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international atomic energy agency

the **abdus salam** international centre for theoretical physics

H4.SMR/1519-6

"Seventh Workshop on Non-Linear Dynamics and Earthquake Prediction"

29 September - 11 October 2003

Case Histories: Seismic Hazard Assessment

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International Atomic Energy Agency

Case Histories: Seismic Hazard Assessment

Aybars Gürpinar, Section Head, ESS
IAEA

Paks NPP

Paks NPP is located in Hungary on the Danube about 100 kms south of Budapest. There are four WWER 440/213 units in operation. The original design did not include seismic loads.

A 'preliminary' seismic hazard study was performed in 1992 by an international consulting company that recommended a ZPA value of 0.35g associated with a site specific RS. This study was commissioned by the plant.

Paks NPP (Cont'd)

The Hungarian regulatory body commissioned a review of this study by a national committee headed by a professor of geology from the Hungarian Academy of Sciences. This committee confirmed that the hazard values proposed by the international consultant company were appropriate for the Paks NPP site.

The Hungarian regulatory body asked the IAEA to review the seismic hazard in 1993.

Paks NPP (Cont'd)

The same international company was recruited to perform the study in detail and with much more new local data. The new data included:

- MEQ monitoring
- Geophysical profiles including across the Danube
- Site vicinity geological mapping
- Large number of boreholes
- Trenches

Paks NPP (Cont'd)

The aim of these investigations was to clarify the uncertainties related to the potential of faulting in the near region and the site vicinity.

After these investigations a PHSA was performed in which a number of alternative seismotectonic models were considered with different weights.

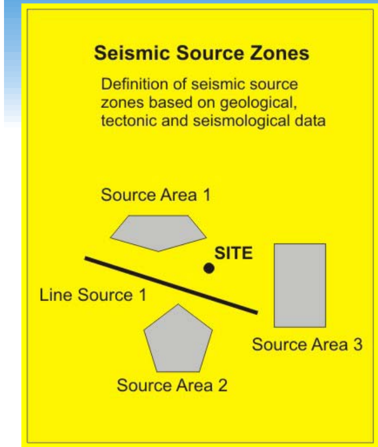
The IAEA monitored all the investigations and reviewed the final PSHA and agreed with the final results (the 10^{-4}/yr value of the ZPA was 0.25g).

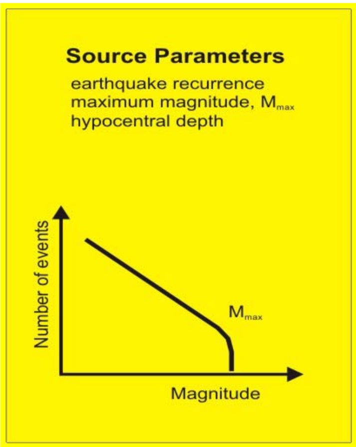
Paks NPP (Cont'd)

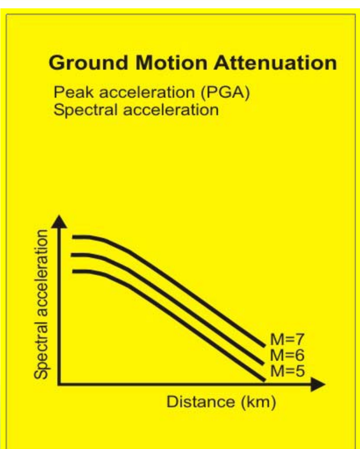
More recently an extended PHSA was performed for the external events Probabilistic safety Assessment of the Plant using the same seismotectonic models. The following slides are from this study. The study was commissioned by the Paks NPP and conducted by Mr. L. Toth (Seismological Institute in Budapest).

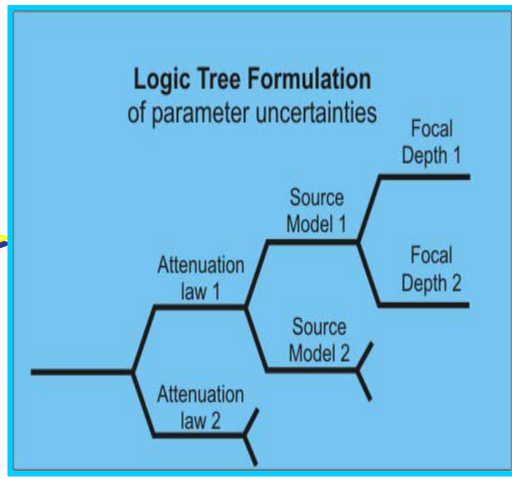
Systematic process

five steps are involved in the assessment of seismic hazard

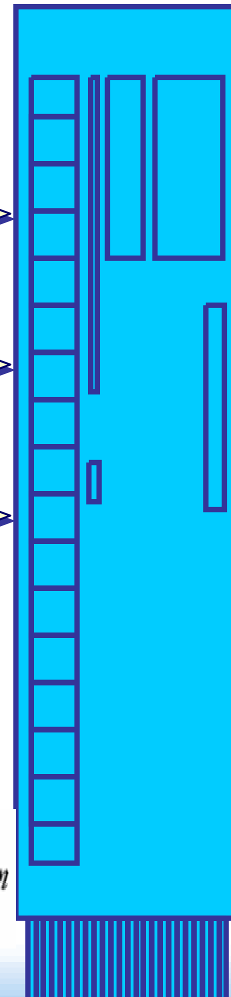


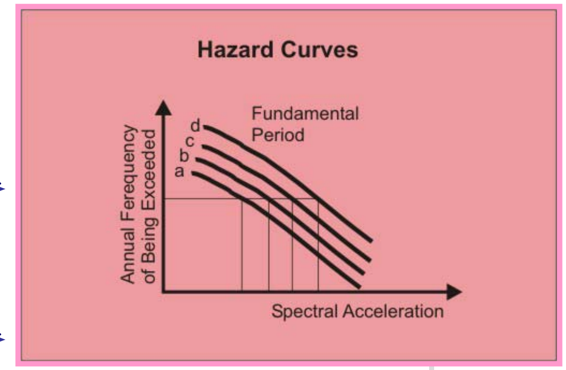


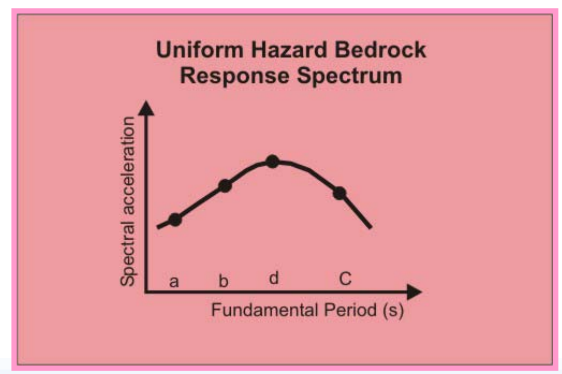




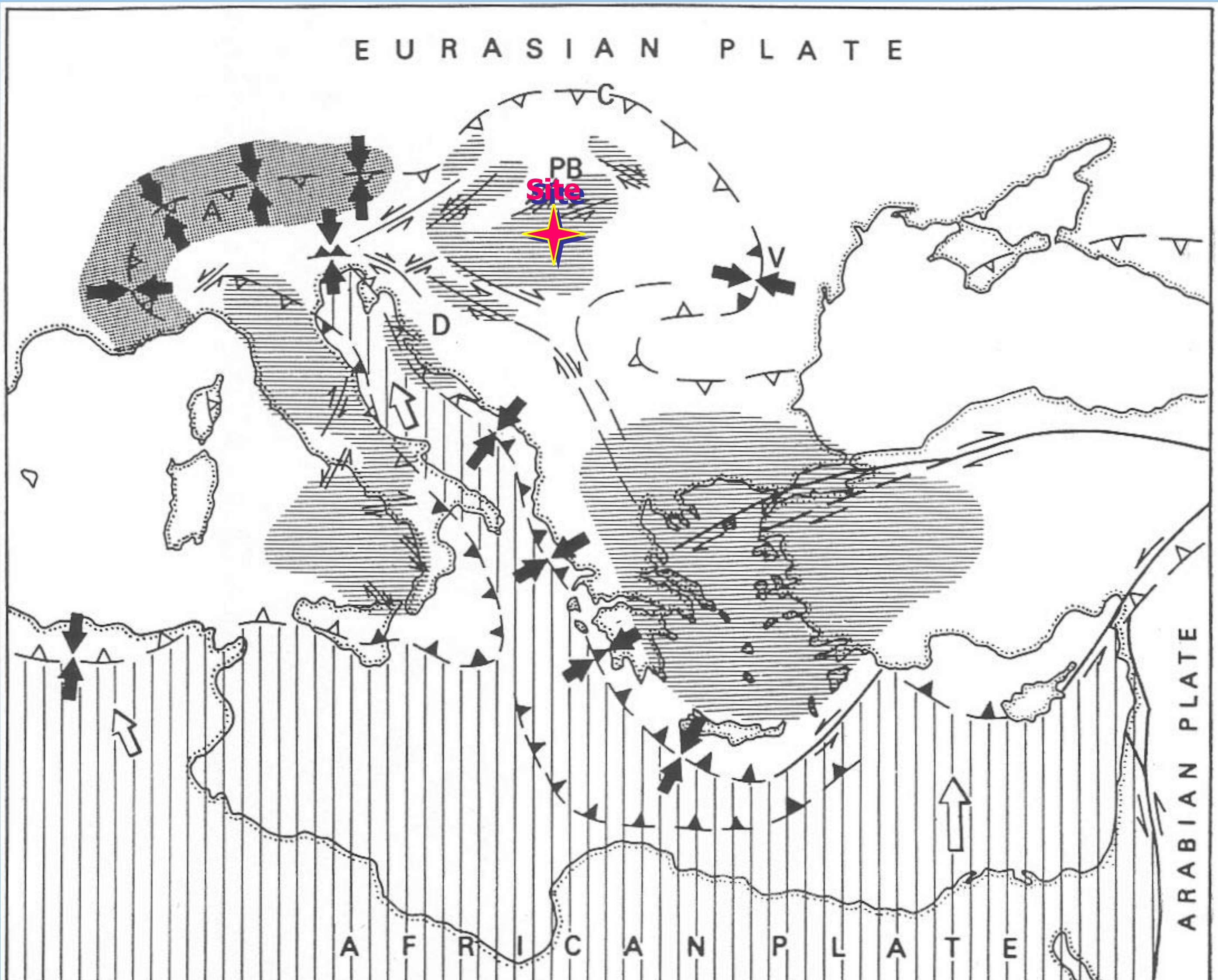
$$\nu(z) = \sum_{n=1}^{N} a_n(m^0) \int_{m=m^0}^{m^u} \int_{r=0}^{\infty} f_n(m)\, f_n(r|m)\, P(Z > z|m,r)\, dr\, dm$$



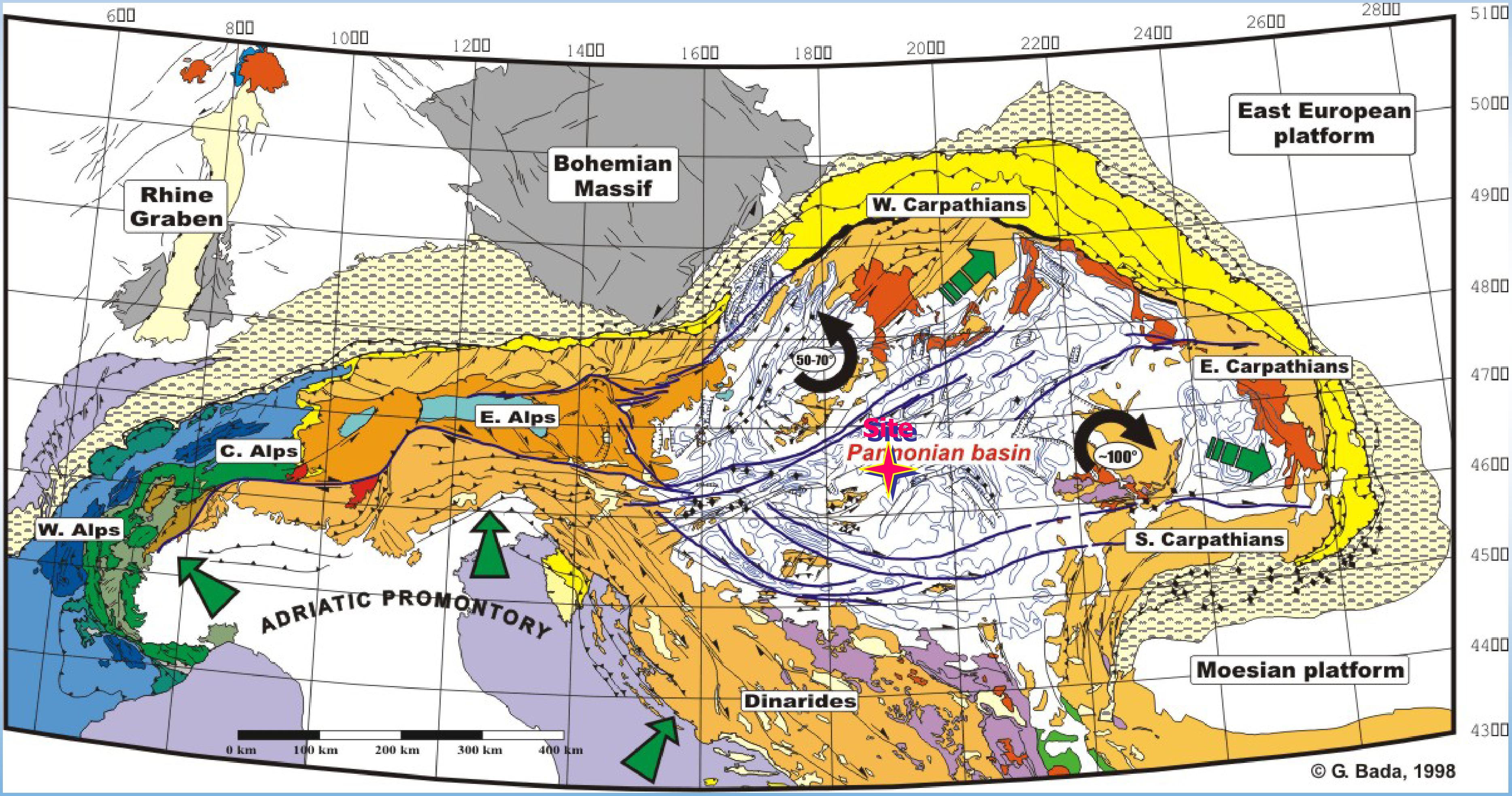




Tectonic features of the Alpine-Mediterranean region

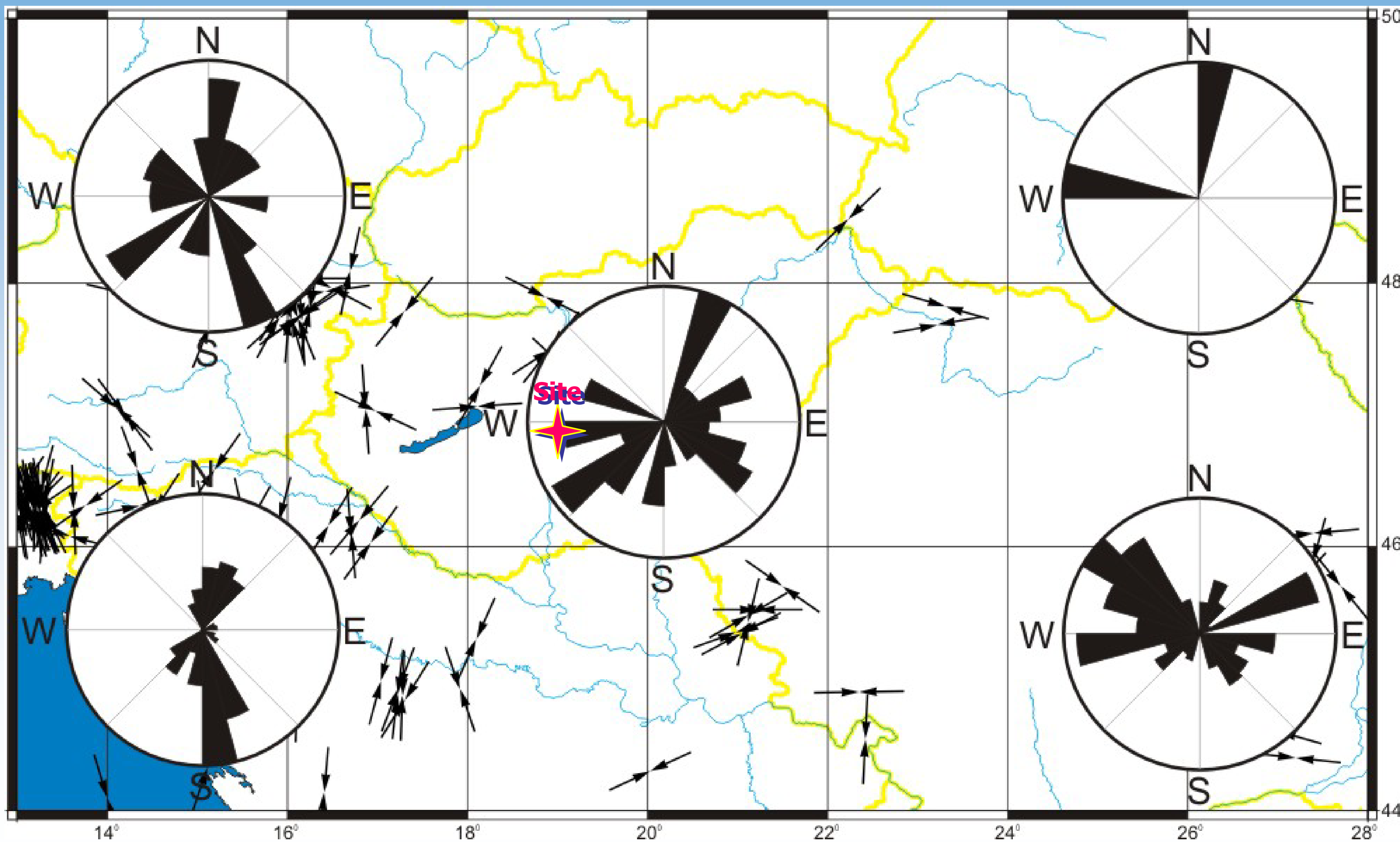


Tectonic map
of the Alpine-Carpathian-Pannonian system

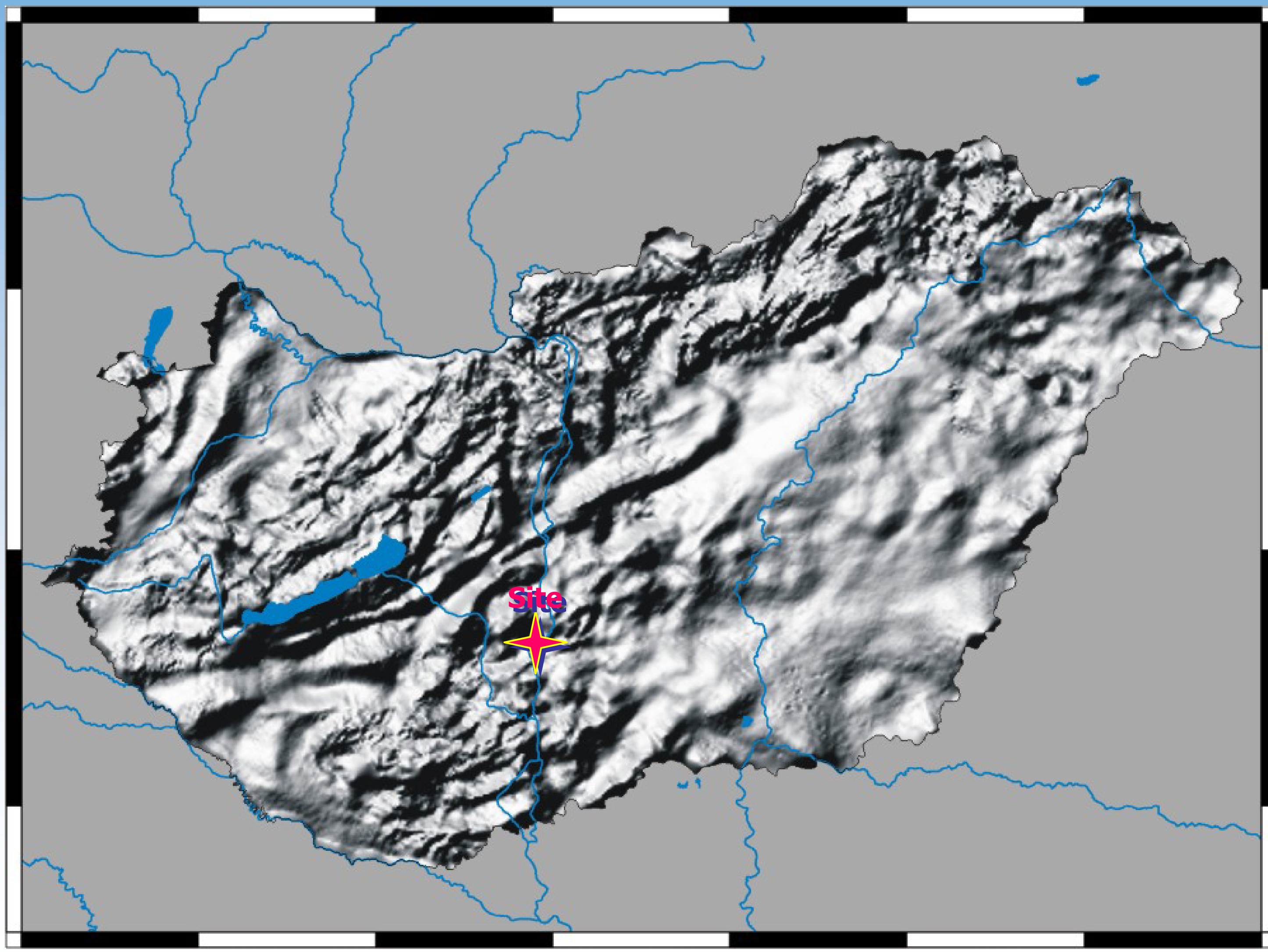


Regional investigations

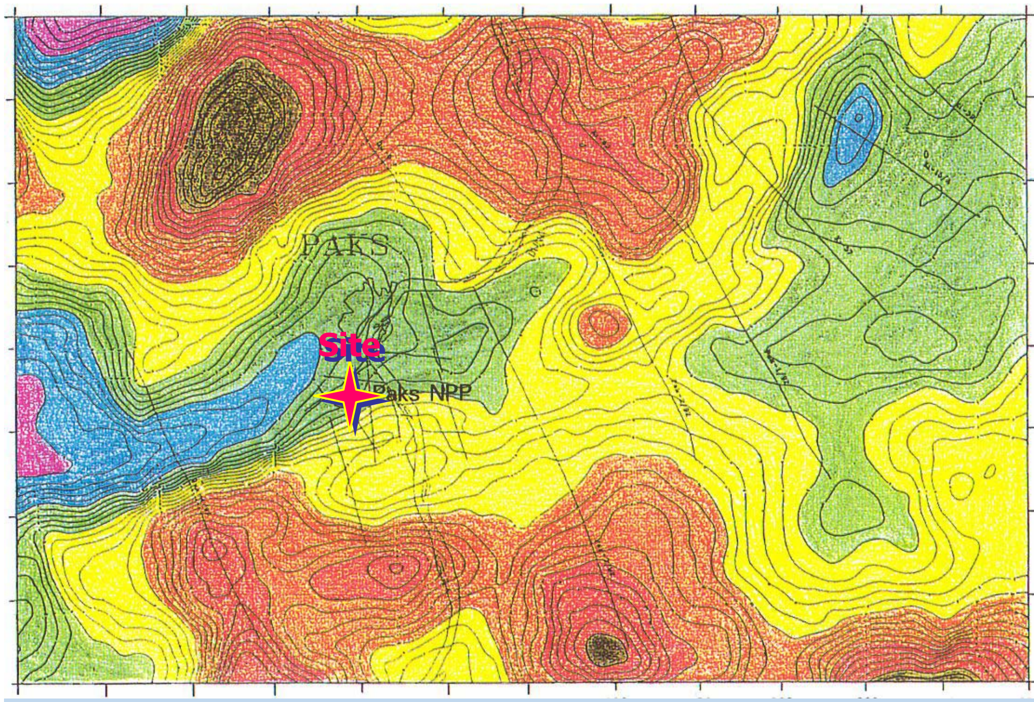
Stress directions
in the Alpine-Carpathian-Pannonian system



Bouguer anomaly map of Hungary

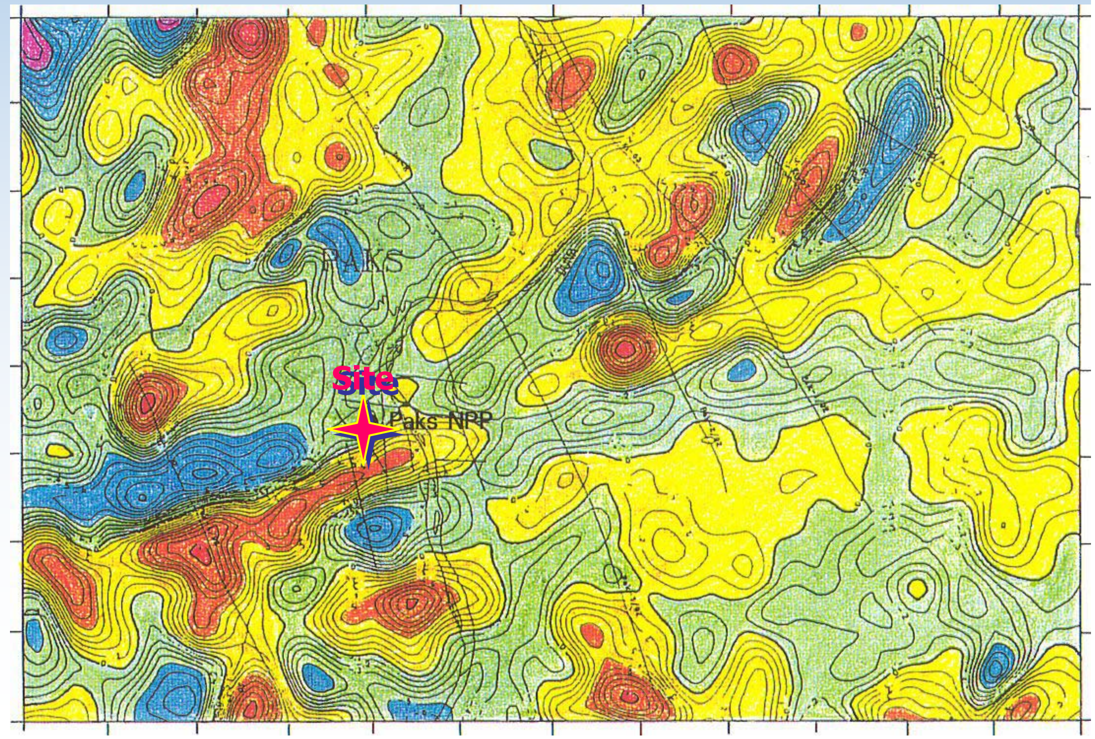


Site vicinity investigations

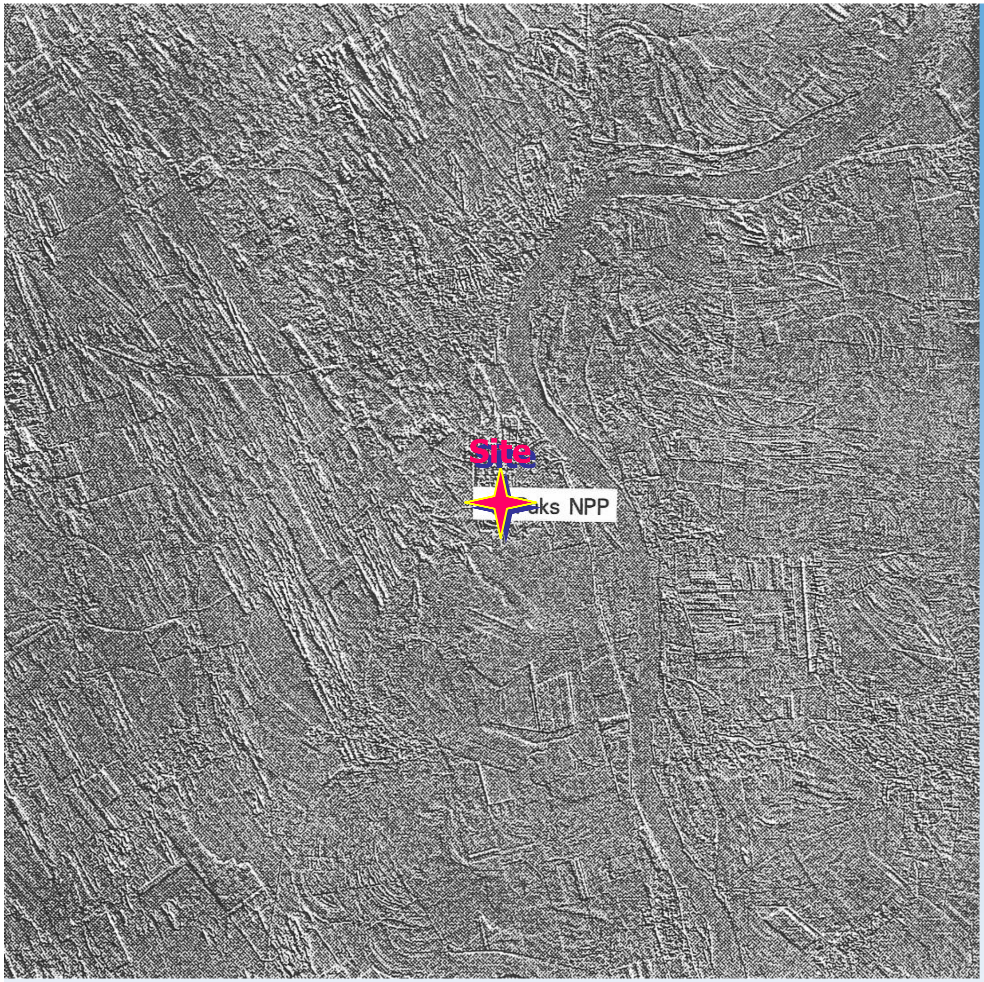


Bouguer anomaly map
of the Paks site vicinity

Residual gravity anomaly map
of the Paks site vicinity

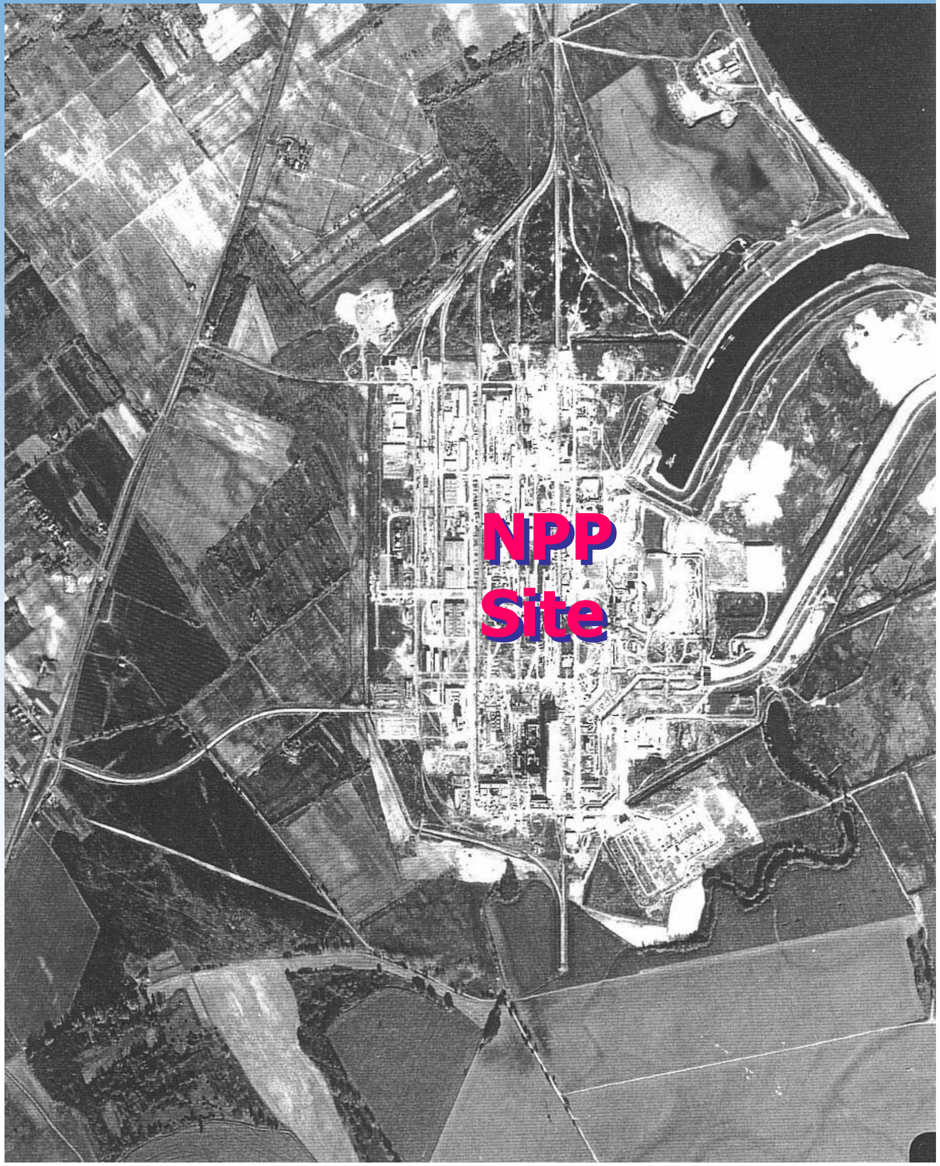


Site vicinity investigations

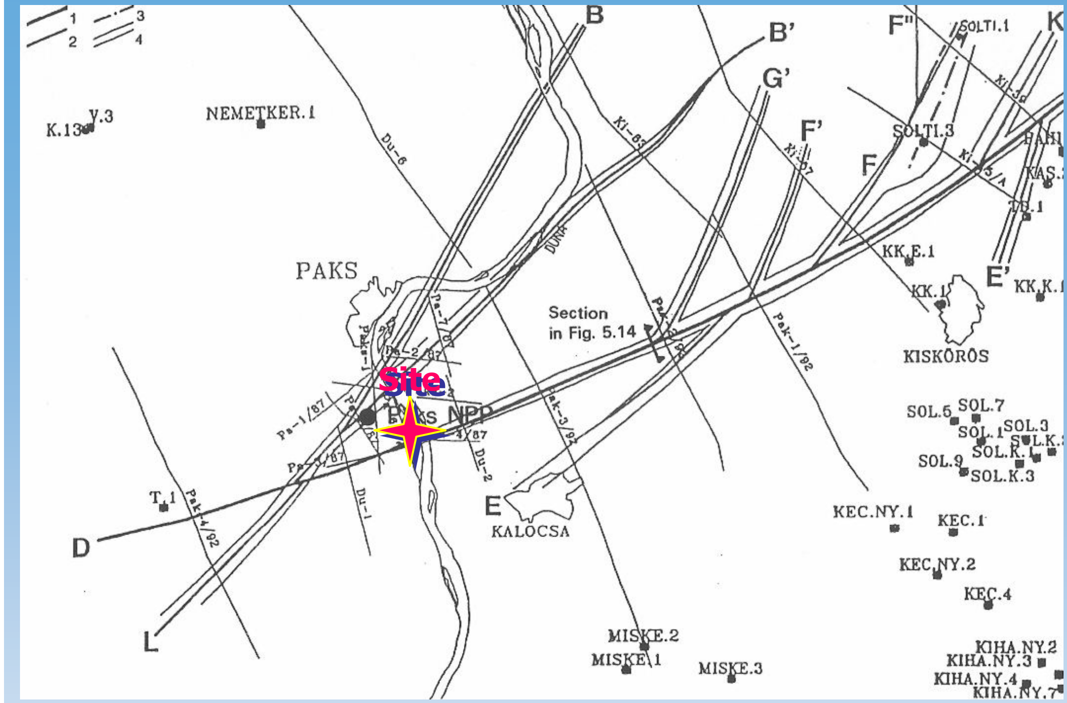


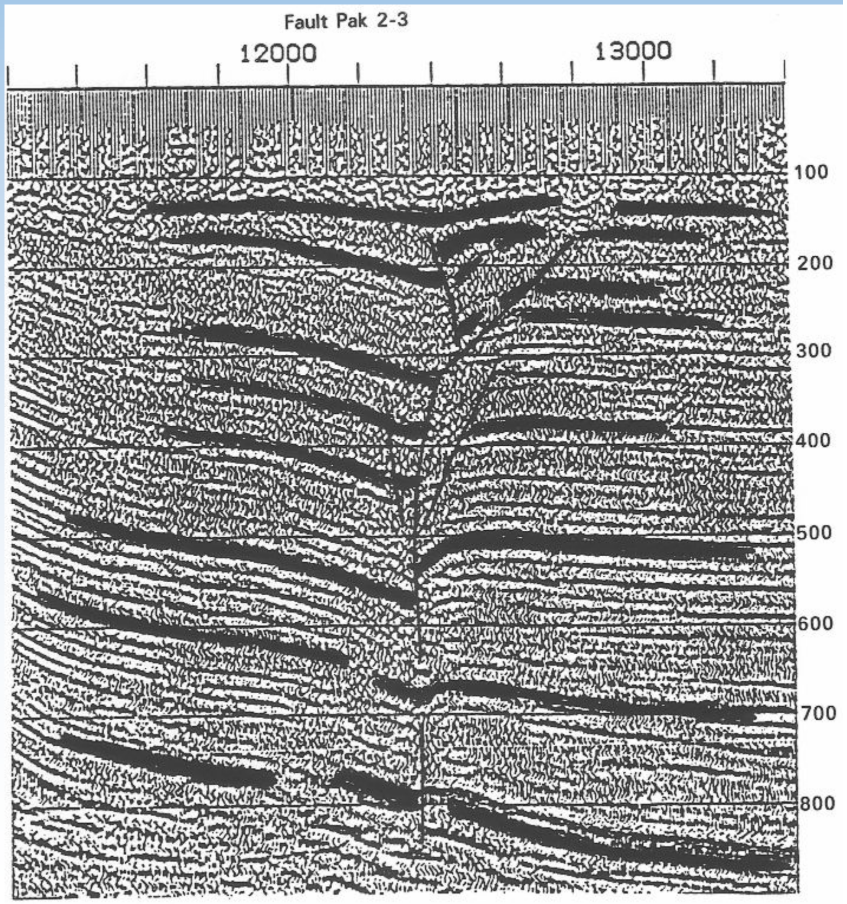
Satellite imagery
around Paks area

Areal photograph
near the Paks site



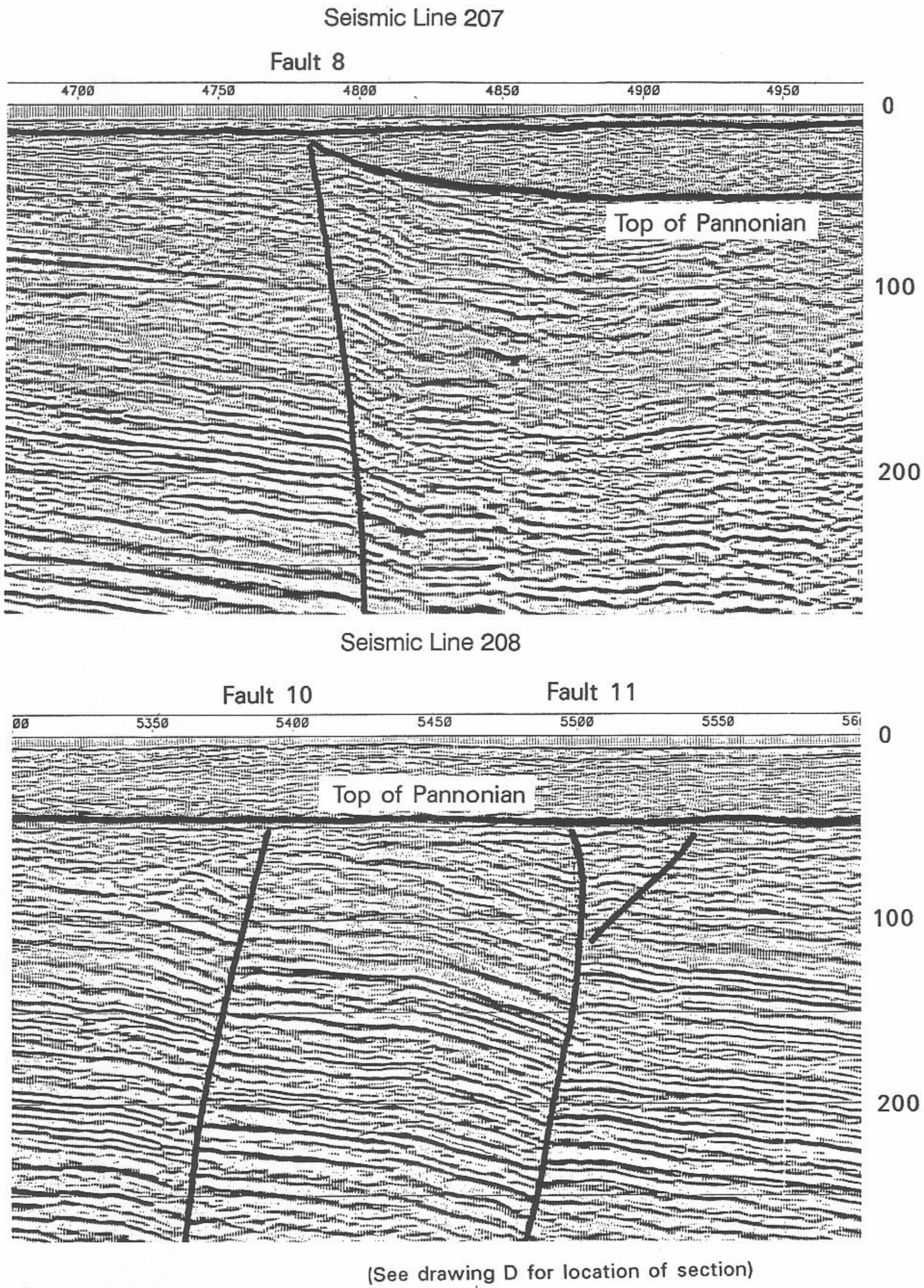
Site vicinity investigations





Geophysical profile
PAK-2

Site area investigations

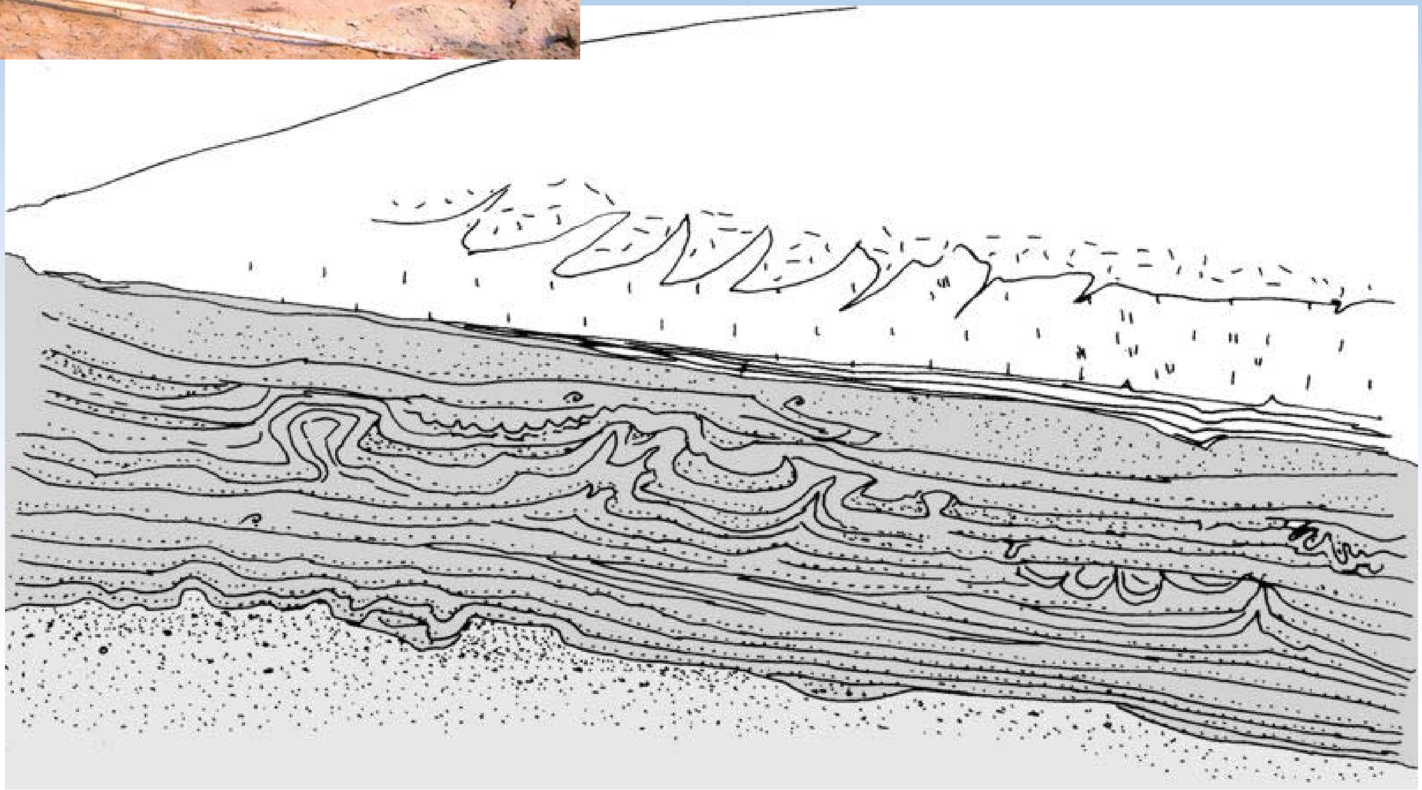


Tóth et al (1995)

- ✓Geological
- ✓Geotechnical
- ✓Hydrogeological
- ✓Boreholes
- ✓Excavations
- ✓...

Examples of Danube shallow seismic lines

Paleoseismological information



Bicske (Hungary)
After Magyari et al.

Major historical earthquakes in Hungary

1763 Komárom - M 6.3

Seismological Database: Historical data

Major historical earthquakes in Hungary

1810 Mór – M 5.4

DISSERTATIO

DE

TERRAE MOTU

IN GENERE, AC IN SPECIE

MÓRENSI

ANNO 1810. DIE 14. JANUARII ORTO.

K. M. Tud. Egyetemi FÖLDRENGÉSI OBSERVATORIUM.

CONSCRIPTA

A

PAULO KITAIBEL

MEDICINAE DOCTORE, CHEMIAE ET BOTANICAE PROFESSORE PUBL. ORD.

ET

ADAMO TOMTSÁNYI

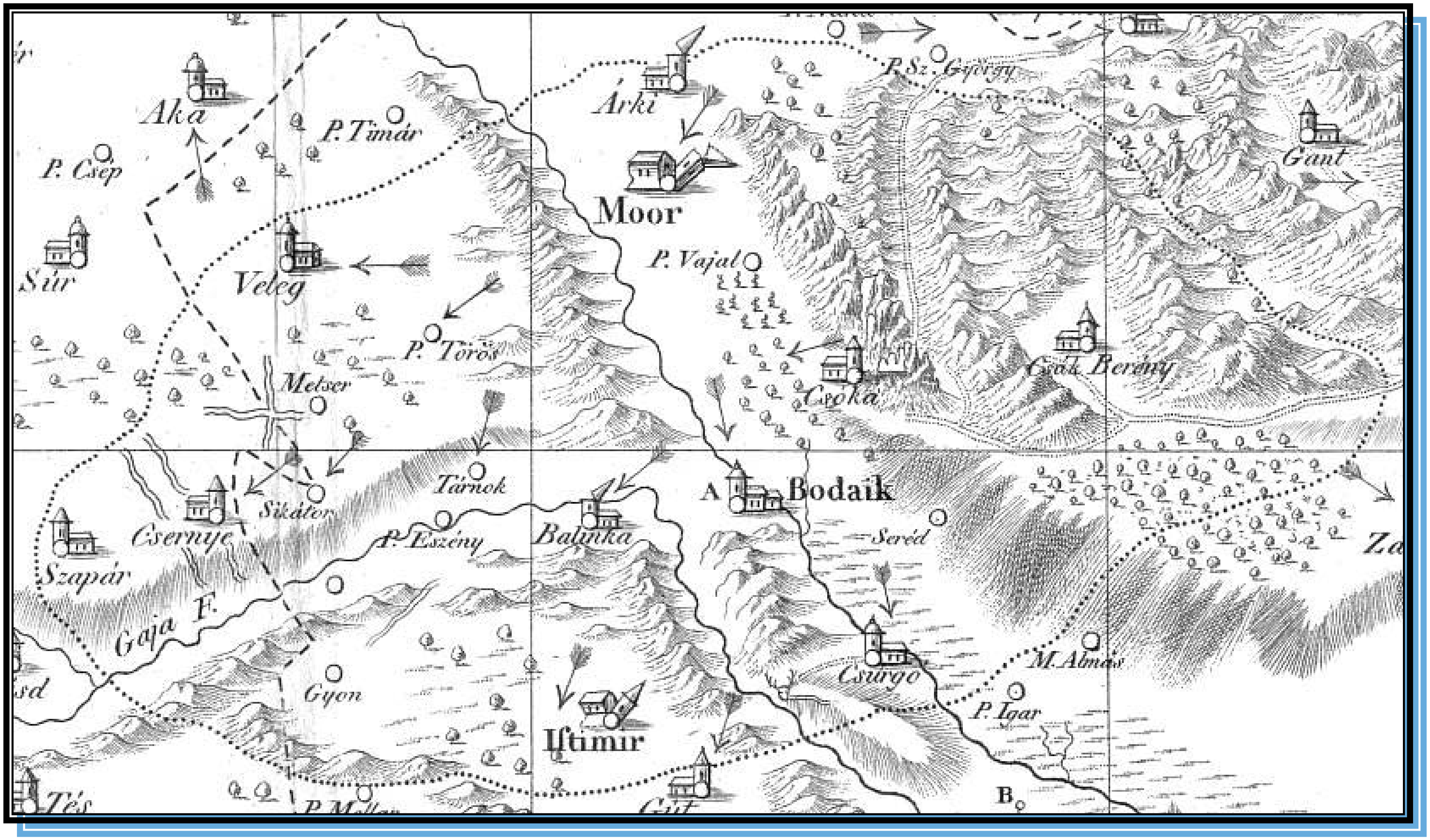
PHYSICAE, ET MECHANICAE PROFESSORE PUBL. O.

PER REGIAM SCIENTIARUM UNIVERSITATEM PESTINENSEM JUSSU ALTIORI PRO INVESTIGATIONE DICTI TERRAE MOTUS AD LOCI FACIEM EXMISSIS.

BUDAE,

TYPIS REGIAE UNIVERSITATIS HUNGARICAE.

1814.



Aka
P. Timár
P. Csép
Súr
Veleg
P. Törös
Metser
Sikátor
Tárnok
Csernye
Szapár
P. Eszény
Balinka
Gaja F.
Gyon
Iſtimir
Tés
Árki
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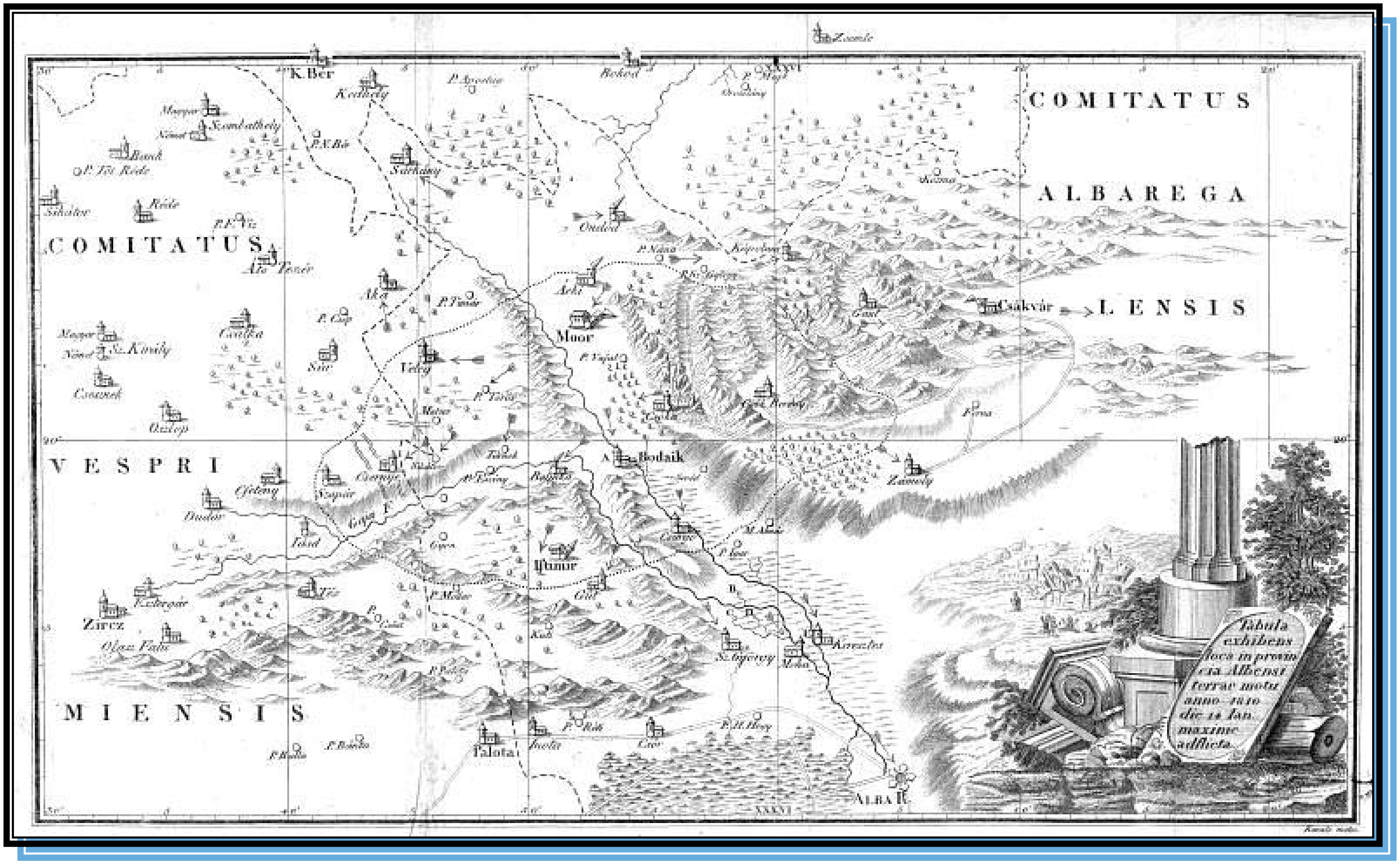
Gant
Csák Berény
Bodaik
Seréd
Csurgo
M. Almás
P. Igar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K. Bér
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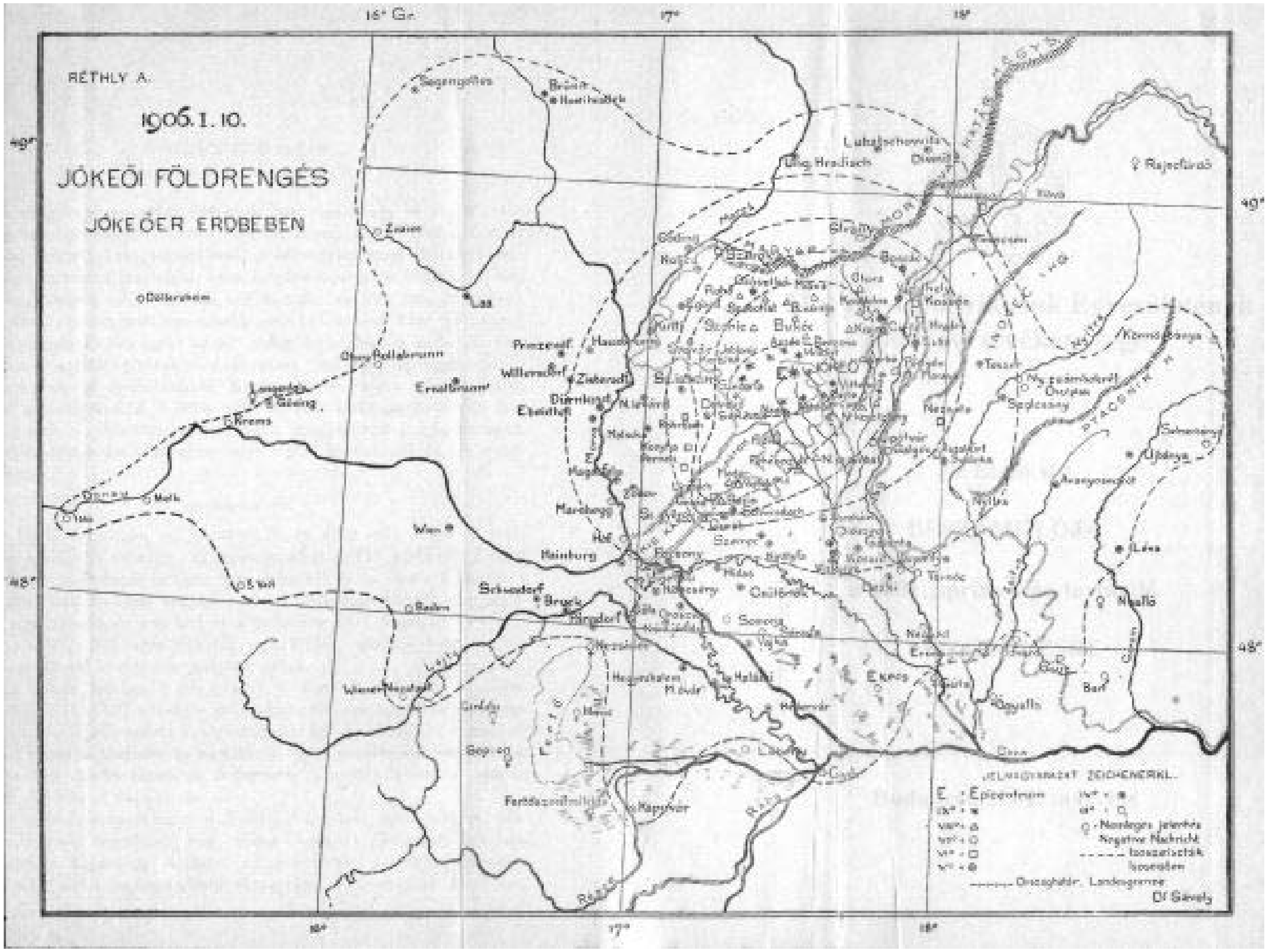
Csákvár
Isztimér
ALBA R.

Major historical earthquakes in Hungary

1906 Jókő, M 5.7


RÉTHLY A.
1906. I. 10.
JÓKEŐI FÖLDRENGÉS
JÓKEŐER ERDBEBEN

Major historical earthquakes in Hungary

1956 Dunaharaszti
M 5.6

Seismological Database: Historical data

Micro-seismic monitoring

„The most direct evidence to establish whether a tectonic feature should be considered active is seismicity. To be useful, accurately located earthquakes are required. While good information about larger historical earthquakes exists in Hungary, for about the past 200 years, these are not well enough located to resolve which tectonic features are active. Moreover, such larger events occur infrequently and do not provide the needed timeframe. To close this knowledge gap, a network of high quality digital seismographs should be installed capable of locating earthquakes as small as magnitude 2.0 within about 100 km of the Paks NPP site. 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 near site vicinity. … Recorded earthquakes should be routinely located, analyzed and interpreted to evolve a confident tectonic model in the Paks plant region."

(Final Report: SEISMIC SAFETY REVIEW MISSION FOR THE REVIEW OF TECTONIC STABILITY OF SEISMIC INPUT FOR THE PAKS NPP, Organized by the IAEA, November 1993)

The system encompasses a network of ten seismic stations within about 50 km of Paks (in the middle of Hungary) and a data centre in Budapest to collect and analyse the data. The field stations consist of a three component short period seismometer in a pit, a digital recorder and time signal receiver housed in a heat insulated steel container building.

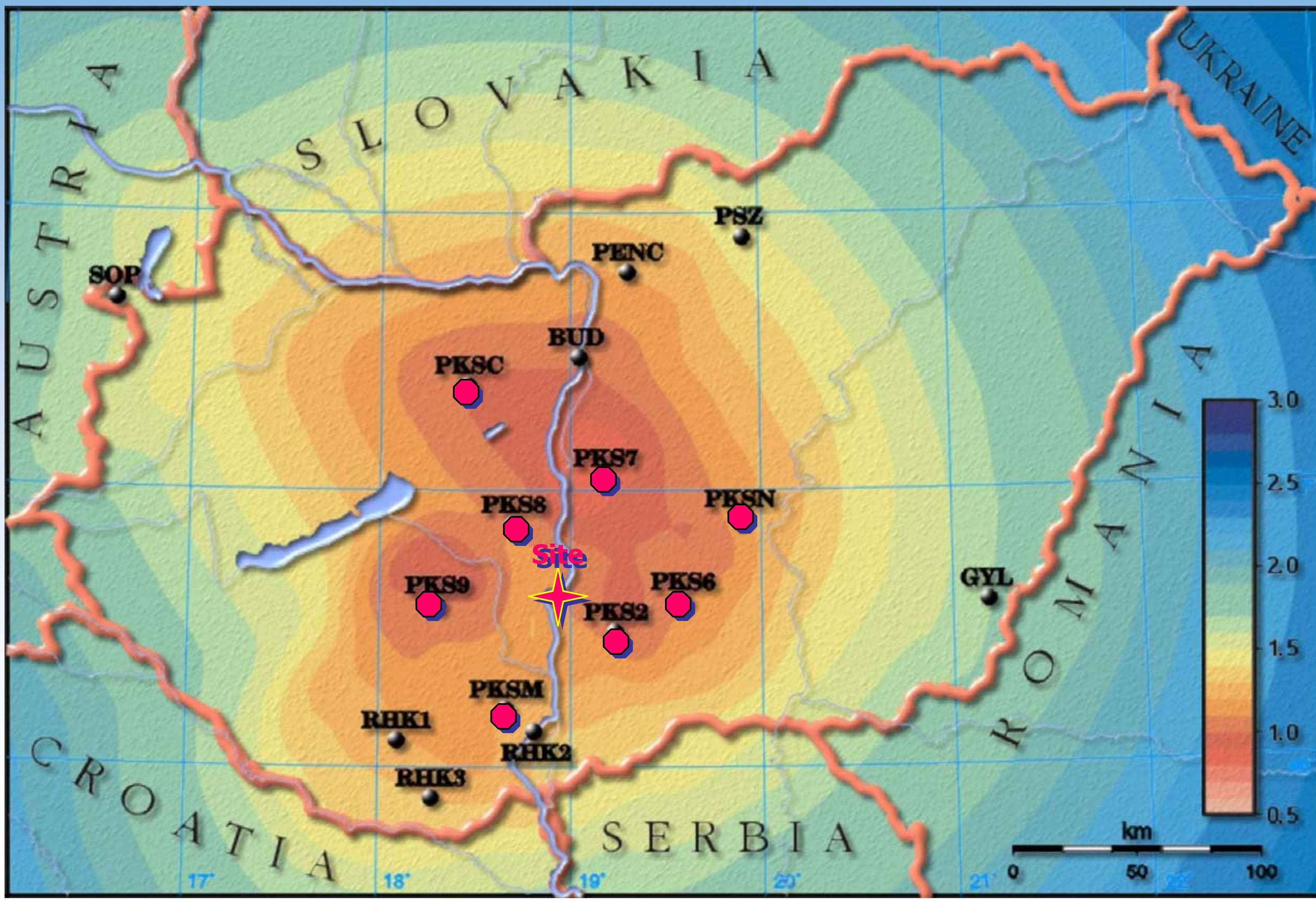
(GeoRisk, 1995)



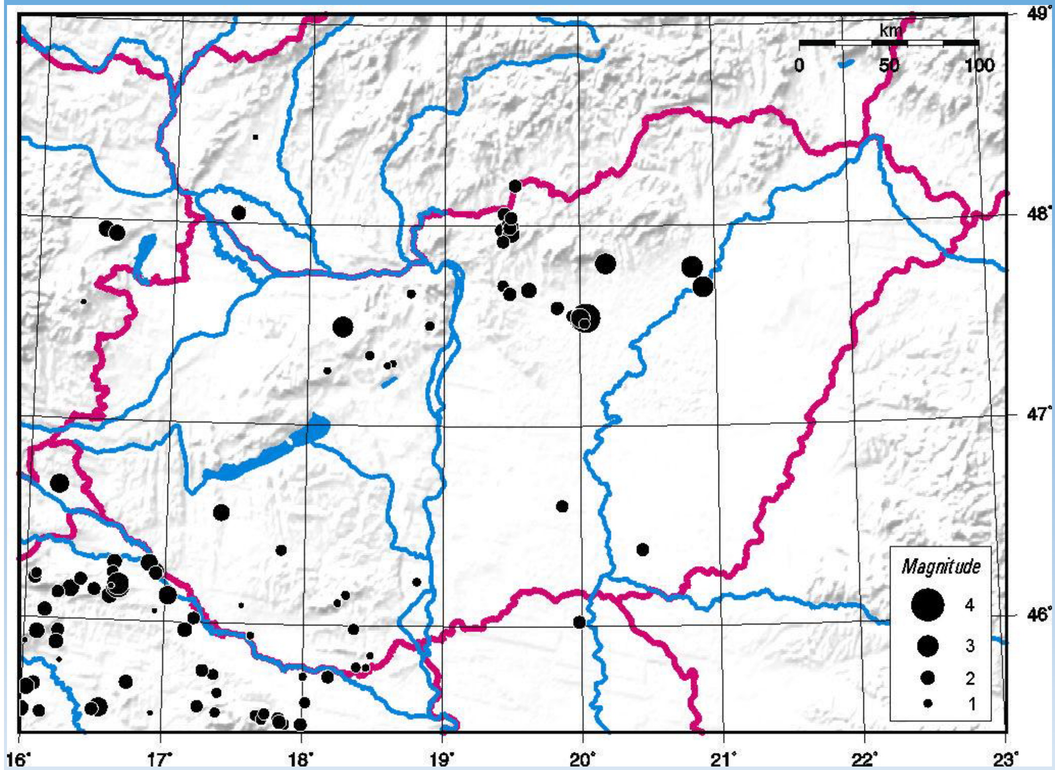

International Atomic Energy Agency

Network detection capability

4 stations, S/N>10, at average noise conditions



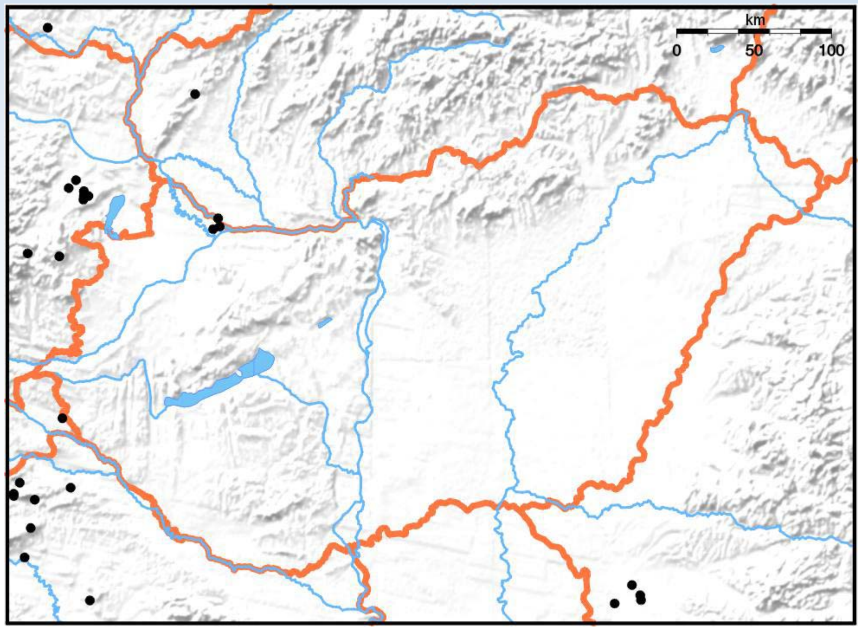
Seismological Database: Site specific instrumental data



LMN events in 2002

- 112 seismic events (0.1< ML<3.7)
- 9 earthquakes were reported as felt

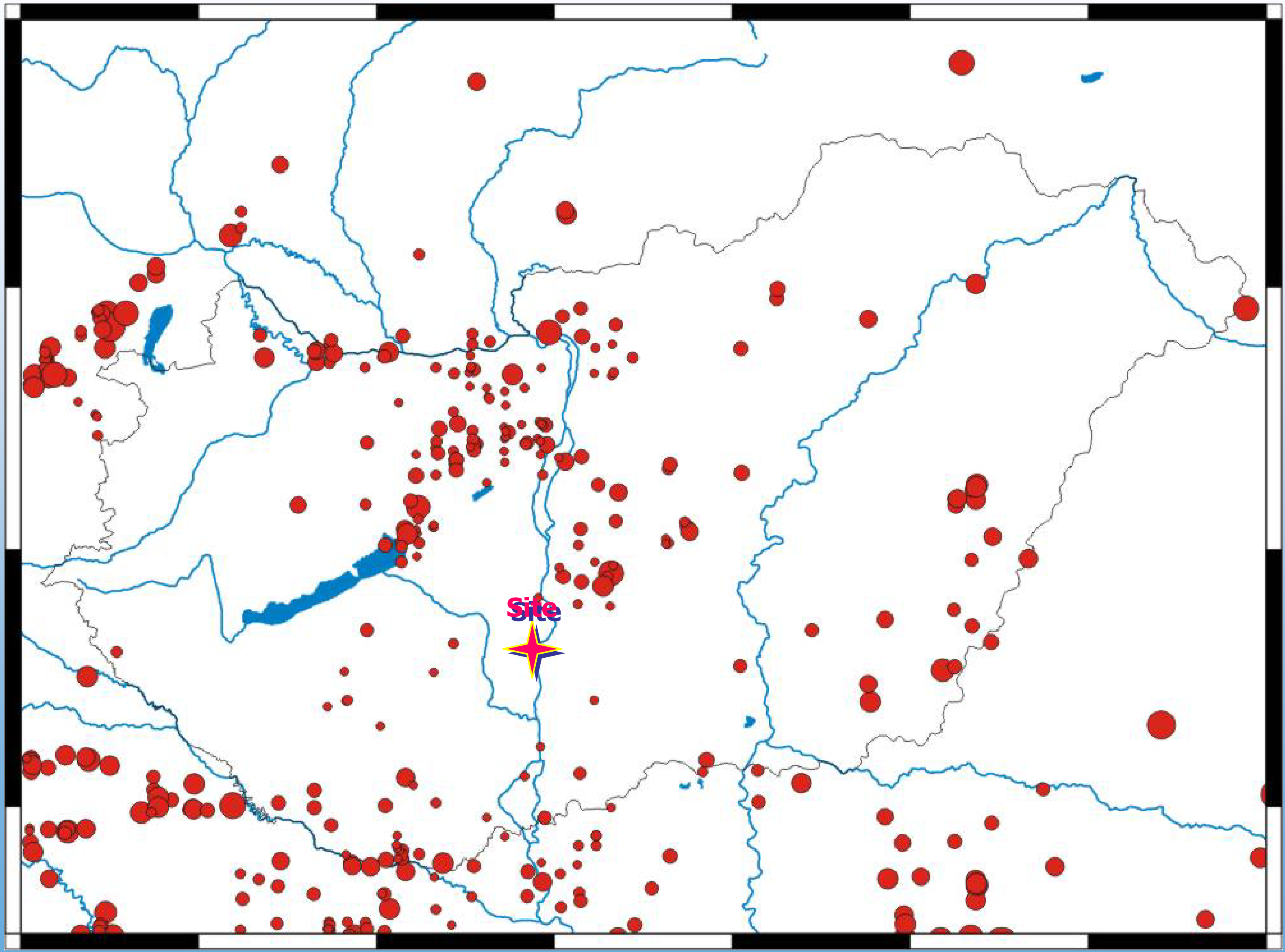
NEIC events in 2002

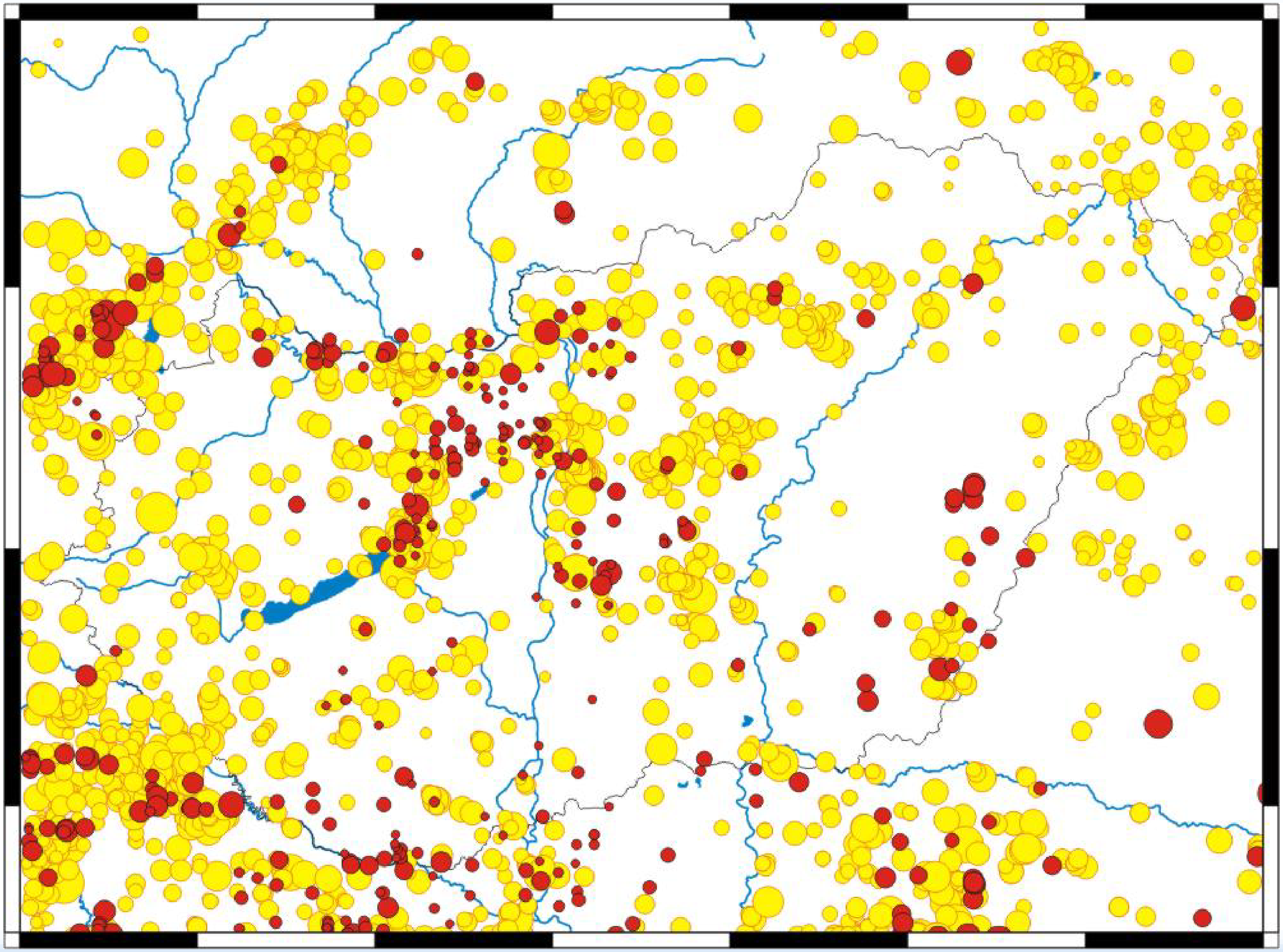


Seismological Database: Site specific instrumental data

More than 500 small events detected since 1995

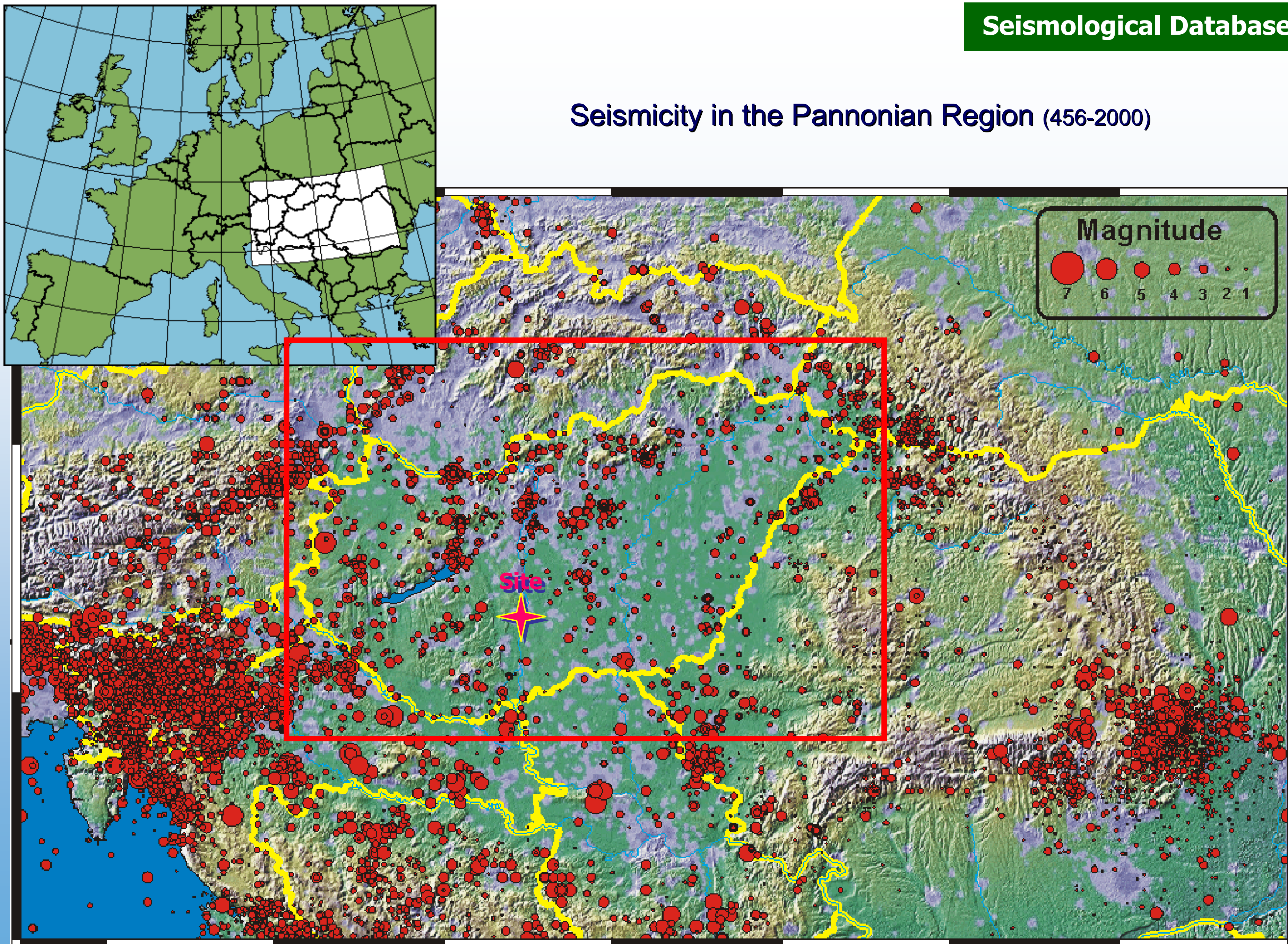
red circles – recent (1995-2002) earthquake epicenters yellow circles – historical seismicity (456-1994)

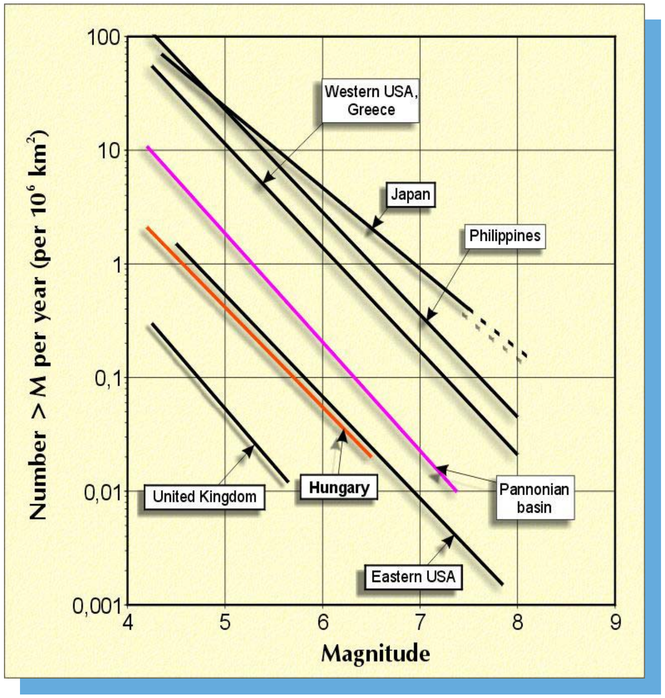




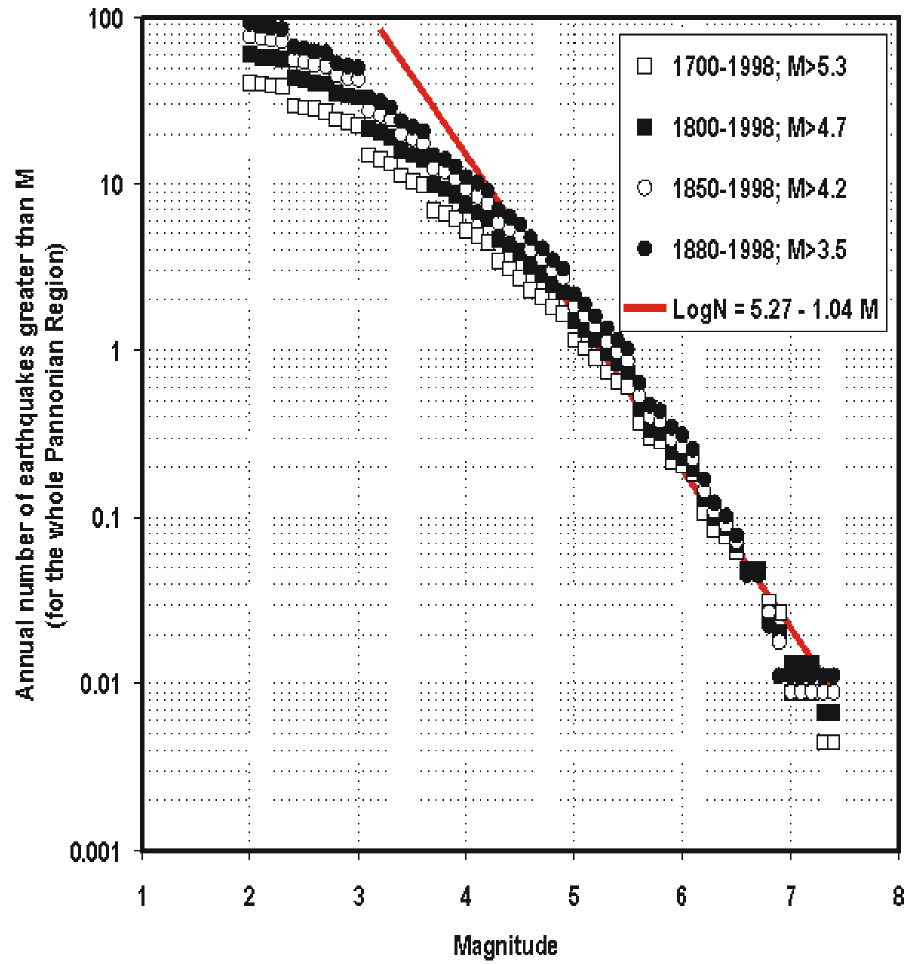
Seismological Database

Seismicity in the Pannonian Region (456-2000)



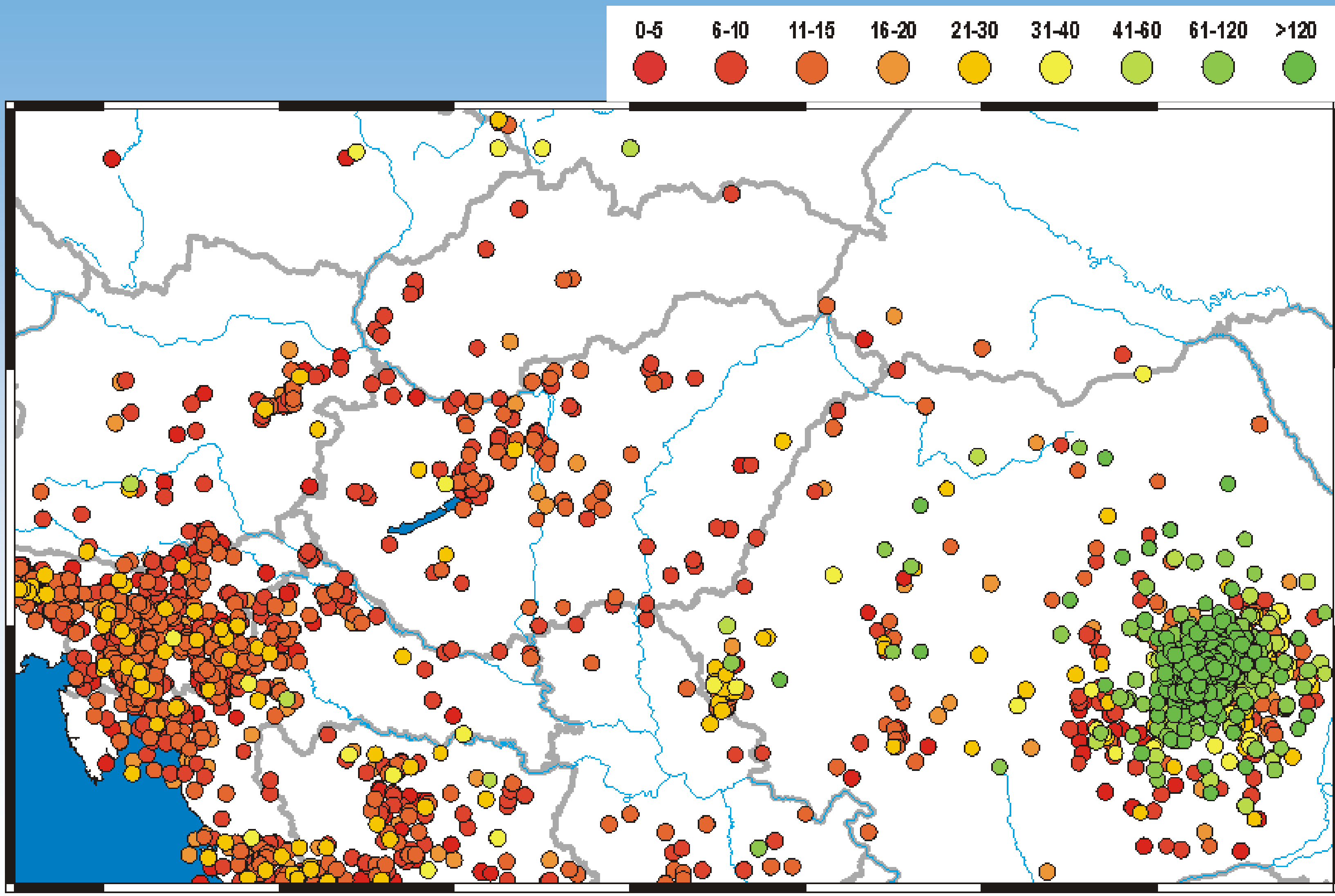


Number > M per year (per 10^6 km^2)
100
10
1
0,1
0,01
0,001
Western USA, Greece
Japan
Philippines
Pannonian basin
United Kingdom
Hungary
Eastern USA
4
5
6
7
8
9
Magnitude

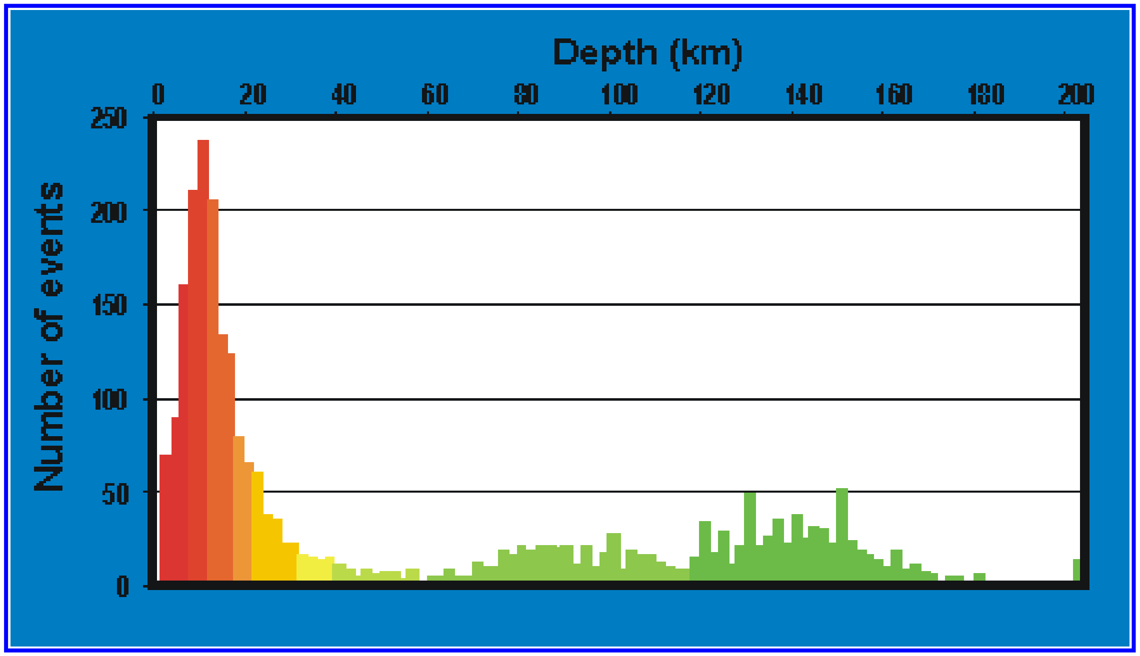


Annual number of earthquakes greater than M (for the whole Pannonian Region)
100
10
1
0.1
0.01
0.001
1700-1998; M>5.3
1800-1998; M>4.7
1850-1998; M>4.2
1880-1998; M>3.5
LogN = 5.27 - 1.04 M
1
2
3
4
5
6
7
8
Magnitude

Depth distribution of earthquakes in the Pannonian Region



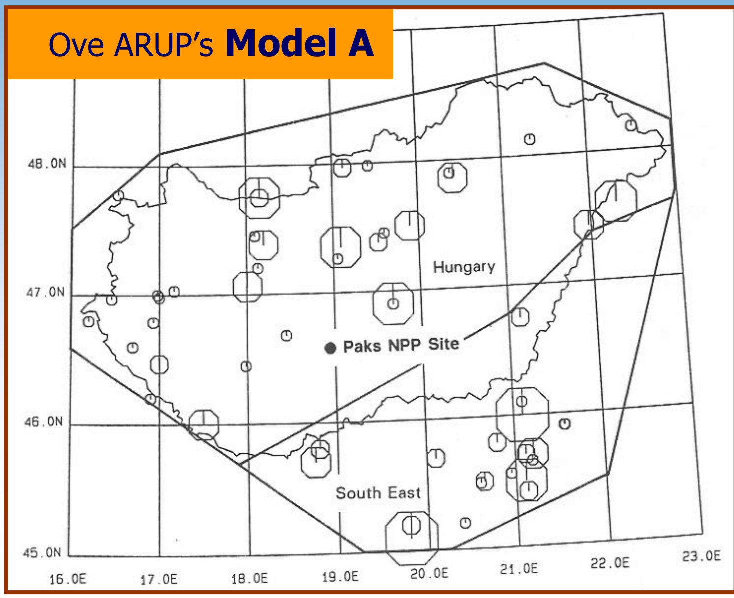
Identification of seismic sources



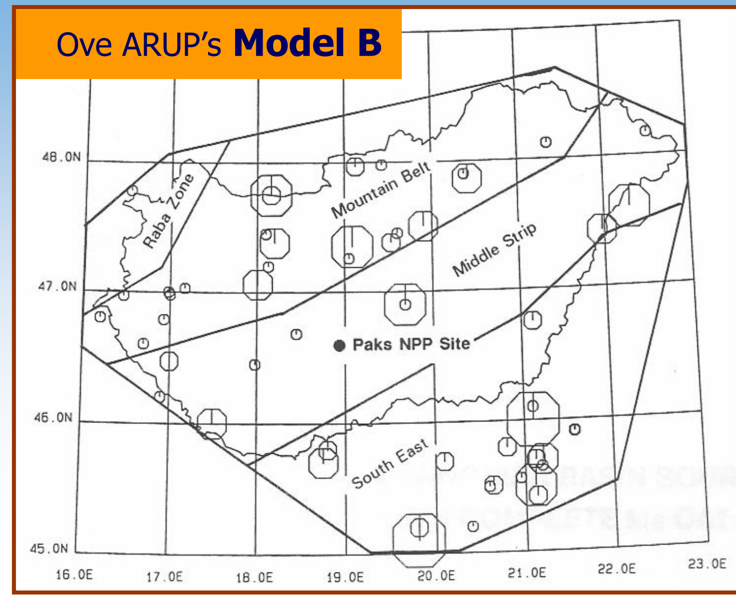
- <20% have depth information (uncertain)
- Three depth provinces
  - Shallow depth (6-15 km)
  - Intermediate depth (70-110 and 125-160 km) in the Vrancea

Identification of seismic sources

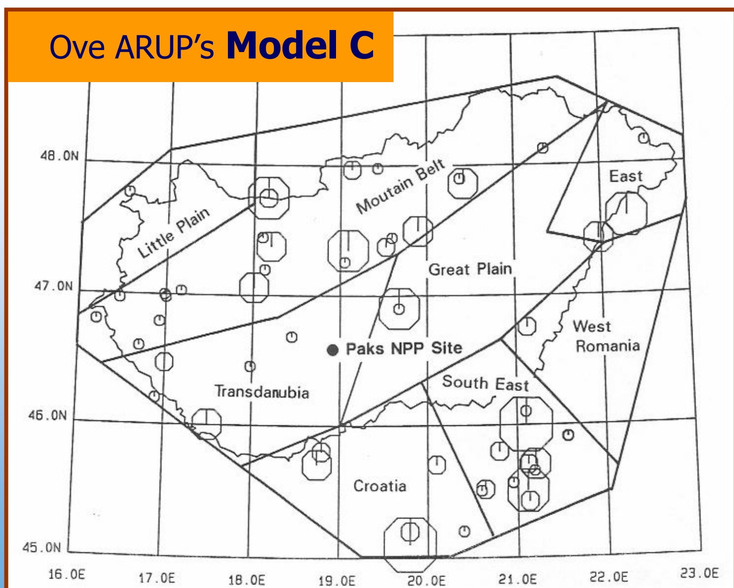
Ove ARUP's **Model A**



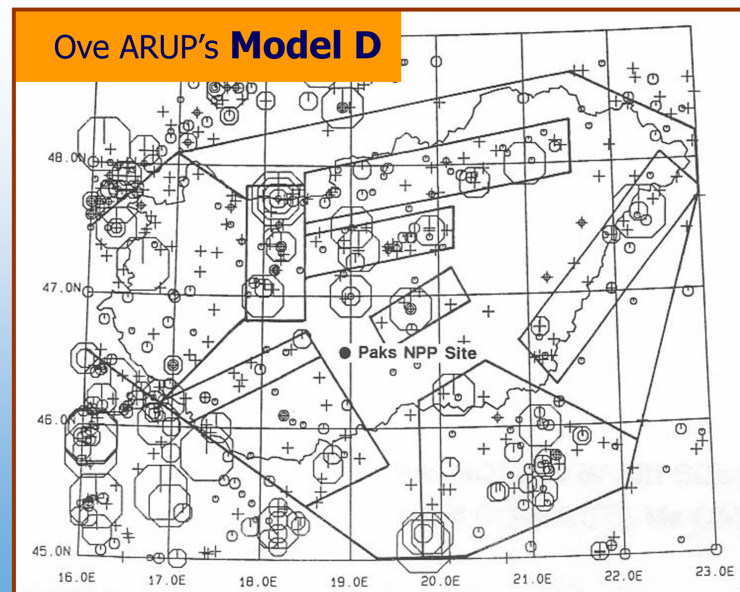
Ove ARUP's **Model B**



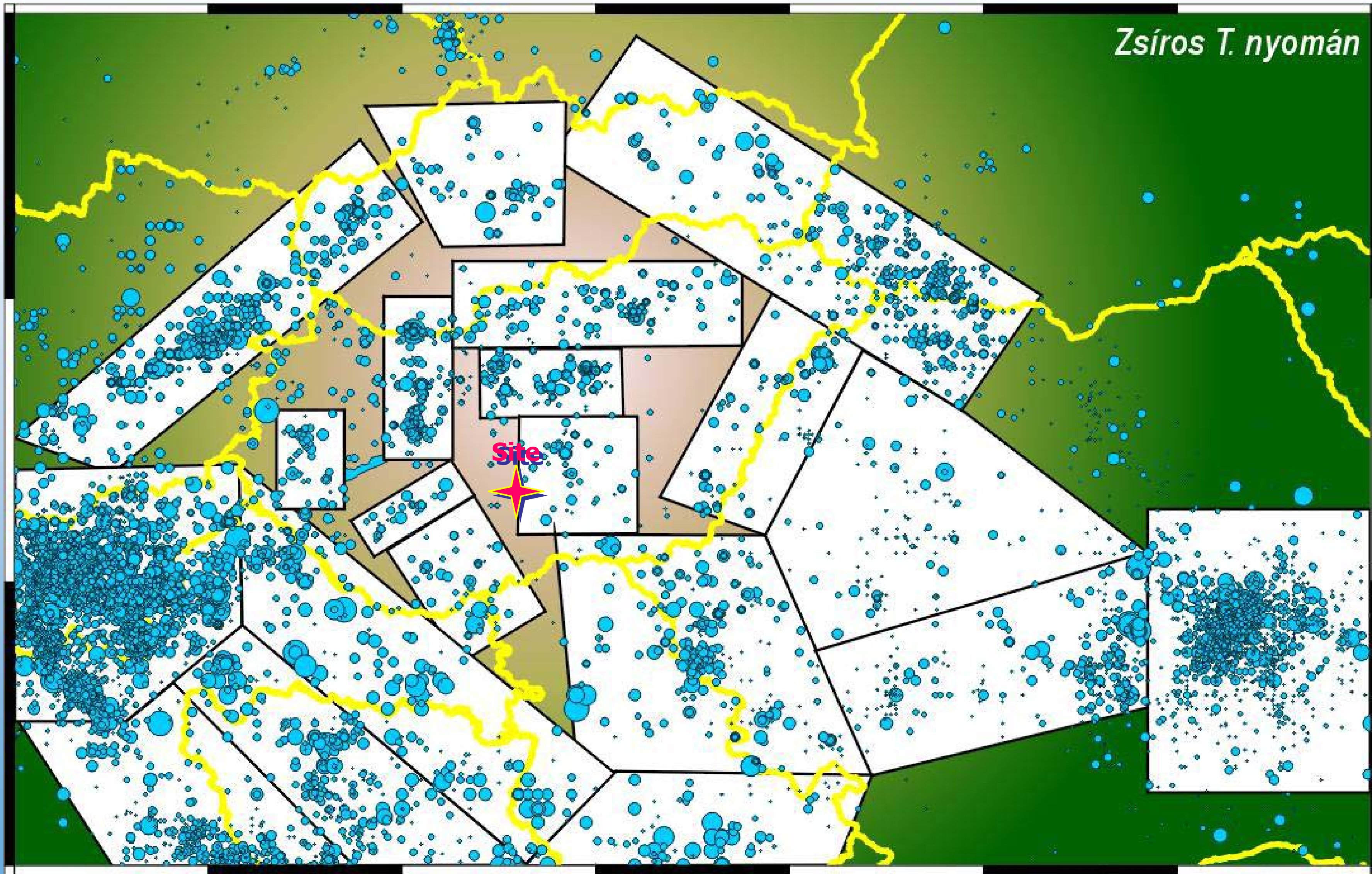
Ove ARUP's **Model C**



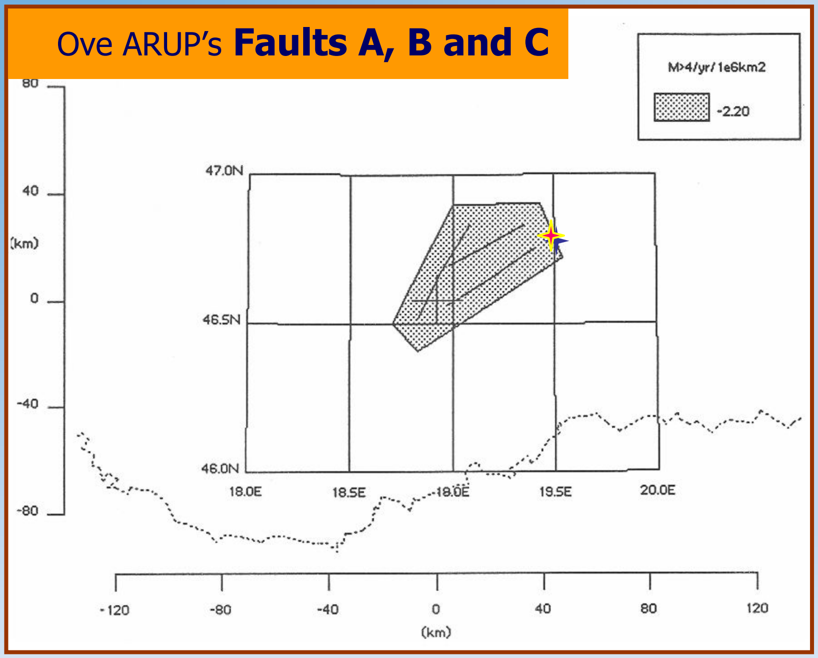
Ove ARUP's **Model D**

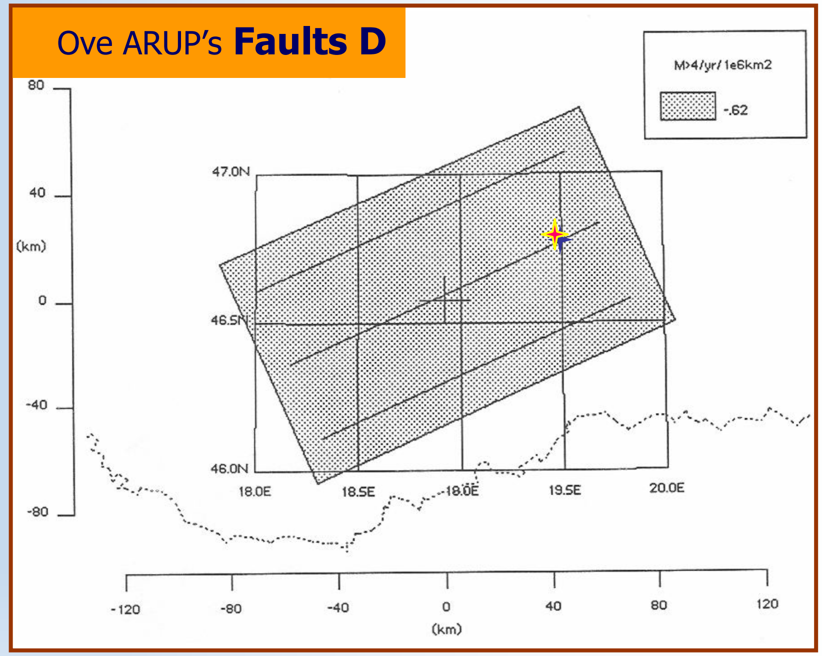


Evaluation of seismic sources



Identification of seismic sources





➢During the re-evaluation of the site, one of the most discussed question was, whether the tectonic structures in the site vicinity had been active during the recent tectonic regime.

➢The conclusion was, that the probability of recent activity and existence of a capable fault is very low.

(During the last years no seismic activity has been recorded around the site. These results confirm the adequacy of the source-models used in the probabilistic earthquake hazard analysis, and demonstrate the conservatism of the parameters of the source zones.)

Step 2

Assessment of earthquake recurrence and M_{max}

IAEA SAFETY STANDARD SERIES No. NS-G-3.3 – CONSTRUCTION OF A REGIONAL SEISMOTECTONIC MODEL

Characterization (4.16-4.26 and 4.30-4.32)

Each seismic source is characterized by

- maximum magnitude
- earthquake recurrence model
- uncertainties in the parameters of the model

✓ **For fault sources:**

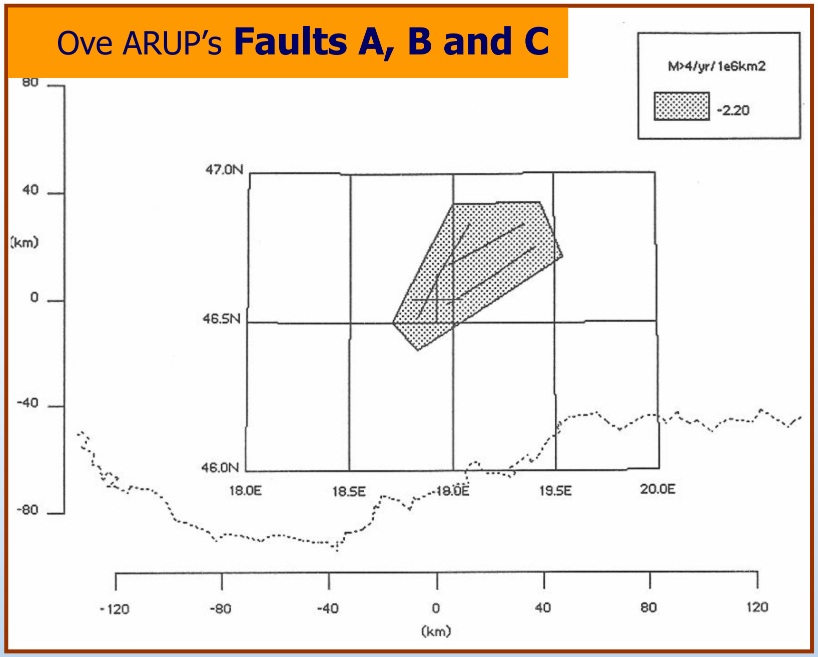
- ✓ M_{max} is calculated from empirically based magnitude–area relationships
- ✓ Recurrence relationships are developed from the slip rates and segmentation point failure probabilities

✓ **For source zones:**

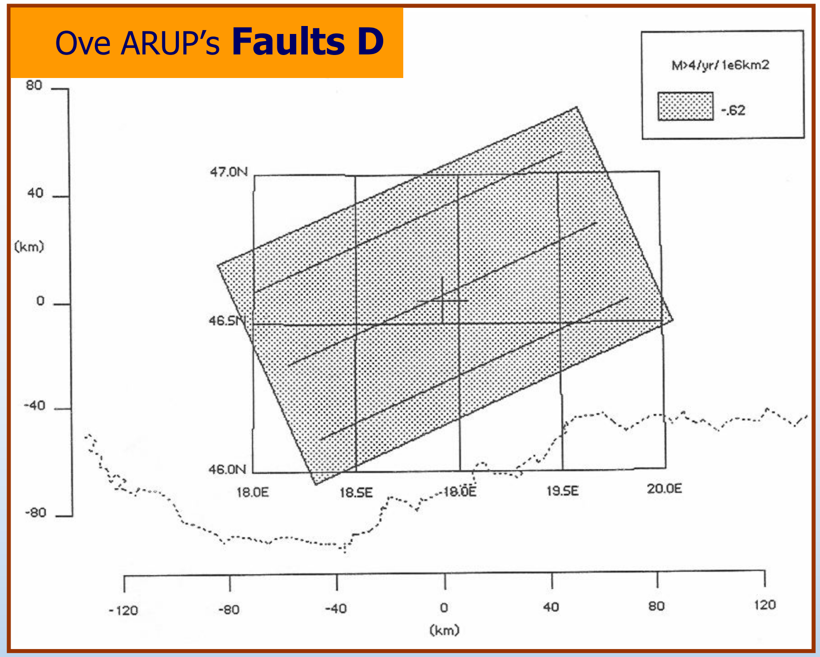
- ✓ historical and instrumental seismicity form the primary data for characterization of maximum magnitudes and recurrence

Characterization of seismic sources

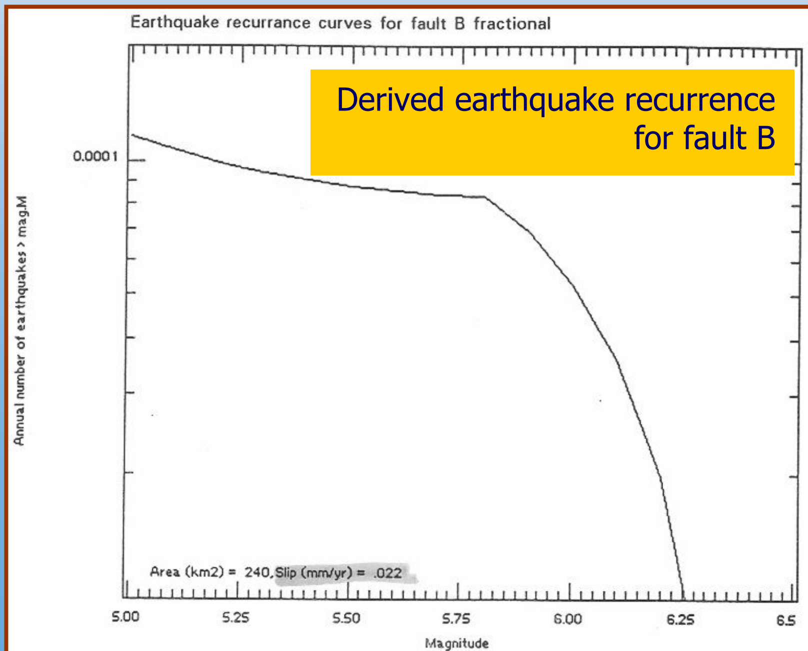
Ove ARUP's **Faults A, B and C**



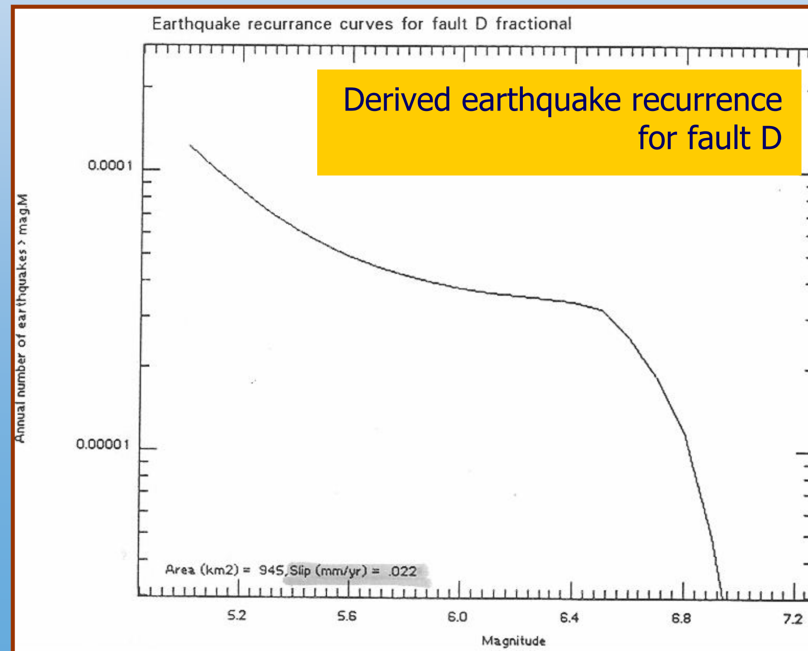
Ove ARUP's **Faults D**



Derived earthquake recurrence for fault B

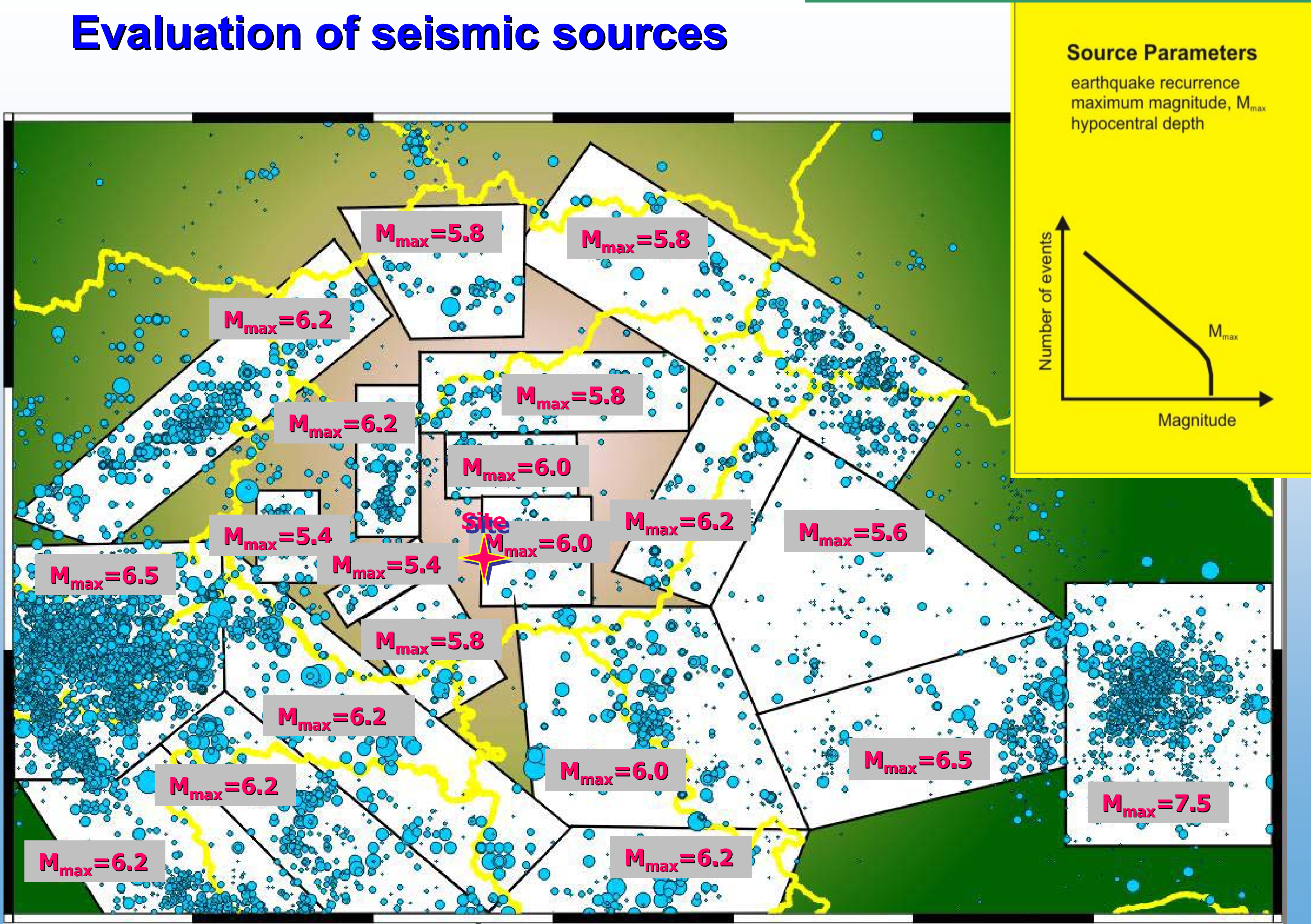


Derived earthquake recurrence for fault D



Characterization of seismic sources

Evaluation of seismic sources



Step 3

Ground motion attenuation

IAEA SAFETY STANDARD SERIES No. NS-G-3.3 –

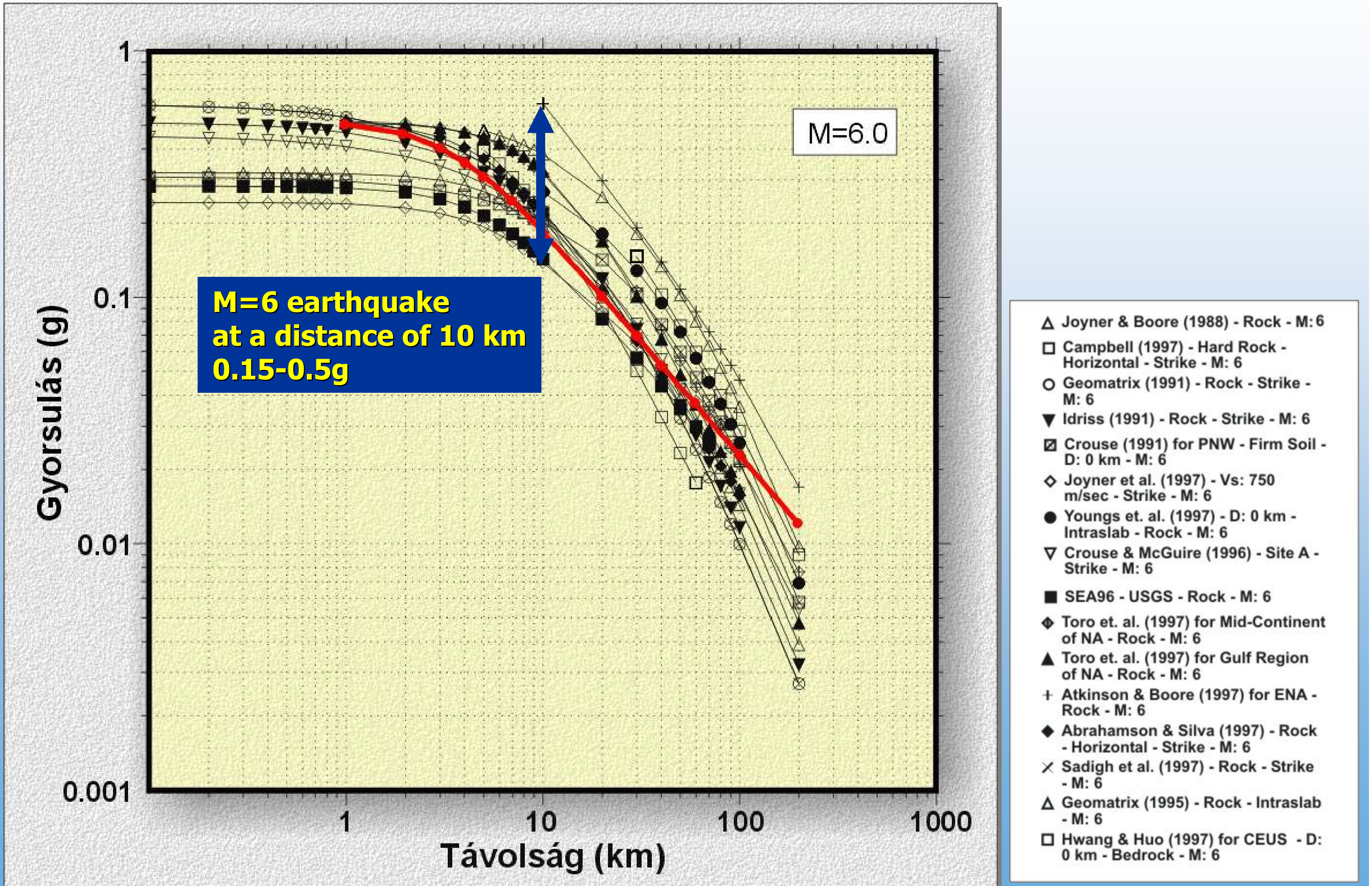
(5.13)

A ground motion attenuation function is a probability density function whose parameters depend on the earthquakes and site characteristics.

The standard version is a function of the earthquake magnitude and source distance from the site of interest.

The probability of exceeding a certain value of the ground motion caused by an earthquake of magnitude M **and located at a distance** R **from the site is calculated by means of the ground motion attenuation functions.**

PGA attenuation
(published by different authors)



Step 4

Calculation of seismic hazard

IAEA SAFETY STANDARD SERIES No. NS-G-3.3 – EVALUATION OF GROUND MOTION HAZARD

Identification (5.15-5.19)

- **As developed by Cornell (1968), the probabilistic hazard methodology aims to calculate the annual probabilities that various levels of ground motion will be exceeded at a site.**
- **The probabilistic hazard curve represents the integration, overall earthquake sources and magnitudes, of the probability of occurrence of all possible future earthquakes; and for each earthquake, the probability that a particular value of ground motion is exceeded at the site.**
- **The current practice is to represent the temporal occurrence of earthquakes as a Poisson process. The probability of earthquake occurrence as a function of magnitude is generally represented by an exponential distribution (Gutenberg–Richter).**
- **The result is a hazard curve expressing the annual probability that various levels of the ground motion parameter will be exceeded.**

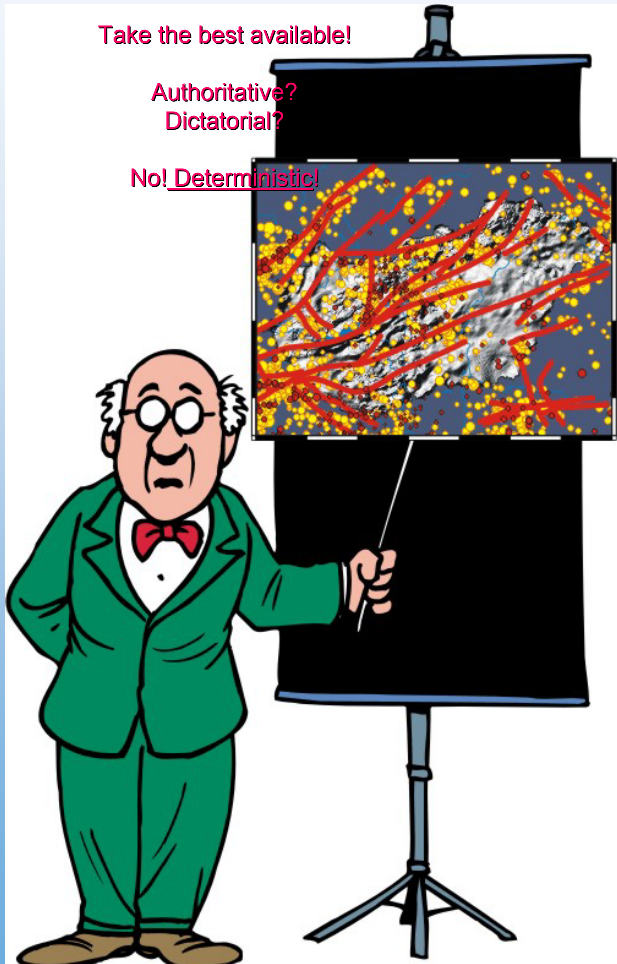
Treating of uncertainties

How to handle uncertainty?

random (aleatory)

lack of knowledge (epistemic)

„An epicenter is a mark made on a map by a man who calls himself a seismologist" – P. Byerly



Take the best available!

Authoritative?
Dictatorial?

No! Deterministic!

Major sources of epistemic uncertainty:

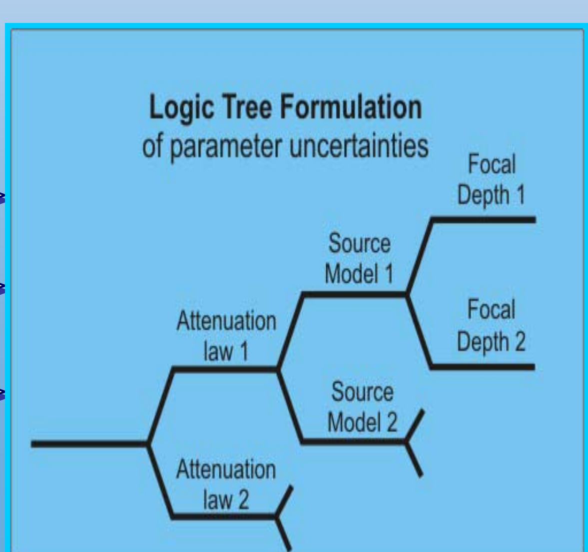
- ✓ **Seismotectonic model**
- ✓ **Source characteristics**
- ✓ **Recurrence, M_{max}**
- ✓ …
- ✓ …

Accommodate alternative models!

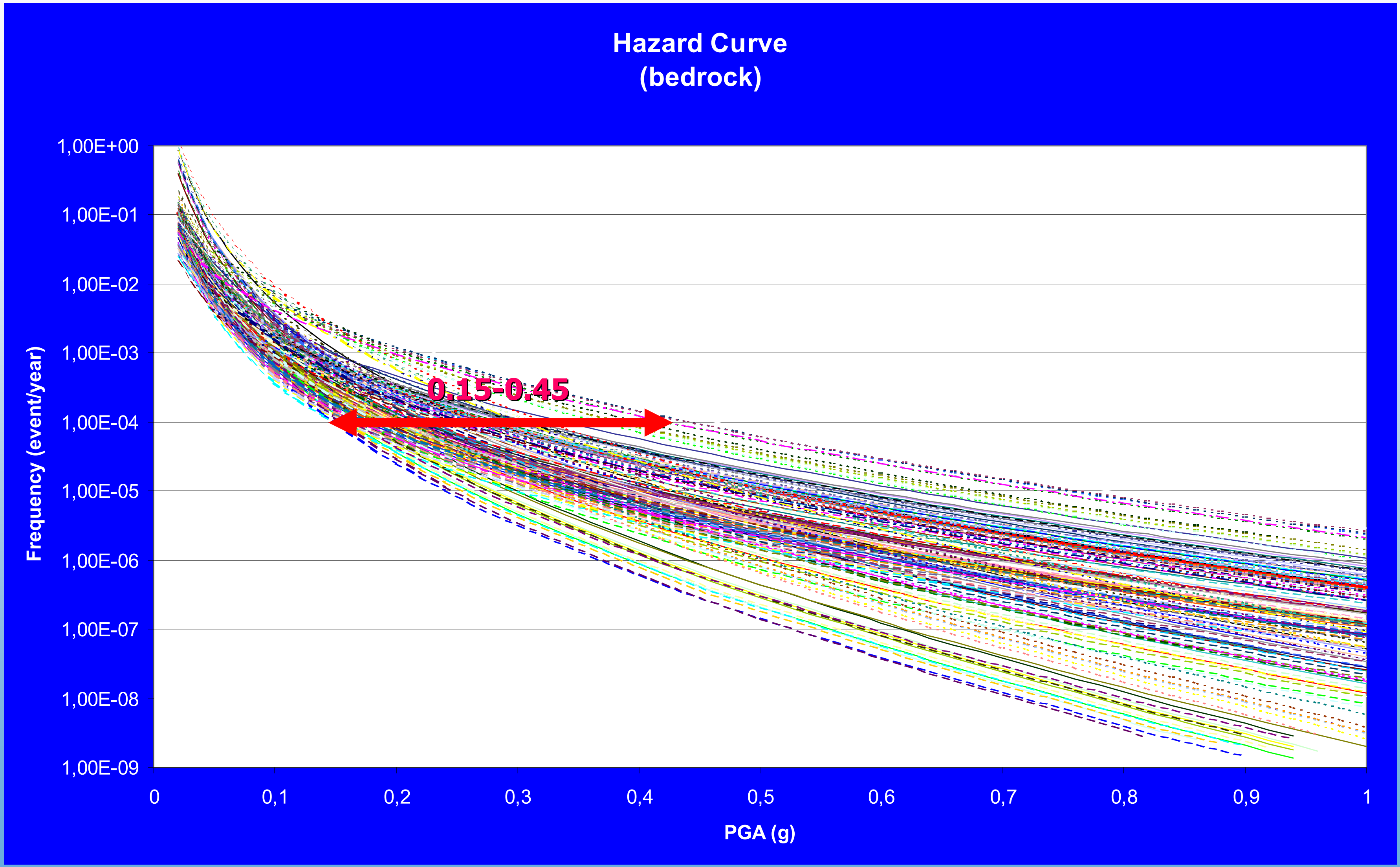
alternative regional tectonic models,
alternative attenuation relationships
alternative values of different parameters
e.g. fault dip, slip rates, max magnitudes

More democratic?

No! Probabilistic!



Paks NPP



Hazard Curve
(bedrock)
1,00E+00
1,00E-01
1,00E-02
1,00E-03
1,00E-04
1,00E-05
1,00E-06
1,00E-07
1,00E-08
1,00E-09
Frequency (event/year)
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
PGA (g)
0.15-0.45

Step 5

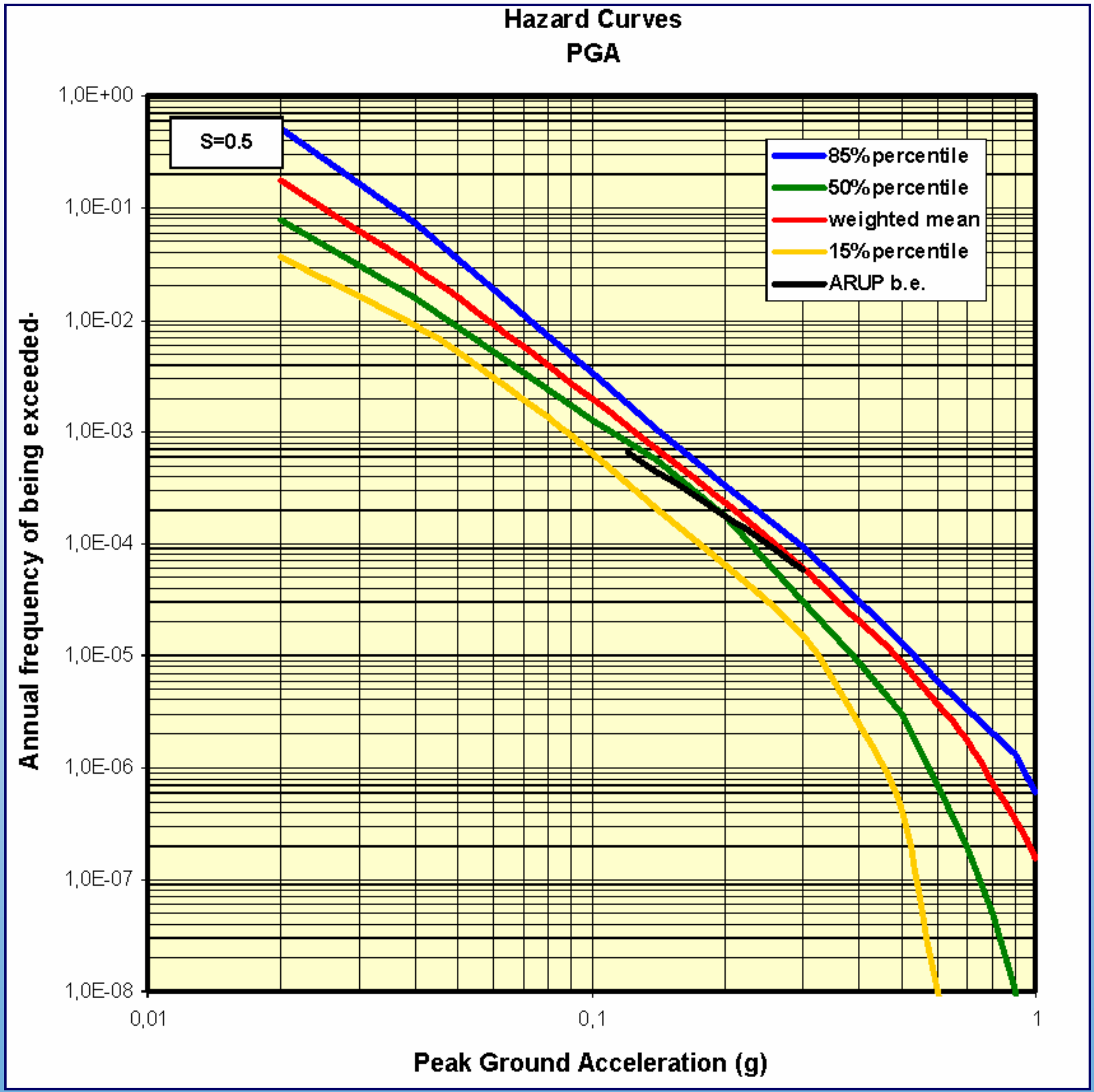
Presentation of the results

IAEA SAFETY STANDARD SERIES No. NS-G-3.3 – Ground motion characteristics

(5.20-…)

- **The basic calculation results in a seismic hazard estimate for a single characterization of a set of seismic sources, including recurrence and maximum magnitude values, and a single ground motion attenuation relation. Thus, the result of this calculation is a single hazard curve that represents the randomness, or <u>aleatory uncertainty</u>, inherent in the location and magnitude of future earthquakes, and in the generation and seismic wave propagation.**
- **There is also uncertainty in the characterizations of seismic sources and ground motion attenuation. This <u>epistemic uncertainty</u>, arises from incomplete knowledge of earthquake processes, limited data, and alternative interpretations of the available data. The methodology explicitly incorporates these uncertainties into the analyses to quantify the uncertainty in the final hazard results.**

Results



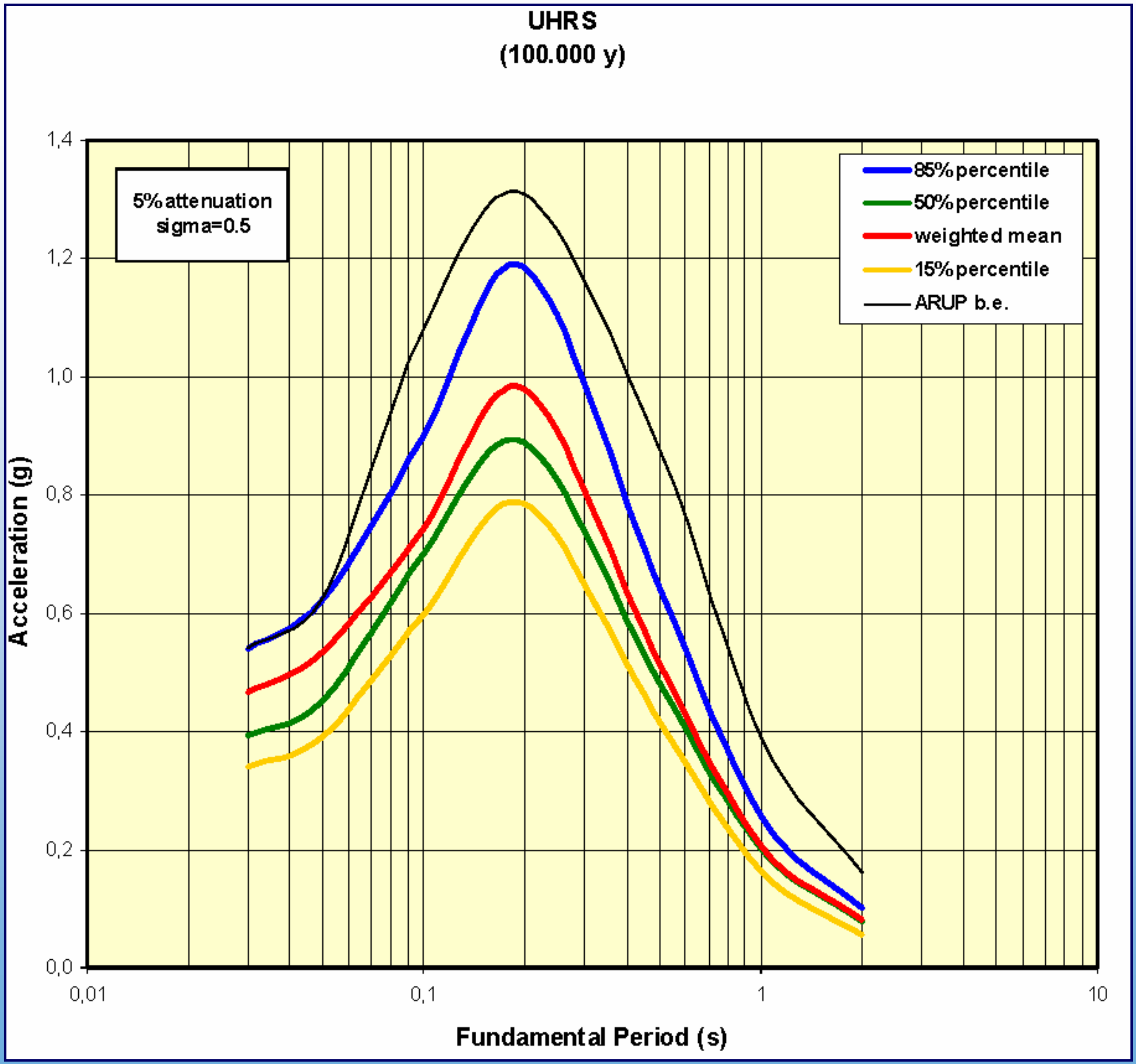
Hazard curves: annual frequencies of peak ground accelerations (PGA) at Paks NPP site

Red line weighted mean, yellow 15%, green 50%, blue 85% confidence levels

Thin black line: best estimate of ARUP (1995)

Results

Uniform Hazard Bedrock Response Spectrum (UHRS) for 10^5 years with damping of 5% at Paks NPP site
Red line weighted mean, yellow 15%, green 50%, blue 85% confidence levels
Thin black line: best estimate of ARUP (1995)



Site response analysis

- Site response analysis has been carried out to propagate the bedrock spectra to the surface taking account the effect of the 27m thick young Quaternary fluvial materials overlying the hard Pannonian deposits. Three input earthquake motions were selected such that their response spectra approximate the bedrock UHRS curves. The site response characteristics have been assessed using effective stress method (by computer code DESRA-2C) taking into account the degradation of the soils due to progressive pore water pressure buildup during an earthquake.

- Time histories of the surface accelerations calculated by effective stress method, shear strain, stress, volume strain and excess pore pressure were computed. These soil characteristics have been computed for the best estimate soil profile, ground water levels drawn for 10^{-4}, 10^{-5}, 10^{-6} probability and all three of applied input bedrock time histories.

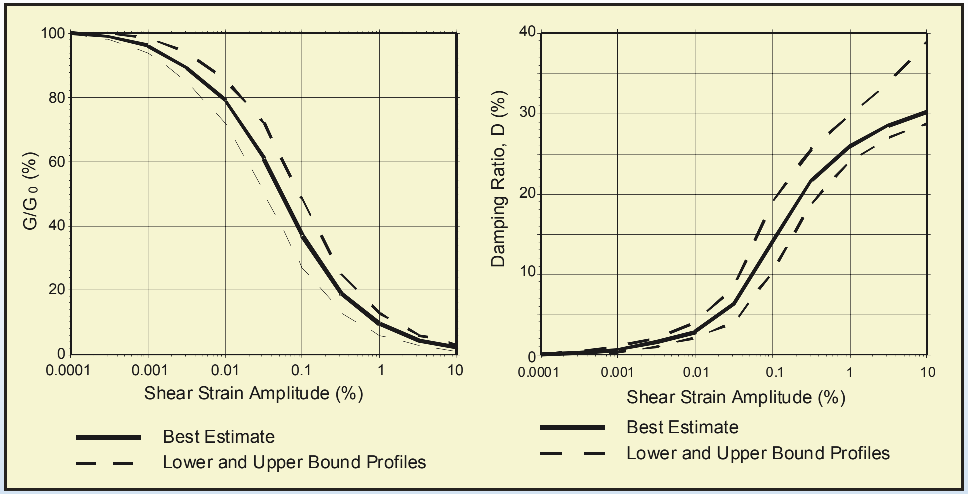
Input parameters – soil properties

Site response analysis

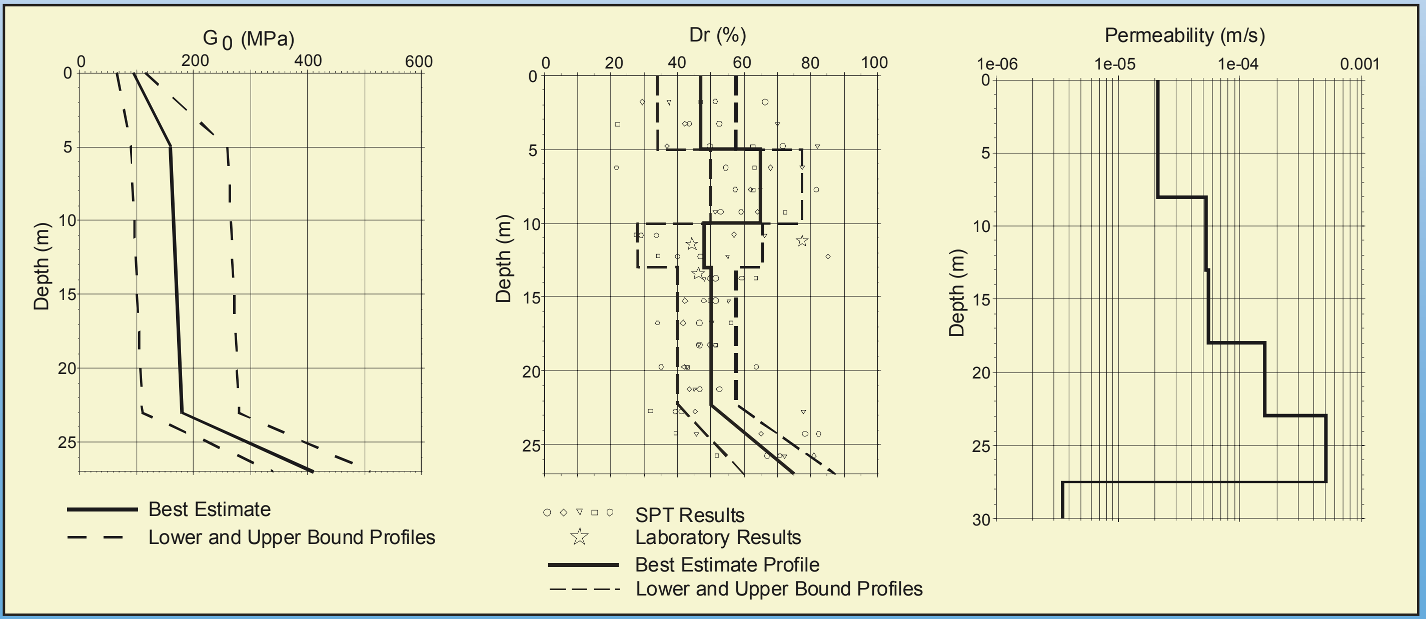
Stratum	Thickness (m)	Depth (m)
Fill	2	0 to 2
Quaternary Fluvio-aeolian strata	6	2 to 8
Quaternary Fluvial Sand and Gravel	7	8 to 15
Quaternary Fluvial Gravel	12	15 to 27
Pannonian deposits		27

Soil parameters

Depth (m)	Density (kg/m³)
0-8	1900
8-18	2000
15-17	2100

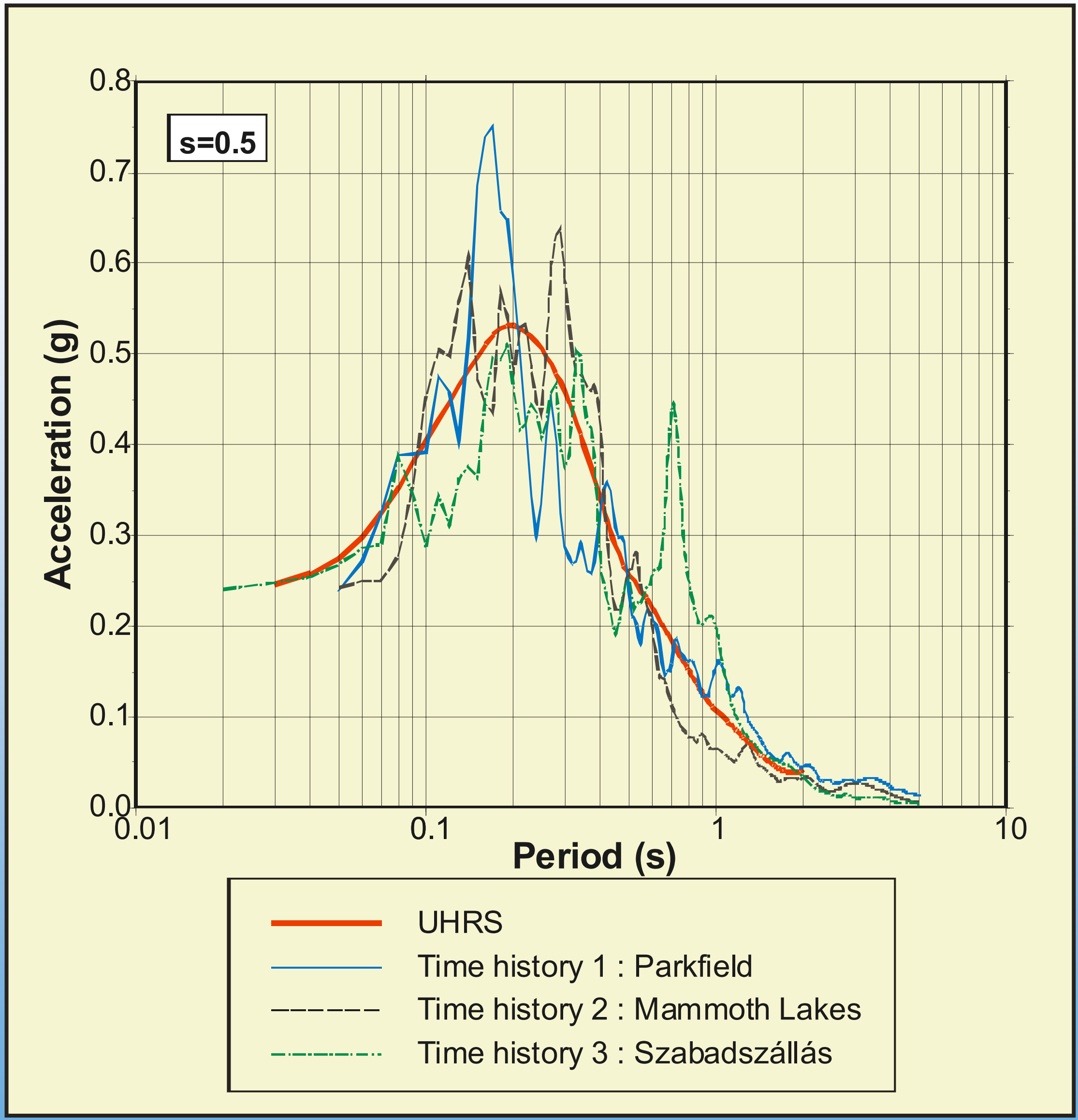


Shear modulus degradation and damping curves



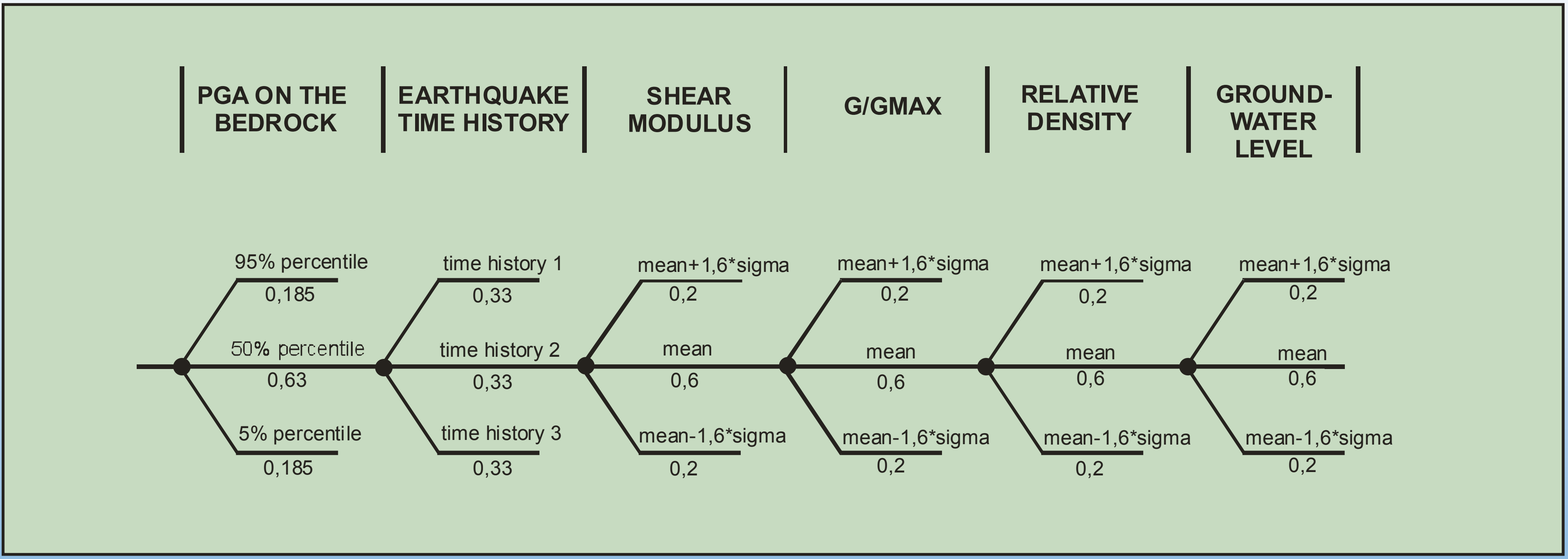
Soil parameter distributions versus depth

Input parameters – ground motion



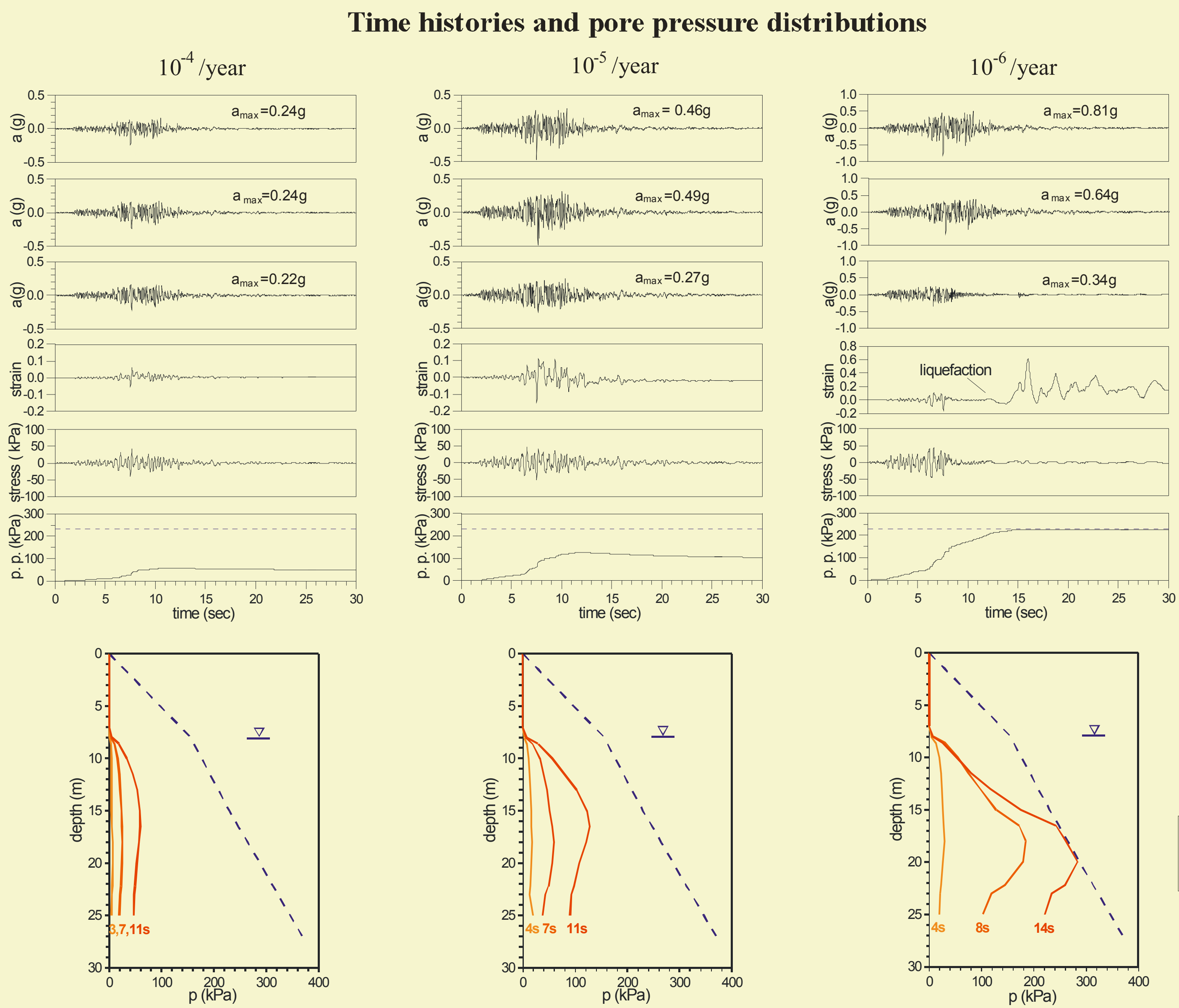
Bedrock UHRS computed for 10^{-4}/year probability level and the response spectra of the three scaled earthquakes used in the site response computations.

Logic tree


PGA ON THE BEDROCK
EARTHQUAKE TIME HISTORY
SHEAR MODULUS
G/GMAX
RELATIVE DENSITY
GROUND-WATER LEVEL
95% percentile
0,185
50% percentile
0,63
5% percentile
0,185
time history 1
0,33
time history 2
0,33
time history 3
0,33
mean+1,6*sigma
0,2
mean
0,6
mean-1,6*sigma
0,2
mean+1,6*sigma
0,2
mean
0,6
mean-1,6*sigma
0,2
mean+1,6*sigma
0,2
mean
0,6
mean-1,6*sigma
0,2
mean+1,6*sigma
0,2
mean
0,6
mean-1,6*sigma
0,2

Results

Site response analysis



Horizontal acceleration on the pannonian surface (bedrock)

Horizontal acceleration on the surface computed by total stress analysis

Horizontal acceleration on the surface computed by effective stress analysis

Shear strain (depth: 16.5m)

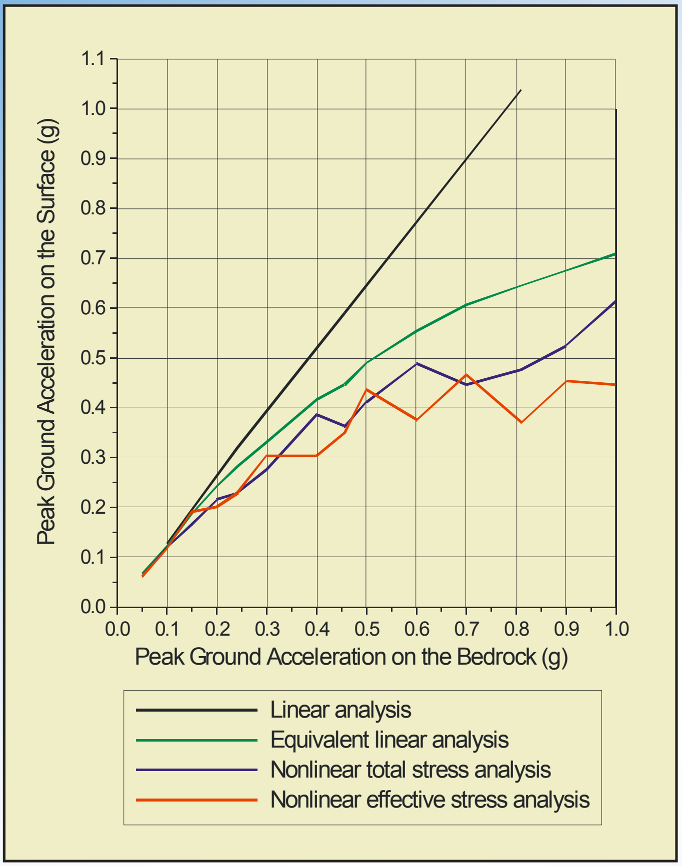
Shear stress (depth: 16.5m)

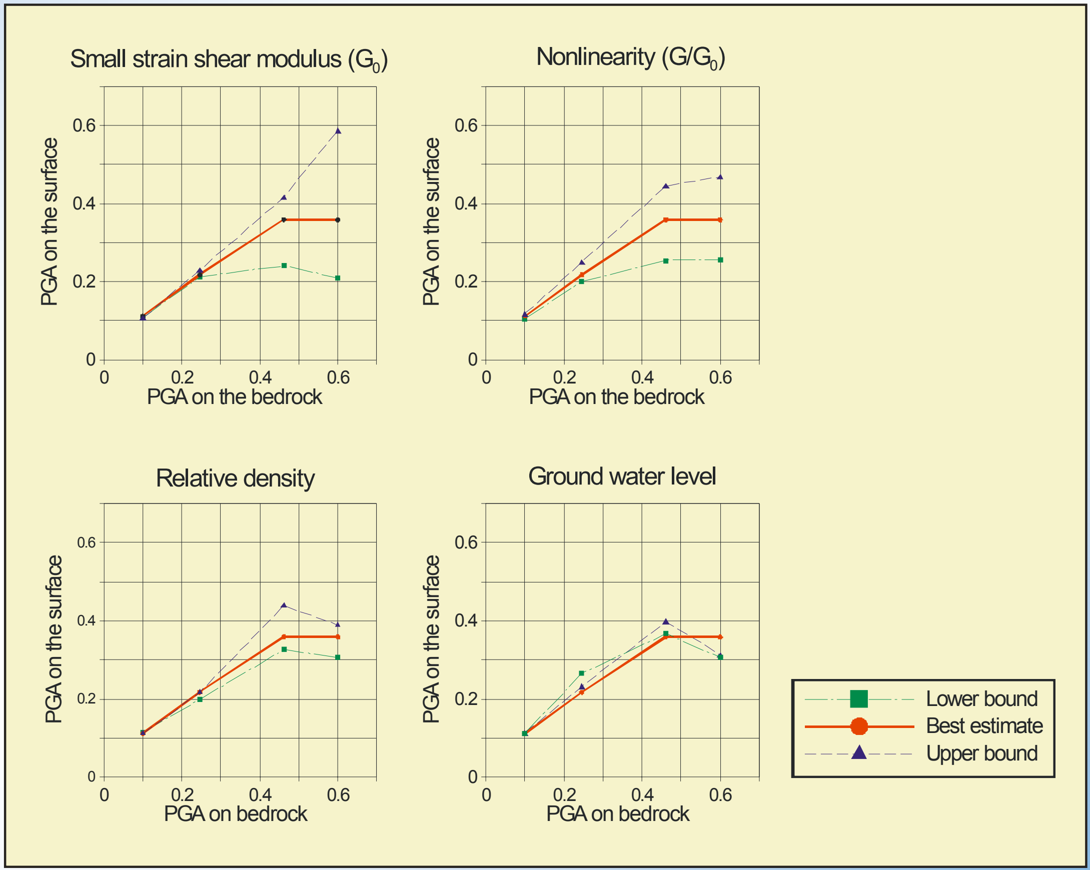
Pore pressure (depth: 16.5m)

Pore pressure distributions versus depth

effective pressure
ground water level

Results



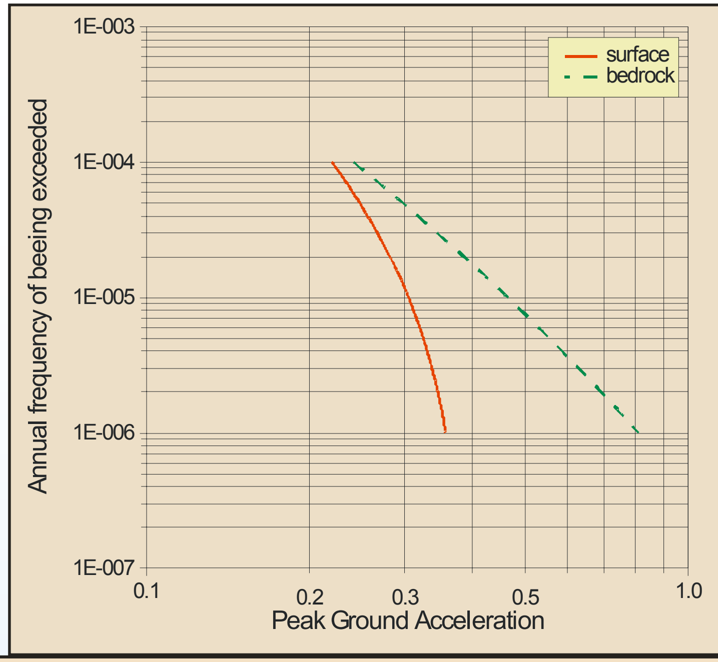


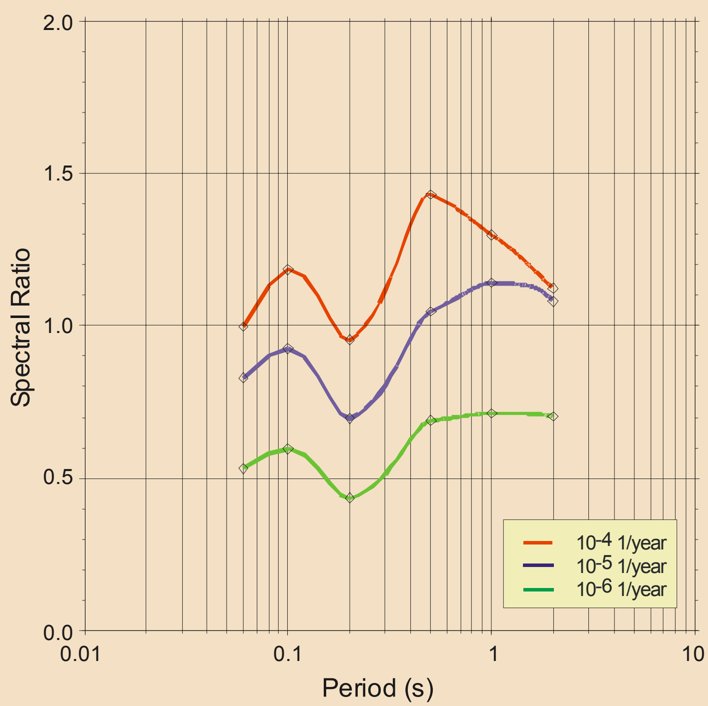
Peak ground accelerations computed by different analytical methods. Surface accelerations have been determined by averaging of the results given by the three applied earthquake.

Sensitivity of surface accelerations to shear modulus, nonlinearity, relative density profiles and ground water level using best estimate moreover the lower and upper bound profiles.

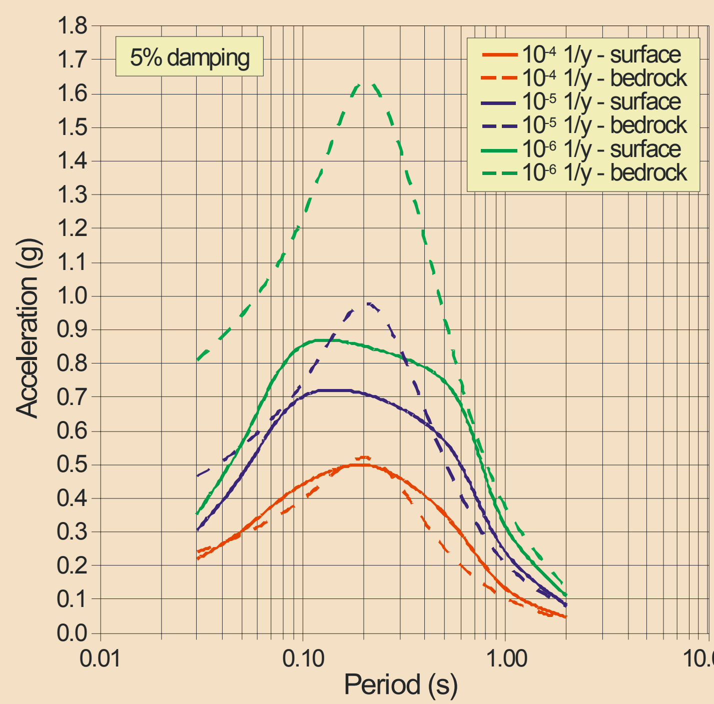
Results

Mean hazard curves computed for the surface and the bedrock.





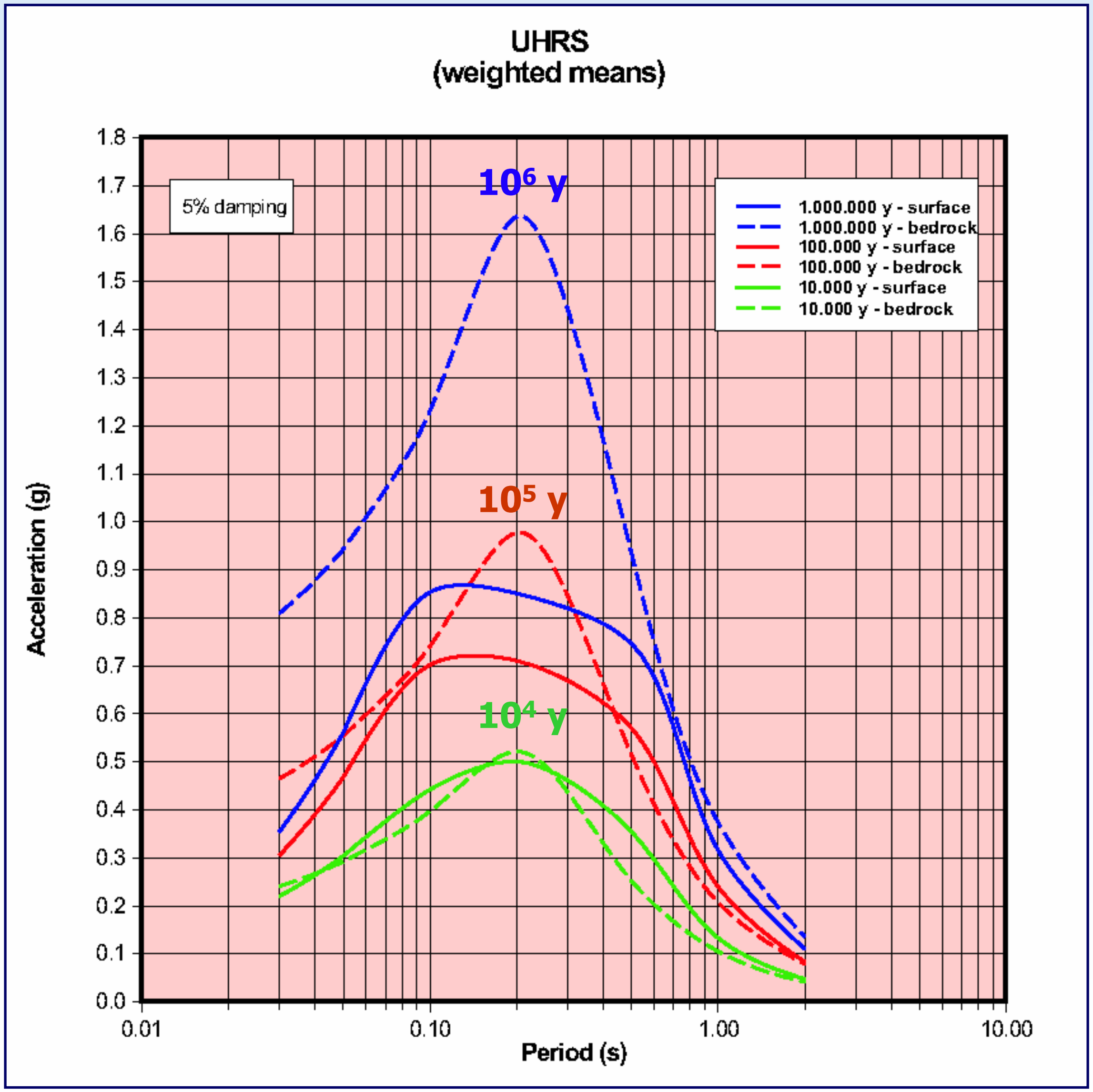
a)



b)

Best estimate (mean) spectral ratios (a) moreover the bedrock and surface UHRS (b) for the three different probability levels. Spectral ratios have two peaks between 0.06 and 2s. For 10^{-4} annual probability these peaks are above 1 therefore broadening of the spectrum can be seen on the surface. For 10^{-6} /year the entire spectral ratio curve is below 1 so the entire surface entire spectrum is below the bedrock UHRS.

Results



Comparison of best estimate (weighted mean) surface and bedrock Uniform Hazard Response Spectra (UHRS) for 10^{-4}, 10^{-5} and 10^{-6} probability with damping of 5% at Paks NPP site