Tackling erosion-accumulation events in a moat sequence from a unique Ottoman memorial place (Szigetvár, SW Hungary) using ^{14}C and geoarcheological data

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Abstract

One of the most influential rulers of the sixteenth century, Sultan Suleyman I, passed away and was buried temporarily near the fortress of Szigetvár in SW Hungary in 1566. Later, a memorial place was erected on the site in the second half of the sixteenth century. The complex was surrounded by a palisade system and a moat on its northern side. The site was fully destroyed in 1692, and the exact location vanished with time. Recent investigations of historical sources complemented by geophysical, archeological, and geoarcheological investigations managed to identify the location of the site, and probe corings revealed the moat system. This study presents the results of complex chronological, sedimentological, and geochemical investigations done on the sediments accumulated in the moat. Based on geoarcheological data, two major changes could have been noted in the nature of the deposit marking erosion and transportation of soil from the banks of the moat. Elevated concentrations of Fe and K, and high MS values mark the effects of fire on the deposit and accumulation of flue ash. A rise in heavy metals in these horizons is attributable to anthropogenic sources related to the destruction of the site. Chronological data comes from dateable artifacts repositied and ^{14}C dates of charred cereal seeds. A Bayesian age model built using ^{14}C ages constrained by written historical data on site use helped us to determine the age of moat construction and the referred erosion-accumulation events. The older event was dated around 1670, which is in line with historical records of the first siege of Szigetvár. The second event postdates 1684 and thus must correspond to the time of the site's final siege and later destruction.

Keywords Geoarcheology · Moat sequence · Erosion-accumulation events · Bayesian age modeling · Seventeenth century · Hungary

Introduction

One of the most prominent political leaders of the sixteenth century was Sultan Suleyman I (30 September 1520–7th September 1566), ruler of the Ottoman Empire, who led 13 successful military campaigns during his reign. He passed away in his tent, erected on a natural high above the Ottoman troops, at dawn on the 7th of September 1566 during his last campaign which he launched to occupy Szigetvár, SW Hungary (Fodor 2019; Pap and Kitanics 2015). He was buried temporarily on site. Later, a tomb/mausoleum (*türbe*) complemented by a mosque and a dervish convent was erected on this site. The date of construction of the main buildings was put between 1577 and 1578 (Fodor 2020; Hancz 2014; Kitanics 2014; Pap et al. 2015; Pap 2019). The mausoleum/tomb complex was surrounded by a palisade. Besides, a

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moat was dug on the northern side to offer further protection (Fig. 1a). The location of this moat is visible on the ground plan of Pál Esterházy prepared in 1664 (Fig. 1b) during the winter military campaign of Miklós Zrínyi aimed at the occupation of the memorial site (Fodor 2020; Hancz 2014; Kitanics 2014; Pap et al. 2015; Pap 2019). In 1664 the complex was partially destroyed and then rebuilt. After the siege of Szigetvár in 1689, the marble walls of the mausoleum/tomb were demolished in 1692, and the location of the complex remained unknown for centuries. As a result of extensive research work on historical sources, numerous field surveys, and geophysical measurements from 2013 onwards (Fodor and Pap 2018; Pap 2019; Pap et al. 2015), the exact location of the site was determined. Probe coring was done on-site aiding the identification of the former moat

system (Gyenizse et al. 2017; Sümegi B.P 2020). Later, a probe trench was constructed to reveal the stratigraphy.

Based on written historical data, the construction of the moat was postulated to the final period of the sixteenth century and assumed to have been in use until the demolition of the tomb (Fodor 2020; Hancz 2014; Kitanics 2014; Pap et al. 2015; Pap 2019).

In our work, sedimentological and geochemistry data have been used to unravel chronological shifts in sedimentation and erosion processes prevailing in the moat. Furthermore, to set up an absolute chronology of the deposits, we turned to radiocarbon dating of organic samples deriving from near the base of the moat. Conventional dates given by ^{14}C dating are not a single calendar date, but a certain time interval with a certain probability expressing the error of

Fig. 1 Location of the mausoleum/tomb of Suleyman the Magnificent and the study site. **a** Geophysical map of the site with the coring point marked. **b** The complex on the ground plan of Esterházy 1664.

c Lithology of the studied moat profile and position of dateable artifacts and ^{14}C -dated samples

the measurement (Aitken 1990, 2003; Bowman 1995; Libby 1965; Suess 1970), which is only 15–50 radiocarbon years presently for Holocene samples (Taylor and Bar-Yosef 2014). Additional uncertainty from the calibration of raw dates to calendar dates can further widen the age span due to the presence of numerous wiggles and plateaus in the calibration curve leading often to multi-decadal, multi-centennial age ranges (40–60 or even several hundred years). A series of ^{14}C dates with known stratigraphy can be fine-tuned using Bayesian modeling approaches, as the a priori information on the stratigraphic position of the samples and their association can help us to adjust imprecision generated by the calibration curve (Bayliss 2007, 2009; Bayliss and Bronk Ramsey 2004; Bayliss et al. 2007; Buck et al. 1991, 1996). The age given by written historical sources dating the site use between 1577 and 1692 and the typochronology of artifacts recovered serves as extra a priori information on the association of the ^{14}C dated samples and are built into the model itself as constraints (Buck et al. 1991, 1996; Gulyás et al. 2018). This paper presents an evolution and chronology of the moat (time of construction and filling, including the timing of potential erosion-accumulation events) using geochemical, sedimentological data as well as a combination of ^{14}C dates and written historical sources on site use.

Material and methods

Lithostratigraphy, sampling

Samples were taken from the profile of the moat, after cleaning of the surface, at 10-cm intervals for sedimentological, geochemical, and chronological investigations (Gyenizse et al. 2017; Sümegi 2020) in line with the protocol established for geoarchaeological investigations (Evans 1978; Evans and O'Connor 1999; Rapp et al. 2006). Further samples of ca. 30 L were taken and wet-sieved to retrieve organic remains suitable for dating and paleoecological studies. Results of the latter are not discussed in the present paper. Samples were air-dried, and their color was determined using the Munsell color chart (Munsell 1954). Furthermore, the main visual characteristics of the samples was also described and categorized according to the system of Troel-Smith (1955).

^{14}C dating and age modeling

Four charred cereal grains have been retrieved for AMS ^{14}C dating from the middle and lower parts of the profile via wet-sieving using a German flotation device (Jacomet and Kreuz 1999; Weiss and Kislev, 2004) (Fig. 1c, Table 2). Samples were ultrasonically washed and dried at room temperature. Surficial contaminations were removed by pretreatment with

weak acid etching (2% acetic acid) followed by the ultrasonic ABA treatment before graphitization (Hertelendi et al. 1989, 1992, 1995; Molnár et al. 2013). Measurements were done in the internationally renowned AMS laboratory of Debrecen, Hungary (DeA). Received conventional ^{14}C ages were converted to calendar ages using the software Oxcal 4.2 (Bronk Ramsey and Lee 2013) and the most recent Intcal20 calibration curve (Reimer et al. 2020). Calibrated ages are reported as age ranges at the 2σ confidence level (95.4%) to establish a more consistent absolute chronology. After calibration, the results gained were assessed to see if ranges are influenced by plateaus in the Intcal20 curve. To reduce such potential bias, a single-phase Bayesian chronological model was constructed using relative archeostratigraphic information. The model was constrained primarily by the written historical data of site use (1577–1692). During the fieldwork, several datable artifacts (an Ottoman Turkish silver coin (*medini*), a denarius of Mathias II, and a Turkish knife) have come to light from the top part of the profile (Fig. 1c). The *medini* was in use from 1623 and probably repositioned to the moat towards the end of the site use as seen from its stratigraphic position similarly to the denarius and the Turkish knife. The denarius of Matthias II was minted in Körmöcbánya (Banská Kremnica, Slovakia) between 1613 and 1619. Though in secondary position, absolute ages inferred for the artifacts retrieved from the deposits (Table 1) could also help to cross-check the validity of the chronological model output.

Magnetic susceptibility analysis

Magnetic susceptibility measurements were done to aid stratigraphic interpretations and tackle any potential changes (e.g., pedogenesis, inwash of organic matter, soils, fire) that may have altered the concentration and nature of magnetic minerals present in the deposit. Environmental magnetic analyses were implemented on bulk samples (An et al. 1991; Crowther 2003; Harvey et al. 2003). Prior to the start of the measurement, all samples were crushed in a glass mortar after weighing. Then, samples were cased in plastic boxes of 10 cm^3 and dried in air in an oven at 40°C for 24 h. Afterwards, magnetic susceptibilities were measured at a frequency of 2 kHz using an MS2 Bartington magnetic susceptibility meter with a MS2E high-resolution sensor

Table 1 Stratigraphic position and chronology of artifacts retrieved from the moat

Depth (cm)	Artifact	Inferred age range (cal AD)
75–76	Denarius of Mathias II	1613–1619
94–95	Ottoman Turkish para (<i>medini</i>)	1623–1692
94–94	Ottoman Turkish knife with bone handle	1578–1692

(Dearing 1994). All of the samples were measured three times, and the average values of magnetic susceptibility were computed and reported.

Grain size measurement

Grain size analyses were performed on an OMEC Easysizer 20 laser wet dispersion particle size analyzer after sample pretreatment. The instrument is equipped with a circulating wet sample feeding system. A single, red He–Ne laser of 2.0 mw at a wavelength of 0.6328 mm is used in the system. The instrument adopts the full Mie theory. Diffracted light intensity was measured by 54 sensors over a wide range of angles. The measuring range of the unit is 0.1–500 µm. Constants of 1.33 for the refractive index of water, 1.544 for the refractive index of solid phases (valid for quartz, and most clay minerals and feldspars), and an absorption index of 0.1 were applied. Ultrasonic duration with a circulating speed of 2500 was set to 2 min. Repeatability is within < 3% uncertainty. One gram of sample was treated with 10 ml 10% H₂O₂ in a 50-ml glass beaker overnight to remove organic materials. Then, it was treated with 10% HCL overnight to remove carbonates. Pre-treated samples were dispersed in 50 ml solution adding 5% sodium hexametaphosphate ((NaPO₃)₆) known as Calgon to avoid grain flocculation and were kept agitated using an ultrasonic bath and a propeller stirrer before transferring into the measurement unit. Grain size classes were determined in accordance with the Wentworth scale of grain size distribution (Blott and Pye 2001). However, for the clay fraction, the upper boundary of 4.6 µm was considered in accordance with the general practice used in laser particle size analysis.

Mineralogical composition

The X-ray diffraction (XRD) measurements were carried out on a Rigaku Ultima IV XRD (x-ray: CuKα, 40 mA, 50 kV, slit: 3–60° 2θ, interval: 0.05°, velocity of goniometer 1°/min) at the Department of Mineralogy, Petrology, and Geochemistry of the University of Szeged. Air-dried samples were ground to 50 µm in an agate mortar before the analysis. Minerals were identified primarily by the position of their basal reflections. Specific values were used for characterization of mineral types. Semi-quantitative mineralogical composition was calculated via integral intensity calculations of areas under the diagnostic peaks.

Geochemistry

Loss on ignition (LOI) (Dean 1974) was obtained by weighing after 10 h of calcination at 550 and 900 °C. Chemical composition of the samples for selected major elements (Sr, Ba) was recorded via the flame AAS technique in a PerkinElmer

Optima 7000DV ICP-OES spectrometer using conventional standards of known concentrations. The method of Hungarian Standards Institution (2006) was followed for the preparation of acid leachates (Buzás 1993). In addition, X-ray fluorescence was also employed to assess bulk chemistry using a RIGAKU Supermini wavelength dispersive X-Ray fluorescence spectrometer (tube 3 kW Pd anode, 50 kV, 50 mA). EZScan was the applied measuring method. The time of measurements from fluorine to uranium was 40 min. Major elements (MgO, Al₂O₃, SiO₂, K₂O, CaO, Ti₂O, Fe₂O₃) were determined on fused beads of samples mixed with lithium tetraborate (ratio sample/flux 2:1). Trace elements measured were Ni, Cu, Zn, Sr, Rb, Zr, Pb, P, S. Reproducibility is better than 2%. In the case of major elements, the accuracy of the measurements, as determined by using international standards, is 0.8–1.5 rel. % and around 5–8 rel. % for trace elements. All samples were measured twice, and the arithmetic mean was used for data analysis. Major element concentrations are expressed as wt%, volatile-free.

Statistical analysis

To identify the major sedimentation units of similar characteristics in the moat sequence representing erosion-accumulation events and intervening normal accumulation, all data has been subjected to cluster analysis. For the clustering, we adopted the Wards method using the City Block similarity measure. In order to identify the main factors controlling sediment accumulation in the moat, the measured grain size, geochemical, and magnetic susceptibility data has been subjected to factor analysis using a covariance matrix and a varimax rotation to maximize the loadings of the variables in the components. As the analysis is sensitive to extreme values and outliers, data was converted to Z-scores calculated as $(X_i - X_{avg})/X_{std}$, where X_i is the variable and X_{avg} and X_{std} are the series average and standard deviation, respectively, of the variable X_i .

Results

Sedimentology, geochemistry

The bedrock is given by yellowish-brown, calcareous loess overlain by dark brown (10 YR 3/2) clayey silt with a high organic content (Figs. 1c and 2, Table 2). This horizon embedded numerous charcoal pieces and must correspond to a paleosol horizon. The overlying layers represent the actual fill of the moat. It is made up of yellowish-brown (10 YR 4/2) organic-rich clayey silt embedding charcoal, plant remains, bones, and mollusk shells. Thus, the actual fill is a mixture of the original bedrock material and inwashed surface soil of Ottoman age deriving from the banks of the

moat. For the interpretation of the lithological and sedimentological features, one must bear in mind that the moat must have been under water during the major part of its use with minimal silting up and periods of increased sediment input must correspond to site abandonment following site destruction. The deposit exhibits minor lamination throughout the entire sequence with clearly observable flame structures at the base and the margins of the moat marking deposition in

water. The upper half meter of the sequence is given by a mixture of construction debris and soil representing the final infill of the moat as a result of surface leveling done in the eighteenth century (Figs. 1c and 2, Table 2).

Magnetic susceptibility (MS) of the studied samples ranged between 47.2 and $58.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (Fig. 2, Table 3). The majority of the samples fall within the range of 47.75 and $52.6 \times 10^{-8} \text{ kg}^{-1} \text{ m}^3$ corresponding to the

Fig. 2 Results of sedimentological and magnetic susceptibility analyses done on samples of the moat profile

Table 2 Stratigraphy and observed lithological features of the moat profile of Szigetvár

Depth (cm)	Type	Lithology				MS ($10 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$)
		Troels-Smith type	Color	Munsell	Texture	
0–20	Plowed modern soil	Sh2As2	Greyish-brown	10 YR 4/3	Mixed	49.4
20–40	Mixed debris and soil	Sh1As2Lc1	Reddish-brown	10 YR 3/6	Blocky	50.3
40–250	Ditch infill	Sh2As2	Yellowish-brown	10 YR 4/2	Slightly laminated	42.7–42.9
250–260	Ice Age paleosol	Sh1As3	Dark brown	10 YR 3/2	Porous	54.3

Table 3 Results of ^{14}C analyses done on samples of the moat sequence

Sample	Depth (cm)	Lab code	Material	^{14}C ages		Calendar ages (cal AD)				Modeled ages (cal AD)			
				BP	$\pm 1\sigma$	From	To	Mean	$\pm 2\sigma$ error	From	To	Mean	$\pm 2\sigma$ error
1	160–175	DeA-15040	A charred Hordeum seed	193	28	1647	1942	1774	168	1662	1689	1674	14
2	175–190	DeA-15038	A charred Hordeum seed	167	26	1662	1968	1794	174	1659	1683	1670	12
3	220–235	DeA-15034	A charred Hordeum seed	304	27	1495	1652	1570	90	1650	1676	1663	12
4	235–250	DeA-15036	A charred Hordeum seed	148	27	1668	1976	1808	168	1647	1674	1661	14

bedrock material into which the moat was dug. Values characterizing the underlying paleosol (230–260 cm) and the overlying topsoil, debris (40–0 cm) also fall into the upper end of this range.

The dominant component of the material is silt with relatively uniform proportions ranging between 84 and 88% for the major part of the moat. The lowest values are confined to levels of the modern topsoil and mixed soil, debris horizon alone. The clay content follows the same pattern with more or less uniform low values of 10–12% for the part representing the bedrock material of the ditch. The corresponding organic content of the samples (LOI550) are also low in general (2.5–3.5%) in agreement with grain size data (Fig. 2). In three horizons (180–170 cm, 130–80 cm, 40–0 cm), there is a reduction in the ratio of silt-sized particles accompanied by an increase in organic (to 5–6%), clay content (to 16 and 20%, respectively), and MS values (Fig. 2). The two intervals between 110–130 and 170–180 cm have the highest MS values of $56\text{--}58.6 \times 10^{-8} \text{ m}^3 \times \text{kg}^{-1}$ recorded, clearly marking a change in the nature of the deposit. Here the organic content reaches 5–6.5% parallelly with an increase in the clay content to 16–18%. A ca. 8–10% reduction in the silt-sized particles, a slight increase in the sand content is also notable here compared to values observed for the underlying horizons (Fig. 2). In the intervals between 180–170 and 130–80 cm, there is also an increase in the carbonate content compared to the underlying horizons. All these indicate a significant input of clay, organic-rich sediment with a considerable carbonate content into the moat, probably representing eroded soil covering the surrounding areas. These two

zones are marked as erosion-accumulation events I and II on Fig. 2.

The dominant minerals in the moat sequence are clay minerals (43.28% on average), quartz (39.04% on average), and calcite (13.48% on average) (Fig. 3) with additional minerals of muscovite, chlorite, feldspars, and dolomite being also present in minimal proportions (0.56–1.48% on average). The proportion of the dominant kaolinite/illite stays relatively constant (around 44%) in the entire sequence with the exception of two intervals of significant decrease (between 180–160 and 110–80 cm), where a parallel increase in all other minerals except for calcite is notable. Variations in the concentration of calcite follow a similar pattern to that of the clay minerals. The observed changes in the mineral composition similar to that of the grain size and magnetic susceptibility data of Fig. 2 point to 2 marked transformations in sediment accumulation in the moat again (Fig. 3).

The entire sequence can be divided into two major units based on the output of cluster analysis done on magnetic susceptibility, grain size, mineral compositional, and geochemical data (Fig. 4). These two units clearly correspond to the visually observable stratigraphic units of the moat sequence. Group 1 represents the upper 40 cm, i.e., the leveled soil and construction debris. Group 2 from a depth of 40 cm down to the base of the moat corresponds to the actual original fill (Fig. 4). Group 2 can be further subdivided into 2 subgroups (a, b) each having 2 additional components (a1, a2, b1, b2). The recorded parameters of grain size, LOI, geochemistry, and mineral composition stay relatively constant in the samples of

Fig. 3 Mineralogical composition of the moat sequence

Fig. 4 Results of cluster analysis depicting 2 major units with 4 subunits in group 2

group 2b2 (140–150 cm and 200–250 cm). Thus, we can interpret these to represent the characteristic undisturbed moat deposits. However, the samples of groups 2a1 and 2a2 (50–100 cm and 160–190 cm) significantly deviate from those of group 2b2, signaling marked shifts in the nature of sediment accumulation in the moat (Figs. 2 and 3). Samples of group 2b1 slightly differ from those of 2b2.

These marked changes in the lithology probably represent periods of major dry sediment input from the nearby areas.

The referred marked changes in the nature of the deposit are clearly visible on the results of geochemical analyses as well (Fig. 5). Group 1 corresponding to the uppermost 40 cm of the sequence is generally characterized by higher concentrations of all lithogenic (Ca, Mg, Ba, Na, Mn, Fe,

Fig. 5 Results of geochemical analyses done on samples of the moat profile

Al, and K) and biogenic (P,S) elements in line with chemical processes characterizing pedogenesis (Ghaemi et al. 2011; Kizilkaya 2004) (Fig. 5). The concentration of some anthropogenic metallic elements (Cu, Ni, Pb, Zn, Cr) generally bound to clays is also slightly elevated in this unit of the leveled topsoil, while SiO_2 remains low compared to the other intervals of the sequence. The concentration of all lithogenic, anthropogenic, and biogenic elements remains relatively low and constant in the major part of group 2 (2b1, 2b2) representing the original moat fill. A marked increase is observable between the depths of 160–190 and 50–110 cm, respectively. This uniform increase of all elements, which are generally enriched in soils, clearly indicates erosional soil input into the moat (Ghaemi et al. 2011; Kizilkaya 2004) in both referred depth intervals in line with MS and grain size data. Elevated potassium concentrations between the depths of 170–180, 110–130, and 60–90 cm

again significantly higher than recorded at the base of the sequence, most likely derived from flue ash accumulating in the moat as a result of intensive site burning (Fig. 5). High MS values, higher than those of the paleosol and the modern soil (Fig. 2), here may hint to the effects of burning bringing about the accumulation of finely dispersed iron oxide particles in the sediment.

In the same depth intervals where marked changes in the nature of the deposit must be postulated (160–190 and 70–110 cm), recurring increases in lead, chromium, copper, zinc, and nickel (Fig. 5) indicating contamination from anthropogenic sources rich in the referred elements are also visible.

Factor analysis of all geochemical, sedimentological data revealed the presence of 4 major factors controlling sediment accumulation capturing 85.8% of the total variance (Fig. 6, STables 1 and 2). Factor 1 has high positive loading on Fe, Mn, Na, Al, P, S, and Ba, i.e., generally lithogenic elements

Fig. 6 Results of factor analysis combined with those of cluster analysis on sedimentological and geochemical data

connected to pedogenesis. Factor 2 has high loadings on Mg and Ca, i.e., carbonate-forming elements and K. Factor 3 has high loadings on all metallic anthropogenic elements as well as LOI550, magnetic susceptibility, and clay-sized particles. Factor 4 has the highest loading on lead. As seen on Fig. 6, there is a clear positive shift in all factor values in the formerly mentioned depth interval of 190–170 cm highlighting important shifts in the nature of sediment accumulation. In the interval between 130 and 80 cm, all factors except factor 2 display significant positive shifts, again hinting to the erosion and accumulation of non-moat deposits.

Chronology

Results of ^{14}C dating are depicted in Table 3. Conventional ^{14}C ages are relatively uniform with the exception of sample 3, where the received conventional age is older. After calibration, the age of sample 3 is placed between 1495 and 1652 cal AD with a mean of 1570 ± 90 cal AD years. This is congruent with the period where historical records placed the construction of the main buildings, i.e., between 1577 and 1578 (Fodor 2020; Hancz 2014; Kitanics 2014; Pap et al. 2015; Pap 2019). After simple calibration, the mean calibrated ages and the upper age ranges of the remaining 3 samples (samples 1, 2, and 4) fall outside the period of documented site use (1578–1692). Although the lower boundary age ranges of 1647, 1662, and 1668 cal AD do represent

the second half of the seventeenth century, the upper age boundaries extend to the second and last thirds of the twentieth century (Table 3, Fig. 7). To understand the causes of such widely calibrated age ranges in our case, one must observe the shape of the Intcal2020 calibration curve for the period of 1500 and 1950 cal AD (Fig. 7, right).

There are significant departures from the linear relationship between radiocarbon ages and calendar ages between ca. 1530 and 1630, 1730–1800, 1830–1900, and 1900–1950 cal AD, resulting in four major plateaus visible on the Intcal20 calibration curve (Fig. 7, right). As a result, a single radiocarbon date range produces two or more separate calendar year ranges leading to anomalously widely calibrated age ranges (Fig. 7). This bias attributable to the shape of the calibration curve is relevant in all measured samples. The plateau between 1530 and 1630 cal AD on the Intcal20 calibration curve places our sample 3 (DeA-15034) to older lower age ranges than real. Conversely, a similar plateau on the calibration curves from 1730 cal AD results in a shift to younger upper age ranges in the remaining samples (Fig. 7). After the introduction of the constraint of written record of site use (1578–1692), the constructed age model is better confined and received calendar ages are more congruent with our understanding of actual site use (Table 3, Fig. 7).

Based on the modeled ages, sediment accumulation in the moat must have started around 1651 ± 36 cal AD years and come to an end around 1684 ± 36 cal AD years at a depth

Fig. 7 Chronology of the dated lower part (250–160 cm) of the moat inferred from combined Bayesian modeling of ^{14}C data (red band) and dates of site use known from written historical sources (1578–1692) (blue band)

of 160 cm (Fig. 7, Table 3). The lowermost 90 cm of the moat sequence thus captures a timespan of ca. 20–30 years. The remaining part clearly postdates 1684 cal AD and must capture a timespan of ca. 8 years until the tomb destruction. It is interesting to note how close the mean modeled ages of the lower two adjacent samples (DeA-15036, DeA-15034) are with only a couple of years difference (1661 ± 14 cal AD and 1663 ± 12 cal AD years). The same can be said about the upper two adjacent samples too, corresponding to the depth interval between 160 and 190 cm where the first marked change in the sedimentation was noted (DeA-15038, DeA-15040: 1670 ± 12 cal AD and 1674 ± 14 years). This clearly highlights relatively rapid sediment accumulation.

Discussion

Based on our chronological data, the moat offering protection to the tomb of Suleyman at Szigetvár must have been in use for a period of ca. 40 years starting between 1651 ± 36 cal AD years and 1692 cal AD. Sediment accumulation however was by no means uniform as seen from the complex sedimentological, geochemical investigations of samples deriving from the moat. Two major changes are notable in the sequence seen in elevated elemental concentrations, magnetic susceptibility, grain size, and organic content values, which may hint to destruction of the site by fire (seen in elevated values of K and MS) and accompanying temporal sediment erosion and input from the nearby areas. Based on our chronological data, the older event must be placed to around 1670 ± 12 and 1674 ± 14 cal AD years. This data is almost perfectly in line with historical dates marking the destruction of the site during the winter campaign of the Hungarian troops led by Miklós Zrinyi in 1664 (Fodor 2020; Hancz 2014; Kitanics 2014; Pap et al. 2015; Pap 2019). According to the available information, the site was set on fire and soaring temperatures must have melted the lead metal tiles covering the mosque and the mausoleum resulting in an increased input of heavy metals into the debris eroded and transported into the moat.

Based on its stratigraphic position and our chronological data, the second marked change in sedimentation recorded by sedimentological and geochemical data in the upper part of the sequence, most likely corresponding to another destruction of the site, clearly postdates 1684 ± 36 cal AD years and might be dated to the last third of the seventeenth century. According to the historical records (Fodor 2020; Hancz 2014; Kitanics 2014; Pap et al. 2015; Pap 2019), during the second blockade of the site in 1688/1689, the Christian troops who occupied the site melted the lead metal tiles of the mosque and chapel complex for the preparation of bullets and trade. This would explain the elevated levels of heavy metals in the coeval moat deposits.

To sum up, geoarcheological records such as moat sequences record information on the nature of sedimentation and erosion processes acting in and around a site during its use. In this way, their comprehensive analysis complemented by absolute dating may help refine our views of site evolution known from written records. Sedimentological and geochemical changes were observable in the moat deposits of Sultan Suleyman's mausoleum complex hallmark, two major erosion-accumulation events when material was intensively transported to the moat from the neighboring areas most likely attributable to site destruction. Relying on an absolute chronology, these events may be linked to two military campaigns in 1664 and 1688/89.

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Author contribution All authors contributed to the study conception and design. Methodology, format, samplings, analysis investigation, interpretation of geoarcheological data, radiocarbon dating and age model building, and multidisciplinary interpretation: Sándor Gulyás, Pál Sümegi, Andrea Torma, Mihály Molnár. Relevant historical and site-specific information provision, multidisciplinary interpretation: Norbert Papp, Pál Fodor, Péter Gyenizse, and Máté Kitanics. Writing—original draft preparation: Sándor Gulyás, Pál Sümegi. All authors commented on and contributed to the writing of the revised versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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