of the intensity of magnetisation to the magnetic field (H) that is responsible for it.

Magnetisation A vector quantity, in a body, defined by the magnetic moment per unit volume.

Magnitude A numerical quantity derived from instrumental records that is characteristic of the energy released by an earthquake.

Microearthquakes and Macroearthquakes Microearthquakes have magnitudes less than 3,0, whereas macroearthquakes have magnitudes to or greater than 3.

Microtremor An ambient ground vibration with extremely small amplitude (of a few micrometers). This vibration can be produced by natural and/or artificial causes such as wind, sea waves and traffic disturbances. Microtremors are sometimes called microseisms.

Migrate To plot dipping reflections in their true spatial positions rather than directly beneath the point midway between the shotpoint and centre of the geophone spread. Usually limited to the plane of the section, though properly three-dimensional positions should be (and sometimes are) considered.

Milligal mgal = 10^{-6} cm/sec^2. A unit of gravitational acceleration.

Moho Mohorovičić discontinuity: Seismic discontinuity which separates the earth's crust and mantle. Situated an average of about 30 km below the continents and about 10 km below the oceans. Characterised by an increase of P-wave velocity to about 8 km/sec.

Multiple Seismic energy which has been reflected more than once.

Mute To change the relative contribution of the components of a record stack with record time. In the early part of the record the long offset traces may be muted or excluded from the stack because they are dominated by refraction arrivals or because their frequency content after NMO correction is appreciably lower than other traces. The transition where they begin to contribute may be either abrupt or gradual. Any channels may be muted for certain portions, to keep ground roll or noise bursts out of the stack.

Neotectonics Tectonics related to the most recent movements of faults. For seismic regions, the tectonics of the Quaternary area.

NPP Nuclear Power Plant.

PGA Peak Ground Acceleration.

Noise Any undesired signal: a disturbance which does not represent any part of a message from a specified source. Seismic energy which is not resolvable as reflections. In this sense noise includes microseism, shot-generated noise, tape-modulation noise, harmonic distortions, etc. Sometimes divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is noncoherent). To the extent that noise is random, it can be attenuated by a factor of n by compositing n signals from independent measurements. Disturbances in observed data due to more or less random inhomogeneities in surface and near-surface material.

Normal moveout The variation of reflection arrival time because of variation in the shotpoint to geophone distance (offset) which causes an increase of the length of the reflection travel path.

Nuclear precession magnetometer Magnetometer, utilising nuclear resonance; the resonance frequency is proportional to the absolute magnetic field strength.

Offset The distance from the shot point to the nearest geophone group centre. Often resolved into components: perpendicular offset, the distance at right angles to the spread line, and in-line offset, the distance from the projection of the shot point onto the line of the spread. Sometimes the distance between shot point and the centre of any geophone group, or the distance between shot point and any geophone.

Paleomagnetism Study of natural remanent magnetisation in order to determine the intensity and direction of the earth's field at the time the materials were magnetised.

Pattern An array of shotholes or geophones. Shot arrays are used to cancel noise waves or to distribute the charge for improving shot efficiency. Geophone patterns are used to cancel unwanted noise trains and random noise. The array characteristics are often illustrated by a directivity pattern diagram.

Pleistocene The earlier epoch of the Quaternary, extending from the end of the Pliocene, about 2.4 million years ago until the beginning of the Holocene

Predictive deconvolution Use of information from the earlier part of a seismic trace to predict and deconvolve the latter part of that trace; as opposed to deconvolution based on the characteristics (such as frequency spectrum) of the same portion of the trace.

Primary Energy which has been reflected only once and hence is not a multiple.

Profile (1) The series of measurements made from a shot point location into a recording spread. Additional shots from the same general shot point location into the same spread are part of the same profile even though different shot holes may be used. However, if the same spread is shot into from a different shot point location it is a different-profile, or if the same shot point is shot into a different spread it is also a different profile. **(2)** A refraction profile also denotes the collection of individual profiles (as defined in (1) above) shot from the same shot point. Use of the term for both the component profiles and for the aggregate sometimes produces confusion. "Refraction set" is also used for the aggregate. **(3)** A drawing showing a vertical section of the ground along a line. **(4)** A graph of a measured quantity against horizontal distance, as in a gravity profile.

PSHA Probabilistic Seismic Hazard Assessment.

P wave compressional wave or longitudinal wave.

Quaternary Epoch of the Cenozoic era, covering ca 2 million years of geological time from the end of the Pliocene (Tertiary) to the beginning of the Holocene.

Rayleigh wave = R wave A type of seismic wave propagated along the surface. Particle motion is elliptical and retrograde in the vertical plane containing the direction of propagation and its amplitude decreases exponentially with depth.

Reflection The energy or wave from a shot or other seismic source which has been reflected (returned) from an elastic impedance contrast or series of contrasts within the earth.

Reflection coefficient The ratio of the amplitude of a reflected wave to that of the incident wave. For normal incidence on an interface which separates media of densities 1 and 2 and velocities V1 and V2, the reflection coefficient for plane wave is: In the more general case the plane wave reflection coefficient may be found by solving Knott's equations. A negative reflection coefficient indicates phase inversion. The ratio of the reflected energy to the incident energy is the reflection coefficient squared.Refraction wave Waves which travel from a point source obliquely downward to and along a relatively high velocity formation or marker and thence obliquely upward. Snell's law is obeyed throughout the trajectory. Angles of incidence and of emergence at the marker are critical angles. Typically, refracted waves following successively deeper markers appear as first arrivals with increasing range (shot to detector distance). Refracted waves following different markers may occur at different arrival times for any given range. Such waves cannot arise for angles of incidence less than the critical angle for any given marker. At the critical angle, the refracted wave path (and its travel time) coincides with that of a wide angle reflection.

Refractor = refraction marker: A relatively high velocity extensive layer, underlying lower velocity layers, which transmits a refraction wave nearly horizontally.

Region A geographical area, surrounding and including the Site, sufficiently large to contain all the features related to a phenomenon or to the effects of a particular event.

Response Spectrum A plot of the maximum response of a family of oscillators, each having a single degree of freedom with fixed damping, as a function of natural frequencies of the oscillators when subjected to the acceleration of the ground movement caused by the earthquake or other vibratory motion input at their supports. (It may be noted that a response spectrum is not a spectrum in its real meaning).

Reverberation Multiple reflection in a layer, usually the water layer in marine work; singing. Sometimes distinction is made between the case where water is so deep that the successive multiples are discrete and the case where they blend together into a more or less steady oscillation. Reverberations sometimes occur on land records also but are most commonly encountered in marine shooting.

River terrace A near-horizontal benchlike feature or a valley side, representing part of the valley floor before father down-cutting by the river.

Schlumberger electrode array Electrode arrangement used in resistivity surveying, consisting of four colinear electrodes, with the outer two serving as current sources and the inner two, which are closely spaced at the midpoint of the outer pair, serving as measuring points.

Sediment consolidated particles of minerals (clastic, organic or chemically precipitated) deposited usually in water and forming sedimentary rocks in lithification.

Sedimentary rock The group of rocks formed from the lithification of deposited particles of pre-existing rocks (elastic sediments), organic remains or chemical precipitates.

Seismic waves Elastic waves that are propagated through a medium by elastic deformation. Waves generated by an explosion or earthquakes within the earth or on its surface. There are four main types of seismic wave: primary waves, secondary waves, Rayleigh waves, and Love waves.

Seismic wave attenuation A decrease in the amplitude of seismic waves during transmission from the earthquake source to a site.

Seismogenic structure Structures that display earthquake activity, or that manifest historical surface rupture, or effects of palaeosesmicity, Seismogenic structures are those considered likely to generate macroearthquakes within a period of concern.

Seismotectonic province A geographic area characterised by similarity of geological structure and seismicity.

Shale A laminated fine-grained sedimentary rock composed mainly of clay minerals.

Shear wave = S wave = transverse wave: a body wave in which the particle motion is perpendicular to the direction of propagation.

Short-path multiples A multiple reflection in which energy is reflected back and forth over a small portion of the section, commonly the weathered zone or a water layer. Short-path multiples tend to blend with the primary pulse, extending it.

Signal-to-noise ratio = S/N: The energy of a desired event divided by all remaining energy (noise) at that time. Sometimes the energy of the desired event is measured with respect to the total energy at that time, S/(S + N). Difficult to determine in practice because of the difficulty in separating out the signal constituting the desired events. One must presuppose some characteristic of the signal to effect the separation.

Silt A fine-grained sediment, of particle size 1/16-1/256 , i.e. between the clay and sand grades.

Siltstone A clastic sedimentary rock formed from lithified silt grade sediments.

Simple multiple A long path multiple which has undergone only three reflections (that is, twice reflected from deep interfaces and once from the shallow interface at the base of the weathering or at the surface.)

Site The area containing the plant, defined by a boundary and under effective control of the plant management.

Site area The immediate area of the site on which the structures of the nuclear power plant are situated, and for which detailed field and laboratory geotechnical investigation are required.

Siting The process of selecting a suitable site for nuclear power plant, including appropriate assessment and definition of the related design bases.

Sparker A seismic source in which an electrical discharge in water is the energy source.

Spherical divergence The decrease in wave strength (energy per unit area of wavefront) with distance as a result of geometric spreading. For a spherical wave traveling through the body of a medium away from a point source, varies inversely as the square of the distance the wave has traveled. For energy which travels along a surface the analogous term is cylindrical divergence, which varies inversely as the distance.

Spread The layout of geophone groups from which data from single shot are recorded simultaneously.

SSE Safe Shutdown Earthquake.

Stacking Composite or sum of seismic traces which correspond to the same reference point or middle point but which are from different profiles and have different offset distances. The records are corrected for statics and normal moveout before stacking. The objective is to attenuate random noise, multiple reflections, surface waves, refractions, diffractions, etc. relatively to primary reflection events.

Static corrections Time shift needed because of the irregularity of the surface. They compensate elevation variation, low velocity or weathering layer variation and distance from the datum level. After static corrections one can assume that the source and all the geophones are on a level datum surface. Called "static" because the amount of shift is the same for all points on any given trace.

Strain The deformation of a body of rock as a result of stress and expressed as the ratio of the change or volume to the original volume.

Stratigraphy The study of the sequence and correlation of stratified rocks, comprising the description and naming of rocks (lithostratigraphy), their relative dating by means of fossils (biostratigraphy), and the definition of geological time (chronostratigraphy).

Streamer A marine cable incorporating pressure hydrophones internally as an integral part, designed for continuous towing through the water.

Stress A force (tensional, compressional or sheer) exerted on a body and producing a corresponding deformation (strain).

Strike The direction along a rock stratum at right angles to the true dip.

Strike-slip movement Purely horizontal relative displacement.

Subsidence The settlement or sinking of surficial geological materials on a regional or local scale.

Surface faulting The permanent offset or tearing of the ground surface by differential movement across a fault during an earthquake.

Surface waves Energy which travels along or near the surface; ground roll. . Includes Rayleigh, Love, hydrodynamic, Stoneley waves, etc.

TAR (true amplitude recovery) A process for removing the effects of variable gain in the field recording the effects of spherical divergence, and other time-dependent energy decay.

Tear fault (wrench fault, transcurrent fault) A fault in which the movement is horizontal, i.e. along the strike of the fault. This results from stress configuration in which the maximum and minimum principal stresses are horizontal, whereas the intermediate principal stresses is vertical.

Tectonics A branch of geology dealing with the broad architecture of the upper part of the Earth's crust in terms of the origin and historical evolution of regional structural or deformation features.

Tectonic map A map showing major structural features produced by uplift, downwarp, or faulting, with the more significant lineations associated with such features. The term is usually applied to maps covering large areas while maps of smaller areas showing the same features are called structural maps.

Telluric method Use of voltage gradients developed in the earth by naturally flowing electrical currents to study variations in earth resistivity.

Thrust fault A low-angle reverse fault.

Trace equalisation Adjusting a seismic channel so that the amplitudes of adjacent traces are, comparable in the sense of having the same RMS value over some specified interval.

Transfer function Filter characteristics in the frequency domain as represented by the amplitude vs. frequency and phase angle vs. frequency curves. Contains the same information as the impulse response in the time domain and convertible into the impulse response through the Fourier transform.

Trough An elongate depression in the Earth's surface which may also be a sedimentary basin.

Tufa Calcium carbonate deposited from solution in water, e.g. stalactites and stalagmites found in caves and travertine found around not springs.

Tuff A rock composed of consolidated volcanic ash.

UHRS Uniform Hazard Response Spectra.

Unconformity A planar or irregular surface separating groups of rocks of different ages, the older of which have beer folded and eroded, the younger being laid down on the erosion surface. An unconformity thus represents a considerable time interval.

Uphole shooting The successive detonation of a series of charges at varying depths in a shot-hole in order to determine the velocities of the near surface formation and (sometimes) the variations of record quality with shot depth. Used to establish weathering thickness.

Vibroseis A seismic method in which a hydraulic vibrator is used as an energy source to generate a wave train of controlled frequencies.

Wavelength The distance between successive similar points on two wave cycles measured perpendicularly to the crest, where v = wave velocity, f = frequency and k = wave number. Wavenumber = k: The number of wave cycles per unit distance; reciprocal of wavelength. Weathering = low velocity layer = LVL: A zone of low velocity material near the surface at the base of which the velocity abruptly increases. The seismic weathering is usually different from the geological weathering so that the term LVL is preferable. Frequently the base of the weathering is the water table. Sometimes the weathering velocity is gradational; sometimes it is fairly sharply layered. Weathering velocities are typically 450 to 750 sec (after 150 to 50 sec for the first few feet) compared to subweathering velocities of 1500 sec or greater.

Weathering corrections A correction of seismic reflection or refraction times to remove the delay in the LVL. The simplest correction is based on uphole times from shots in the subweathering layer.

Closing remarks

The only nuclear power plant in Hungary is the Paks Nuclear Power Plant. The four blocks of type VVER-44V-213 were put into operation between 1982 and 1987. Thus the first block already reached about half of its life-time. Therefore it became necessary to maintain the technical standards and conditions according to the requirements of the 1990's and to introduce changes warranted by the international development of nuclear technology. The Paks NPP generates nearly half of the national electricity demand and it makes vital the safe and continuous availability of its capacity. These facts justify the application of all possible measures to increase nuclear safety.

An analytical work called AGNES (Advanced General and New Evaluation of the Safety of Hungary's nuclear power plant) started in 1991 and lasted several years. Its aim was to repeat all systems analyses both for breakdown and accident situations and to apply modern ones introduced in the international practice since the planning of the Paks NPP such as the PSA (probability safety assessment) methods. The program was concluded in the late summer of 1994 and it proved that the operation of the nuclear plant is satisfactory even by the standard of the most sophisticated analyses. At the same time it pointed out those areas where safety should further be increased and set up a priority of measures to be taken. Based on the above assessment a continuous modernization of the power plant is being implemented. The staff of the power plant has relied on the control of the International Atomic Energy Agency (IAEA) and World Association of Nuclear Operators (WANO). The above organizations inspected the NPP six times in recent years, which also considerably contributed to the maintenance and advancement of nuclear safety.

One aspect of safety enhancement is the re-evaluation of seismic hazard which is the subject of the present collection of review articles. The most important geological facts are shortly summarized from the regional scale progressively down to the site area.

The Pannonian Basin is bounded to the west by the Eastern Alps, from the north to the south by the Carpathian Mountains, and to the southwest by the Dinarides. The tectonics of the region are complex with the African Plate subducting under the Dinaride Mountains and colliding with the Eurasian Plate at the Alps, while the basin is an area of thinning and extension with the Eurasian Plate subducting under the basin along the line of Carpathians. From about 60 million years ago the Pannonian Basin expanded to the east and reached its present size about 12 million years ago.

The earthquake data show that the Dinarides are relatively active, reflecting the collision and subduction in this area but only one small part of the Carpathian subduction zone is still active. This is the Vrancea area at the southeastern end of the Basin about 500km to the east of the NPP. Another concentration of seismic activity is seen on the SW-NE trending Mur-Murz line about 300km to the northwest of the NPP.

On the near regional scale, which comprises the great Hungarian Plane to the east of the NPP the Transdanubian hills to the west and the Transdanubian Central Range to the northwest, seismic reflection lines and deep boreholes show that the area is underlain by pre-Miocene rocks which show discontinuities and fault zones having a WSW-ENE trend across the basin. Major features include the Balaton and Kapos lines and the Szolnok Flysch Zone. It is believed that these strike-slip features are associated with the extension of the basin prior to 12 million years ago. The basement rocks are generally covered by Neogene sediments which can attain thickness up to 6 km. The Neogene consists of an early to middle Miocene (23 to 12 million years old) heavily faulted and folded sedimentary and volcanic basement fill and the subsequent less than 12 million years old Pannonian deposits. Quaternary deposits (younger than 2.4 million years) cover large areas in Hungary. In many areas these comprise wind blown sand and silts and form Loess deposits. In the Danube flood plane the river cut a wide pass through the Loess and deposited alluvial material. Assuming constant sedimentation it can be shown that the net subsidence rate in Southeast Hungary has decreased from about 0,5 mm/year at the beginning of the Pannonian to about 0,1mm/year during the Quaternary.

The distribution of earthquake within Hungary is relatively uniform and seismic activity is lower than that outside of the country. Most earthquakes occur between depths of 10 km to 14 km and many occur between 5 km and 9 km. Attenuation of ground motion with distance is somewhat greater than in other areas of the world with low to moderate seismicity.

In the site vicinity the Pannonian deposits are about 700 m thick and they are generally overlain by Quaternary material. The quaternary immediately under the NPP is a river terrace deposit that is about 30 m thick and is at least 45,000 years old. In places it is overlain by recent aeolian sands and silts. Within the current flood plane to the southwest and east of the NPP the surface material is recent (Holocene) and to the west is older quaternary loess which at depth may be up to 1 million years old.

Deep seismic reflection surveys show many faults within the Pannonian deposits. The data suggest the faulting generally follows the WSW-ENE direction and some faulting in the SW-NE direction. One such fault zone appears to pass directly beneath the NPP. Many of the faults seem to extend up to the shallowest level. But the technique can discern only about 100 meter below ground level. In the 30 km radius from the NPP only 10 earthquakes have been observed in the last several hundred years, all with magnitudes less than 3,5.

Shallow seismic measurements have also been carried out both on land and along the Danube and these confirm the presence of faulting in the upper Pannonian deposits. None of these sections, however, indicate any fault passing into the overlying quaternary. Where data are available the quaternary is shown not to be faulted.

Conclusions of the detailed geological, seismological, geophysical and geomorphologic studies can be summarized as follows:

– the presence of a capable fault can be ruled out with high probability,

– the power plant meets stability standards against OBE (operation basis earthquake i.e. the maximum predictable quake of 100 year recurrence period with the internationally accepted probability of occurrence),

– the vulnerable part of the power plant can be reinforced to meet stability standards against SSE (safe shutdown earthquake i.e. the maximum predictable earthquake of 10 000 year recurrence period with the internationally accepted probability of occurrence),

– a seismological monitoring system has been established and it is recording continuously. Detailed statistics of minor tremors will greatly help in improving the accuracy of the determination of both OBE and SSE.

Editors