E&G Quaternary Science Journal
Volume 60 / Number 1 / 2011 / 153-169 / DOI 10.3285/eg.60.1.11
www.quaternary-science.net
GEOZON SCIENCE MEDIA
ISSN 0424-7116

The Loess Chronology of the Island of Susak, Croatia

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Abstract: A high-resolution infrared stimulated luminescence (IRSL) and radiocarbon dating study was performed on the loess-paleosol sequence from the island of Susak, situated in the North Adriatic Sea in Croatia. The dating results show that a detailed Late Pleistocene record is preserved on Susak, correlating to the marine Oxygen Isotope Stages (OIS) 5 to 2, with a very thick Middle Pleniglacial record predominating. Due to its extraordinary thickness (which is recorded to be up to 90 metres), the loess on Susak is unique in this area. The numerous paleosols intercalated in the loess give evidence for climate variations which were warmer than in other loess regions (e.g. the Carpathian Basin). The great thickness of the OIS3 deposits correlates to the general increased dust accumulation in Europe during that time. Based on numerical ages a correlation of the loess on Susak with the loess in North Italy and the Carpathian basin, a more detailed time-based reconstruction of climate and environment changes in the study area was achieved.

[Löss-Chronologie der Insel Susak in Kroatien]

Kurzfassung: Zahlreiche infrarot optisch stimulierte Lumineszenz (IRSL)- und Radiokohlenstoff (14C)-Datierungen wurden an mächtigen Löss-/Paläobodenabfolgen der Insel Susak in der nördlichen Adria von Kroatien durchgeführt. Die Datierungsergebnisse zeigen, dass eine sehr detaillierte spätpleistozäne Sedimentabfolge auf Susak erhalten geblieben ist, die mit den marinen Sauerstoff-isotopenstadien (OIS) 5 bis 2 korreliert. Hervorzuheben ist ein besonders mächtiges und gut gegliedertes Mittelpleniglazial. Aufgrund der großen Mächtigkeit von bis zu 90 m bildet der Löss auf Susak ein einzigartiges außerordentlich hoch aufgelöstes Klimaarchiv in dieser Region. Die zahlreichen im Löss zwischen geschalteten Paläoböden weisen auf Klimavariationen, die auf Susak wärmer gewesen sind als beispielsweise im benachbarten Karpatenbecken. Die große Mächtigkeit der Abfolge korreliert mit den während des OIS 3 allgemein höheren Staubakkumulationen in Europa. Basierend auf den nummerischen Altern kann die Löss-/Paläobodenabfolge aus Susak mit denen aus Norditalien und dem Karpatenbecken verglichen werden und ermöglichen eine detailliertere zeit-basierte Rekonstruktion der Klima- und Umweltveränderungen im Arbeitsgebiet.

Keywords: *Susak, Croatia, loess-paleosol sequence, geochronology, IRSL dating, radiocarbon dating*

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1 Introduction

Evidence of Pleistocene climatic changes can be found in more or less continuous terrestrial sediment records like loess-paleosol sequences. Great efforts are made into the high resolution sampling and investigation of loess records using different disciplines and methods with the purpose of identifying climate oscillations and environmental changes (Buylaert et al., 2008; Stevens et al., 2008; Bokhorst & Vandenberghe, 2009). The correlation with oxygen isotope stages (OIS) and the GRIP data (GRIP Members, 1993) is a common practice. However, a robust and detailed chronology is mandatory to make a reliable correlation possible.

Loess and loess-like deposits in the North Adriatic region are found along the fringes of mountain chains like the Alps and the Apennines in Italy and along the coast and islands of Croatia. During the last Glacial period, the sea le-vel of the Mediterranean was about 100 metres lower than today (Van Straaten, 1970; Cremaschi, 1987; Amorosi, et al., 1999). Therefore, the North Adriatic was an extended and closed basin exposed to a strong input of fluvial Alpine material carried by the river Po and other tributaries. The thickness of the loess and loess-like deposits in the North Adriatic area is relatively small, only up to a few meters (Ferraro, 2009), but the deposits are widely distributed. In Italy, loess and loess derivatives can be found on fluvial terraces (Cremaschi et al., 1990), on moraines and fluvio-glacial deposits e.g. Val Sorda (Ferraro, 2009; Ferraro et al., 2004), or on the carbonate platform (Coudé-Gaussen, 1990) where they cover the carbonate basement and fill caves and shelters (Cremaschi, 1987; Peresani et al., 2008). Along the Croatian coast and on the islands loess and loess derivatives are common. In Istria loess can be found in the south, in Premantura and Mrlera, and in the north-west, in Savudrija (Durn, Ottner & Slovenec, 1999; Durn, et al., 2007) as well as on the islands of Unije, Velike and Male Srakane, Krk and Lošinj in the Kvarner region and on the islands Hvar and Mljet in South Dalmatia, with reported thickness ranging from a few meters up to about 20 m (Bognar, 1979). In Savudrija loess is up to 4 m thick and covers terra rossa (Durn, Ottner & Slovenec, 1999; Durn et al., 2003, 2007). The influence of loess was recognised by Durn, Ottner & Slovenec

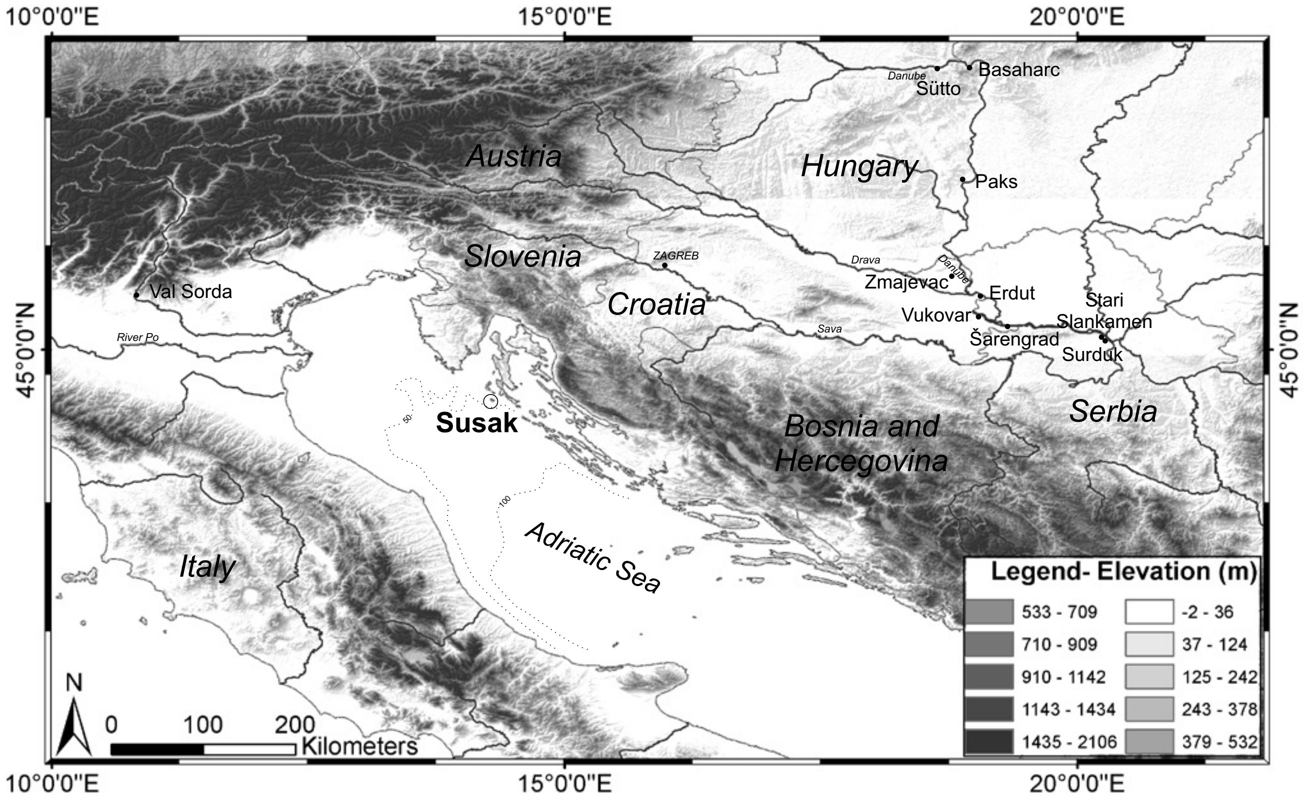

Fig. 1: Geographical setting of the Island of Susak in Croatia and its relation to the river Po in North Italy and to the Danube loess region with indicated locations of loess-paleosol sections used for correlation. Elevation map for the area is prepared using the DEM image obtained from ASTER GDEM (product of METI and NASA).

Abb. 1: Geographische Lage der Insel Susak in Kroatien sowie die Lage der für die Korrelation wichtigen Löss-/Paläoboden-Aufschlüsse in der Po-Region in Norditalien und entlang der Donau. Die Höhenlinien beziehen sich auf ein digitales Höhenmodell basierend auf ASTER GDEM-Daten (METI und NASA).

(1999) and Durn et al. (2007) in the upper parts of terra rossa profiles in Istria. The most extraordinary loess-paleosol record of this area is the one found on the island of Susak in Croatia (Fig. 1). The genesis and the composition of the deposits on the island have been a matter of interest and discussion for a long time, since the two past centuries (Fortis, 1771; Marchesetti, 1882; Kišpatić, 1910; Šandor, 1914; Mutić, 1967; Wein, 1977; Bognar, 1979; Bognar et al., 1983; Cremaschi, 1987; 1990; Bognar & Zámbó, 1992; Bognar, Schweitzer & Kis, 2002; Bognar, Schweitzer & Szöőr, 2003; Lužar-Oberiter et al., 2008; Mikulčić Pavlaković et al., 2011; Wacha et al., 2011). Based on the mineralogical investigations of the deposits from Susak, most of the researchers concluded that the provenance of the material is the river Po plain, situated in the northern part of Italy. Cremaschi (1990) stated that the deposition of loess on Susak is related to the 100 metres drop of the sea level in the Mediterranean during the last glacial period. Recently, the loess-paleosol record on Susak has been successfully dated using infrared stimulated luminescence (Wacha et al., 2011). These first results showed that most of the loess-paleosol record correlates to Oxygen Isotope Stage (OIS) 3, but the deposition age of the stratigraphically older and younger part of the sequence has not yet been determined.

In Croatia, loess and loess-like deposits are well known from the north of the country, on the Bilogora Mountain, around Đakovo, and the eastern part of the country along the river Danube, in Baranja, Srijem and on the Fruška gora (gora = mountain). Loess deposits in this region were investigated by Šandor (1912), Gorjanović-Kramberger (1912, 1915, 1922), Bronger (1976, 2003), Bognar (1979), Galović & Mutić (1984), Poje (1985, 1986), Mutić (1990) and others. The first age estimates of these deposits were presented by Singhvi et al. (1989), using the thermoluminescence (TL) dating method, and by Galović et al. (2009) using the infrared stimulated luminescence (IRSL).

Fig. 2: Photo of Kalučica bay on the easternmost cape of the island, with the characteristic dissected morphology of the Susak loess sequence.

Abb. 2: Foto der Kalučica Bucht am östlichsten Kap der Insel mit der charakteristischen morphologischen Ausprägung der Lösse auf Susak.

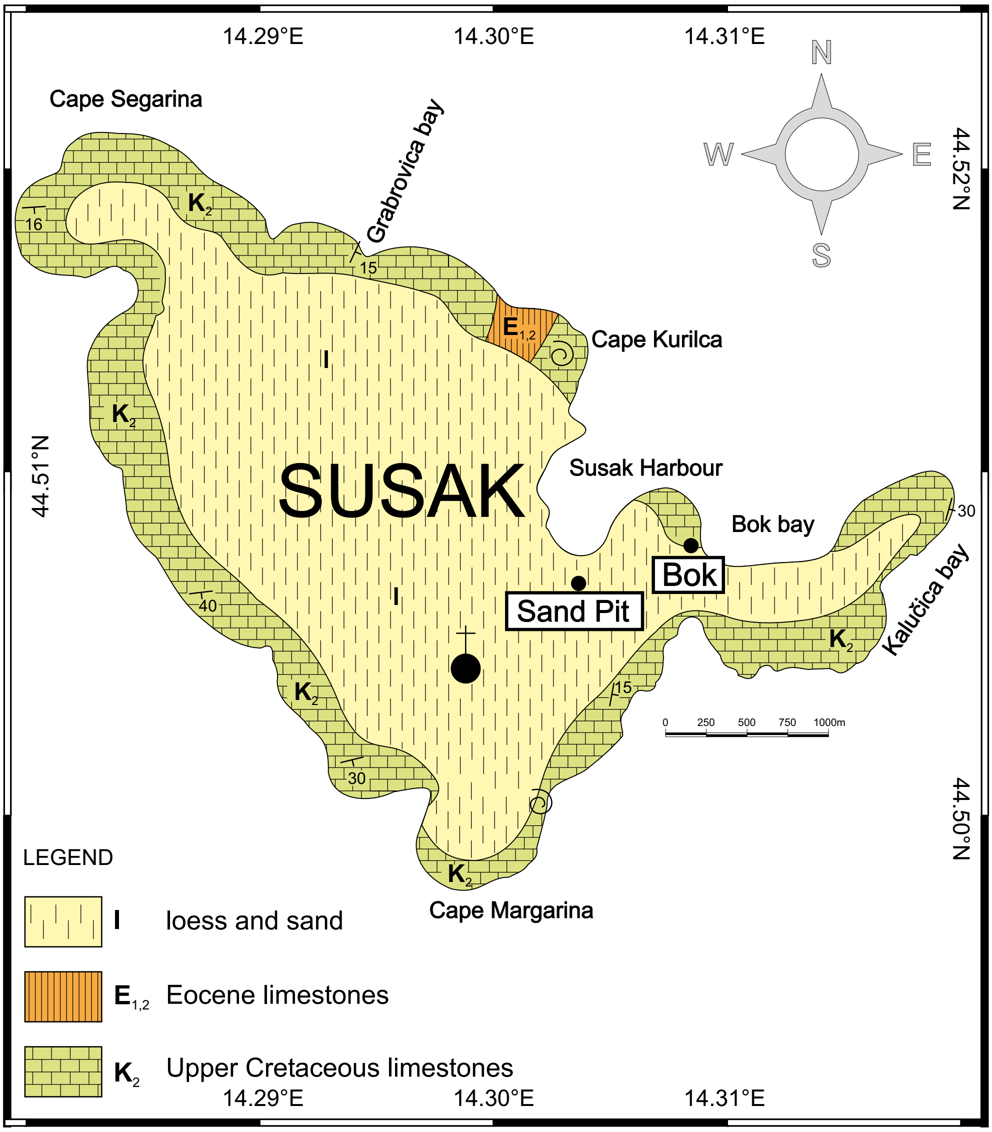

Fig. 3: Geological map of the Island of Susak (simplified after Mamužić*, 1965).*

Abb. 3: Geologische Karte der Insel Susak (vereinfacht nach Mamužić*, 1965).*

Fig. 4: Carbonate basement covered with the red paleosol which represents the beginning of the Quaternary loess-paleosol sequence on Susak. (Photo by E. Schmidt.)

Abb. 4: Karbonatisches Basement mit überlagerndem roten Paläoboden, der den Beginn der quartären Löss-/Paläoboden-Sequenz repräsentiert (Foto: E. Schmidt).

In this study the geochronological framework of the loess record from the island of Susak presented in Wacha et al. (2011) is significantly improved by new infrared stimulated luminescence (IRSL) and radiocarbon data. Furthermore, the detailed loess-paleosol sequence is compared with the contemporaneous loess deposits from the North Adriatic Basin and the Pannonian (Carpathian) Basin and an attempt of a chronostratigraphical correlation is given. The loess provinces mentioned above differ in many ways. The loess in the Adriatic region is often neglected when major correlations of loess in Europe are made. In this study the differences and similarities of these two genetically different loess provinces are summarized and they are correlated based on their chronology.

The aim of this study is to establish a more detailed geochronological framework for the unique loess record on the Island of Susak in the North Adriatic Sea as a basis for further high-resolution proxy studies including grain-size and palaeomagnetic approaches (Wacha et al., in preparation) and to settle the Quaternary sediment succession of the Island in a wider context, that of the North Mediterranean and Pannonian (Carpathian) area.

Fig. 5: Three macroscopically visible tephra layers were detected intercalating the Susak loess-paleosol sequence, described in more detail by Mikulčić Pavlaković et al. (2011). a) TF1 – a thin yellow layer of the lowermost, oldest tephra; b) the thin brown paleosol with patches of orange-yellow middle tephra (TF2); c) TF3 – the uppermost and stratigraphically youngest most tephra intercalating loess on Susak is found as a thin olive green layer.

Abb. 5: Drei makroskopisch sichtbare Tephralagen sind den Löss-/Paläobodenabfolgen auf Susak zwischen geschaltet. A) TF1 – dünne gelbe Lage der untersten und stratigraphisch ältesten Tephra; b) TF2 - dünner brauner Paläoboden mit taschenartigen Anreicherungen einer orange-gelben Tephra; c) TF3 – oberste und stratigraphisch jüngste Tephra als oliv-grüne Lage im Löss zwischen geschaltet.

2 Geological setting and the sediment succession

The island of Susak is situated in the western part of the Kvarner Archipelago in the North Adriatic Sea in Croatia (Fig. 1). It is the outermost and quite isolated island with an area of 3.8 km^2. The highest peak is at 96 m above sea level (asl). Susak is located between 44.50° and 44.52°N and 14.28° and 14.32°E. The geomorphology of the island has all characteristics of a loess plateau (Bognar, Schweitzer & Szöőr, 2003) dissected by numerous gorges, steep bluffs and gullies (Fig. 2). Human activity during historical times had and still has a major influence on the morphology and erosion of the island because the island is a wine yard area since Roman times resulting in numerous artificial plateaus.

Geotectonically, Susak belongs to the West Istrian autochton of the Northern Adriatic Carbonate Platform (Mamužić, 1973). The basement of the island is made of Upper Cretaceous limestones (Fig. 3 & 4). On the northern coast, Eocene limestones can be found (Mamužić, 1973). The bedrock is covered by up to 90 metres of Quaternary sediments, recently described by Cremaschi (1990), Bognar, Schweitzer & Szöőr (2003), Mikulčić Pavlaković et al. (2011) and Wacha et al. (2011). Pliocene and Pleistocene sediments are usually transgressive on the Jurassic and Cretaceous carbonates of the Istrian platform, and on Neogene or Paleogene deposits in the Po basin as seen in cores from the North Adriatic Sea (Kalac, et al., 1995). The Quaternary deposits on Susak are made of loess, loess derivatives and sand, and are intercalated by numerous paleosols and at least three tephra layers (Fig. 5).

Wacha et al. (2011) and Mikulčić Pavlaković et al. (2011) described altogether four smaller sections from the Eastern part of the island in more detail (Fig. 3). In the bay of Bok (Fig. 3) a red paleosol, overlain by a second red paleo-sol, covers the carbonate basement (Fig. 4). The thickness of these red paleosols is up to 100 cm but changes laterally. On some locations on the island only one red paleosol is exposed. The paleosols are separated with septarian carbonate concretions, up to 20 cm in diameter. Sandy loess covers the red paleosols and is in its lower part lithified forming a sandstone bench. In the upper part of the sandy loess horizon vertical carbonate concretions up to 10 cm long are found. Secondary carbonates are described in more detail by Bognar & Zámbó (1992) and Mikulčić Pavlaković et al. (2011) and indicate strong water percolation from the upper part of the section. The lower part of the loess-paleosol sequence on Susak is dominated by three about 1 metre thick paleosols, two of them brown and one orange-brown in colour. In the upper part of the loess sequence numerous thin brown paleosols are exposed, some of them containing dispersed charcoal and charcoal pieces (Fig. 6). The charcoal pieces found in two horizons were investigated by Bognar, Schweitzer & Szöőr (2003). They concluded that these remains are the results of forest fires, caused by self-inflammation or human activity and determined the Pinus sylvestris group of tree species from the charcoal. In the middle part of the loess-paleosol record homogenous and laminated sand can be found, in a form of a few centimetres thick layers and dune sand. The sand indicates stronger wind activity, a near-distance transport and a very likely local source of the material. The transition from sand into loess is mostly gradual. The general trend of loess coarsening upwards was observed by Mikulčić Pavlaković et al. (2011) and is supported by the results of grain-size analysis from an ongoing study (Wacha et al., in preparation). Three tephras were detected intercalating the loess of Susak; two in a form of continuous layers (TF1 and TF3) and one as accumulations (pockets) in a thin brown paleosol (TF2) (Fig. 5). The sedimentological, geochemical and mineralogical properties of loess, sand, paleosols and the tephras are presented in more detail by Mikulčić Pavlaković et al. (2011). In Fig. 7 all the investigated and sampled sections are presented along with the indicated sample positions and IRSL and radiocarbon ages.

Fig. 6: A detail from the upper part of the Sand Pit section showing the weakly developed brown paleosols with dispersed charcoal remains and the IRSL and radiocarbon dating results.

Abb. 6: Detailansicht der schwach entwickelten braunen Paläoböden (OIS 3) mit zahlreichen Holzkohleresten aus dem Sand Pit-Aufschluss sowie den IRSL- und ^{14}C-Datierungsergebnissen.

3 Dating methods

3.1 Luminescence Dating

Loess has proved to be excellent material for luminescence dating (Frechen, Horváth & Gábris, 1997; Lu, Wang & Wintle, 2007; Roberts et al., 2003; Roberts, 2008; Novothny, Horváth & Frechen, 2002; Novothny et al., 2009, 2010; Schmidt et al., 2010) because it fulfils the basic dating assumption which is the complete bleaching of the latent luminescence signal in the mineral grains (quartz and feldspar) prior to deposition. Aeolian transportation of dust is a good mechanism for the fulfilment of such an assumption because during transport the particles are exposed to sunlight which releases most of the trapped charges in the crystal lattice of the minerals and resets the dosimeter to zero. After the deposition and after the material had been buried, the minerals are again exposed to the natural radioactivity of the surrounding sediment. This ionizing radiation moves the charges from their original position into charge traps caused by impurities or crystal lattice defects, from where they can only be released by additional energy. Releasing these electrons from the traps and their recombination with the positive charges in the crystal lattice results in the emission of light (luminescence), and can be measured by a photomultiplier in the laboratory. With time the amount of such dislocated charge grows, meaning that the luminescence signal is proportional to the depositional age of the sediment. The intensity of the luminescence signal increases with the deposition age of the sediment. The equivalent dose (D_e) is a measure of the past radiation and, if divided by the dose rate, gives the time elapsed since the last exposure of the sediment to sunlight, i. e. the deposition. The principles of luminescence dating are given in detail by Aitken (1985, 1998), Wintle (1997), Bøtter-Jensen, McKeever & Wintle (2003) and Preusser et al. (2008, 2009) and a more recent review about luminescence dating of loess is presented by Roberts (2008).

Twenty-one samples were collected in 2008 using light-proof plastic tubes, by pushing or hammering into a previously cleaned loess wall. Additional material was taken for dose rate determination by gamma spectrometry. In this study we applied the same sample preparation procedure for the extraction of the polymineral fine-grained material, as described in Wacha et al. (2011).

The same protocols and measurement procedures were used as presented in Wacha et al. (2011), because they have proved to be satisfactory. All measurements were performed using two automated Risø TL/OSL-DA15 readers at the Leibniz Institute for Applied Geophysics equipped with a ^{90}Sr/^{90}Y β-source, with dose rates of 0.101 Gy/s and 0.096 Gy/s, respectively, for fine grains mounted on aluminium discs.

Fading tests were performed on the same aliquots which were previously used for D_e measurements for all samples using the suggestion of Huntley & Lamothe (2001) and Auclair, Lamothe & Huot (2003). The same measuring conditions were used as for the D_e evaluation. The mean of the six aliquots was used for fading corrections and their standard errors. The fading rates (g-values) were calculated according to Huntley & Lamothe (2001) using the same integration limits as for the D_e calculation. The g-values were used for age corrections.

The dose rates of the sediment were measured by gamma spectrometry with a HPGe (High-Purity Germanium) N-type coaxial detector in the laboratory at the Leibniz Institute for Applied Geophysics. 700 g of dried and homogenized material was used for the measurements. Each sample was placed into a Marinelli-beaker and cap sealed to avoid the loss of ^{222}Rn in the ^{238}U decay chain and stored for a minimum of four weeks in order to re-establish the radioactive

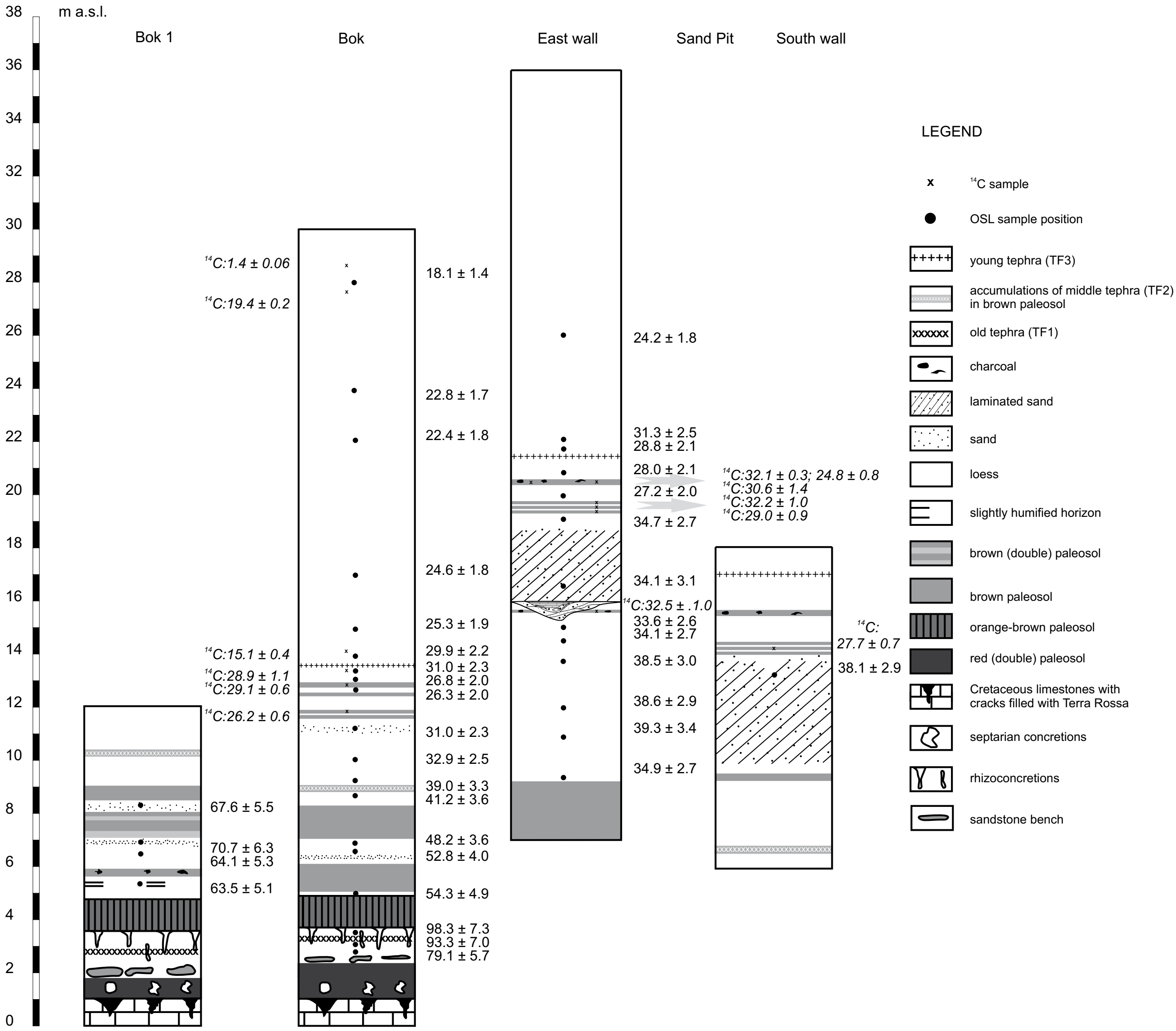

Fig. 7: The investigated loess-paleosol sections on Susak, with indicated IRSL and radiocarbon sampling positions and age estimates, and their correlation.

Abb. 7: Die untersuchten Löss-/Paläobodenaufschlüsse auf Susak mit IRSL- und ^{14}C-Probenpositionen und Altersergebnissen sowie die Korrelation der Horizonte.

equilibrium. The measuring time was one day. The measured activities of ^{40}K; and ^{210}Pb, ^{234}Th, ^{214}Bi and ^{214}Pb radionuclides from the ^{238}U; and ^{228}Ac, ^{208}Tl and ^{212}Pb radionuclides from the ^{232}Th decay chains were used for the calculation of potassium, uranium and thorium contents, respectively. The radioactive equilibrium was assumed for the decay chain, which is normally the case for loess; no radioactive disequilibrium was detected by gamma spectrometry. Cosmic dose rates were corrected for the altitude and sediment thickness (Prescott & Hutton, 1994). The alpha efficiency was estimated to a mean value of 0.08 ± 0.02 for polymineral IRSL (Rees-Jones, 1995). The water content was assumed to be from 15 ± 5% to 20 ± 5%, depending on the depth (Pécsi, 1990). For the calculation of the total dose rate the conversion factors published by Adamiec & Aitken (1998) were used. A systematic error of 2% is included for the gamma spectrometry. An error of 10% is estimated for the cosmic dose. The uranium, thorium and potassium contents, as well as the total dose rates, the cosmic dose rates, the g-values, the uncorrected and corrected ages are given in Table 1.

3.2 Radiocarbon dating

In this study seven new radiocarbon ages are presented, six from the Bok section and one from the Sand Pit section. Among them four samples were molluscs (Hv 25895–25898) and three were charcoal remains (Hv 25899–25901). The specific activity of ^{14}C was measured radiometrically by proportional counters (Geyh, 1990, 2005) at the Leibniz Institute for Applied Geophysics (LIAG). The radiocarbon ages were converted into calibrated calendar ages using the radiocarbon calibration curve based on coral samples and program after Fairbanks et al. (2005). The sample positions are shown in Fig. 7 and the calibrated and uncalibrated ages are given in Table 2. The radiocarbon ages presented in Wacha et al. (2011) are shown as well.

4 Dating results

Altogether 37 luminescence and 13 radiocarbon samples were measured from the loess sequence on Susak to set up a chronological framework for the very detailed sediment archive. Results from the dosimetry, the equivalent doses, g-values, the uncorrected and corrected age estimates are given in Table 1 and the dating results are given in Fig. 7. The uncalibrated and calibrated radiocarbon ages are given in Table 2.

The uranium, thorium and potassium contents range from 2.17 to 4.74 ppm, 7.63 to 15.67 ppm and 1.14 to 1.91%, respectively. The dose rates of the sediment for the fine-grained material range from 2.46 to 4.40 mGy/a, with a mean value of 3.53 ± 0.20 mGy/a which is typical for European loess (see Frechen, Horváth & Gábris, 1997; Galović et al, 2009; Novothny et al. 2009; Schmidt et al., 2010).

The D_e values from fine-grain feldspar are between 49.1 ± 2.5 Gy to 276.9 ± 14.0 Gy. For the samples collected at the Bok section, the D_e values show a systematic increase with depth, with a few exceptions and inversions. None of the dose response curves indicated luminescence signal saturation. The calculated age estimates are in good stratigraphic order. For the Sand Pit section the D_e values and the calculated ages are quite uniform with a slight increase of age with depth. Fading corrections were performed for all samples indicating only low anomalous fading rates. The calculated g-values range from 1.3 to 2.7%/decade which is very low compared to other locations (e.g. Serbian loess (Schmidt et al., 2010) or Hungarian loess (Novothny et al., 2010)). Fading corrections were done, and the uncorrected and corrected ages, as well as the g-values, are presented in Table 1.

At the Bok section an almost continuous increase of age with depth can be seen (Fig. 8). The lowermost loess with the abundant carbonate accumulations and intercalated by the oldest tephra (TF1; Fig 5a & 7) yielded age estimates ranging from 98.3 ± 7.3 ka to 79.1 ± 5.7 ka. According to the IRSL dating results from the loess underlying and covering the oldest tephra (TF1), the age of the tephra is between 98.3 ± 7.3 ka and 93.3 ± 7.0 ka. The sample collected from the same loess horizon, but a few metres away from the investigated section gave an age of 79.1 ± 5.7 ka. This horizon is covered by an orange-brown paleosol. The latter soil formation took place prior to 54.3 ± 4.9 ka, which is the IRSL age of the loess covering the orange-brown paleosol. The next 4 metres of the sequence are made of three brown paleosols, one of them containing the middle tephra (TF2; Fig. 5b & 7). In the middle part of this interval a sand layer is present, giving an IRSL age of 52.8 ± 4.0 ka. The age of the thin brown paleosol with the tephra patches (TF2) is between 41.2 ± 3.6 ka and 39.0 ± 3.3 ka (Fig 5b). Above this paleosol about 20 metres of loess is exposed. The IRSL ages from the loess range from 39.0 ± 3.3 ka to 18.1 ± 1.4 ka, for the loess immediately covering the paleosol with the tephra (TF2), and the stratigraphically youngest loess collected at this section, respectively. In this interval, four thin brown paleosols, some of them with charcoal remains, and another tephra layer (TF3) (Fig. 5c) are intercalated in the loess. IRSL age estimates from the loess below and above this thin tephra are between 31.0 ± 2.3 ka and 29.9 ± 2.2 ka. The radiocarbon ages of charcoal remains collected from the thin brown paleosols gave calibrated ages of 26.2 ± 0.6 ka and 29.1 ± 0.6 ka and are in excellent agreement with the IRSL ages. The radiocarbon age of molluscs collected from below TF3 is in agreement with IRSL ages and calibrated radiocarbon ages from charcoal, whereas the mollusc sample taken from the top of TF3 shows an age of 15.1 ± 0.4 ka, which is very likely underestimated for this part of the sequence, probably due to contamination with younger mollusc species. Two mollusc samples were collected in the uppermost part of the section, from the youngermost exposed loess. The radiocarbon age of 19.4 ± 0.2 ka is in excellent agreement with the uppermost collected IRSL sample. The radiocarbon age of 1.4 ± 0.06 ka from molluscs collected on top of the section correlates to modern species which were very probably washed out from the modern soil.

Mikulčić Pavlaković et al. (2011) described a second section in the bay of Bok. At the Bok1 section, four luminescence samples were collected from the loess covering the orange brown paleosol (Fig 7). The IRSL age estimates range from 70.7 ± 6.3 ka to 63.5 ± 5.1 ka. This interval of the section – loess intercalated with brown paleosol – gave a slightly higher ages than the stratigraphical equivalent at the Bok section. These horizons fill the time gap between the orange-brown paleosol and the brown paleosol at the Bok section and can hence be correlated with each other and interpolated. The differences between these two nearby sections could be a result of a different paleorelief evolution and possible erosion.

The Sand Pit section starts with a thick brown paleosol which is covered by about 8 metres of loess. This loess gave age estimates ranging from 39.3 ± 3.4 ka to 33.6 ± 2.6 ka. The thin brown soil on the top of this loess horizon containing charcoal yielded a calibrated radiocarbon age of 32.5 ± 1.0 ka and is in excellent agreement with the IRSL ages. Loess is covered by a few meters thick laminated sand horizon which gave an IRSL age estimate of 34.1 ± 3.1 ka. Within error limits, the age is in agreement with the calibrated radiocarbon age. Another sample from this laminated sand horizon was taken from the South wall of the investigated section and yielded an age of 38.1 ± 2.9 ka. The charcoal collected from the thin brown paleosols, yielded radiocarbon ages ranging from 32.2 ± 1.0 ka to 24.8 ± 0.8 ka (Fig. 6 & 7). A deposition of the laminated sand during a very short time period is very likely. The cross-laminated sand is of aeolian origin (Mikulčić Pavlaković et al., 2011) and probably represents a dune (Cremaschi, 1990). The upper part of the Sand Pit section consists of loess which is in its lower part intercalated by the youngest tephra (TF3; Fig. 5c & 7). IRSL age estimates of the loess from below and above the tephra gave 28.0 ± 2.1 ka and 28.8 ± 2.1 ka, respectively, and within error limits correlate to the IRSL ages from samples taken from the stratigraphically same position at the Bok section. The uppermost sample collected from the Sand Pit section gave an IRSL age of 24.2 ± 1.8 ka. About ten metres of loess is still covering the investigated section, but unfortunately this part of the section was not reachable for sampling during our fieldwork. In Fig. 7, the IRSL and the radiocarbon dating results are presented. They show an excellent correlation for both sections.

5 Discussion

Wacha et al. (2011) presented the first infrared stimulated luminescence (IRSL) dating results for the loess from Susak including thirteen samples. In their study a part of the loess-paleosol sequence was investigated only from the easternmost part of the island. The present study gives an improved,

Tab. 1: Sample list with depth below surface, results from the dosimetry, the SAR IRSL measurements, g-values, the uncorrected and corrected ages for fine-grained feldspar. The dose rate is the sum of the dose rates of the alpha, beta, gamma and cosmic radiation.

Tab. 1: Probenliste mit Tiefe unter Geländeoberkante, Dosimetrie-Daten, SAR-IRSL-Messungen, g-values, unkorrigierten und korrigierten Altern für die Feinkornextrakte. Die Dosisleistung ist die Summe aus Alpha-, Beta- und Gamma- sowie kosmischer Strahlung.

	Sample name	Sample ID	Depth (m)	Uranium (ppm)			Thorium (ppm)			Potassium (%)			Cosmic dose (mGy/a)			Dose rate (mGy/a)			De (Gy)			g-value (%/decade)			Uncorrected age (ka)			Corrected age (ka)[1*]		
Bok Section	Sus08-16	1753	2.00	3.30	±	0.01	9.87	±	0.03	1.23	±	0.01	0.150	±	0.015	3.16	±	0.19	49.1	±	2.5	1.7	±	0.2	15.5	±	1.2	18.1	±	1.4
	Sus13	1438	8.00	3.84	±	0.05	11.90	±	0.13	1.28	±	0.02	0.062	±	0.006	3.48	±	0.20	65.4	±	3.3	2.1	±	0.1	18.8	±	1.5	22.8	±	1.7
	Sus08-15	1752	8.50	4.10	±	0.02	13.89	±	0.04	1.61	±	0.01	0.062	±	0.006	4.03	±	0.22	74.5	±	3.7	2.1	±	0.3	18.5	±	1.4	22.4	±	1.8
	Sus08-14	1751	13.00	3.84	±	0.02	12.02	±	0.06	1.51	±	0.01	0.036	±	0.004	3.66	±	0.21	77.0	±	3.9	1.7	±	0.03	21.0	±	1.6	24.6	±	1.8
	Sus08-13	1750	15.00	3.50	±	0.01	9.72	±	0.03	1.31	±	0.01	0.030	±	0.003	3.16	±	0.19	67.8	±	3.4	1.8	±	0.1	21.4	±	1.7	25.3	±	1.9
	Sus12	1437	15.80	4.52	±	0.05	14.48	±	0.12	1.70	±	0.02	0.028	±	0.003	4.26	±	0.24	106.1	±	5.4	2.0	±	0.1	24.9	±	1.9	29.9	±	2.2
	Sus11	1436	16.30	4.15	±	0.05	13.26	±	0.13	1.68	±	0.03	0.027	±	0.003	4.01	±	0.22	104.6	±	5.3	1.9	±	0.1	26.1	±	2.0	31.0	±	2.3
	Sus08-12	1749	17.00	3.99	±	0.02	12.69	±	0.04	1.67	±	0.01	0.026	±	0.003	3.90	±	0.22	88.6	±	4.4	1.8	±	0.03	22.7	±	1.7	26.8	±	2.0
	Sus08-11	1748	17.60	3.81	±	0.03	12.12	±	0.06	1.62	±	0.01	0.025	±	0.002	3.74	±	0.21	84.2	±	4.2	1.7	±	0.1	22.5	±	1.7	26.3	±	2.0
	Sus08-10	1747	18.80	2.94	±	0.02	10.57	±	0.06	1.31	±	0.01	0.023	±	0.002	3.06	±	0.17	79.6	±	4.0	1.9	±	0.1	26.0	±	2.0	31.0	±	2.3
	Sus08-9	1746	19.80	4.11	±	0.02	13.27	±	0.04	1.60	±	0.01	0.022	±	0.002	3.92	±	0.22	110.3	±	5.6	1.7	±	0.1	28.1	±	2.1	32.9	±	2.5
	Sus10	1435	20.80	4.19	±	0.08	13.33	±	0.14	1.76	±	0.03	0.021	±	0.002	4.09	±	0.23	128.8	±	6.5	2.3	±	0.4	31.5	±	2.4	39.0	±	3.3
	Sus9	1434	21.30	3.50	±	0.05	10.04	±	0.12	1.40	±	0.02	0.021	±	0.002	3.26	±	0.19	108.4	±	5.5	2.3	±	0.4	33.2	±	2.6	41.2	±	3.6
	Sus08-8	1745	23.00	3.48	±	0.01	11.06	±	0.03	1.43	±	0.01	0.019	±	0.002	3.20	±	0.18	130.6	±	6.6	1.8	±	0.1	40.8	±	3.1	48.2	±	3.6
	Sus08-7	1744	23.60	2.71	±	0.01	9.24	±	0.03	1.38	±	0.01	0.019	±	0.002	2.77	±	0.16	124.8	±	6.4	1.7	±	0.1	45.0	±	3.5	52.8	±	4.0
	Sus08-6	1743	25.00	2.58	±	0.02	8.38	±	0.05	1.14	±	0.01	0.018	±	0.002	2.46	±	0.15	112.8	±	5.7	1.8	±	0.02	45.9	±	3.6	54.3	±	4.9
	Sus08-18	1755	26.70	3.27	±	0.01	11.28	±	0.03	1.46	±	0.01	0.018	±	0.002	3.18	±	0.18	261.2	±	13.1	1.9	±	0.1	82.1	±	6.2	98.3	±	7.3
	Sus08-17	1754	27.00	3.38	±	0.02	11.33	±	0.06	1.44	±	0.01	0.018	±	0.002	3.20	±	0.18	249.7	±	12.6	1.9	±	0.1	77.9	±	5.9	93.3	±	7.0
	Sus08-5	1742	28.00	4.09	±	0.03	15.67	±	0.08	1.91	±	0.01	0.018	±	0.002	4.18	±	0.22	276.9	±	14.0	1.9	±	0.02	66.2	±	4.8	79.1	±	5.7
Bok1	Sus08-4	1741	21.90	2.17	±	0.01	7.63	±	0.04	1.36	±	0.01	0.020	±	0.002	2.58	±	0.15	140.2	±	7.8	2.3	±	0.2	54.3	±	4.4	67.6	±	5.5
	Sus08-3	1740	23.00	3.48	±	0.03	12.02	±	0.06	1.44	±	0.01	0.019	±	0.002	3.47	±	0.19	193.7	±	11.1	2.5	±	0.4	55.8	±	4.5	70.7	±	6.3
	Sus08-2	1739	23.50	3.55	±	0.03	11.92	±	0.06	1.43	±	0.01	0.019	±	0.002	3.47	±	0.20	177.3	±	10.0	2.4	±	0.2	51.0	±	4.1	64.1	±	5.3
	Sus08-1	1738	24.70	3.83	±	0.02	12.80	±	0.06	1.50	±	0.01	0.019	±	0.002	3.70	±	0.21	181.8	±	10.1	2.7	±	0.2	49.1	±	3.9	63.5	±	5.1

Sand Pit section	Sus8	1433	10.00	4.16	±	0.05	13.32	±	0.14	1.60	±	0.03	0.050	±	0.005	3.97	±	0.22	80.0	±	4.0	2.0	±	0.1	20.1	±	1.5	24.2	±	1.8
	Sus08-24	1761	14.00	3.57	±	0.02	11.17	±	0.04	1.55	±	0.01	0.033	±	0.003	3.53	±	0.20	106.2	±	7.7	2.0	±	0.2	26.1	±	2.0	31.3	±	2.5
	Sus5	1430	14.50	4.74	±	0.05	14.99	±	0.14	1.73	±	0.03	0.032	±	0.003	4.40	±	0.24	105.7	±	5.3	2.0	±	0.1	24.0	±	1.8	28.8	±	2.1
	Sus4	1429	15.30	4.40	±	0.05	13.44	±	0.10	1.71	±	0.02	0.030	±	0.003	4.14	±	0.23	101.1	±	5.1	1.5	±	0.2	24.5	±	1.8	28.0	±	2.1
	Sus3	1428	16.20	4.30	±	0.05	12.81	±	0.12	1.68	±	0.03	0.028	±	0.003	4.02	±	0.23	94.8	±	4.8	1.6	±	0.1	23.6	±	1.8	27.2	±	2.0
	Sus2	1427	17.00	2.32	±	0.04	7.77	±	0.11	1.31	±	0.02	0.027	±	0.003	2.61	±	0.16	75.9	±	3.8	1.9	±	0.1	29.1	±	2.3	34.7	±	2.7
	Sus1	1426	18.00	2.31	±	0.04	8.12	±	0.09	1.15	±	0.02	0.024	±	0.002	2.50	±	0.15	79.0	±	4.0	2.0	±	0.1	31.7	±	2.5	38.1	±	2.9
	Sus7	1432	19.50	3.57	±	0.04	11.03	±	0.11	1.37	±	0.02	0.023	±	0.002	3.35	±	0.19	91.4	±	4.6	2.4	±	0.5	27.3	±	2.1	34.1	±	3.1
	Sus6	1431	20.70	3.71	±	0.05	11.09	±	0.12	1.40	±	0.03	0.022	±	0.002	3.42	±	0.20	96.6	±	4.9	1.9	±	0.1	28.2	±	2.2	33.6	±	2.6
	Sus08-23	1760	20.80	3.50	±	0.02	10.85	±	0.04	1.50	±	0.01	0.021	±	0.002	3.42	±	0.20	93.2	±	4.9	2.4	±	0.2	27.2	±	2.1	34.1	±	2.7
	Sus08-22	1759	22.20	3.56	±	0.02	11.86	±	0.04	1.51	±	0.01	0.020	±	0.002	3.54	±	0.20	105.7	±	5.6	2.7	±	0.2	29.8	±	2.3	38.5	±	3.0
	Sus08-21	1758	23.80	4.18	±	0.02	13.86	±	0.04	1.64	±	0.01	0.019	±	0.002	4.03	±	0.22	126.9	±	6.7	2.2	±	0.1	31.5	±	2.4	38.6	±	2.9
	Sus08-20	1757	25.40	4.11	±	0.05	13.27	±	0.12	1.57	±	0.03	0.018	±	0.002	3.90	±	0.22	122.6	±	7.4	2.4	±	0.3	31.5	±	2.6	39.3	±	3.4
	Sus08-19	1756	26.80	3.83	±	0.01	12.05	±	0.03	1.74	±	0.01	0.018	±	0.002	3.65	±	0.20	113.2	±	5.7	1.3	±	0.3	31.0	±	2.3	34.9	±	2.7

**After calibration of the Risø Reader for fine-grained material mounted on Al discs, the data from samples presented in Wacha et al. (2011) were recalculated because the new dose rates of the reader were lower than previously used. In the table the complete Susak data set is presented.*

precise and very detailed geochronological framework of the investigated loess-paleosol sequence which resulted from denser sampling.

Wacha et al. (2011) used the single aliquot regenerative-dose (SAR) protocol on polymineral fine-grained material separated from loess for the determination of the equivalent doses (D_e). Furthermore, fading tests and fading corrections were carried out and a few samples were additionally measured using the older multiple aliquot additive-dose (MAAD) protocol for an easier correlation with previously published data, like recently published in Galović et al. (2009). The results showed that the loess-paleosol record on Susak correlates to the Oxygen Isotope Stage (OIS) 3 with the fading corrected data ranging from 50.3 ± 3.5 ka to 27.5 ± 3.5 ka. The ages calculated after the MAAD protocols are between 38.0 ± 2.2 ka and 15.1 ± 1.1 ka and hence underestimating the results of the SAR measurements and the true deposition age of the deposits. Underestimation of these ages is expected due to the anomalous fading of feldspar infrared stimulated (IRSL) signals (Wintle, 1973; Spooner, 1994). Nevertheless, both protocols gave data which led to the same conclusion, that the loess-paleosol record on Susak is an amazing and very detailed OIS3 record. Mikulčić Pavlaković et al. (2011) presented four more IRSL ages from a further nearby section in the bay of Bok on Susak. This IRSL dating study used the same methodological approach as discussed in Wacha et al. (2011) which was proved to be successful. The IRSL ages range from 90.0 ± 6.8 ka to 80.8 ± 5.0 ka. The results presented in these previous publications do not cover the complete loess sequence but concentrate only on the middle part. Therefore, additional samples were collected with the aim to fill previous sampling gaps and to extend the numerical framework to the oldest and youngest deposits and so get a very detailed geochronological record of the last interglacial/glacial cycle.

The stratigraphically oldest soil found on the island is the fossil terra rossa, named that way by Bognar, Schweitzer & Szöőr (2003) (FTR according to Mikulčić Pavlaković et al., 2011), seen in the cracks of the limestone basement. Bognar, Schweitzer & Szöőr (2003) assumed the age of the fossil terra rossa to be 3 to 4 million years BP, but no evidence was provided for such statement. It is still not known, i.e. there are still no exact data about the age of the thick red paleosols which cover the carbonate basement of the island. Bognar, Schweitzer & Szöőr (2003) suggested that the red paleosol presents the lower or the lowermost Pleistocene. Paleomagnetic measurements carried out by Bognar, Schweitzer & Szöőr (2003) showed negative inclination in the red paleosol, so they correlated the apparent polarity change to the Brunhes-Matuyama boundary (0.78 Ma; Spell & McDougall, 1992; OIS19). They also correlated the red paleosol with the Paks Double (PD) type paleosol from the Hungarian loess stratigraphy. The PD type paleosol belongs to the Hungarian "old loess series",

Tab. 2: Uncalibrated and calibrated radiocarbon dating results. The results were calibrated using the FAIRBANKS *et al (2005) calibration curve spanning from 0 to 50,000 years BP and transferred in ka B. P. in order to make the radiocarbon results better comparable with luminescence ages. *radiocarbon dating results presented in* WACHA *et al. (2011). +Radiocarbon ages are by definition "Age before 1950".*

Tab. 2: Unkalibrierte und kalibrierte Radiokarbon-Datierungsergebnisse. Die Daten wurden mittels der Kalibrationskurve nach FAIRBANKS *et al. (2005), welche von 0 bis 50.000 Jahre reicht, kalibriert und in ka B.P. umgerechnet, um eine bessere Vergleichbarkeit der Radiokarbonalter mit dem Lumineszenz-datierungen zu gewährleisten. +Radiokarbonalter sind per Definition „vor 1950". * Radiokarbonalter aus* WACHA *et al. (2011).*

Sample name	Radiocarbon age ka B.P.+			Calendar age cal. B.P.			Calendar age ka cal. B.P.			Material type
Hv 25696*	24215	±	750	29023	±	923	29.0	±	0.9	charcoal
Hv 25697*	26890	±	950	32176	±	1042	32.2	±	1.0	charcoal
Hv 25698*	26810	±	200	32103	±	261	32.1	±	0.3	charcoal
Hv 25699*	23040	±	600	27650	±	696	27.7	±	0.7	charcoal
Hv 25700*	27150	±	910	32458	±	986	32.5	±	1.0	charcoal
Hv 25701*	25515	±	1170	30602	±	1390	30.6	±	1.4	charcoal
Hv 25895	1510	±	60	1391	±	60	1.4	±	0.1	molluscs
Hv 25896	16240	±	200	19365	±	202	19.4	±	0.2	molluscs
Hv 25897	12950	±	290	15073	±	371	15.1	±	0.4	molluscs
Hv 25898	24095	±	900	28888	±	1092	28.9	±	1.1	molluscs
Hv 25899	24300	±	455	29097	±	571	29.1	±	0.6	charcoal
Hv 25900	21765	±	420	26156	±	546	26.2	±	0.6	charcoal
Hv 25901	20755	±	640	24814	±	836	24.8	±	0.8	charcoal

also called Paks series, corresponding to OIS 9–24 (PÉCSI, 1993). In loess from below this PD paleosol in the type locality at the Paks section the Brunhes-Matuyama boundary was identified (PÉCSI, 1993). There is no evidence for such pedostratigraphical correlation of paleosols from Susak with paleosols from Hungary key loess sections and hence this approach is questionable. DURN, OTTNER & SLOVENEC (1999), DURN (2003) and DURN et al. (2007) investigated terra rossa and loess from Istria (Savudrija) and based on similarities with loess deposits on Susak described by CREMASCHI (1990) tentatively proposed an Eemian age of the red paleosol below the loess complex in Savudrija, but without any dating results. They also showed the importance of Late Pleistocene loess as parent material of these paleosols in Istria. MIKULČIĆ PAVLAKOVIĆ et al. (2011) concluded that the source material of the thick red paleosol which covers the carbonate and can be seen in the basement of the loess sequence in the bay of Bok on Susak is of a predominantly aeolian origin (loess) with a minor influence of material remained after limestone karstification and that they are similar to Istrian terra rossa. Loess covering the red paleosol on Susak showed age estimates ranging from 98.3 ± 7.3 ka to 79.1 ± 5.7 ka and so numerically correlates to OIS5c–a and 4, respectively. Based on these dating results, and the assumed aeolian origin of the red paleosols covering the carbonate basement on Susak and similar red paleosols below loess from Istria, we can conclude that soil formation on Susak took place during the last interglacial optimum or any older interglacial period and that the oldest loess from Susak deposited prior to OIS5e, probably in OIS6 or any other glaciation predating the Eemian. The OIS5 interglacial was marked by three distinct high sea level stands (SURIĆ & JURAČIĆ, 2010). During OIS5e the sea level stand was the highest, up to a few meters higher than today (LAMBECK & CHAPPELL, 2001). The OIS5a is characterized by two sea level high stands, around 84 ka and 77 ka BP, with sea level above -14 m, and low sea-stand in between, at around 80 ka BP (SURIĆ & JURAČIĆ, 2010). The sea level of the Adriatic Sea was about 100 metres lower than today (CREMASCHI, 1990; AMOROSI, et al. 1999; LAMBECK et al., 2004) during a part of the Upper Pleistocene making the North Adriatic a vast basin exposed to various sedimentary processes as well as to aeolian activity during the glacials which resulted in loess deposition.

Red paleosols are often reported to underlie loess in the Pannonian basin in Hungary (KOVÁCS, 2008) and in China (e.g. BRONGER & HEINKELE, 1989) and are found on different rock type basements, representing the beginning of loess deposition. The origin of such paleosols is still under discussion (e.g. KOVÁCS, 2008) but the aeolian origin is probable (YANG & DING, 2004). The age of these paleosols very likely belongs to the Pliocene (BRONGER & HEINKELE, 1989; DING et al., 1999; KOVÁCS, 2008). Such red paleosols are the result of specific climatic conditions and should be correlated only in that context. Correlating these paleosols based only on their physical properties, without any dating results, can lead to wrong geochronological conclusions.

The age of the tephra (TF1) found in loess covering the red paleosol is between 98.3 ± 7.3 ka and 93.3 ± 7.0 ka (Fig. 5a). Based on these ages, the mineral and geochemical characteristics (MIKULČIĆ PAVLAKOVIĆ et al., 2011), the tephra could be related to the Middle and South Italian volcanic provinces.

The oldest loess is covered by an orange-brown paleosol up to 150 cm thick. The pedogenesis of this paleosol took place after 93.3 ± 7.0 ka (or 79.1 ± 5.7 ka, if the sample Sus08-5 is considered, which was not collected directly from the investigated outcrops but a few meters away) and before 54.3 ± 5.7 ka, which is the age estimate from the thin loess horizon covering the thick orange-brown paleosol in the Bok section. This orange-brown paleosol is widespread

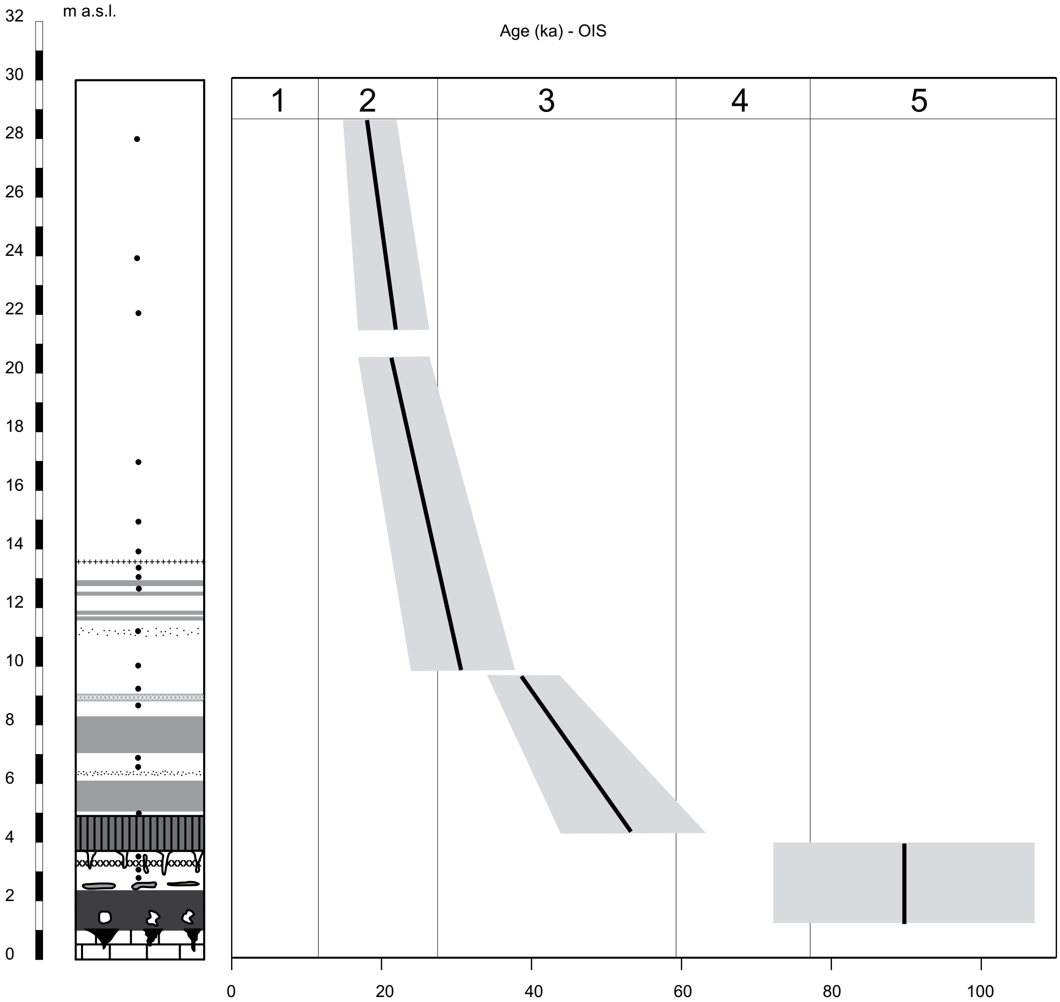

Fig. 8: The sketch of all IRSL dating results from the Bok section. A continuous increase with depth is evident, showing an increased accumulation of loess during the OIS3 and OIS2. Part of the OIS4 deposits are missing in this section but can be found at the Bok1 section (see legend in Fig. 7).

Abb. 8: IRSL-Datierungsergebnisse des Bok-Aufschlusses. Die IRSL-Alter sind stratigraphisch konsistent und nehmen mit der Tiefe zu. Die Ergebnisse zeigen eine verstärkte Staubakkumulation während des OIS3 und OIS2. Teile von OIS4 sind erodiert und fehlen in diesem Aufschluss, sind aber im Bok 1-Aufschluss vorhanden (Legende in Abb. 7).

over the island and with a more or less constant thickness. Bognar, Schweitzer & Szöőr (2003) correlated this orange-brown paleosol with the Mende Base (MB)-type paleosol from Hungarian stratigraphy. Wintle & Packman (1988) and Frechen, Horváth & Gábris (1997) proved that the age of the MB paleosol is significantly older than the last interglacial (OIS5e). At the Süttő section in Hungary, the OIS5 is represented by a MB-type paleosol (Novothny et al., 2009). The results from this study discarded such correlation completely. The orange-brown paleosol is covered by 4 to 5 metres thick loess. This loess is intercalated by brown paleosols and sand layers and a thin brown paleosol containing patches of the orange-yellow middle tephra (TF2). At the Bok section two, up to 100 cm thick, brown paleosols are developed while at the Bok 1 section the situation differs. There, alterations of loess and sand are intercalated by two brown paleosols, one of them containing charcoal pieces, and one double paleosol i.e. a brown paleosol directly overlain by another brown paleosol. This horizon gave IRSL age estimates ranging from 54.3 ± 4.9 ka, measured from loess collected between the orange-brown and the first brown paleosol at the Bok section, and 41.2 ± 3.6 ka, sample collected below the TF2 containing paleosol. At the Bok 1 section the IRSL age estimates showed slightly older ages ranging from 70.7 ± 6.3 ka to 63.5 ± 5.1 ka. Based on the IRSL results we can conclude that this sequence very likely correlates to OIS4. The differences between these two investigated sections are probably due to the differences in the paleorelief. It is very likely that a part of the record is missing at the Bok section. A layer of thin loess covering the orange-brown paleosol at the Bok section might be the evidence for the later statement.

The brown paleosol covering the thin loess horizon was correlated to the Basaharc Lower (BA)-type paleosol from the Hungarian loess stratigraphy by Bognar, Schweitzer & Szöőr (2003). When compared to the new IRSL dating results of this study and data presented by Frechen, Horváth & Gábris (1997), who showed that the BA paleosol formed during the antepenultimate interglacial, such a statement can be discarded.

Indent estimates of loess from below and above the paleosol containing the middle tephra (TF2) range from 41.2 ± 3.6 ka to 39.0 ± 3.3 ka (Fig 5b). This tephra layer was found on several locations on the island and hence is an excellent marker horizon for better correlation. The tephra layer was investigated by Mikulčić Pavlaković et al. (2011) and could be correlated to the Campanian Ignimbrite eruption of the Phlegraean Fields, which was dated around 39 ka (De Vivo et al., 2001).

On top of the paleosol with TF2 patches about 20 metres of loess is exposed. In the lower part of this loess a sand layer and four thin brown paleosols are present. The IRSL ages are in stratigraphic order, as presented in Figs. 7 and 8, showing a continuous loess deposition during OIS3. Four radiocarbon samples were collected: two charcoal samples from the thin brown paleosols and two samples from loess molluscs. The radiocarbon ages are in agreement with the IRSL dating results. The youngest tephra (TF3) (Fig 5c), which is exposed in this part of the sequence, has IRSL age estimates ranging from 31.0 ± 2.3 ka to 29.9 ± 2.2 ka and could be related to the Middle and South Italian volcanic provinces based on the geochemical analysis, mineral composition and vitroclast morphology (Mikulčić Pavlaković et al., 2011). The youngest sample collected from the top of the section, at the highest accessible position, gave an IRSL age estimate of 18.1 ± 1.4 ka and represents the loess accumulated during a period of increased dust accumulation most likely during the last glacial maximum (OIS2). This IRSL age is in agreement with the radiocarbon dating results of molluscs collected from loess.

The steep loess wall of the Sand Pit sections shows similarities with the upper part of the Bok section. There, only loess and laminated sand are exposed correlating to OIS3. The contact with the carbonate basement is not exposed; the sequence starts with a thick brown paleosol which is older than 34.9 ± 2.7 ka and 39.3 ± 3.4 ka, which are IRSL age estimates of the loess covering the brown paleosol. This paleosol very likely correlates with the second brown paleosol (the upper one) from the Bok section. At the Sand Pit section the middle tephra (TF2) was previously found in the South Wall but was not exposed during our fieldwork. The main difference between the two investigated sections (Bok and Sand Pit) is the predominance of cross-laminated sand in the Sand Pit section which probably represents a dune. Such aeolian sands are often seen on the islands in the Adriatic Sea (Marković-Marjanović, 1976; Borović et al., 1977; Korolija et al., 1977; Bognar et al., 1992; Pavelić, Kovačić & Vlahović, 2006) but they have scarcely been investigated (Pavelić et al., submitted). The sand on Susak very likely came from a proximal source. An erosional channel which was seen in the Sand Pit section on the East Wall was a result of local, short and intensive water activity. Four brown paleosols containing charcoal remains, which can be seen in the lower part of the loess covering the dune sands, gave calibrated radiocarbon age estimates ranging from 32.2 ± 1.0 ka to 24.8 ± 0.8 ka and are in excellent agreement with IRSL dating results (Fig. 6); the loess below the first paleosol gave an IRSL age of 34.7 ± 2.7 ka and the loess above the fourth, the uppermost paleosol yielded an IRSL age of 28.0 ± 2.1 ka. The youngest tephra layer (TF3) is clearly visible above the uppermost paleosol. Its IRSL age estimates range from 28.8 ± 2.1 ka to 28.0 ± 2.1 ka and is in agreement with the IRSL ages from the samples collected at the Bok section. The uppermost collected loess gave an age estimate of 24.2 ± 1.8 ka and so correlates to OIS3. This sample location is covered by at least 10 metres of loess; this part of the sequence probably correlates to OIS2.

When comparing both major investigated sections, a strong similarity is evident. Minor differences are very likely due to the evolution and shape of the paleorelief. Such sediment succession is representative for the eastern part of the island and a similar situation was exposed on the southern part of the island. But still no outcrops are available on the northern and the western part, the part of the island which morphologically forms a plateau. It would be interesting to know the succession of the depo-sits in the thickest location and its relations to the carbo-nate basement. The question about the great thickness of the deposits and the sediment succession in the northern part of the island and its relation to the carbonate bedrock still remains open.

In northern Italy, the Val Sorda loess-paleosol sequence is located in the river Po basin. Along the Danube, the Zmajevac section in eastern Croatia, Stari Slankamen and Surduk sections in Serbia and the Süttő section in Hungary were chosen for correlation and comparison (Fig. 9). These sections were selected because of their detailed geochronological studies allowing a correlation with the last interglacial-glacial cycle. These two major loess areas differ in climatic conditions during periods of increased dust deposition in the Upper Pleistocene, hence providing different loessevolution. If we place Susak in a wider perspective and compare it with coeval loess-paleosol sequences from nearby regions, the most amazing thing is the great thickness of the deposits on such a small island in the Northern Adriatic Sea and the fact that such a sequence remained preserved. Loess has been found on other nearby islands in the area (Unije, Velike and Male Srakane, Lošinj), but only as a few metres thick local appearances. Durn, Ottner & Slovenec (1999) and Durn et al. (2003) recognised the influence of Upper Pleistocene loess in upper parts of terra rossa profiles from Istria. Further north, in the river Po plain region, loess can also be found, but there no such amazing thicknesses have been registered. The most representative loess-paleosol sequence in North Italy is the Val Sorda sequence (Ferraro et al., 2004, Ferraro, 2009; Fig. 9). This section is about 6 metres thick, starts with a rubefied clayey paleosol covering fluvioglacial deposits and consists of about 4 metres of loess intercalated by three chernosem paleosols (Ferraro et al., 2004; Ferraro, 2009). Ferraro et al. (2004) concluded that the periods of loess deposition alternated with three stable phases of interstadial pedogenesis under steppe climate. Loess has been dated by means of radiocarbon and IRSL methods and gave age estimates ranging from 63.3 ± 6.7 ka to 18.7 ± 2.1 ka. These data presented in Ferraro (2009) were measured using the multiple aliquot additive dose (MAAD) method and may require a correction for anomalous fading. The published IRSL ages can be compared and are in agreement with those from the study on Susak. Dating results of artefacts from the Fumane Cave in Northern Italy, also containing loess, were correlated with the Aurignacian cultural layer which represents the OIS3 (Peresani et al., 2008). At the Bagaggera loess sequence TL dating results of artefacts also showed an OIS4 to OIS2 age (Cremaschi et al., 1990), with soil formation during most of OIS3. The rubefied clayey paleosol at the bottom of the Val Sorda sequence can very likely be correlated with the red paleosols covering the carbonate basement on Susak and the red paleosol described in Savudrija in Istria (Durn et al., 2003). The OIS 5 (5e – Last Interglacial paleosol) paleosols in the Carpathian basin are usually chernozem-type paleosols. At the Zmajevac section the second paleosol from the top is correlated to OIS5 (Galović et al., 2009). In the Serbian stratigraphy the OIS5 paleosol is termed S1 and is also of chernozem-type (Antoine et al., 2009; Marković et al., 2007, 2009). In the Hungarian loess sections, the OIS5 paleosol is a forest steppe-type paleosol (Frechen, Horváth & Gábris, 1997; Novothny, Horváth & Frechen, 2002). At the Süttő section (Novothny et al., 2011), based on a detailed geochronological investigation and grain-size analysis, the paleosols correlated to OIS5 were divided into interstadials and the reddish-brown paleosol, below the chernozem-like paleosol, was correlated to OIS5e (Fig. 9). The overlying chernozem-like paleosol was correlated to OIS5c, which was a warm and drier interstadial. The two thinner brown steppe-like paleosols intercalated by a thin loess layer, indicate a shorter and/or less warm and humid interstadial period, most likely correlating to the 5a substage. The subdivision of the red paleosols on Susak is still not possible; detailed investigations are required. These different paleosol types in different geographical regions are a clear evidence for different paleoclimatic conditions during coeval periods.

In the Carpathian (Pannonian) basin OIS4 is represented only by loess deposition (Fig. 9), while on Susak the Early Pleniglacial record is probably incomplete. A thin loess horizon intercalated with thin brown paleosols and occasionally with sand is exposed at the Bok section. The loess covering the orange-brown paleosol in the Bok 1 section (Fig. 7) can also be correlated to OIS4. Loess accumulation during OIS4 is also evidenced in the Val Sorda section in a small amount (Ferraro, 2009). Novothny et al. (2011) reported an increase in sand content for the Lower Pleniglacial (OIS4) loess due to a colder and drier climate and increased wind intensity in Süttő.

In the Pannonian (Carpathian) basin OIS3 is characterised by soil development during the interstadials alternating with loess accumulation during stadials. In Zmajevac (Fig. 9) in Eastern Croatia, one weakly developed paleosol correlates to OIS3 (Galović et al., 2009). In loess from Serbia the Middle Pleniglacial (OIS3) is represented by a weakly developed paleosol complex (called L1S1 in Serbian stratigraphy, Marković, Kostić & Oches, 2004; Marković et al., 2004, 2005, 2006, 2007, 2008, 2009). A single, weakly developed chernozem is described from the Ruma section (Marković et al., 2006), a weakly developed double paleosol at the Petrovaradin brickyard (Marković et al., 2005), the Batajnica (Marković et al., 2009) and Irig sections (Marković et al., 2007) and multiple paleosol at the Stari Slankamen (Schmidt et al., 2010) and Surduk (Antoine et al., 2009) sections (Fig. 9). In Hungary, Novothny et al. (2011) reported a brown paleosol in Süttő, previously termed MF1 in the Hungarian loess stratigraphy (Novothny, Horváth & Frechen, 2002; Frechen, Horváth & Gábris, 1997). On Susak, increased dust deposition interrupted by many soil forming periods is evidenced for the Middle Pleniglacial period. In the bay of Bok on Susak at least five thin brown paleosols are intercalated in the loess but it is even very likely that more of such weak paleosols are present. Beside these weakly developed paleosols, two thick brown paleosols are present as well, possibly correlating with the Hengelo or Denekamp Interstadials of the NW European stratigraphy, both correlating to OIS3. The great thickness of the OIS3 deposits on Susak is the result of the generally increased dust accumulation in Europe (Frechen, Oches & Kohfeld, 2003; Machalett et al., 2008) as well as a suitable geographical and morphological position in the North Adriatic basin, which was very likely a vast plateau with a large material input from the extended floodplain of the river Po and its tributaries. The numerous paleosols give evidence that the climate on Susak was milder than in the Carpathian basin. Three brown paleosols are described in the Val Sorda sequence in North Italy (Ferraro et al., 2004; Ferraro, 2009). Novothny et al. (2011) concluded that at Süttő the climate had an intermediate character, which was between the wetter climate in the Western European loess sequences and the drier loess successions in the southern Carpathian basin. A relatively "warmer" climate was proposed for the Irig section in Vojvodina by Marković et al. (2007). On Susak, loess deposition was continuous and intensive from OIS3 to 2, if compared with the Carpathian basin. Based on the numerous paleosols found intercalating aeolian deposits on Susak an even "warmer" climate is assumed for the North Adriatic area.

6 Conclusion

As a part of an ongoing multidisciplinary study, IRSL dating of loess-paleosol sequences from Susak was applied to provide a detailed geochronological framework. The results indicate that the deposits on Susak are a very detailed Last Glacial-Interglacial record. Within error limits, the results are in stratigraphic order, showing a quasi-continuous record spanning from OIS5 (and possibly OIS6 or older) to OIS2. The most impressive sequence is the Middle Pleniglacial (OIS3) record, including evidence for intensive dust accumulation, interrupted by numerous soil forming processes and two volcanic events. The IRSL dating results are in excellent agreement with the radiocarbon dating results. Although dating results are consistent for both dating methods, a more precise method should be used for estimating the volcanic activity. The grain size of the tephras on Susak does not allow the use of the Ar-Ar dating method. Nevertheless, mineralogical and geochemical investigations of the tephras (Mikulčić Pavlaković et al., 2011) showed that the volcanism involved could be related to the Italian volcanic provinces. The red paleosol covering the carbonate basement on Susak correlates at least to OIS5 but an older age can not be excluded. A more detailed investigation regarding the age of the oldest exposed paleosol is needed. Such red paleosols are typical for the whole North Adriatic area.

If the loess record on Susak is correlated with the Danube loess-paleosol sequences of the Carpathian basin, the differences are obvious. Loess deposition in the Carpathian basin was continuous, interrupted by interglacial or interstadial soil-forming processes as evidenced by in thick continuous paleosol layers. On Susak the deposition of aeolian

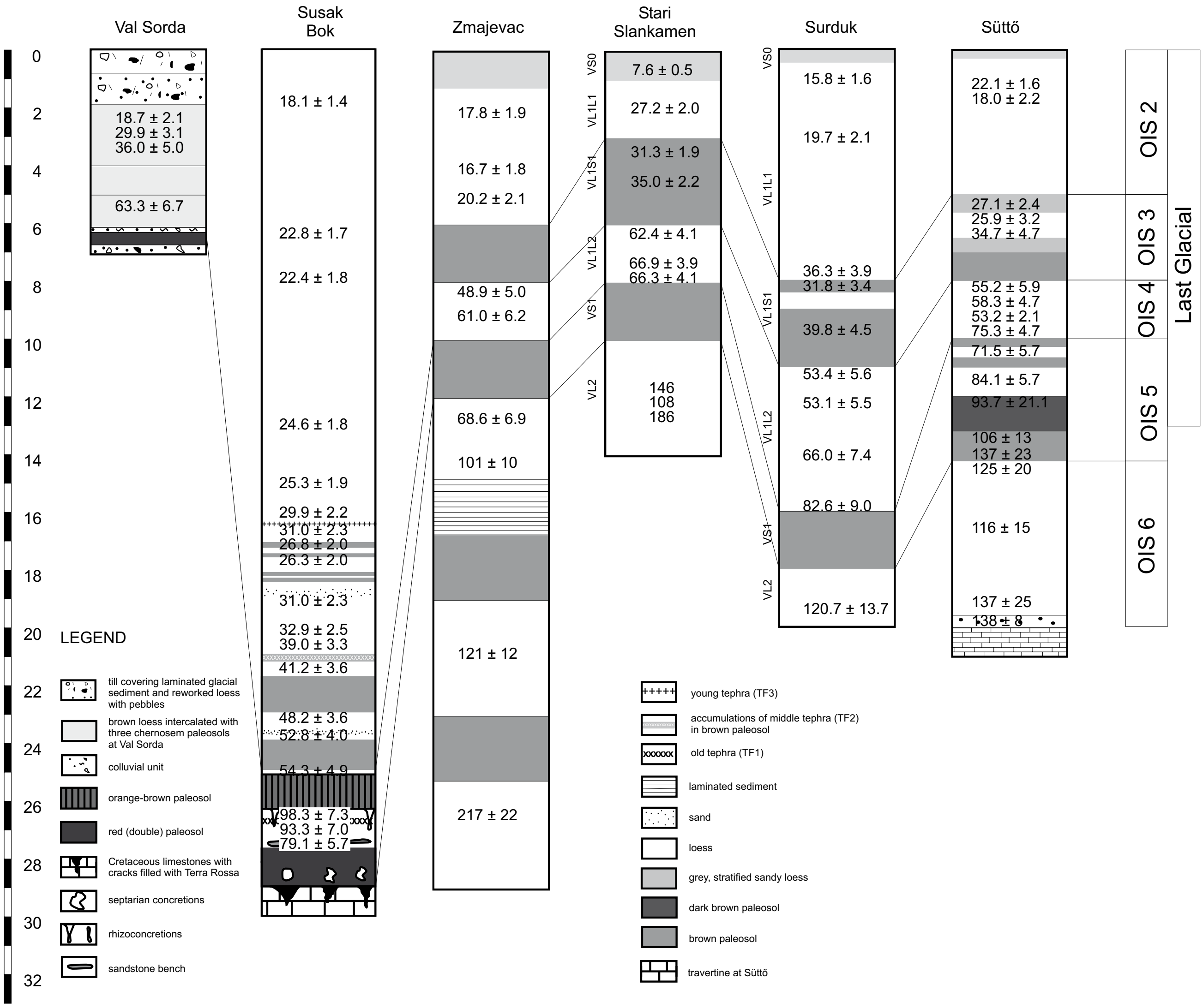

Fig. 9: Bok section, selected to be the most representative section on Susak, correlated with the Val Sorda section in North Italy (Ferraro, 2009), Zmajevac in East Croatia (Galović et al., 2009), Stari Slankamen (Schmidt et al., 2010) and Surduk (Antoine et al., 2009; Fuchs et al., 2008) in Serbia and Süttő in Hungary (Novothny et al., 2009; 2010).

Abb. 9: Der Aufschluss Bok mit der für Susak repräsentativsten Löss-/Paläobodenabfolge und die Korrelation mit den Aufschlüssen Val Sorda in Norditalien (Ferraro, 2009), Zmajevac in Ostkroatien (Galović et al. 2009), Stari Slankamen (Schmidt et al., 2010) und Surduk (Antoine et al., 2009; Fuchs et al., 2008) in Serbien und Süttö in Ungarn (Novothny et al., 2009, 2010).

sediment was more often interrupted by soil forming processes, as evidenced by the numerous paleosols, some of them are well developed, some probably representing only initial pedogenesis. The same major climatic shifts during the Last Glacial are responsible for the development of the deposits on Susak, as in the Carpathian and Pannonian basin. The main difference is the aridity of the climate involved. The climate on Susak was very likely more humid and milder than in other regions.

The detailed geochronological framework presented in this work is an excellent base for future high-resolution investigations of climate proxies. Such studies are in progress.

The loess-paleosol succession on Susak proves that the North Adriatic region is a separate and unique periglacial environment and should not be neglected when investigating the global Glacial-Interglacial evolution.

7 Acknowledgements

This research has been financed by the DAAD (German Academic Exchange Service); the Leibniz Institute for Applied Geophysics (LIAG), Hannover, Germany; the Croatian Ministry of Science, Education and Sports, Projects Nr. 0181001, 0183008 and 183-0000000-3201. This work could not be possible without the help of colleagues of S3 from LIAG, especially Linto Alappat and Alexander Kunz. The authors wish to thank Dr. Lidija Galović for many fruitful discussions and her support and to Ira Wacha-Biličić for correcting English. Help from Dr. Francesca Ferraro and Prof. Dr. Davor Pavelić, who supplied us with the needed literature, is appreciated. We are grateful to Prof. Dr. Goran Durn and Dr. Ágnes Novothny for their criticism and constructive comments of an earlier version of the manuscript.

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