

On the magnitude and possible return period of the historical earthquake in ancient Savaria, 455 AD (Szombathely, West Hungary)

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KEYWORDS

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Abstract

In 455 AD a strong, presumably $M \geq 6.0$, earthquake occurred in or near the ancient town Savaria, the present Szombathely, West Hungary. According to the certainly incomplete earthquake catalogue, since then no similar significant seismic event occurred during the last 1500 years in this area which is currently considered inactive. Conclusions of this study are: (1) According to contemporary written historical sources (*Annales Ravennates* and biographical information about the life of Saint Severinus), the earthquake that destroyed Savaria and occurred in 455 AD had a magnitude of $M \geq 6.0$. (2) In order to support the aforementioned magnitude value calculations were necessary. As the historical seismicity of the area is not known sufficiently an independent geodynamical approach – in parallel to the Gutenberg-Richter relationship – was used to estimate the return interval of earthquakes $M \geq 6$. It was found in both cases that in the Szombathely region the recurrence time of earthquakes $M6$ and $M6.5$ is 1000 and 3000 years. Consequently, the earthquake activity of the Szombathely region is significantly lower than that of the Pannonian Basin in general.

1. Introduction

Despite our incomplete knowledge of past earthquakes it is an accepted presumption, however not yet completely established, that all seismically active areas are already known. This hypothesis may be misleading and can lead to erroneously low values of seismic hazard. There exist areas considered inactive having a memory of strong earthquakes within the past. Such a case presents the earthquake destroying Savaria in 455 AD (present Szombathely in West Hungary; $47^\circ 13.78' N$, $16^\circ 36.28' E$). This seismological event is important for historians, as it has had an impact on the history of the region. It has also an important societal issue, as it indicates that there is a geological structure in the region capable to generate a destructive earthquake. And finally, it is important for earthquake research, because such a large seismic event is very rare in the area; similar magnitude events have not occurred since centuries (Earthquake Catalogue, Geodetic and Geophysical Institute, 2016). The earthquake hazard of such areas in the absence of adequate knowledge of historical seismicity cannot be determined with usual methods of earthquake hazard assessment.

After presenting some examples from different areas, this study – as an example of the aforementioned problem – presents the data related to the earthquake in 455 AD connected with the destruction of the capital Savaria of the Roman province Pannonia Prima Savaria, and with the end of Romans in Pannonia. The study reviews the tectonic units of the region, followed by applications of the statistically based Gutenberg-Richter (1944) relationship which uses a local earthquake catalogue completed for purposes of the present study, and the deterministic

Kostrov equation (1974), which estimates the time required for accumulating energy for an earthquake $M \geq 6.0$ in the apparently inactive area of Szombathely.

2. Earthquakes in areas allegedly inactive

There are territories located within active seismic zones which for a long time did not produce any significant earthquakes. The Bam event ($M6.6$) struck South-Eastern Iran (Wang et al., 2004). The shock completely destroyed the Bam citadel, the largest adobe building in the world. The fortress was built between the third and seventh century. This only slightly earthquake-resistant fortress had been existing for nearly fifteen centuries without any significant harm, and it was only ruined by the earthquake in 2003. This may mean that before 2003 Bam and its direct surrounding could not be considered as an earthquake-prone area.

Previously, in the absence of information, despite being surrounded by the seismically active Himalayas, the area of the kingdom of Bhutan has been considered free of large seismic events during the last centuries. Nevertheless, recently – based on historical documents – it was shown that a large destroying earthquake of magnitude 8.0 ± 0.5 had occurred there around May 4th, 1714 (Hetényi et al., 2016). A paleoseismic study carried out by Le Roux-Mallouf et al. (2016) detected two large seismic events in southern central Bhutan. One happened between the seventeenth and eighteenth century, the second one in the Middle Ages. The instrumental record carried out between January 2013 and April 2014 detected more than 400 events in Bhutan and surrounding

regions with local magnitudes of 0.5 to 5.6 (Diehl et al., 2014, 2017). It should be noted that in this region - in Assam (NE from Siliguri) - a devastating earthquake (Oldham, 1899) happened in 1897 with an estimated moment magnitude of 8.0.

On the other hand, unexpected seismic events took place also in intraplate areas previously considered inactive. Such were the three earthquakes in New Madrid (1811-1812) (December 16, 1811 M_w 7.2–7.3; January 23, 1812 M_w 7.0; February 7, 1812 M_w 7.4–7.5) (Hough et al., 2000) or the Charleston earthquake that occurred August 31st, 1886, with estimated magnitude M_w 6.9–7.3 (Chapman et al., 2016). The two events which hit Kaliningrad (enclave of Russia) on the considered inactive Russian plate during September 21, 2004 (M_w 5.0 and 5.2) were also unexpected (Rogozhin, 2011).

The common feature of the above mentioned earthquakes is that they had emerged in previously considered aseismic areas and there exists no other recorded historical earthquake in the region. Similar to these intraplate events is the earthquake that took place in the western part of the Pannonian Basin in 455 AD, the subject of this study.

3. Historical sources on the Savaria earthquake

Herein, an attempt is made to estimate the strength of the earthquake at ancient Savaria on the basis of analysis of two contemporary sources. These are the *Annales Ravennates* and the *Vita Sancti Severini* written by Eugippius. The work of Eugippius does not contain dates. Therefore, a very important source for this study is Thomson's (1982) book on the decline of the Western Roman Empire, in which the author links the events of Severinus's biography to years.

The only contemporary information from late Roman times about the Savaria earthquake comes from *Annales Ravennates*. Annals are a late-antiquity genre that flourished in the first millennium. They are usually written rather in a concise way. The most important element of the annals is the date - it tells the events grouped by year. The *Annales Ravennates* can be considered as the official chronicle of the city of Ravenna or of the already disintegrating Western Roman Empire. It survived its fall (AD 476) and followed the events up to 539. It remained in a copy made between 1500 and 1510 (Salzman, 1990), which were first time published in 1553 (Cuspiniani, 1553). It can be found in the two-volume late antique *Fasti vindobonenses* which are in the Vindobonensis manuscript MS. 3416 of the Österreichische Nationalbibliothek. In the literature *Annales Ravennates* is also called as *Anonymus Cuspiniani* or *Chronicon Ravenae*. According to Bischoff and Koehler (1939) an unpublished copy of *Annales Ravennates* remained from the 11th century in the Dombibliothek of Merseburg (Germany). The nineteenth-century critical and interpretative publications citing this document refer to the *Annales* under different names: *Annales Ravennatenses* (Holder-Egger, 1876) or by Mammsen (1892) as *Chronica Italica*. More recently the *Annales* are discussed in

Salzman (1990), where the results of previous researches are summarized.

According to Salzman (1990) the *Annales* is a reliable source of historical events of the late Roman and early Middle Ages. The annals written in Ravenna as a source of seismological data were found also reliable by Alexandre in his critical work on the earthquakes between 394 AD and 1259 AD (1990). Guidoboni and Ebel (2009) came to the same conclusion. They state that *Annales*, as the official chronicle, could contain only officially established important events and it was jealously guarded and it is a reason why it survived. In addition to the Savaria earthquake the *Annales Ravennates* reports seven further earthquakes between 408 and 502 AD (408 Rome, 429 Ravenna, 443 Rome, 455 Savaria, 467 Ravenna, 492 Ravenna, 501 Ravenna, and 502 Ravenna): "...it is very fact of having been inserted into the Annals of the city that makes it legitimate to suppose that they were earthquakes that may have had a destructive impact..." (Guidoboni and Ebel, 2009).

As to the earthquake of Savaria in the *Annales Ravennates* the following short entry can be found: „Valentiniano III. et Autemio consulibus, eversa est Savaria a terrae motu VII. id. Septembris, die veneris“ („During the consular time of Valentinian and Anthemius Savaria was destroyed by an earthquake on Friday, September 7th“ author's transcription). From the list of consuls it can be stated that Valentinianus and Anthemius were consuls in 455 AD. Based on this information it seems to be clear that the earthquake in Savaria took place in 455 AD. The fact that among the listed seismic events only the Savaria earthquake occurred outside Italy and quotation in the *Annales* that "Savaria was destroyed" lead to the conclusion that the earthquake was strong and destructive.

According to Alexandre (1990), the date of the earthquake is Wednesday September 9th, not September 7th as described in *Annales Ravennates*. The work of Carolus Sigonius (1524-1584) dealing with the fall of the Western Roman Empire contains several earthquake data (Sigonius, 1575). Here, July 10th in 455 AD, is the date of the earthquake of Savaria (the source of Sigonius's data is unknown to the author). The memory of the earthquake was preserved in notable catalogues of the 19th century (Perrey, 1846; Mallet, 1852) with a reference to Sigonius and not to the *Annales Ravennates*. According to few sources later, the earthquake date was September 7th, 456 AD. Their reasoning was that September 7th in 455 was on a Wednesday. In 456 it was a Friday (see e.g. Herwig, 2001; Lotter 2003). However, it seems more likely that in the *Annales* the day was written incorrectly than the year. This argument is supported by the fact that the *Annals* have a strictly annual arrangement of events. More important, that the chronicler does not indicate the year by number, but by the names of the consuls Valentinian and Anthemius. In 456 the consul was Avitus, who hold this title alone. The correctness of the 455 year is also supported by the fact that, according to many historians (e.g. Kunc, 1880; Balics, 1901), the

earthquake occurred during the first year of Gothic rule. The Goths occupied Pannonia in 455.

Our knowledge of the damaging European earthquakes of the first millennium is probably fairly incomplete, and this is especially true for the period preceding the fall of the Western Roman Empire. Alexandre's critical catalogue (1990), an almost complete compendium of all the known sources, mentions altogether 202 proven Western European events from 394 AD to 1259 AD. Eight of them before 476 AD are listed with given epicenter location.

There are practically no data which can be used to estimate the magnitude of the earthquakes within this period. An interesting independent reference has enabled us the examination of this issue in the case of the Savaria earthquake. In the biography of Saint Severinus "*Apostle to Noricum*", written before 511 AD by the late-antique Roman monk and historian Eugippius (around 460 – around 535) (Eugippius, 1969; Schwarcz, 2015) the following entry was found: "*His auditis habitatores oppidi memorati incredulitati veniam postulant monitis viri Dei sanctis operibus paruerunt ieiuniisque dediti et in ecclesia per triduum congregati errata praeterita castigabant gemitibus et lamentis. Die autem tertio, cum sacrificii vespertini sollemnitas impleretur, facto subito terraemotu ita sunt barbari intrinsecus habitantes exterriti, ut portas sibi Romanos cogerent aperire velociter. Exeuntes igitur conciti diffugerunt, aestimantes se vicinorum hostium obsidione vallatos, auctoque terrore divinitus noctis errore confusi mutuis se gladiis conciderunt. Tali ergo adversariis interneccione consumptis divino plebs servata praesidio per sanctum virum armis didicit pugnare caelestibus*". („When they had heard these things, the inhabitants of Comagenis begged forgiveness for their unbelief, and obeyed with holy works the admonitions of the man of God. They made a fast, and assembled in the church for the space of three days, reproaching their past sins with groans and lamentations. But on the third day, during the celebration of the evening sacrifice, there was a sudden earthquake; and the barbarians who dwelt within the city were so terror smitten that they compelled the Romans to open the gates for them in haste. Then they rushed out tumultuously, and scattered, supposing themselves besieged and surrounded by near foes; and their terror was augmented by divine influence, so that, in the wanderings and confusion of the night, they slew one another with the sword. Thus utter destruction consumed the enemy; and the people, saved by the divine aid, learned through the saint to fight with heavenly arms." author's transcription).

Thompson, an eminent expert of the era, states that the town where Severinus from Asturis (today Zwentendorf in Austria) arrived before the end of 455 AD was Comagenis (today Tulln an der Donau) and the earthquake which happened after Severinus' arrival was the Savaria earthquake (Thompson, 1982). The distance between Szombathely and Tulln an der Donau is approximately 130 km (Fig. 1). Because the barbarians according to Eugippius (Eugippius, 1969) were frightened and ran

outdoors, the local earthquake intensity in Comagenis had to be between $I=5$ and $I=6$ in accordance with European Macroseismic Scale (Grünthal, 1998). For the Pannonian Basin on the basis of statistical analysis of 100 seismic events Szeidovitz (1990) got the following relationship

$$I = 2.80 + 1.44 \cdot M - 1.50 \cdot \ln R$$

where R is the focal distance. In case of Comagenis (Tulln an der Donau) and Savaria (Szombathely) R , assuming a typical focal depth in the region 10 km, is 130.5 km and the magnitude should have been around 6.8. If $R = 100$ km, a magnitude of 6.5 is obtained. Since in the Pannonian Basin on the basis of calculations carried out by Tóth et al. (2006) the maximal magnitude is $M_{\max} = 6.5$ (Tóth et al., 2006) it is assumed that the quake was closer than 130 kilometres to Tulln an der Donau at a distance 25-30 km from Savaria (Szombathely) in NNW direction, where the epicentral intensity in case of $M = 6.5$ and focal depth 10km is $I_0 \approx 10$ The epicentrum could not be very far from Savaria (Szombathely), as – in accordance with information mentioned in *Annales Ravennates* – it could destroy the city. There exist similar cases from the Pannonian Basin where earthquakes at great distances caused panic. The Komárom earthquake for example (June 28th, 1763 $M6.5$) (Varga et al, 2001) 130 km away in Sopron caused panic among the members of the guard of the Fire Tower (Csatkai, 1923). Similarly, panic and minor damage were generated by this event in the city of Buda, within the range of 110 km (Szeidovitz, 1990).

There are no traces of paleoseismicity, but 4-6 cm sand geysers can be observed around the city. On the preserved Roman ruins no clear earthquake related damages were detected so far in Szombathely. At the same time Buócz et al. (1991) reports on severely deformed road surfaces that came to light during the excavations in the city, what may prove a strong earthquake occurrence.

4. Seismicity and geodynamics of the Szombathely (Savaria) area

In this chapter the earthquake activity and tectonic structures in the vicinity of Savaria (Szombathely) are reviewed.

4.1. Seismicity of the region

Only a few places in the Pannonian Basin are reported where earthquakes $M \geq 6$ occurred over the past few centuries. But not any place is known where such a major event was repeated - this also applies to the earthquake in Szombathely (Savaria).

The Hungarian earthquake catalogue (Earthquake Catalogue, 2016) is considered complete for events $M \leq 6$ only from 1400 onwards. The result of the statistical survey based on it shows that in the Pannonian Basin there is only one $M \leq 6$ event on average in 200 years. The catalogue contains all in all five earthquakes between 455 and 1000 and from 1001 to 1500 only 74 events, which

is only 0.04% of more than 20,000 seismic events known (Earthquake Catalogue, 2016).

For present studies an earthquake catalogue was compiled for the wider environment of Szombathely (within a radius of 50 km). It contains, with the exception of the event of 455 AD, 403 earthquakes (Table 1, Fig. 2), covering mainly the last 100-150 years. Only 2 events happened before 1500, 9 before 1700, and 38 before 1800. From the 19th century 54 quake are known, from the 20th century 124. The remaining 184 events happened between 2000 and 2015. These figures clearly demonstrate that data on earthquakes of the Middle Ages and earlier periods have almost been entirely lost. The catalogue is complete for events $M \geq 4.7$ after 1800, for events $M \geq 3.5$ since 1880, for events $M \geq 2.0$ since 1990 (Bus et al., 2009; Tóth et al., 2002). In the list of 403 events, except for an event in 1585, there are no earthquakes of $M \geq 5.0$. The earthquake energy released during such an event is less than 0,5% of the energy released by an

earthquake $M \geq 6.0$. The Savaria event in 455 AD is estimated as $M \geq 6.0$.

The earthquake activity in the Szombathely region is lower than the average in Pannonian Basin and also considerably lower than its close environment. Here, the maximum magnitude value (M_{max}) assigned on seismological basis is about 5.2 - 5.4, while the Western and Eastern part from the investigated area $M_{max} \geq 6.5$ (Tóth et al., 2006). The distribution of earthquake epicentres in the vicinity of Szombathely is diffuse, and the relationship towards specific faults is not established (Fig. 2). The area is characterized by shallow focus seismicity. The earthquakes occurred typically at depths from 10 to 15 km in the upper part of the earth's crust above the brittle-ductile transition.

4.2. Tectonics of the area

Szombathely is located in the Alpine-Carpathian orogenic belt characterized by extensional basin formation

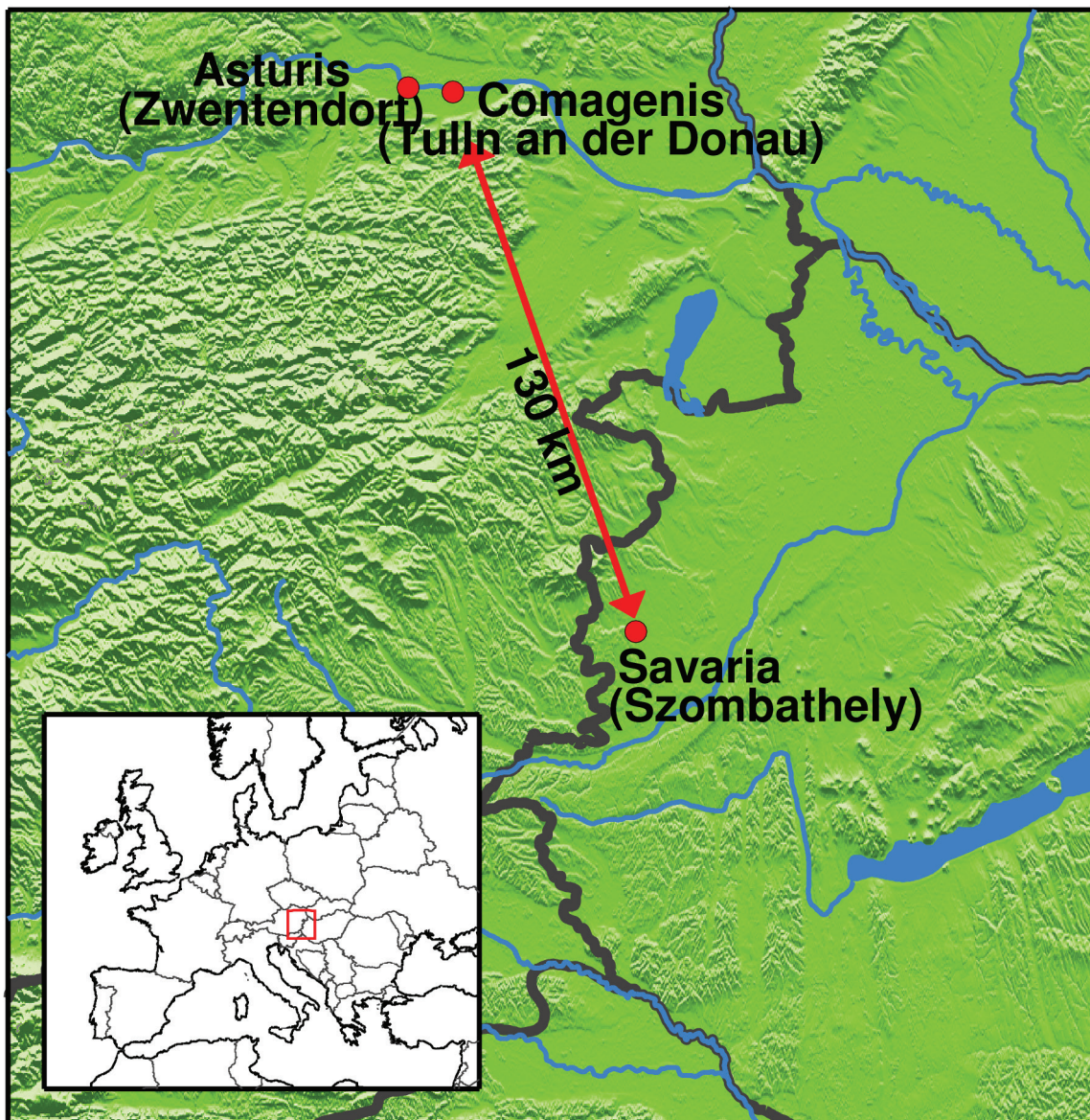


Figure 1: DEM map and distance between Comagenis (Tulln an der Donau) and Savaria (Szombathely).

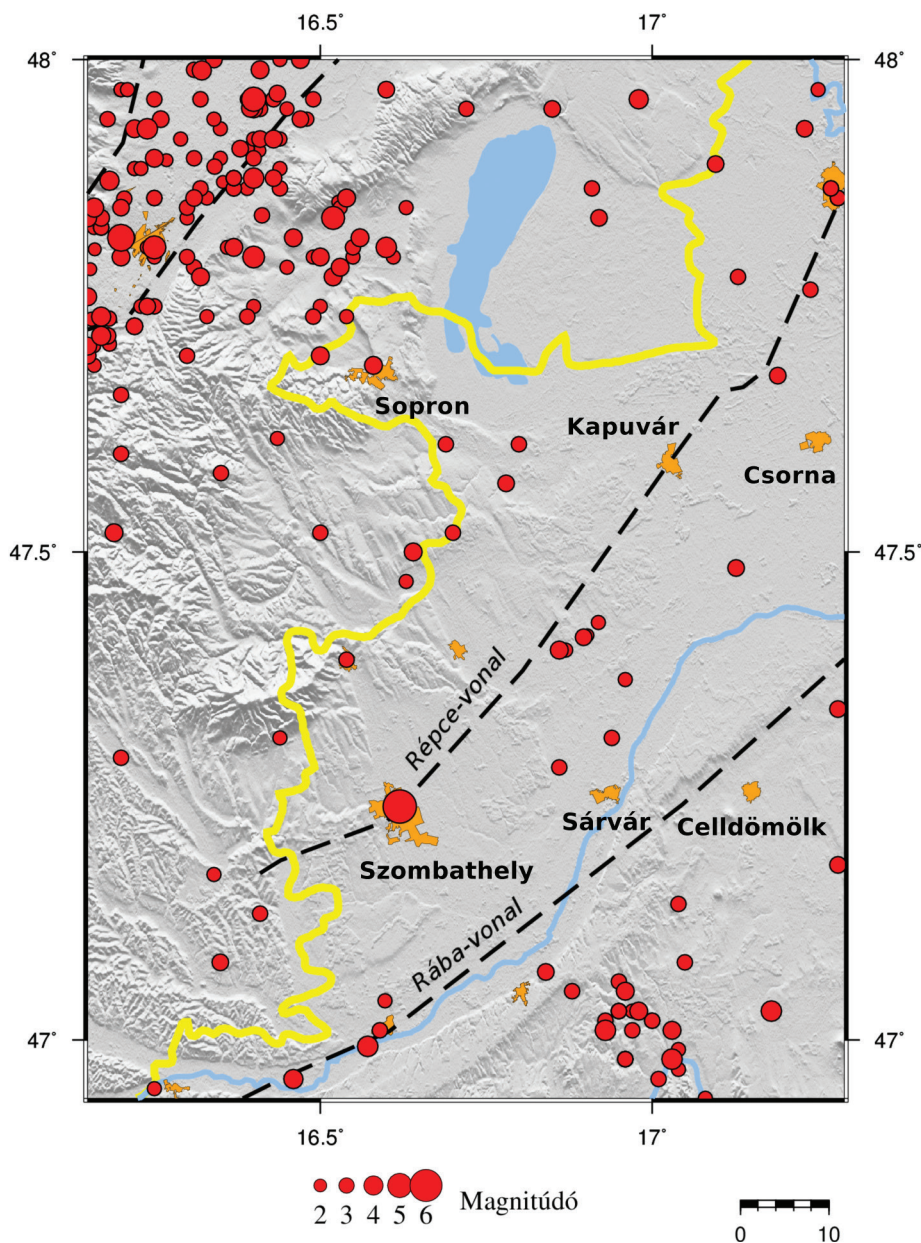


Figure 2: Earthquake epicentres in broader environment of Savaria (Szombathely) (after Earthquake Catalogue, 2016). Of the three tectonic lines of the map (marked with dashed black lines) only the Mur-Mürz valley has significant earthquake activity. The Rába line is unrelated to known earthquakes in the area of Szombathely. The BÉlbaltavár area (47.0°N, 16.8°E) in its vicinity is characterised by few seismic events ($M \leq 4.4$) which are not related to this tectonic line. According to our current knowledge, the Répce line is seismically inactive.

which began in the Miocene. Basin inversion of Pliocene-Quaternary times is related to changes from the state of tension to the state of compression controlling basin formation and subsidence. This process resulted in the formation of a deep rooted strike-slip zone that might penetrate the entire crust (Horváth, 2007). In the vicinity of the suspected epicentre of the 455 AD earthquake there are three EW oriented left lateral strike-slip faults (fault systems) with azimuths 60°-65°.

The seismically active region, 60-70 km westward from Szombathely, is extending from the Mur-Mürz Valley in Austria to the southern Vienna Basin (Fig. 2). This region is the most seismically active one in Austria. It produced 14 earthquakes since 1201 with $M > 5$ (Hammerl

and Lenhardt, 1997; Hausmann et al., 2010). This part of Austria suffered from the earthquake that struck Neulengbach (1590; $M = 5.5-6.0$) and from the seismic event in the middle of the fourth century, which strongly damaged the Roman settlement Carnuntum (Decker et al., 2006). There, paleoseismological investigations carried out in the Vienna Basin showed that several earthquakes in a magnitude range between $M_{6.3}$ and M_7 occurred during the last 120 ka BP. This means that the seismic capacity of the Vienna Basin is significantly higher as it was supposed to be on the basis of historical earthquakes (Decker et al, 2006; Hintersberger et al., 2018).

The Rába line forms the Western border of the Transdanubian range. It is located 30 km east from Szombathely

and is covered with thick Neogene deposits. Unlike its northern part, the Rába line south of Győr cannot be considered seismologically active. The BÉlbaltavár area in its vicinity (47.0°N, 16.8°E) is characterised by few seismic events ($M \leq 4.4$) which are not related to this tectonic line (Zámolyi et al., 2010; see also Fig. 2).

It is unlikely that the aforementioned two tectonic features have unleashed the earthquake destroying Savaria in 455 AD. Probably the situation is the same in the case of the third fault system, the Répce line, which forms the Eastern border of the Austrian Alps and is located in the immediate vicinity of Szombathely (Császár, 2005). It is also covered by thick sediment layers, what makes it difficult to detect earthquake-induced features

on the surface. Between the Répce and the Rába lines the thickness of the Pliocene–Quaternary sediment cover is increasing (thickening about 1.5 to 2 kilometres). In addition, a positive regional gravity anomaly was detected between the Répce and the Rába lines (Fig. 3), possibly a reflection of the lateral density inhomogeneity in the structure of the Earth’s crust. Along this deep tectonic feature, in principle, stress may arise, which had not been observed so far.

What is important in evaluating the past earthquake activity is that the Rába and Répce faults, described by oil prospection, do apparently not penetrate the sediments of the Quaternary, the accumulation of which began more than one and a half million years ago (Császár,

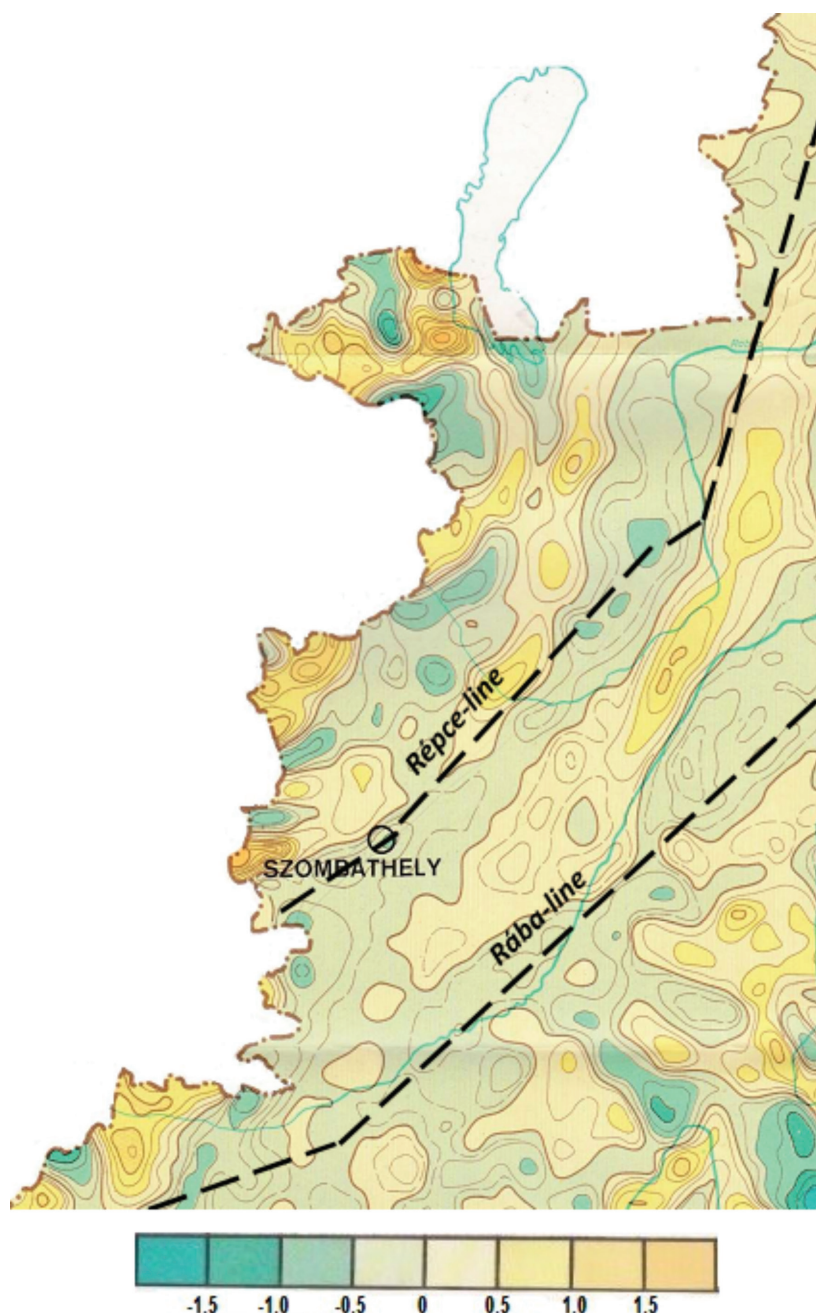


Figure 3: Residual gravity anomaly map of Western Hungary (distance of isolines: thick line 0.250 mGal or 2.50 $\mu\text{m/s}^2$; thin line 0.125 mGal or 1.25 $\mu\text{m/s}^2$) (Kiss, 2005). The map shows the positive gravity anomaly between the Répce and Rába lines.

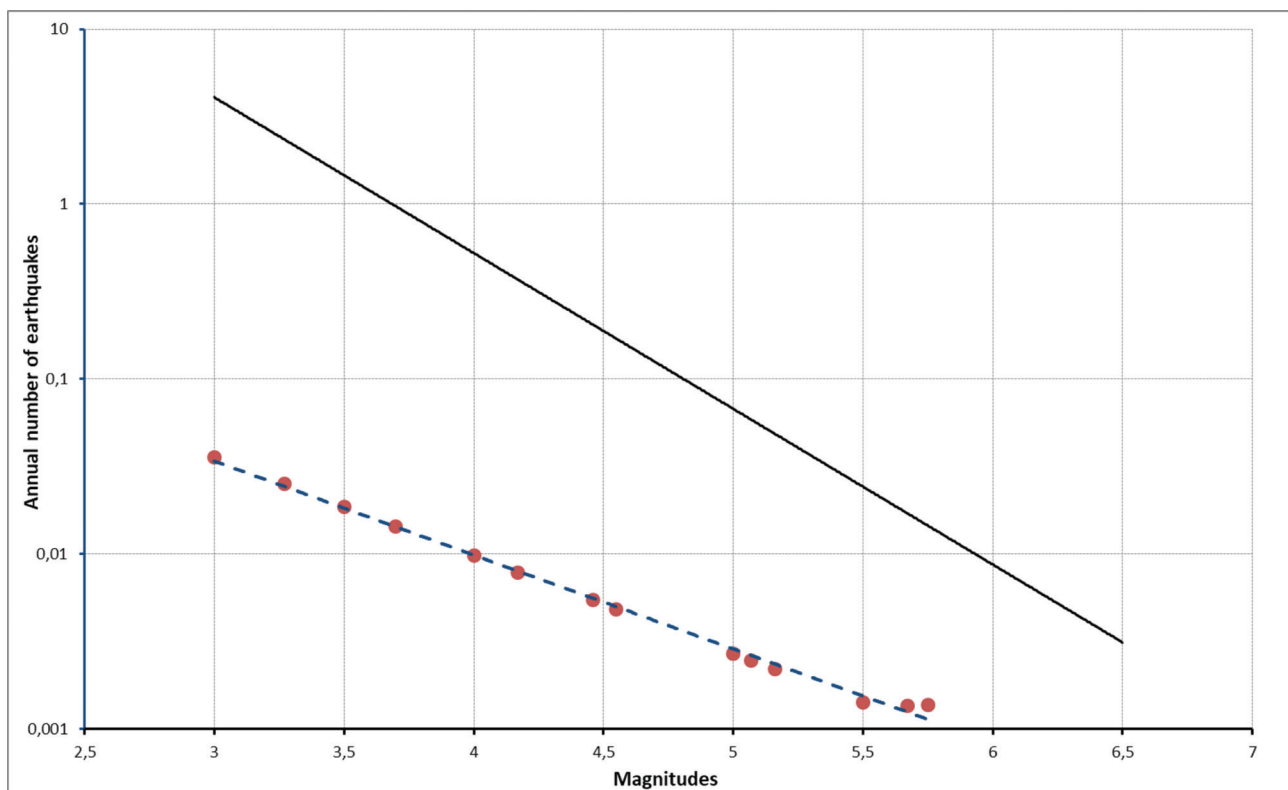


Figure 4: Magnitude recurrence curve for the vicinity of Szombathely(50 km around the city) marked with dashed line [$\lg N = 0.23 - 0.56 \cdot M$ ($r^2 = 0.987$)] and in the entire Pannonian Basin ($44.0^\circ - 50.0^\circ N$; $13.0^\circ - 28.0^\circ E$) represented by a solid line [$\lg N = 3.28 - 0.89 \cdot M$ ($r^2 = 0.984$)], where N is the number of events having a magnitude $\geq M$.

2005). There is also no sign of seismological activity of these lines both in the past and in the present.

5. The possibility of recurrence of a significant earthquake in the area of Szombathely

To estimate the return time of a potentially possible strong earthquake, similar to the 455 AD, in a first step, the Gutenberg-Richter relationship (1944) was used. The calculation is based on the already mentioned regional catalogue (Table 1) which contains seismic events within a radius of 50 km around Szombathely. Results obtained from this region were compared to the seismicity of the whole Pannonian Basin ($44.0^\circ - 50.0^\circ N$; $13.0^\circ - 28.0^\circ E$) (Fig. 4). Data required for calculating the earthquake activity in the Pannonian Basin were taken from Earthquake Catalogue, 2016.

In case of the Szombathely area the recurrence time for M6 earthquakes is 1400 ± 300 years, while for M6.5 it is 2600 ± 300 years. The return time proved to be much shorter in the case when the seismic data for the whole Pannonian Basin was considered. In this case 110 ± 40 years was obtained for M6 and 330 ± 70 years for M6.5. Hence the earthquake activity of Szombathely region is significantly lower than that of the whole Pannonian Basin.

Considering the very limited data available for the historical seismicity of the Szombathely area the recurrence time of the earthquake of 455 AD was estimated also by using space geodetic data. The calculations were based on the assumption that the source of the earthquake completely lost its accumulated elastic energy in 455 AD.

The question is then: How much time is needed to accumulate the energy for an earthquake M6 or M6.5?

The GPS determined fault parallel strain rate $\dot{\epsilon} = \frac{\partial \epsilon}{\partial t}$ (where ϵ is the strain) in the Mur-Mürz zone and in the Western part of the Pannon Basin (with reference to the Bohemian Massif) is $\dot{\epsilon} \approx 10^{-8}$ /year. The principal contraction strain rate is $\approx 10^{-7}$ /year in NW-SE direction (Bus et al., 2009).

$\dot{\epsilon}$ data obtained from GPS observations is based on the short time interval and assumes linear, monotonous deformation in time. Therefore, it should be handled with some caution. Observations with extensometer (oriented in NW-SE direction), on the basis of a 20 year continuous data set at the Sopronbánfalva Geodynamic Observatory (50 km north of Szombathely) show that the $\dot{\epsilon} = \frac{\partial \epsilon}{\partial t}$ is a time-varying quantity in local scale (Mentes, 2008, 2012) what is obviously a warning when interpreting the GPS strain rate data.

Using constant over time regional strain rate values obtained from GPS observations, it is possible to estimate the length of time required for energy accumulation necessary to generate an $M \geq 6.0$ earthquake. For this purpose a modified version of the Kostrov (1974) equation

$$\dot{\epsilon} = \frac{\sum_{i=1}^M \sum_{n=1}^N M_{0ni}}{2\mu\Delta t\Delta V} \quad (1)$$

has been used, where μ serves for the shear modulus ($\approx 3 \cdot 10^{10} \text{ Nm}^{-2}$). In (1) the first summation counts the number of seismic sources, whereas the second counts moment tensors M_0 each earthquake source having a volume of ΔV during a time interval Δt . The strain rate in general form is (Kreemer et al., 2002):

$$\frac{1}{2} [\dot{\epsilon}_{\varphi\varphi} + \dot{\epsilon}_{\theta\theta}] + \left[\frac{1}{4} (\dot{\epsilon}_{\varphi\varphi} + \dot{\epsilon}_{\theta\theta})^2 - \dot{\epsilon}_{\varphi\theta} \right]^{1/2} \quad (2)$$

If $\dot{\epsilon}_{\varphi\varphi} = \dot{\epsilon}_{\theta\theta}$ and $\dot{\epsilon}_{\varphi\theta} \leq \dot{\epsilon}_{\varphi\varphi} = \dot{\epsilon}_{\theta\theta}$ we gain the linear strain denoted as $\dot{\epsilon}$ from geodetic observations. Consequently, the orientation of the seismic strain is replaced within a seismic source by its average. Therefore in (1) the strain rate instead of M_{0ni} can be written as:

$$\dot{\epsilon} \approx \frac{\sum_{n=1}^N M_{0n}}{2\mu\Delta t\Delta V} \quad (3)$$

Based on the compilation of local catalogues for different source zones, it seems that usually the value of M_{0ni} is determined almost exclusively by the largest seismic event. Therefore, the summation can be omitted and (3) will be (Varga, 2011)

$$\Delta t \approx \frac{M_0}{2\mu\dot{\epsilon}\Delta V} \quad (4)$$

(where M_0 is the seismic moment of the largest seismic event)

It is assumed - to some extent arbitrarily - that after the earthquake in 455 AD, the focal volume ΔV was completely exhausted and therefore equation (4) can be used to estimate the Δt time needed to stress accumulation for an earthquake with magnitude above 6.0. Of course, in an earthquake source, seismic events follow each other not according to such a simple accumulation/depletion model. Moreover, it may happen that in a given place an earthquake occurs only once, and it does not recur.

For (4) values of M_0 and ΔV were estimated using experimental equations:

- Hanks and Kanamori (1979) approximated M_0 by $\log M_0 = 2/3 (M + 10.7)$. Consequently, $M_0 = 1.26 \cdot 10^{11} \text{ Nm}$ for M6.0 and for M6.5 it is $2.92 \cdot 10^{11} \text{ Nm}$. It should be mentioned that the empirical equation obtained by Hanks and Kanamori has been successfully applied by Grüntal (1999) and Grüntal and Wahlstöröm (2003) for the compilation of the earthquake catalogue for central, northern and northwestern Europe.
- $\log(\Delta V) = 3.58 + 1.47M$ - for $5.3 < M < 8.7$ (Báth and Duda, 1964) Therefore, ΔV for M6.0 is $2.51 \cdot 10^{12} \text{ m}^3$ and $1.36 \cdot 10^{13} \text{ m}^3$ in the case of M6.5. Of course, the value of the volume thus calculated should be considered a rough approximation. Nevertheless, the reliability of ΔV values is supported by the fact that Varga (2011) received a similar ΔV value for M6 by a completely different method. A similar volume in the case of the M6.5 Amatrice-Norcia (Central Italy) earthquake sequence was found by Bignami et al. (2019).

Using these numerical values in (4) the time required to accumulate the energy needed for an earthquake can be estimated. For $\dot{\epsilon} \approx (10^{-8} - 10^{-7}) \cdot \text{year}^{-1}$ the corresponding Δt value in the cases of M6 and M6.5 earthquakes is $(1.0 \pm 0.1) \cdot 10^3$ and $(3.0 \pm 0.2) \cdot 10^3$ year respectively. These results are the same as those obtained with the Gutenberg-Richter (1944) equation by using the catalogue compiled for the wider environment of Szombathely.

6. Conclusions

Historical sources prove that there was certainly a destructive earthquake in 455 AD, and the ancient Roman city of Savaria was severely damaged (destroyed) by this strong seismic event. The comparison of data from *Annales Ravennates* and Eugippius' data on Saint Severinus' life suggests that the earthquake had a magnitude $M \geq 6$.

Based on recent seismic data, the region is so far not considered active. However, it should be considered as an area with a higher level of seismic hazard due to the analysed historical sources related to the earthquake of 455 AD.

The regional strain rate required to describe the tectonic processes in the area of potential seismic source zone on the basis of GPS observations is $\dot{\epsilon} \approx 10^{-8}/\text{year} - 10^{-7}/\text{year}$. The necessary time for the accumulation of energy to generate a $M \geq 6.0$ earthquake is of the order of thousand year. A similar result was obtained with the use of the Gutenberg-Richter equation (1944). Therefore, regardless of the nowadays incomplete knowledge of earthquakes of the remote past, it is imaginable, why in the area of Szombathely the destructive earthquake of 455 AD has not happened yet for the second time.

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year	m	day	lat	long	M	year	m	day	lat	long	M
455	9	7	47,24	16,62	6,3	1887	3	22	47,81	16,60	2,5
1230	0	0	47,80	16,50	4,7	1888	4	9	47,81	16,55	2,9
1281	5	18	47,81	16,25		1888	4	9	47,80	16,55	2,5
1538	8	30	47,69	16,58		1888	4	12	47,78	16,52	3,7
1585	0	0	47,50	16,30	5,5	1888	4	12	47,79	16,53	3,7
1590	5	28	47,69	16,58		1888	4	12	47,74	16,54	2,5
1615	2	20	47,50	16,30	4,1	1888	4	13	47,80	16,61	2,5
1626	4	23	47,93	16,22		1888	4	15	47,81	16,60	2,5
1654	7	8	47,50	16,30	4,1	1888	4	21	47,69	16,58	2,5
1705	0	0	47,81	16,25		1888	4	25	47,79	16,45	2,5
1712	4	10	47,81	16,25	4,4	1888	9	4	47,86	16,54	3,5
1712	6	24	47,80	16,50	3,7	1889	3	27	47,52	16,50	2,9
1712	6	25	47,80	16,50		1889	4	10	47,74	16,49	2,9
1712	6	26	47,80	16,50		1890	7	15	47,01	16,59	2,5
1718	6	15	47,80	16,20	4,7	1892	1	18	47,82	16,46	
1749	6	8	47,81	16,25	4,7	1892	1	19	47,82	16,46	3,7
1763	0	0	47,93	16,22	3,5	1892	1	19	47,85	16,63	2,5
1763	4	8	47,69	16,58	3,5	1892	12	17	47,75	16,50	2,5
1766	8	5	47,81	16,60	4,1	1893	1	25	47,92	16,43	3,5
1766	8	16	47,94	16,48	3,5	1895	12	30	47,87	16,37	2,9
1768	2	26	47,81	16,25	3,5	1898	9	28	47,92	16,41	3,3
1768	2	27	47,82	16,20	5,3	1898	9	29	47,87	16,37	2,9
1768	2	27	47,81	16,25	2,5	1898	9	30	47,96	16,39	2,5
1768	2	27	47,89	16,22	2,5	1898	10	1	47,90	16,40	2,9
1768	2	28	47,89	16,22	2,5	1898	10	3	47,91	16,39	2,5
1768	3	5	47,70	16,30	3,5	1898	11	27	47,72	16,18	2,5
1768	3	21	47,81	16,25	2,5	1899	1	14	47,91	16,39	2,5
1768	3	24	47,81	16,25	2,5	1899	6	11	47,91	16,39	2,5
1768	5	1	47,81	16,25	2,5	1899	6	11	47,96	16,49	2,9
1769	2	5	47,81	16,25		1899	6	11	47,96	16,40	2,5
1774	1	15	47,84	16,45	4,1	1899	8	25	47,94	16,48	2,7
1774	1	15	47,95	16,85	3,2	1899	12	12	47,81	16,24	2,5
1775	7	8	47,69	16,58	2,7	1899	12	12	47,85	16,30	2,9
1778	12	3	47,81	16,25		1901	1	2	47,39	16,54	2,5
1791	8	29	47,81	16,37	3,5	1901	1	4	47,39	16,54	2,9
1802	10	29	47,81	16,25	2,5	1901	8	4	47,78	16,32	3,5
1802	11	25	47,81	16,25	2,9	1901	8	10	47,78	16,32	2,5
1813	5	5	47,70	16,50	3,2	1901	9	5	47,79	16,31	2,9
1813	5	5	47,70	16,50	3,5	1902	1	15	47,69	16,58	2,7
1813	6	3	47,69	16,58	2,9	1902	5	17	47,69	16,58	2,5
1841	7	13	47,81	16,25	3,7	1902	5	18	47,84	16,30	2,7
1843	8	14	47,69	16,58	2,9	1902	10	1	47,52	16,19	3,5
1858	11	28	47,81	16,25	2,5	1904	4	9	47,29	16,20	2,9
1861	3	8	47,81	16,25	2,5	1905	2	20	47,74	16,39	2,9
1868	9	19	47,81	16,25	2,5	1905	4	7	47,29	16,20	2,5
1868	12	19	47,81	16,25	2,5	1905	4	9	47,88	16,37	2,5
1870	9	3	47,97	16,21	2,5	1905	4	9	47,88	16,37	2,5
1874	3	20	47,96	16,25	2,9	1907	4	1	47,82	16,21	2,9
1876	6	25	47,72	16,18	2,9	1907	11	2	47,31	16,94	2,9
1880	11	9	47,24	16,62	2,5	1907	11	2	47,37	16,96	2,5
1880	11	9	47,39	16,54	2,7	1907	11	25	47,81	16,25	2,7
1884	9	2	47,89	16,23	2,5	1908	2	19	47,66	16,50	
1884	9	2	47,81	16,25	3,7	1908	2	19	47,84	16,52	4,7
1884	12	7	47,95	16,72	2,9	1908	2	19	47,89	16,44	2,5
1885	3	22	47,24	16,62	2,2	1908	9	30	47,69	16,58	2,5
						1910	2	3	47,40	16,87	2,5

Table 1: Earthquake catalogue for the wider environment of Szombathely (within a radius of 50 km) between 455 and 2015 (Earthquake Catalogue, Geodetic and Geophysical Institute, 2015).

Table 1: Continued.

year	m	day	lat	long	M
1910	2	6	47,81	16,25	2,7
1910	8	19	47,52	16,70	2,9
1915	10	7	47,81	16,25	2,9
1916	1	6	47,40	16,86	3,5
1919	2	22	46,96	16,46	4
1919	11	12	47,81	16,25	3,5
1922	12	22	47,57	16,78	3,2
1923	11	17	47,75	16,24	3,2
1927	2	0	46,96	16,46	
1927	12	30	47,81	16,25	2,9
1927	12	31	47,81	16,25	
1928	4	2	47,73	16,22	2,9
1928	4	3	47,81	16,25	2,9
1928	12	11	47,61	16,69	2,9
1928	12	11	47,61	16,69	
1929	10	15	47,52	16,19	2,7
1930	11	19	47,81	16,36	2,7
1933	8	27	47,92	16,29	2,7
1933	8	27	47,92	16,29	
1934	1	13	47,88	16,43	3,2
1934	11	14	47,73	16,22	3,2
1935	11	18	47,86	16,31	3,2
1936	8	15	47,88	16,37	2,9
1937	10	31	47,94	16,47	
1937	10	31	47,94	16,47	3,2
1938	11	8	47,96	16,40	4,9
1938	11	8	47,80	16,40	4,5
1938	11	8	47,85	16,42	
1939	1	4	47,81	16,25	2,9
1939	1	4	47,81	16,25	
1939	1	21	47,85	16,53	2,7
1939	4	16	47,74	16,33	2,7
1939	8	19	47,78	16,32	3,2
1939	8	20	47,78	16,32	
1940	3	24	47,96	16,40	2,7
1940	9	14	47,96	16,40	2,7
1942	10	19	47,88	16,37	2,9
1943	11	29	47,69	16,58	2,5
1943	12	25	47,81	16,25	2,9
1946	4	29	47,81	16,25	2,9
1948	7	9	47,81	16,25	3,2
1949	8	3	47,60	16,20	2,9
1950	10	16	47,88	16,37	2,9
1951	1	5	47,81	16,25	3,2
1951	2	4	47,70	16,30	2,5
1951	4	22	47,84	16,52	2,5
1951	10	14	47,91	16,39	2,5
1953	7	22	47,17	16,34	
1953	7	23	47,17	16,34	2,7
1953	10	28	47,80	16,49	2,7
1953	10	29	47,80	16,49	
1954	3	10	47,87	16,32	2,9
1954	7	9	47,72	16,18	2,9
1954	12	3	47,81	16,25	
1956	3	31	47,05	16,96	2,5
1956	3	31	47,05	16,96	2,5

Table 1: Continued.

year	m	day	lat	long	M
1956	4	1	47,01	16,97	2,9
1956	4	1	47,05	16,96	2,5
1956	4	2	47,01	16,97	2,5
1956	4	26	47,05	16,88	2,9
1956	4	28	47,05	16,96	3,5
1956	4	28	47,05	16,96	2,5
1956	4	30	46,98	16,96	2,9
1956	5	1	46,98	16,96	2,9
1956	5	1	47,05	16,88	2,5
1956	5	2	47,06	16,95	3,1
1956	5	2	47,03	16,95	2,9
1956	5	2	46,98	16,96	2,9
1956	5	2	47,03	16,95	3
1956	5	2	47,02	16,93	2,8
1956	5	2	47,03	16,95	2,9
1956	5	2	47,03	16,95	2,9
1956	5	2	47,03	16,91	0,7
1956	5	3	46,98	16,96	2,9
1956	9	26	47,94	16,26	3,2
1957	12	3	47,07	16,84	3,2
1957	12	4	47,05	16,78	2
1958	1	30	47,95	16,41	2,9
1958	1	31	47,84	16,92	3,2
1959	7	10	47,92	16,43	2,7
1959	9	22	47,86	16,31	2,7
1961	1	12	47,78	16,32	2,7
1961	6	7	47,03	16,97	2,5
1963	12	2	47,88	16,40	4,1
1963	12	2	47,88	16,37	2,9
1963	12	5	47,88	16,37	
1964	2	17	47,70	16,30	2,9
1964	6	30	47,50	16,50	
1964	6	30	47,60	16,30	
1964	9	21	47,80	16,40	2,9
1964	9	22	47,81	16,37	
1964	12	31	47,72	16,18	3,2
1965	4	1	47,88	16,37	2,9
1965	5	23	47,86	16,25	2,9
1965	5	29	47,86	16,25	2,9
1965	7	8	47,90	16,25	3,5
1966	8	3	47,81	16,25	2,9
1966	12	18	47,86	16,33	2,5
1967	10	18	47,96	16,43	2,9
1968	3	13	47,81	16,25	2,9
1968	3	14	47,81	16,25	
1969	11	3	47,78	16,32	3,2
1969	12	30	47,78	16,32	3,2
1970	4	9	47,81	16,25	2,9
1971	3	24	47,75	16,24	2,9
1971	5	4	47,73	16,22	3,2
1972	4	15	47,73	16,22	2,9
1972	6	10	47,87	16,91	2,8
1972	8	27	47,88	16,25	1,1
1974	4	22	47,29	16,71	
1974	5	27	47,80	16,25	2,7
1974	11	27	47,85	16,20	2,5

Table 1: Continued.

year	m	day	lat	long	M
1978	1	22	47,82	16,56	3,5
1979	1	22	47,75	16,40	2,7
1979	5	24	47,50	16,64	3,7
1979	5	24	47,50	16,64	2,5
1979	5	24	47,47	16,63	2,5
1979	7	8	47,80	16,20	3,5
1980	6	10	47,81	16,25	2,9
1980	10	7	47,81	16,25	2,7
1981	4	12	47,80	16,30	2,9
1982	2	2	47,85	16,20	3,2
1984	7	23	47,08	16,35	3,2
1985	6	5	47,95	16,40	3,6
1986	1	22	47,31	16,44	2,5
1988	9	16	47,63	16,20	
1989	1	26	47,03	16,98	3,6
1989	2	23	47,28	16,86	3,1
1989	3	5	47,16	17,00	
1991	1	27	47,87	16,44	2,9
1991	5	2	47,93	16,24	4,2
1991	5	2	47,92	16,40	2,5
1991	5	2	47,96	16,32	3,1
1991	5	2	47,93	16,35	2,5
1991	6	17	47,90	16,35	2,3
1991	9	2	47,76	16,94	
1992	3	31	47,91	16,38	3,2
1992	8	11	47,92	16,44	2,7
1992	8	12	47,80	16,25	2
1992	8	12	47,87	16,39	2,7
1992	8	13	47,96	16,41	2,7
1992	10	23	47,61	16,80	2,9
1993	3	14	47,75	16,25	2,9
1994	1	20	47,86	16,74	
1994	4	17	47,75	16,23	2,5
1994	6	14	47,91	16,31	
1995	12	15	47,82	16,23	
1996	1	8	47,84	16,59	2,7
1996	1	9	47,96	16,49	3,4
1996	1	12	47,78	16,33	
1996	3	14	47,86	16,21	3
1997	1	22	47,90	16,80	
1997	5	13	47,80	16,30	2,4
1997	7	8	47,52	16,44	2,3
1997	7	19	47,84	16,37	2,7
1998	2	1	47,95	16,72	2,7
1998	3	11	47,93	16,42	2,2
1999	5	5	47,80	16,30	2,6
1999	6	9	47,46	16,49	1,3
1999	7	26	47,82	16,48	3,2
1999	10	23	47,71	16,23	2,5
2000	7	11	47,93	16,43	2,5
2000	7	11	47,96	16,50	4,4
2000	7	12	47,96	16,40	2,5
2000	7	12	47,92	16,46	2,8
2000	7	12	47,94	16,40	3,2
2000	7	15	47,92	16,40	0,9
2000	7	16	47,91	16,45	2,8

Table 1: Continued.

year	m	day	lat	long	M
2000	7	16	47,92	16,43	2,4
2000	7	26	47,44	16,30	
2000	9	5	47,94	16,46	2,1
2000	12	6	47,31	16,44	2,3
2001	3	11	47,88	16,39	2,7
2001	4	18	47,53	16,41	1,2
2001	4	26	47,27	16,59	
2001	6	7	47,86	16,31	2,4
2001	6	13	47,59	16,35	
2001	7	1	47,73	16,19	4,1
2002	5	3	47,94	16,32	2,5
2002	7	29	47,58	16,33	
2002	9	21	47,93	16,56	2,5
2003	2	3	47,90	17,09	3,2
2003	7	17	47,91	16,41	2,6
2003	8	9	47,00	16,60	3,8
2003	8	10	47,01	16,63	2,4
2003	8	10	46,99	16,56	
2003	9	3	47,77	16,62	2,7
2004	6	25	47,44	16,93	2,5
2004	6	25	47,44	16,96	2,8
2004	6	28	47,62	16,44	2,9
2004	6	28	47,62	16,38	2,5
2004	7	28	47,51	16,40	
2004	9	11	47,91	16,42	2,8
2004	9	28	47,55	16,32	2,9
2004	10	9	47,03	16,96	2,2
2004	10	21	47,49	16,44	
2005	4	19	47,00	16,51	
2005	4	27	47,55	16,44	2,4
2005	6	4	47,78	16,24	
2005	7	25	47,88	16,23	
2006	2	3	47,95	16,95	2,1
2006	3	15	47,30	16,44	2
2006	4	4	47,85	16,25	2,2
2006	6	30	47,91	16,24	2,5
2006	7	1	47,85	16,24	2,8
2006	11	7	47,89	16,53	2,1
2007	1	11	47,92	16,34	2,2
2007	1	11	47,93	16,33	2
2007	2	5	47,72	16,20	2,5
2007	3	3	47,40	16,93	3,1
2007	5	5	47,72	16,65	2
2007	9	4	47,57	16,74	2,6
2007	9	5	47,76	16,34	1,2
2007	9	28	47,85	16,27	2,9
2008	4	23	47,36	16,81	2,3
2008	4	23	47,35	16,75	2,2
2008	10	14	47,89	16,29	2,8
2008	10	14	47,88	16,30	2,3
2008	10	14	47,89	16,29	1,3
2008	11	17	47,69	16,20	2,5
2008	12	10	47,78	16,23	1,2
2009	1	25	47,75	16,18	2,3
2009	1	25	47,74	16,19	2,4
2009	4	6	47,26	16,50	2,2

Table 1: Continued.

On the magnitude and possible return period of the historical earthquake in ancient Savaria, 455 AD (Szombathely, West Hungary)

year	m	day	lat	long	M
2009	7	27	47,88	16,36	1,3
2009	7	27	47,89	16,32	2,5
2009	7	27	47,90	16,30	2,3
2009	7	27	47,91	16,25	2,7
2009	7	27	47,87	16,36	2
2009	10	20	47,86	16,32	2,1
2009	11	9	47,90	16,27	2,2
2009	11	19	47,85	16,28	0,9
2009	11	19	47,89	16,30	2,2
2009	11	19	47,88	16,29	2,8
2010	1	20	47,88	16,31	2
2010	4	18	47,76	16,33	1,1
2010	6	24	47,94	16,40	2,5
2010	7	18	47,85	16,25	2,4
2010	8	26	47,04	16,58	3,2
2010	9	11	47,88	16,31	2,3
2010	12	18	47,96	16,42	2,7
2010	12	18	47,95	16,40	2,2
2011	2	22	47,77	16,19	1,5
2012	4	27	47,72	16,21	0,8
2012	8	12	47,81	16,23	1,1
2012	11	15	47,76	16,27	2,4
2012	12	28	47,56	16,51	1,1
2013	9	20	47,96	16,47	3,8
2013	10	2	47,94	16,41	1,4
2013	10	2	47,95	16,41	1,5
2013	10	2	47,93	16,38	1,2
2013	10	2	47,96	16,44	3,7
2013	10	2	47,96	16,41	2,3
2013	10	3	47,95	16,38	1,3
2013	10	3	47,59	16,35	1,3
2013	10	6	47,83	16,20	1,9
2013	10	14	47,94	16,42	1,5
2013	10	23	47,94	16,43	2,1
2013	12	11	47,81	16,24	2,5
2013	12	30	47,45	16,90	2,3
2014	2	1	47,62	16,74	1,2
2014	2	15	47,93	16,26	1,5
2014	3	31	47,95	16,41	1,7
2014	5	7	47,60	16,34	1,2
2014	5	22	47,64	16,34	0,9
2014	6	8	47,86	16,21	2,4
2014	6	16	47,58	16,34	1,4
2014	12	27	47,85	16,58	1,6
2015	1	23	47,95	16,33	0
2015	8	15	47,96	16,34	2,1
2015	8	15	47,87	16,50	2,2
2015	8	15	47,94	16,33	1,9
2015	8	15	47,92	16,36	2,1
2015	8	15	47,95	16,34	1,6
2015	8	15	47,94	16,40	1,9
2015	8	15	47,87	16,47	1,8
2015	8	15	47,94	16,35	2
2015	8	15	47,95	16,33	1,2
2015	8	15	47,95	16,37	1,4
2015	8	15	47,95	16,39	1,8
2015	8	16	47,95	16,37	1,6