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Secondary effects generated by earthquakes: Liquefaction occurrences in and around Hungary

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Abstract

Soil liquefaction have been observed and documented at least eight times during moderate to larger magnitude historical and recent earthquakes in Hungary. Surface manifestations of liquefaction were reported from Komárom (1763, 1783, 1822), Mór (1810), Érmellék (1829, 1834), Kecskemét (1911) and Dunaharaszti (1956) earthquakes. In the study, we give a brief description of these earthquakes and make available reports that demonstrate the occurrence of soil liquefaction. Where available, we describe local subsoil conditions and information regarding ground water level. Distribution of horizontal ground accelerations possibly caused by these historical earthquakes has been modelled by ShakeMap program. Simulations indicate horizontal PGA of 0.2 – 0.3 g in areas where liquefaction occurred.

Keywords Earthquake · Liquefaction · Acceleration · Subsoil

1. Introduction

Although, most of the building damages are caused by ground shaking during earthquakes, different secondary effects such as soil failures can also product serious consequences. Soil failures include rock falls, landslides, surface cracks, and liquefaction that probably cause the most serious damages. The shaking can be amplified by loose surface layers and lateral inhomogeneities.

Liquefaction usually occurs at loose saturated granular soils, where the strong earthquake shaking decreases the pore space. This densification increases pore-water pressure between the soil grains in undrained conditions. In this case vertical effective stress decreases entailing descent of shear strength. If the pore-water pressure rises to a level approaching the weight of the overlying soil, the granular layer temporarily behaves as a viscous liquid rather than a solid medium. Adverse effects of it can take many forms including flow failures, lateral spreads, ground oscillation, loss of bearing strength and settlement. In flat land, the liquefaction phenomenon is often accompanied by flood of ditches by wet sand, sand boils, mud volcanoes, soil settlements, etc.

The most susceptible types of sediments are the clay-free deposits of sands and silts; occasionally gravels can also liquefy.

Liquefaction occurs worldwide, generally during moderate to great earthquakes. In case of historical earthquakes, it can be recognized from the contemporary records of eyewitnesses and from different imageries.

Appearances of liquefactions can also be observed during moderate earthquakes (M 4.5-5) under unfavorable soil conditions and high groundwater level. Empirical boundary equations between magnitude (M) and maximum distance (R_{max}) for liquefaction have been developed by Kuribayashi and Tatsuoka (1975), Papadopoulos and Lefkopoulos (1993), Galli (2000) and Wang et al. (2006) from liquefaction induced phenomena that occurred during past earthquakes. The equations show that this type of ground failure can already happen during earthquakes of magnitude about 4.5 within a narrow epicentral area. For example, Wang et al. (2006) relationship is described by Eq. 1. According to this, liquefaction can occur within 20 km and 56 km in case of magnitude 5 and 6, respectively.

$$\log R_{max} = 2.05(\pm 0.1) + 0.45M \qquad (1)$$

Hungary, or as geographically mostly referred, the Pannonian Basin is situated in the territory between the high seismicity Mediterranean area and the East European Platform which can be treated as nearly aseismic. Based on the magnitude recurrence parameters, the region can be characterized as a seismically moderately active area (Tóth et al. 2002). In the 45.5-49.0 N and 16.0-23.0 E bounded geographical region of 206,117 km^2 area (Fig. 1), the return period of magnitude 6 earthquake is about 125 years while magnitude 5 events occur in every 15 years on average. The average annual number of magnitude 3 earthquakes is 4, whilst of magnitude 2 events is about 30. Majority of the events occur primarily between 6 and 15 km below ground level and many occurring between 6 and 9 km. In the Pannonian Basin, the picture inferred from focal mechanism solutions is rather diffuse, however thrust and strike-slip faulting seems to be dominant; the NNE-SSW and NE-SW directions of maximum horizontal stresses are typical.

Earthquake damage statistics show that the frequency of high damage earthquake (M 5.5-6) is about 40-50 years, while moderately damaging earthquake occur in every 15-20 years in Hungary.

Most part of Hungary are low-lying plains covered by young Holocene fluvial sediments with high ground water level. Consequently, the area is disposed to development of liquefaction. Despite the moderate seismicity, several liquefaction cases have been documented during larger historical earthquakes, for example in Komárom (1763, 1783, 1822), Mór (1810), Érmellék (1829, 1834), Kecskemét (1911) and Dunaharaszti (1956) (Fig.1).

In this study, we give a brief description of these earthquakes and make available some reports that demonstrate the occurrence of soil liquefaction. Where available, we describe the local subsoil conditions and information regarding ground water level.

Most of the earthquakes listed occurred before the start of instrumental recordings. Macroseismic observations and contemporary records are the only primary information to reconstruct hypocenter data in case of these historical events.

Magnitudes, focal depth and shaking intensity are estimated from the macroseismic information. From engineering point of view, the major parameter for characterization of the quake is the horizontal ground acceleration caused by the earthquake. Two of the mentioned events, the 1911 Kecskemét and 1956 Dunaharaszti earthquakes already have instrumental hypocenter determination as they were recorded by the seismic network at the time. However, the dynamic range of those early analogue seismograph were relatively low, the instruments close to the epicenter were saturated. Consequently, we have to rely on macroseismic data to assess the maximum ground motion amplitudes even for these events. Alternatively, we can use analogues of recently recorded earthquakes.

Distribution of horizontal ground accelerations possibly caused by these historical earthquakes has been modelled by ShakeMap program (Field et al. 2003). After some calibration for the given local site conditions, the theoretical distributions of horizontal ground accelerations have been calculated for the particular magnitude and depth events. For the attenuation with distance, a mix of attenuation laws published by Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) have been used with weights of 0.2 – 0.2 – 0.6 respectively. During the simulation of ground acceleration, site effects were taking into account by V_{S30} (the average S wave velocity in the upper 30 m) distribution assessed from topographic slope (Wald and Allen 2007).

Attenuation relationships use momentum magnitude to describe the strength of the earthquakes. For events before digital recordings, Mw magnitude has to be estimated by us using available empirical formulae. Many of such regression formulae have been published for different magnitude measures or intensity (Ekström and Dziewonski 1988, Ambraseys and Free 1997, PEGASOS 2002, Bungum et al 2003, Grünthal et al 2009).

In the catalogue published by Zsíros (2000), Mm "macroseismic magnitude" is given for each early historical earthquake.

$$Mm = 0.68\ (\pm 0.02)\ I_0 + 0.96\ (\pm 0.07) \log(h) - 0.91\ (\pm 0.10) \qquad (2)$$

$$Ms = 1.03\ Mm + 0.02 \qquad (3)$$

In our working catalogue PEGASOS (2002) formula have been used to estimate Mw from Ms

$$Mw=(Ms+2.52)/1.37 \quad \text{if } Ms \leq 6.1 \qquad (4)$$

$$Mw=Ms \quad \text{if } Ms > 6.1 \qquad (5)$$

Grünthal et al. (2009) proposed Mw estimation directly from intensity and depth if available:

$$Mw = 0.667\ I_0 + 0.30 \log(h) - 0.10 \qquad (6)$$

or

$$Mw = 0.682\ I_0 + 0.16 \qquad (7)$$

if depth information is not available.

Based on a harmonization check of Mw within the central, northern, and northwestern European earthquake catalogue Grünthal et al. (2009) concluded that the generated Mw are mostly underestimated by about 0.1 magnitude units for Hungarian earthquakes.

2. Liquefaction occurrences and the simulated surface accelerations

2. 1. Komárom earthquakes of 1763, 1783 and 1822

On June 28, 1763 a strong earthquake occurred in Komárom. This was the largest known earthquake in Hungary. The intensity of the quake was IX on the EMS scale at the epicenter. According to Zsíros (2000), magnitude of 6.3 was estimated from macroseismic data what corresponds to Mw 6.5. The quake is likely to be linked to the Rába-Hurbanovo-Diósjenő structural line. Two different tectonic units are separated by the Rába-Hurbanovo-Diósjenő line (Varga et al 2001): the basement is formed by East Alpine formations from NW of the line, while Mesozoic formations usual in the Transdanubian Mountain belt can be found at SE directions. Based on geophysical studies, strike slip movements are suggested along the fault line.

The main damage was reported from the town of Komárom located on the left bank of the river Danube after the earthquake. The earthquake destroyed a third of the city, more than 120 were wounded and 63 fatalities were also recorded. Two-three storey public buildings and houses of rich people were seriously damaged. The simple one-storey houses of poorer people that were constructed from wood and adobe, suffered only less damages (Szeidovitz 1990).

In addition to building damage, soil liquefaction and damage resulting from liquefaction can be concluded from contemporary accounts. A collection of contemporary reports can be found in the book of "*A Kárpát-medencék földrengései, 455-1918*" (The earthquakes of the Carpathian Basins, 455-1918) published by A. Réthly in 1952. Exaggeration and contradiction can be observed in these reports sometimes, but the manifestations of liquefaction in the surface are clearly recognizable.

Based on the reports, many cracks were formed on the surface from which water and muddy, blackish-brown sand came up to the surface. 5 feet high shot of water in arm thickness was observed along the Danube and tiny mud volcanoes arose on the floodplain.

Walking was difficult due to the water and sand on the ground in west of the city of Komárom. The wells got out of water and then filled with sand in the city. Some streets sank approximately by two inches. Building damage due to lateral spreading can be inferred clearly at the old castle. According to the reports, the confluence bastion, "*the turtle's tail*" (Fig. 2) located at the firth of Danube and river Vágh came off and sank down to a depth of three feet. Sand and water came up through the resulting gap which flooded the surrounding castle moat (called Infant-Schantz) in 3-4 feet height in a few minutes. The brownish-black color of the sand which came to the surface, and the sulphurous odor regularly mentioned in the reports both suggest that organic sludge sand had also been brought to the surface.

The liquefaction occurred during the earthquake was fairly extensive. There are reports of liquefaction phenomenon not only from Komárom but from a 55 km NEE elongated area from the town of Győr to Madar (Modrany). However, most of the reports came from the left bank of the river Danube (Fig. 3).

Upcoming sandy water from wells and sand boils were observed at Révfalu (nowadays this village is part of the town of Győr), Csallóköz (Žitný ostrov in Slovakia), Nemesolcsa (Zemianska Olča), Nagykeszi (Veľké Kosihy), Megyercs (Čalovec, formerly Mederč), Kolozsnéma (Klížska Nemá), Kiskeszi (Malé Kosihy), Keszegfalva (Kameničná), Guta (Kolárovo, formerly Guta), Ekel (Okoličná na Ostrove), Csicsó (Čičov), Csallóközaranyos (Zlatná na Ostrove), Örsujfalu (Nová Stráž) and Madar (Modrany) villages (Source: MTA CSFK GGI archive).

ShakeMap simulation of horizontal peak acceleration distribution of the earthquake is shown in Fig. 3. The calculation is based on the assumption that the epicenter of the quake was in Komárom. It is estimated that the maximum horizontal accelerations exceeded 0.3 g in 115 km^2 area of the epicenter. The horizontal PGA was greater than 0.2 g in an area of 900 km^2 and reached 0.1 g at about 5,000 km^2. The simulation resulted 0.1-0.15 g accelerations at Győr and at some settlements in Csallóköz (Žitný ostrov), but soil liquefaction is unlikely at such a low PGA. Consequently, the shaking intensity had to be greater at these sites. An explanation for the discrepancy is the possible strong site effects when the local soil conditions substantially amplify the acceleration on the surface. On the other hand, these data support the assumption that the epicenter of the earthquake was probably located NW from Komárom as proposed by Varga et al. (2001) based on the damage distribution.

A number of larger aftershocks occurred in a few days after the main quake. Magnitude values of these events could not be determined. However, the magnitude of the aftershock occurred on July 9 has to be at least M5 according to equation (1) as liquefactions were reported from Győr and Komárom located from each other as far as 40 km (Réthly 1952).

The second largest earthquake was reported from Komárom on April 22, 1783. For the event, the catalogue by Zsíros (2000) gives VII-VIII epicentral intensity and 5.2 magnitude estimated from macroseismic data (Mw 5.8). The quake caused major damage in Komárom again, but the effects were limited to much smaller area than in the case of 1763 earthquake. Even though, the major aftershock was reported felt as far as from Kalocsa to the south, Eger to the east, Zsolna (Žilina) to the north and Vienna to the west. The strongly shaken area was about 60,000 km^2 (Zsíros 2004).

Small and large cracks have been observed (Réthly 1952) on the soil surface ejecting sandy water in Komárom and Lábatlan. The detected sand boils again suggest the occurrence of soil liquefaction. The formation of soil liquefaction was assisted that the ground water table was very high at the time of the earthquake. As reported by Grossinger, the earthquake was preceded by "*wet winter with lots of rain*". In late January, flood marched down the Danube and "*Upper Hungary*" was covered by thick layers of snow.

From January 1822, earthquake activity has intensified again in Komárom region, and higher activity lasted until the end of the year. The strongest quake (epicentral intensity VI; M

4.2, Mw 5.0) in the earthquake swarm occurred on 18 February 1822. It was observed again in Komárom that water level increased in the wells and some of them cast as Holéczy (1824) and Katona (1824) reported.

According to the results of geotechnical drilling near to the Komárom railway bridge, thick sandy layers was found at a depth between 4-17 m below the surface in the river bed. These sands have small coefficient of uniformity and are very prone to soil liquefaction. Both the clayey and silty layers above and below the sand layers and the intercalations cemented in the mud prevent drainage of pore water. These conditions favor the pore pressure increase and thus the formation of liquefaction.

The extension of these sand layers are less on the banks and have varied distribution. It is also important to note that the elevation of the left bank of the Danube is approximately 10 meters lower than on the right bank. Near to the river the groundwater level is determined by the water level of the Danube. Accordingly, the water table depth relative to the surface is much smaller on the left bank than on the right bank. Ground water levels of around 4-5 m below the ground surface were measured in the boreholes on the left bank while 10-18 m depth were typically measured on the right bank boreholes.

Because of the high water table favors the formation of soil liquefaction, these recently acquired geotechnical data can explain the fact that liquefaction observations have been reported only from the left bank of the Danube.

2. 2. Mór earthquake of 1810

The Mór earthquake occurred on January 14, 1810 and according to calculations, at 8 km depth. For the event, the catalogue by Zsíros (2000) gives epicentral intensity VIII and magnitude 5.4 estimated from macroseismic data (Mw 5.9). The earthquake caused fatalities too. Severe damages to buildings happened in a limited area, in Mór and Isztimér, mainly in the vicinity of Mór Graben. The main shock was followed by more than thousand aftershocks; most of which occurred in the region of Mór. The quake can be linked to the Mór Graben, which is still active, small earthquakes occur regularly in its surroundings.

Kitaibel and Tomtsányi (1814) described evidences of liquefaction, cracks and "springs" that had formed on clayey-sandy soils. According to their observations, liquefaction occurred in Bakonycsernye-Sikátorpuszta, Bakonycsernye-Mecsérpuszta and Nagyveleg but the exact places are not known. The topography of the area is varied and there are numerous streams on the seriously damaged area SW from Mór. Along the slow-flowing sections of the streams, Holocene sediments are deposited. Small fishponds can be found in the stream valleys which suggest shallow groundwater levels on those places. They favor the local occurrence of soil liquefaction, but more accurate conclusions may not be drawn in the lack of more concrete data.

The maximum horizontal acceleration exceeded 0.25 g in the vicinity of the epicentre according to ShakeMap simulation of the earthquake (Fig. 4). The maximum acceleration was greater than 0.1 g, approximately on an area of 1,900 km^2.

2. 3. Érmellék earthquakes of 1829 and 1834

The small Érmellék seismic zone is located along the current Hungarian-Romanian border. Two major earthquakes are known on the area, the 1829 and the 1834 events. The main tectonic line crossing Érmellék (called Mobile Zone) is located between the hill areas of Szilágyság (Sălaj), the Great Hungarian Plain and the depression of Sárrét (Szeidovitz et al. 2002). The continuation of the Mobile Zone is the Gálospetri (Galoş petreu) Graben in Romania. This Graben has a very sharp boundary in the north direction with 600-1000 m difference in the level of Upper Pannonian surface, which separates it from the Piskolti block. According to Szeidovitz, these two earthquakes occurred in this deep graben.

The first stronger quake was generated on July 1, 1829. Its maximum intensity was estimated to be between VII and VIII in Érendréd (Andrid), Érdengeleg (Dindesti), Érvasad (Văsad) and Iriny (Irina) villages. The magnitude computed from the epicentral intensity was 4.9 (Zsíros 2000) and its focal depth was estimated to 13 km (Mw 5.5). The earthquake caused serious damages on about an area of 6,000 km^2 (I ≥ VI EMS) and was felt on about 75,000 km^2 (Zsíros 2006). Liquefaction was observed in Dengeleg and Érendréd. According to István Nyíri (1835), many cracks formed on the ground surface from which bluish sands and water escaped to the surface but the water disappeared on the same day.

The second, much stronger earthquake occurred on October 15, 1834. The epicentral intensity of the quake was set to IX at the MSK scale. According to Zsíros (2000), magnitude of 6.3 was estimated from macroseismic data (Mw 6.5). Greatest damages occurred in Érdengeleg (Dindesti), Érendréd (Andrid), Gálospetri (Galospetreu) and Piskolt (Pişcolt) settlements. The quake was felt on about 230,000 km^2 and 34,000 km^2 area suffered serious damages. The aftershocks have lasted for nearly five years. According to the descriptions, extensive liquefaction developed in Piskolt (Piscolt), Béltek (Beltiug), on the meadow between Vasad and Gálospetri, and in the region of Érendréd and Érdengeleg (Selley 1835; Tatay 1835). Surface cracks, sand boils, sand and mud volcanoes covering large areas were described in all locations.

Exact places of the soil liquefaction and thus the properties of the layers suffered liquefaction are not known. Érmellék is in some places flat, in other hilly area between Berettyó and Ér. The area called Ér Plains lies in a huge valley that spreads out from the river Kraszna to Berettyó. Especially the Szamos, Tisza and Kraszna rivers played a key role in its development. It was a marshy, swampy area before draining out of the 1960s so the area is covered by a very young, Holocene sediment. The ground water level is high, which favors the formation of soil liquefaction.

Distribution of horizontal acceleration of the 1834 Érmellék earthquake computed by ShakeMap simulation is shown in Fig. 5. The largest acceleration exceeded 0.3 g in the vicinity of the epicenter on about 20 km^2. The acceleration was larger than 0.2 g almost on an area of 1,000 km^2 and reached 0.1 g on about 6,800 km^2.

2. 4. *Kecskemét earthquake, 1911*

This earthquake occurred NE from Kecskemét on July 8, 1911 at night. Epicentral intensity value of VIII EMS has been determined. The magnitude of the quake was 5.6 Ms (Mw 5.9) based on instrumental measurements, focal depth was 12 km. The earthquake was felt by the inhabitants in a territory of approx. 85,000 km^2 (I ≥ III EMS). The quake caused significant damages in an area of approx. 6,000 km^2 (I ≥ VI EMS) (Zsíros 2009). 28% of the urban houses have been damaged.

Liquefaction (mud-volcano) could also be observed at the epicentral area after the quake that was described with scientific preciseness in the publications of Ballenegger (1911), Cholnoky (1911) and Réthly (1911, 1912).

The mud-volcano caused by liquefaction had been considered as the epicentre by Réthly (1912) and its co-ordinates had been also specified by him (λ=19° 38' 29", φ=46° 55' 40", h=130 m). The site of the mud-volcano with a diameter of 1.5 m had been excavated as shown in the photo in Fig. 6. Top- and side-views can be found in Fig. 7.

In his study Ballenegger (1911) describes the characteristics of the mud-volcano and surrounding subsoil: *"The sand-volcano had been observed in Kisnyíri dűlő NW of Kecskemét. Here small sand-chines with a maximum height of 3 meters tend in NW-SE direction. Their surface soil is nut-brown sandy loam. Between the sand-chimes in a small basin in a plough-land belonging to Baranyi farm, some light bluish-grey wet sand was discovered in an amount of 25-30 litres on the morning after the quake which found its way to* *the surface through a fissure with a length of 1.5 m and a width of 0.5 cm, its color jarring with the brown soil. ... To find out the original depth of this sand, I have bored a hole on the site. The profile of the borehole is the following:*

0 — 30 cm	«	*brown sandy loam,*
30 —150 cm	«	*darker adherent sand,*
150 — 170 cm	«	*yellow marly sand with small calcic concretions,*
170 — 250 cm	«	*yellow fine-grained sand with black loadstone grains,*
250 — 450 cm	«	*fine-grained blue sand with thin argillaceous bands,*
450 — 600 cm	«	*coarse bluish grey quartz-sand, which is totally identical to the one welled to the surface*

The level of ground water is 5 m here. I could find the same bluish grey coarse sand in stuffs that had been extracted when making wells in this region. I have been monitoring the borehole for several days but there have been no signs of gas generation. As a summary: a small crack evolved here during the earthquake, through which a small amount of sand was taken by the coming up groundwater. No any luminous phenomenon could accompany it. The fissure was closed up soon after the quake. The level of the ground water had raised in wells and the sand taken by the water inwashed the well, but after 24 hours normal water level was recovered."

According to this report liquefaction occurred in the coarse bluish quartz-sand formation starting at a depth of 4.5 m, below the ground water level at 5 m. The existence of clay bands in the upper fine-grained sand formation could bear a part in the evolution of great pore pressure keeping porewater from drainage.

According to ShakeMap simulation maximum horizontal acceleration could be around 0.2 g in the epicentral area (Fig. 8).

Ballenegger's (1911) observations taken in municipal cemeteries are also notable:
"The only fact that could be positively determined was the upward direction of shocks, as at several locations obelisks fitted to pedestals with iron pins fallen down without any deformation of the iron pins. This could happen only if the upward shock coming from below ejected the obelisk."

According to this report maximum vertical acceleration should have been greater than 1 g.

2. 5. Dunaharaszti earthquake, 1956

In the 20th century, one of the most significant earthquakes in Hungary was the Dunaharaszti earthquake on 12th January, 1956. The highest intensity of the Ms 5.6 (Mw 5.9) event was about VIII on the EMS scale (Zsíros 2000). Instrumental epicenter was located near Dunaharaszti, in Dunaharaszti – Taksony – Szigetszentmiklós triangle. The highest damage was also reported from these three settlements. Focal depth of 14 km has been estimated from instrumental data.

The Dunaharaszti earthquake was felt throughout Hungary with the exceptions of the eastern edge and some western parts of the country. It was also reported felt from most part of Slovakia. Building damage occurred within a radius of 37 kilometers in an average ($I \geq 5$). A few damage of poorer quality chimneys were reported from as far as Sződliget to the north, and Kalocsa to the south. In the epicentral area in Dunaharaszti, out of the 3,500 buildings some 3,144 suffered damage. Although, most of the buildings were adobe mud walls constructions and houses without foundations at the time. The quake claimed two casualties, many wounded, and approximately 500 people homeless. After the main shock, hundreds of smaller and larger aftershocks occurred in the region, among which was more noticeable and some felt as well.

Formation of cracks indicating soil liquefaction, as well as sand and mud volcanos have been observed at some settlements particularly in areas close to the Danube. Several cracks of SSW-NNE direction have been observed in the soil in the inn yard of "*Liget Csárda*", at Taksony side of small island in the Soroksári Danube branch (Somogyi 1956). Eyewitnesses claimed that water was ejected into high from the fountain of the Inn. Bluish gray silty sand came to the surface through the 5-8 cm holes found behind the inn and N from the inn (Fig. 9).

At Szigetszentmiklós, sand and mud spurt and siltation of dug wells were observed around Szilágyi, Árpád and Rákóczi streets, near to the Suburban Railway.

The same phenomena were observed in Damjanich and Duna streets (Fig. 10), in areas along the Danube, at Dunaraszti.

In the 1980s and 90s, detailed engineering seismological studies were done in order to examine the relationship between the subsoil and the damage distribution generated during the quake (MÁELGI 1993). A number of engineering geophysics and probing were carried out in the area, as well as changes in the water table were studied. A total of five geological cross-sections have been compiled in the field of Dunaharaszti, two of them parallel with the Danube, and three perpendicular to the river. However, none of the sections go directly into the places where the soil liquefaction was documented. The cross-section located in the western part of the town is parallel to the Danube, and lies 200 m to the east from the Duna street location of documented (Fig. 10) soil liquefaction. On this basis, the loose surface is covered by 1.6-1.7 g/cm^3 density of quicksand with variable 2-5 m thickness. Below, 1-2 m silty, and then again variable thickness of sand-gravel terrace formations. These granular terrace formations are underlain by clay and silty clay at 4-9 m depth below the surface. The depth is decreasing towards the north part of the city. The water table depth ranged from 2-5 m.

These results clearly show that the local site conditions are specifically favorable for liquefaction development in the area.

ShakeMap simulation of horizontal peak ground acceleration distribution of the Dunaharaszti earthquake resulted PGA > 0.2 g in the 220 km^2 area of the epicenter. The horizontal PGA was greater than 0.1 g in an area of 2,600 km^2 and reached 0.05 g at about 8,000 km^2. (Fig. 11)

3. Summary

At least eight liquefaction cases have been documented during historical earthquakes in Hungary and near to the current border. Liquefaction phenomenon (flood of ditches by wet sand, sand boils, mud volcanoes, soil settlement) were reported from Komárom (1763, 1783, 1822), Mór (1810), Érmellék (1829, 1834), Kecskemét (1911) and Dunaharaszti (1956). The magnitude of these earthquakes were in the range of 5.4 – 6.5 Mw. The liquefaction was typically confined to the vicinity of the epicenter, and the intensity was mostly small. The exceptions are the two earthquakes stronger than magnitude 6. According to the reports, the 1763 Komárom and the 1834 Érmellék earthquakes caused soil liquefaction which could be extended to a greater extent and a large area. Building or structural damage caused by the liquefaction phenomenon is proven only in the case of 1763 Komárom earthquake. Based on the descriptions, the old castle near to the firth of Danube and river Vágh has suffered severe damage due to lateral spreading.

The ground accelerations simulations by ShakeMap show horizontal PGA of 0.2 – 0.3 g in areas where liquefaction occurred. However, at some cases the calculated horizontal PGA were only in the range of 0.1 – 0.2 g. This is due to the fact that the modeling can only take into account the variability of the local subsoil through the V_{S30} values determined from topographic slopes.

At most cases of the earthquakes, the exact places where the formation of soil liquefaction took place is not known and the precise physical parameters of the layers are neither available. However, in general it can be concluded that liquefaction always occurred in an area where the subsoil was composed of very young sandy, silty sediments and where the water table was high.

Although the territory of Hungary is seismically moderately active, liquefaction as a secondary earthquake effect is one of the main concerns during site characterization of major industrial/nuclear installations due to the fact that most part of the area is low-lying plains covered by young Holocene sediments with high ground water level.

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Maps were generated with the Generic Mapping Tools (GMT) data processing and display software package (Wessel and Smith 1998).

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Legends

Fig. 1 Seismicity of Hungary. Liquefaction have been documented during earthquakes of Komárom (1763, 1783, 1822), Mór (1810), Érmellék (1829, 1834), Kecskemét (1911) and Dunaharaszti (1956).

Fig. **2** Lateral spreading during the 1763 Komárom earthquake. The confluence bastion, "the turtle's tail" located at the firth of Danube and river Vágh came off and sank down to a depth of three feet. Surface cracks can be seen on the surface on the left side of the Vágh (upper part) (Drawing of Josef Kastner).

Fig. 3 ShakeMap simulation of horizontal peak ground acceleration (PGA) distribution of the 1763 Komárom earthquake. White diamonds on the map indicate liquefaction sites.

Fig. 4 ShakeMap simulation of horizontal peak ground acceleration (PGA) distribution of the 1810 Mór earthquake. White diamonds on the map indicate liquefaction sites.

Fig. 5 ShakeMap simulation of horizontal peak ground acceleration (PGA) distribution of the 1763 Érmellék earthquake. White diamonds on the map indicate liquefaction sites.

Fig. 6 The place of dug up sand volcano generated during 1911 Kecskemét earthquake (photo from MTA CSFK GGI Archive)

Fig. 7 Side and top view drawing of sand volcano generated during 1911 Kecskemét earthquake (Réthly 1911)

Fig. 8 ShakeMap simulation of horizontal peak ground acceleration (PGA) distributionof the 1911 Kecskemét earthquake. White diamonds on the map indicate liquefaction sites.

Fig. 9 Bluish gray silty sand came to the surface through the 5-8 cm holes at Taksony (photo from MTA CSFK GGI Archive)

Fig. 10 Soil liquefaction in Duna street at Dunaharaszti (photo from MTA CSFK GGI Archive)

Fig. 11 ShakeMap simulation of horizontal peak ground acceleration (PGA) distribution of the 1956 Dunaharaszti earthquake. White diamonds on the map indicate liquefaction sites.

Figure 1.

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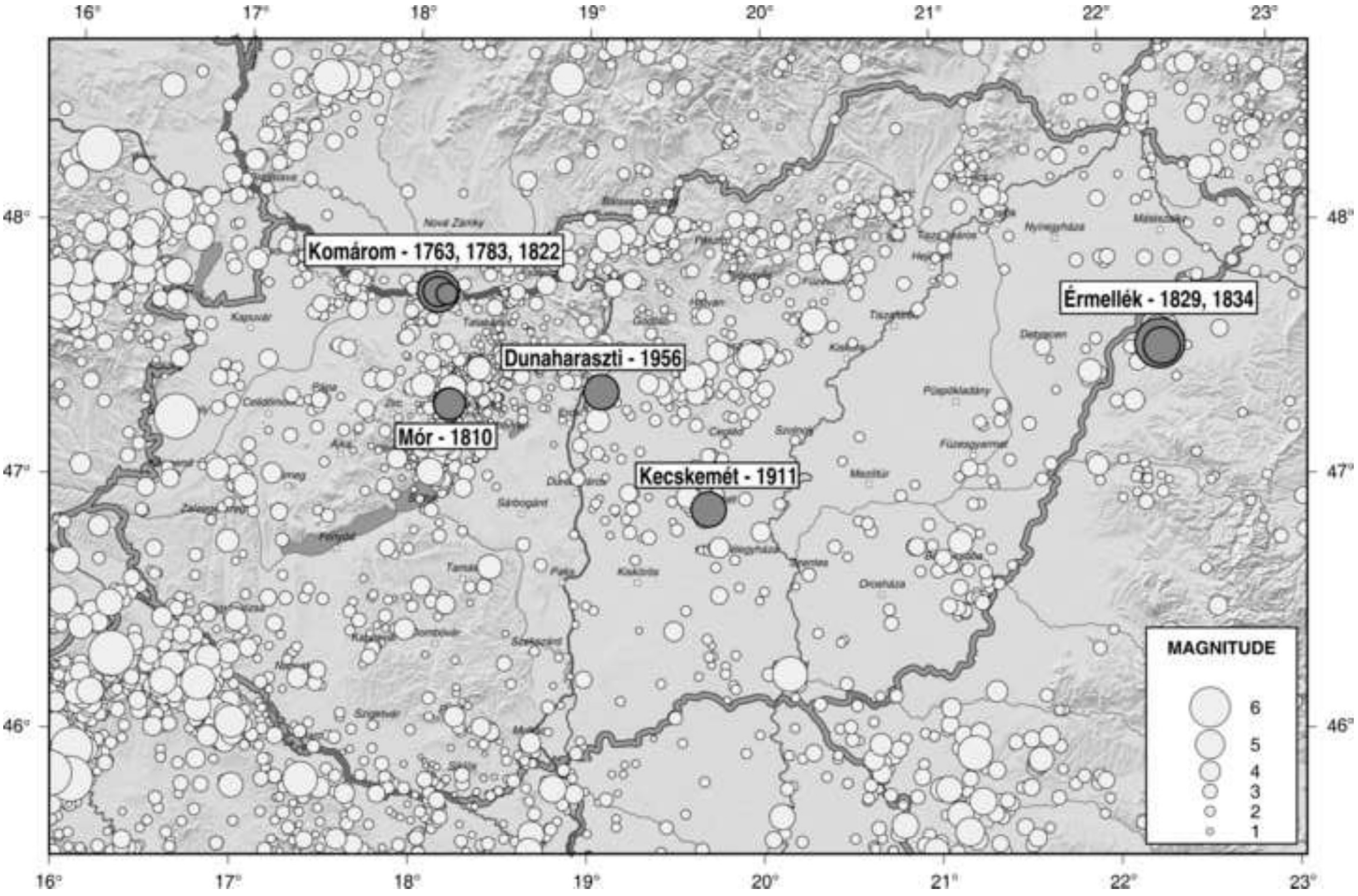

Figure 2.

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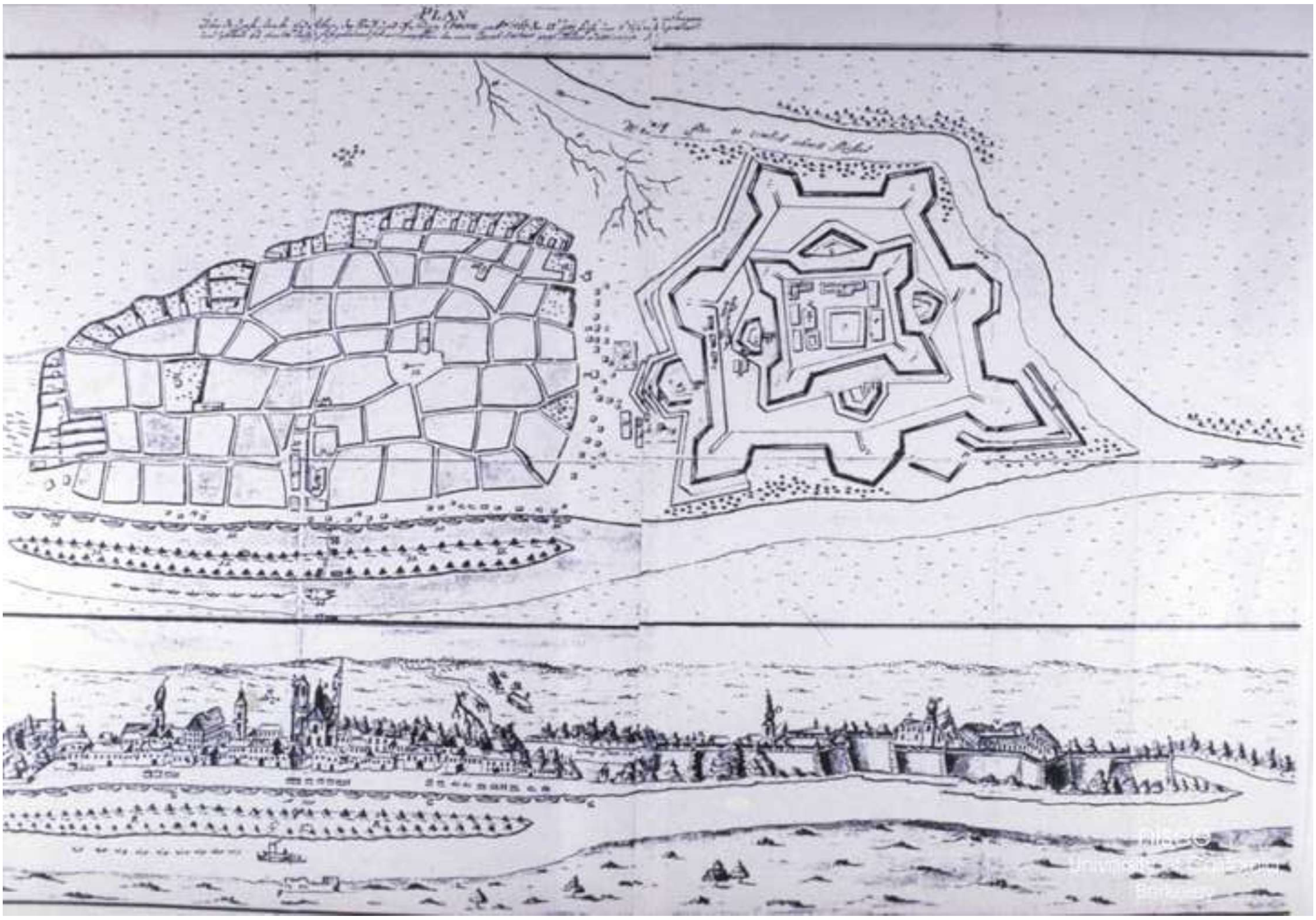

Figure 3.

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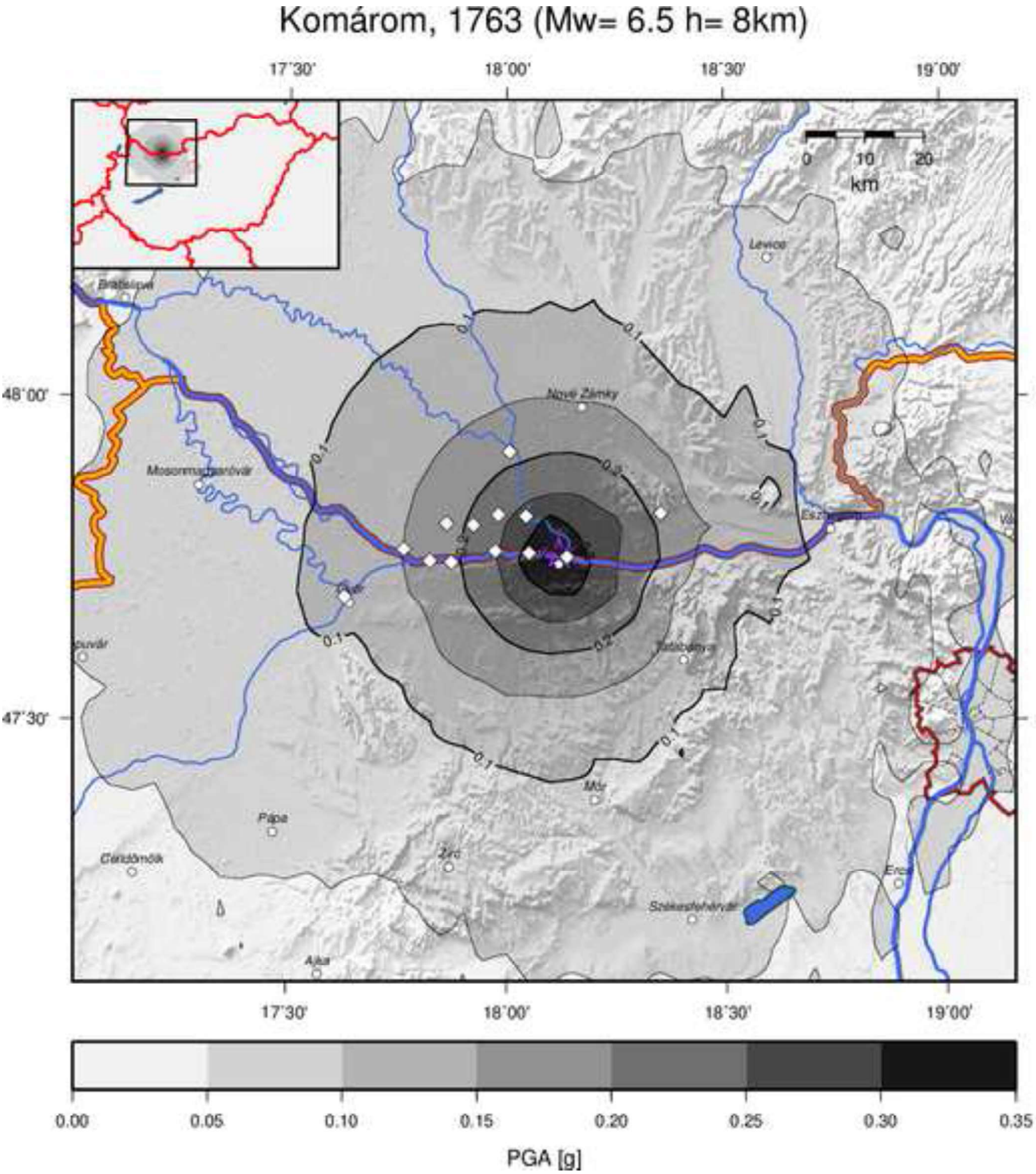


Figure 4.

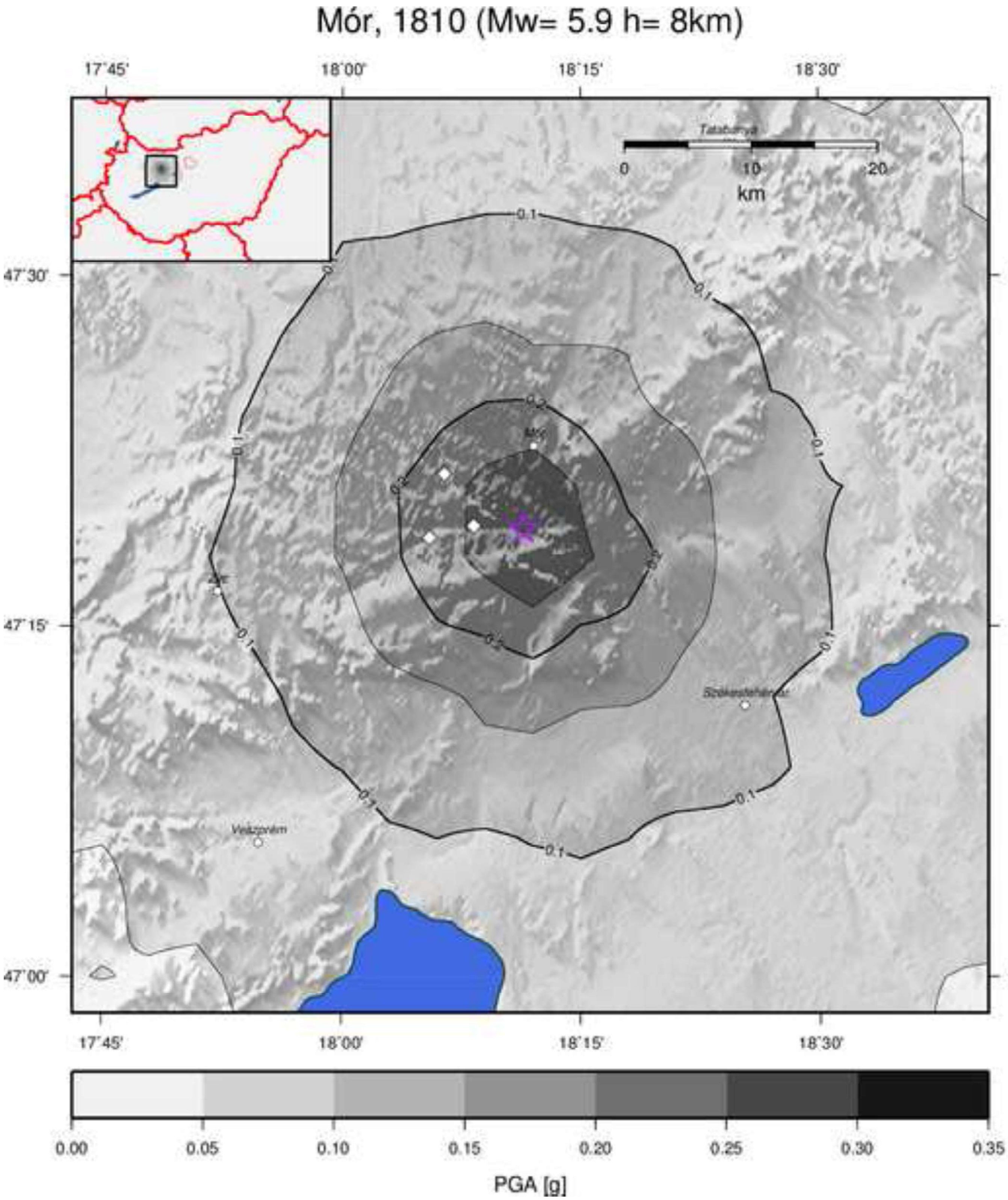

Mór, 1810 (Mw= 5.9 h= 8km)
17˚45'
18˚00'
18˚15'
18˚30'
47˚30'
47˚15'
47˚00'
0
10
20
km
Tatabánya
Mór
Székesfehérvár
Veszprém
0.1
0.2
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
PGA [g]

Figure 5.

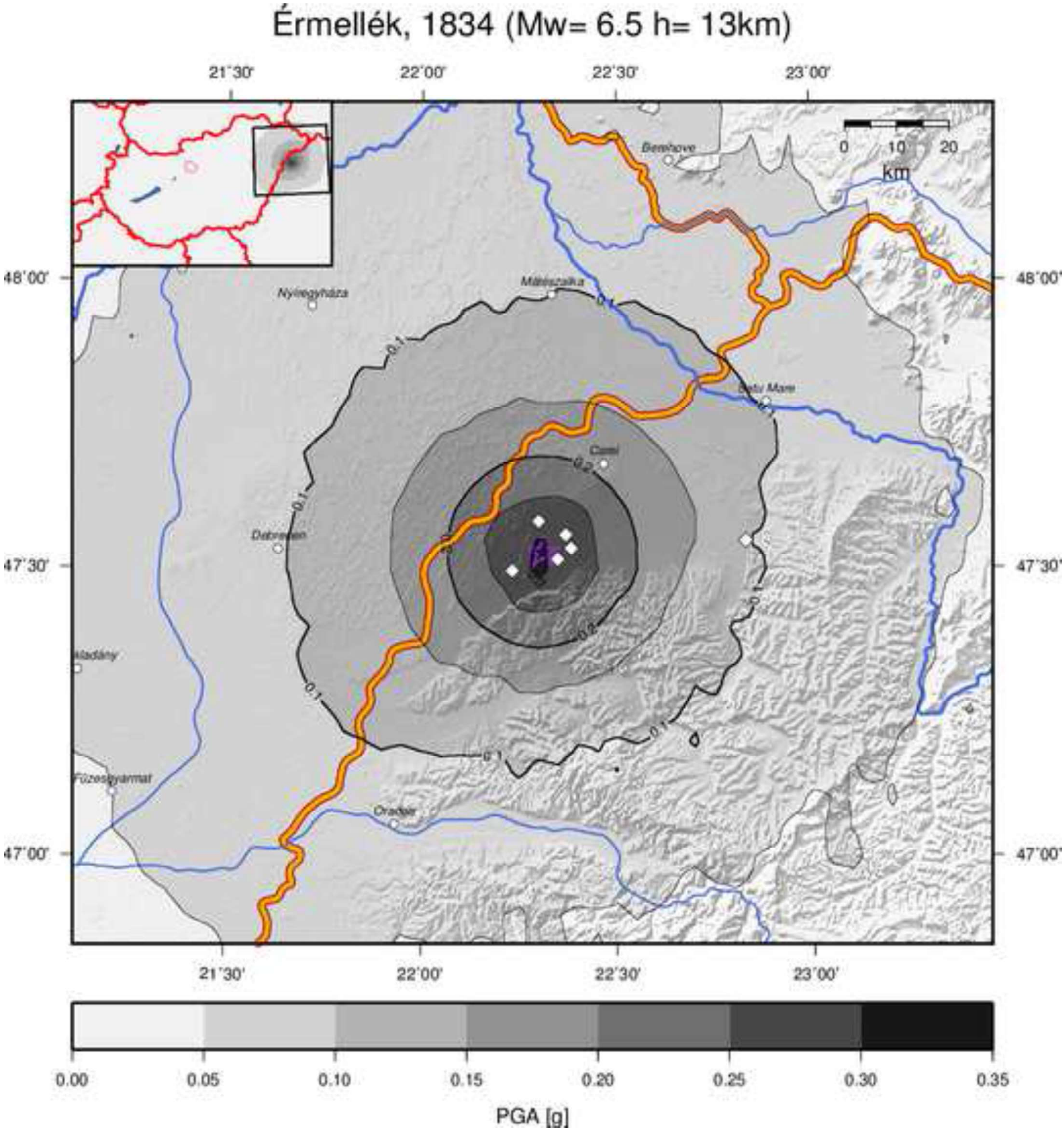

Érmellék, 1834 (Mw= 6.5 h= 13km)
21˚30'
22˚00'
22˚30'
23˚00'
48˚00'
47˚30'
47˚00'
0
10
20
km
Berehove
Mátészalka
Nyíregyháza
Satu Mare
Carei
Debrecen
Oradea
Füzesgyarmat
ladány
0.1
0.2
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
PGA [g]

Figure 6.

Figure 7.

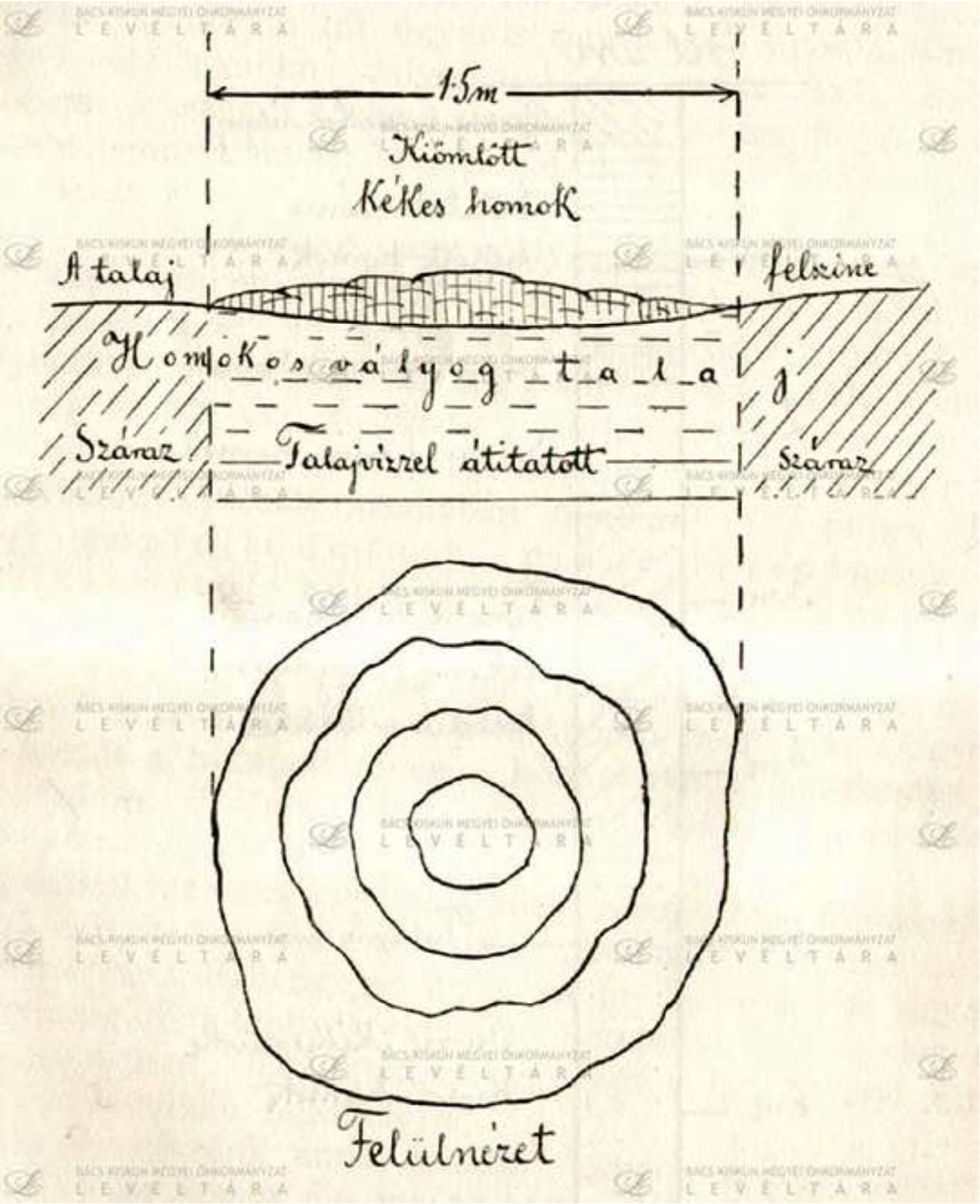

1·5m
Kiömlött
Kékes homok
A talaj
felszíne
Homokos vályog talaj
Száraz
Talajvízzel átitatott
Száraz
Felülnézet

Figure 8.

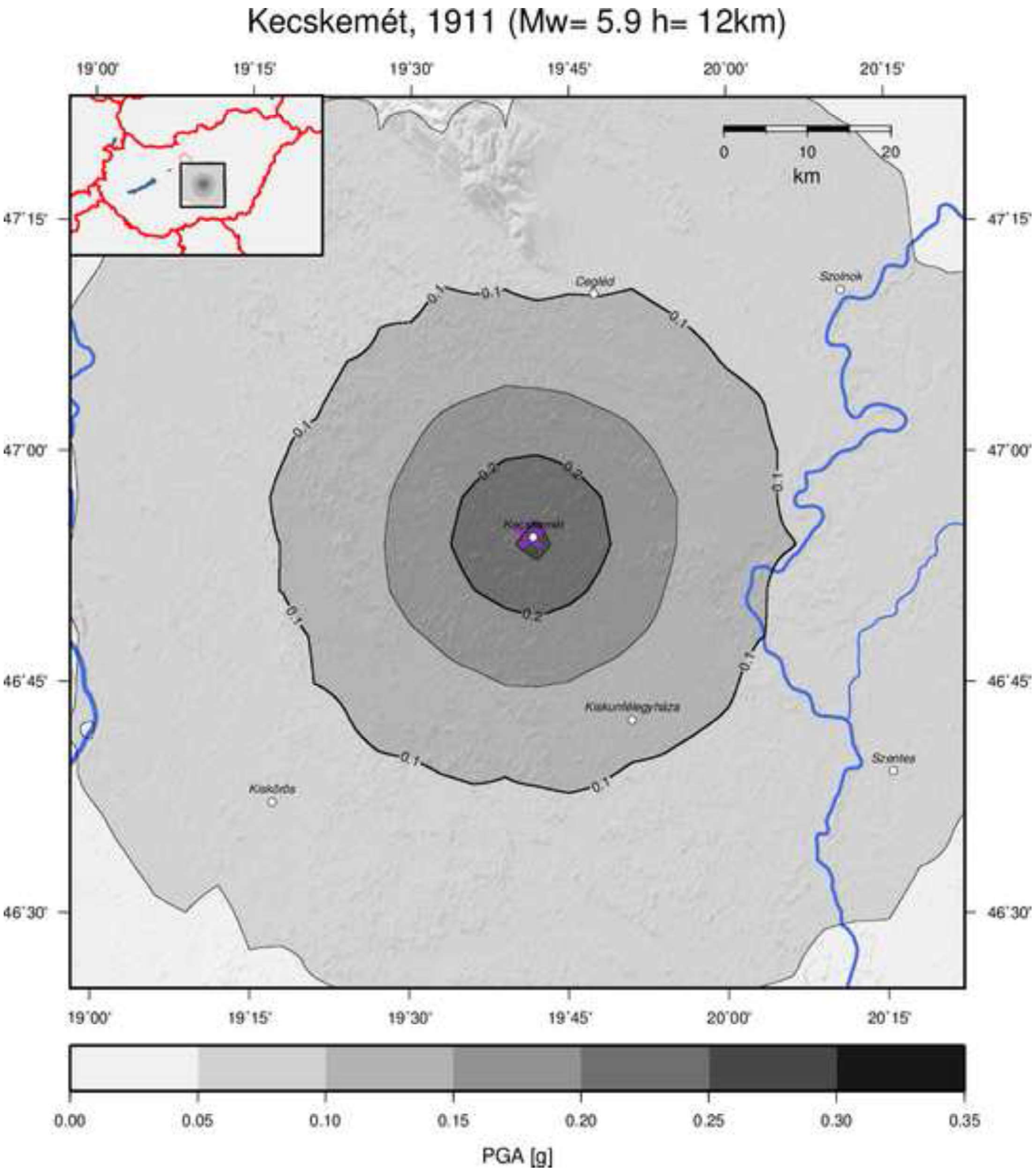
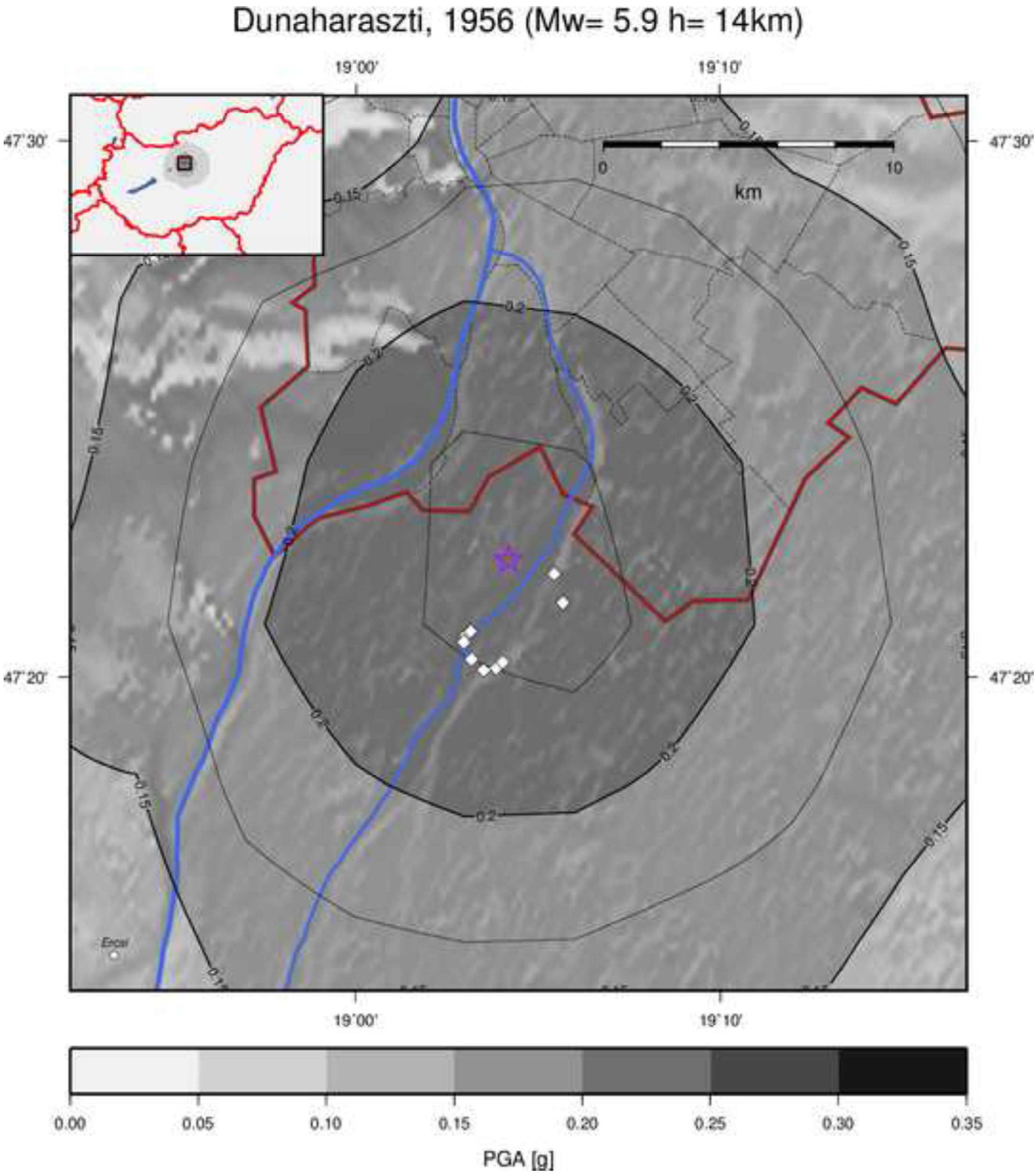

Kecskemét, 1911 (Mw= 5.9 h= 12km)
19°00'
19°15'
19°30'
19°45'
20°00'
20°15'
47°15'
47°00'
46°45'
46°30'
0
10
20
km
Cegléd
Szolnok
Kecskemét
Kiskunfélegyháza
Szentes
Kiskőrös
0.1
0.2
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
PGA [g]

Figure 9.
Click here to download high resolution image

Figure 10.

Figure 11.


Dunaharaszti, 1956 (Mw= 5.9 h= 14km)
19°00'
19°10'
47°30'
47°20'
0
10
km
0.15
0.2
Ercsi
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
PGA [g]