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Charcoal and mollusc shell ^{14}C-dating of the Dunaszekcső loess record, Hungary

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Abstract

Accelerator mass spectrometry (AMS) radiocarbon dating of charcoals and 10 mollusc species (+2 identified at the family level) yield 64 new ages from the Dunaszekcső loess record, Hungary. Charcoal ^{14}C ages are found to be protocol-dependent, with ages obtained from the high temperature (800 °C) fraction of the two-step combustion (TSC) protocol being always the oldest and likely most reliable. One step combustion (OSC) at 1000 °C produces comparable ages with those obtained from the low temperature (400 °C) fraction of the TSC protocol. Discrepancies between the ABA-TSC$_{400}$ and TSC$_{800}$ ages become larger for older, and less well-preserved charcoal fragments. Testing of shell ages against those of charcoals reveals that Succineidae sp., *Chondrula tridens*, *Trochulus hispidus* and members of the family Clausiliidae yield ^{14}C ages that are statistically indistinguishable from charcoals recovered from the same stratigraphic interval, or with the ABA-TSC$_{800}$ charcoal age. Thus, these species show great potential for creating accurate and precise chronologies for loess records within the useful range (<~40 ka) of ^{14}C-dating of land snails. Conservative estimates of 95% uncertainties of the resulting Bayesian age-depth models are in the range of 500-800 yr. However, these uncertainties are strongly dependent on the number of dates available and the resolution of sampling, but they are usually well below those of luminescence chronologies.

Keywords: mollusc; land snail; charcoal; radiocarbon dating; loess; Quaternary

1. Introduction

Loess deposits preserved the ‘fingerprints’ of centennial and millennial scale climatic and environmental changes (Porter and An, 1995; Rousseau et al., 2007; Stevens et al., 2007, 2008; Sun et al., 2012). However, accurate and high-precision chronologies are required to fully utilize and exploit the potential of these key terrestrial archives in reconstructing millennial scale climatic events and understanding their causes and regional consequences. Major obstacles of establishing such loess chronologies are the inherent limitations of luminescence techniques (relatively low precision of OSL/IRSL ages) and often the lack of reliable target materials for radiocarbon dating (e.g. Pigati et al., 2013; Kadereit et al., 2013; Újvári et al., 2014). While charcoal is commonly regarded as a material that can yield reliable ^{14}C ages (Trumbore, 2000; Hatté et al., 2001b), other materials often yield either anomalous ages (rhizolites; Pustovoytov and Terhorst, 2004; Gocke et al., 2011; Újvári et al., 2014), or dates that are compromised by secondary overprinting (organic matter; Gocke et al., 2010, 2011) or vertical migration of organic contaminants in the soil/loess profile (humic substances; McGeehin et al., 2001; Ascough et al., 2011a; Wild et al., 2013). Unfortunately, charcoal is not abundant in loess deposits and so we must turn to alternative materials for ^{14}C-dating. Mollusc shells are often found in loess sediments (Sümegi and Krolopp, 2002; Moine et al., 2008) and may be useful for establishing firm chronologies. However, some basic questions must be addressed before establishing charcoal and mollusc-based ^{14}C-chronologies of loess records: 1) how reliable and reproducible are the ^{14}C ages of charcoals in loess, 2) do some of the mollusc species provide more accurate ages than others, i.e. which species are preferred for ^{14}C-dating of loess, and 3) what are the characteristic uncertainties of Bayesian age-depth models resting on charcoal/mollusc ^{14}C dates?

In this study we present an extensive dataset of 64 radiocarbon ages obtained by AMS ^{14}C-dating of charcoal fragments and shells of various small (<10 mm) mollusc species. These materials were recovered from loess sediments collected in the Dunaszekcső sequence in Hungary. A few of these data have already been published in a companion paper discussing ^{14}C and OSL/IRSL dating of the studied loess record (Újvári et al., 2014), but here we present a more comprehensive ^{14}C dataset. Using different protocols of charcoal combustion we demonstrate that the applied methodology can sometimes have a profound effect on the resulting charcoal ^{14}C ages, with differences between measurements ranging from some hundreds of years up to one/two thousands of years. By comparing the charcoal ages with those obtained from mollusc shells we show that loess records can be dated with a relatively good precision using small molluscs. Although some species such as Succineidae sp. (most probably *Succinella oblonga), C. tridens, T. hispidus,* and the members of the Clausiliidae family show good potential for dating, the spread of reference charcoal ages obtained from a loess layer containing both charcoals and molluscs prevent us from assigning those mollusc species which are the most preferable to use in ^{14}C-dating of loess. This implies that further work is needed on the subject, and that, at least at the present state of knowledge, the best dating strategy is to use multiple mollusc species from each sampled stratigraphic interval to establish loess chronologies.

2. Materials and methods

2.1. Study site and sampling methods

The studied loess-paleosol section is located at Dunaszekcső, Southern Hungary (46°05'25"N, 18°45'45"E, 135 m a.s.l.; Fig. 1) and exposes glacial-interglacial sediments with a thickness of 17 m. After cleaning of the sediment surface, altogether 31 loess samples were collected for radiocarbon dating throughout the profile at various depths from 1010 to 250 cm. Loess cuboids with dimensions of 15 × 5 × 10 cm (length-width-height) at depths of 400, 500, 600 cm, 15 × 5 × 7.5 cm at depths of 820 and 825 cm and 15 × 5 × 5 cm at other depths were cut from the uppermost loess unit. Sample blocks were subsequently disintegrated in the lab by soaking them in distilled water. Charcoals and gastropod shells (Fig. 2) were extracted by washing the sediments through a 1 mm mesh sieve then dried at 50 °C and handpicked using gloves and pre-cleaned forceps to avoid modern carbon contamination. After being identified at the species (or family) level, shells were wrapped in Al-foil and put in closed plastic bags. Also the charcoal samples were handled and packed in a similar way, but separately from land snail shells. The nomenclature of mollusc species follows Welter-Schultes (2012).

2.2. Radiocarbon dating

Gastropod shells and charcoals were further pretreated in the AMS laboratory of the Hertelendi Laboratory of Environmental Studies, Institute for Nuclear Research, Debrecen, Hungary (Molnár et al., 2013a). During this procedure, charcoal fragments were treated using the standard acid-base-acid (ABA) method (Jull et al., 2006), i.e. in a sequence of 1N HCl, rinsing in distilled water, 1M NaOH, rinsing again in distilled water, and then 1N HCl at 75 ºC, for 1-2 hours each step. After the final acid wash, the samples were washed again with distilled water to neutral pH (4–5) and dried at 60 ºC. During the first set of experiments, dried charcoal fragments were combusted in an on-line combustion system using CuO in one step at 1000 ºC (ABA-OSC$_{1000}$), whereas during subsequent runs they were subjected to stepped combustion in pure O_2 gas atmosphere, first at 400 ºC, and then at 800 ºC (ABA-TSC$_{400}$ and ABA-TSC$_{800}$).

Mollusc shells were ultrasonically washed and then all the surficial contaminations and carbonate mineral coatings were etched using weak acid (2% HCl). This etching effectively removed 20–30% of the shell material. Subsequently, acid cleaned shells were dried and put into vacuum tight two finger reaction ampoules (~100 cm^3 inner volume) and dissolved by phosphoric acid. CO_2 was produced by acidic hydrolysis of shells, further purified cryogenically and then graphitized (Molnár et al., 2013a).

All the ^{14}C measurements were done on the graphitized samples using a compact radiocarbon AMS system (MICADAS) developed at the Paul Scherrer Institute and the ETH Zürich (Synal et al., 2007; Wacker et al., 2010), which was installed at the Hertelendi Laboratory of Environmental Studies, Debrecen in 2011 (Molnár et al., 2013b). Conventional radiocarbon ages were converted to calendar ages using OxCal online (version 4.2; Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013).

2.3. Age-depth modeling

Bayesian age modeling has been performed using Bacon (Blaauw and Christen, 2011), based on 56 radiocarbon data out of 57 available from profile 1 of the studied loess record between 8.65 and 2.50 m (Table 1). Combined with an estimated starting date for the first section, accumulation rates are estimated from 27.7 million of Markov Chain Monte Carlo (MCMC) iterations and then these rates form the age-depth model. Accumulation rates in this case were constrained by the following prior information: ‘acc.shape’=1.5 and ‘acc.mean’=10’ for the gamma distribution describing accumulation rates, and ‘mem.mean’=0.7 and ‘mem.strength’=4 for the beta distribution describing the memory effects of accumulation rates. All input age data were provided as ^{14}C yr BP and Bacon used the IntCal13 calibration curve to convert conventional radiocarbon ages to calendar ages. Age modeling was run to achieve 5 cm final resolution.

3. Results and discussion

3.1. Charcoal age accuracy and reproducibility: the effects of applied combustion protocols

Charcoal is produced during pyrolysis accompanying the incomplete combustion of woody plant tissue under conditions of restricted oxygen (Bird, 2006; Braadbart and Poole, 2008; Bird and Ascough, 2012). A characteristic feature of the resulting fire-altered biomass is the presence of chemically stable aromatic ring structures formed by lignocellulose degradation (Schmidt and Noack, 2000; Preston and Schmidt, 2006). Aromatic rings increasingly form ordered microcrystalline domains with increasing pyrolysis temperatures (Bird and Ascough, 2012), leading to higher chemical stability (Goldberg, 1985).

Although charcoals are regarded as relatively resistant to post-depositional alteration (Schmidt and Noack, 2000), there is a growing body of evidence of charcoal degradation and loss by chemical oxidation (Cohen-Ofri et al., 2006; Ascough et al., 2011a,b), physical fragmentation (Gavin, 2003), or fungal degradation (Ascough et al., 2010). Charcoal alteration is mainly controlled by production variables (heat temperature, heating rate, wood properties; Braadbart and Poole, 2008) and the chemistry, especially the pH of the depositional environment (Braadbart et al., 2009). Also, charcoal can readily adsorb a range of soluble chemical contaminants migrating in the sediment column like humic substances, which can have a different ^{14}C age than the charcoal (Alon et al., 2002; Rebollo et al., 2008; Wild et al., 2013). Obviously, this exogenous carbon must be removed prior to radiocarbon dating, which is commonly done by treating the samples with a series of weak acid and base washes (acid-base-acid=ABA treatment; de Vries and Barendsen, 1954; Olson and Broecker, 1958). The initial acid wash with HCl is intended to remove soluble carbonates and other minerals, while the subsequent alkali treatment (NaOH) removes humic substances (Alon et al., 2002; Rebollo et al., 2008). The final acid wash is designed to remove atmospheric CO_2 incorporated into the organic structure during the alkali/base step (Head et al., 1996; Hatté et al., 2001a). While the ABA-technique appears to be a robust method for contaminant removal for a number of samples (Rebollo et al., 2011; Bird and Ascough, 2012), several studies demonstrated that it does not always remove all contaminant carbon, which becomes critical with increasing sample ^{14}C age (Gillespie et al., 1992; Chappell et al., 1996; Douka et al., 2010; Southon and Magana, 2010; Wood et al., 2012).

An alternative pre-treatment technique, called the ABOX-SC method, involves an oxidation step after the acid-base steps, which is followed by stepped combustions at 330, 630 and 850 ºC to remove any final traces of labile carbon (Bird et al., 1999). Although this technique proved to be very effective in removing contamination from old samples (Douka et al, 2010; Wood et al., 2012; Bird et al., 2014), it often leads to large losses in sample material (Bird and Ascough, 2012). Therefore, to test previously published ABA-OSC$_{1000}$ ^{14}C ages of charcoals used as reference ages in comparison with mollusc shell ^{14}C ages (Újvári et al., 2014), radiocarbon ages were obtained in a two-step combustion (400 and 800 ºC) procedure after ABA-treatment in this study. This method was applied on relatively well-preserved charcoals from depths of 8.25 and 8.20 m (Dsz-Ch1 and 2, profile 1; Table 1; Fig. 3), and poorly preserved older charcoal fragments from a depth range of 10.10 to 8.50 m (profile 2, Table 1; Fig. 4).

In a previous study by Újvári et al. (2014) two ABA-OSC$_{1000}$ ages of 25,568±105 and 26,101±110 ^{14}C yr BP were reported from samples Dsz-Ch1 and 2. Since the publication of these ages, the AMS Lab at Debrecen has done extensive chemical blank correction studies using fossil wood samples of known isotopic compositions to better estimate contamination introduced during the chemical preparation of charcoals. These test results indicated that a higher chemistry blank correction is more realistic and has to be applied on the ages published in 2014. Using the new correction factor the above-mentioned ABA-OSC$_{1000}$ charcoal ages were recalculated and are reported here as 25,868±165 and 26,433±178 ^{14}C yr BP (DeA-2917 and DeA-2923; Table 1). In comparison to these ages, another charcoal fragment from the same horizon (Dsz-Ch1) yields slightly older ABA-TSC_{400} and TSC_{800} ages (26,726±142 and 27,320±158 ^{14}C yr BP; Table 1). The age discrepancy between ABA-OSC_{1000} and ABA-$TSC_{400/800}$ ages from the sampled stratigraphic interval (Dsz-Ch1/2) may partly be attributed to real age differences between the charcoals as the individual fragments dated during the two runs were different and were recovered from a 7.5 cm thick sediment layer integrating some hundreds of years of loess deposition. At the same time, it is obvious that some exogenous carbon contamination remained fixed in the charcoal structure after ABA-treatment as demonstrated by the -590±220 ^{14}C yr difference (=~0.26 pMC) between the 400 and 800 ºC fractions. Since the labile carbon was not removed by an additional lower temperature combustion step in the first run, the possibility that those ages are slight underestimates of the true ages cannot be excluded. Two-step combustion ages of coeval and older charcoals from profile 2 further corroborate the above observation of remaining contaminants after ABA-treatment. For samples Dsz/2sz-RC22 and 26, the age differences are -1350±250 and -2260±780 ^{14}C yrs (~0.59 and 0.48 pMC), with the ABA-TSC_{800} ages being consistently older than the ABA-TSC_{400} ages (Table 1; Fig. 4). All these data highlight that ABA-TSC_{800} ages give, or at least are closer to, the real ages of charcoals.

3.2. Charcoal versus shell ages of small molluscs: implications for the 'Limestone problem' and open-system behavior

Early studies documented that land snail shells yield anomalously old radiocarbon ages reaching 3000 yrs offset due to incorporation of old, ^{14}C-free carbonate from the local substrate into shell carbonate. This phenomenon is often quoted as the 'Limestone problem' (Rubin et al., 1963; Tamers, 1970; Evin et al., 1980; Goodfriend and Hood, 1983; Goodfriend and Stipp, 1983; Yates, 1986; Goodfriend, 1987; Zhou et al., 1999; Xu et al., 2011). However, most of these works were biased towards gastropods having relatively large shells (>20 mm) and recent studies by Brennan and Quade (1997) and Pigati et al. (2004, 2010, 2013) demonstrated that reliable ^{14}C ages can be obtained from smaller gastropods (shells <10 mm) that have largely been ignored in previous ^{14}C-dating studies. Beyond the ‘Limestone problem’, another one is to assess whether the shells behaved as close systems with respect to carbon during burial. Open-system behavior is a serious concern in older samples (25–60 ka) where small amounts of contamination cause large bias/errors in ^{14}C ages. Rech et al. (2011) and Pigati et al. (2010, 2013) revealed, by measuring the ^{14}C-activities of very old mollusc shells (800–130 ka) and testing land snail shell ages against plant macrofossil ^{14}C ages, that many fossil gastropod shells do not suffer from major (>1%) open-system problems.

Ten different mollusc species and two additional ones that could be identified only at the family level have been radiocarbon dated in this study, some of them are displayed in Fig. 2. Out of the eleven, shells of 7 mollusc species could directly be compared to reference charcoal ages from samples Dsz-Ch1/2. These shell ages range from 15,844±56 (*Trochulus hispidus*) to 26,979±126 ^{14}C yr BP (Clausiliidae sp.; Table 1). The apparently young ^{14}C age of *T. hispidus* (15,844±56 ^{14}C yr BP) is attributed to open-system behavior.

As shown in Fig. 3, all of the land snail shell ages obtained in the first run overlap within 2σ errors with the ABA-OSC$_{1000}$ charcoal ages from the same sample except for the anomalous age (DeA-2918) mentioned above. Out of the analyzed shells that of Succineidae sp. show one of the lowest age anomalies (-290±220 ^{14}C yr; Dsz-Ch1; Table 1) compared to the conventional age of charcoals obtained by the ABA-OSC$_{1000}$ protocol (Table 1; Fig. 3). At first glance, this observation would confirm previous findings of Pigati et al. (2010, 2013) that the genus *Succinella* may yield reliable ^{14}C ages. However, the Succineidae sp. age is clearly younger than the ABA-TSC$_{800}$ age (second run; Table 1), which is considered to be closer to the real age of sedimentation. The negative age anomalies, ranging from -290±220 to -

1180±210 ^{14}C yr between Succineidae sp. and the ABA-OSC/TSC ages, may indicate minor (<1 %) open-system behavior due to a limited exchange of ^{14}C atoms with the local environment. At the same time, the age obtained from the *V. crystallina* shell is much younger (-600±220 to -1480±210 ^{14}C yr) than the ABA-OSC/TSC ages, also implying some open-system behavior. Both *Chondrula tridens* and Clausiliidae sp. shells, which could not be reliably identified at the species level in lack of the lamellae and plicae-bearing last whorl, provided slightly older ages (420±220, 550±220 and 250±210 ^{14}C yr) compared to ABA-OSC$_{1000}$ dates (Dsz-Ch1/2; Table 1; Fig. 3). These positive ^{14}C age anomalies were first interpreted as being evidences for 'dead' (^{14}C-deficient) carbon incorporation into the shells ('Limestone problem'; Goodfriend and Stipp, 1983) from the local carbonate-rich substrate. Nevertheless, both *C. tridens* and Clausiliidae sp. shell ages most overlap with the ABA-TSC$_{400/800}$ ages in Fig. 3. The minor negative age anomalies compared to the ABA-TSC$_{800}$ age (-470±200, -340±210 and -370±220, Table 1) imply no 'Limestone effect' on these shells. While the *T. hispidus* age are statistically indistinguishable from the older ABA-OSC$_{1000}$ and the ABA-TSC$_{400}$ ages, both *D. ruderatus* and *E. fulvus* yield younger ages, closer to the youngest ABA-OSC$_{1000}$ charcoal age (Table 1; Fig. 3). Obviously, any comparison between charcoals and shells are hindered by the scatter in reference charcoal ages. The age discrepancies between charcoal fragments dated in the first and second runs are partly attributable to the less effective removal of contamination with the ABA-OSC protocol, and that the different fragments were likely to be the end-product of subsequent biomass burning events, so they were likely not entirely coeval. Nevertheless, considering the charcoal ages from sample Dsz-Ch1 it is clear that some small molluscs such as Succineidae sp., *C. tridens*, *T. hispidus*, and the members of the Clausiliidae family are not affected by the 'Limestone effect' and do not suffer from major open-system problems. Thus, these species are likely to be appropriate targets for ^{14}C-dating of loess, but the above findings should be further investigated in subsequent studies of other loess sites where charcoals are available.

A comparison of Succineidae sp. ages with those obtained from shells of *E. fulvus* and *O. dolium* recovered from 2 samples between 6.25 and 5.75 m demonstrates that the latter two display minor age differences (100±180 and -140±160 ^{14}C yrs) compared to Succineidae sp. (Dsz-RC12, 13; anomalies not tabulated in Table 1). While no independent data on the use of *O. dolium* for dating late Quaternary sediments exist, Pigati et al. (2004, 2010) found that shells of live *E. fulvus* show ^{14}C activities that are indistinguishable from live plants and display negligible 'Limestone effect'. If their results could be applied to the fossil record, should be the subject of further testing, as the data presented here are somewhat ambiguous for *E. fulvus* (see Fig. 3, second run).

3.3. Bayesian age-depth model of the studied loess record and associated chronological uncertainties

Bayesian age-depth modeling was performed using 56 AMS ^{14}C dates for profile 1 from 8.65 to 2.50 m. Two ages were omitted in age modeling as they were clear outliers (Table 1), while no preference or extra weight was given to any age data obtained from particular species identified as promising targets for AMS ^{14}C dating in comparison with charcoal ages above. This is because of the scatter in charcoal age data in samples Dsz-Ch1/2 (Fig. 3) that rendered the comparison of charcoal and shell ages somewhat ambiguous. Also, it is believed that such a Bayesian age model includes the treatment of the stochastic nature of how the passing of time (as loess sedimentation proceeds) is recorded in shells of small molluscs. Random, hence unpredictable elements of this process (among others) are the minimal, but in some cases still acting 'Limestone effect' of different magnitudes and the possible minor open-system behavior. It is believed that the Monte Carlo-based age model emerges from this noise imposed on the true age of the sequence, and if a large number of absolute dates are available both from each dated layer and at many depths, the model will represent the real age of loess sedimentation which is an inhomogeneous Poisson process.

The software ‘Bacon’ divided the sequence into 124 vertical sections and accumulation rates were estimated through 27.7 million MCMC iterations, which resulted in an age-depth model presented in Fig. 5. Two post-IR IRSL$_{225}$ ages published earlier (Újvári et al., 2014) are also shown in Fig. 5 to further confirm the validity of the age model. However, OSL and post-IR IRSL$_{290}$ ages (not shown in Fig. 5) are consistently older as discussed in Újvári et al. (2014). The Bayesian age model has a mean 95% confidence range of 464 yr. While the minimum 2σ uncertainty is as low as 238 yr at 4.90 m, the maximum reaches 804 yr at 7.50 m (Fig. 5). Broadening of the 95% confidence interval at around a depth of 7.50 m is due to the lack of ^{14}C ages from 7.75 to 7.15 m in the record (Bennett, 1994).

5. Conclusions

Shells of various mollusc species and charcoal fragments at multiple depths from the Dunaszekcső loess sequence, Hungary were dated by ^{14}C. Charcoal ^{14}C ages were found to be dependent on the applied protocol used, with the ABA-TSC$_{800}$ protocol giving consistently the oldest ages. Since the combustion step at 400 ºC is thought to remove labile, exogenous carbon still present in the charcoal structure after the ABA-treatment, the ages obtained in the 800 ºC combustion step are considered to be the closest to the real age of the sediments. Comparison of charcoal ages with those of land snail shells reveals that some small (<10 mm) molluscs (Succineidae sp., *C. tridens*, *T. hispidus* and members of the Clausiliidae family) appear to yield accurate, reliable ^{14}C ages, although the comparison is somewhat uncertain considering the scatter in charcoal ages. Unfortunately, this prevents us from identifying the best mollusc targets for ^{14}C dating of loess records. Other species, including *E. fulvus*, *D.*

ruderatus and *O. dolium*, may be useful, but further work involving these species is needed to validate this and the above observations. As the Bayesian model for the Dunaszekcső loess record demonstrates, relatively good chronologies can be gained by dating multiple species from depth intervals of 20-30 cm. The resulting age models will likely have 2σ uncertainties on the order of ca. 500-800 yr.

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References

Alon, D., Mintz, G., Cohen, I., Weiner, S., Boaretto, E., 2002. The use of Raman spectroscopy to monitor the removal of humic substances from charcoal: quality control for 14C dating of charcoal. Radiocarbon 44, 1–11.

Ascough, P., Sturrock, C.J., Bird, M.I., 2010. Investigation of growth responses in saprophytic fungi to charred biomass. Isotopes in Environmental and Health Studies 46, 64–77.

Ascough, P.L., Bird, M.I., Francis, S.M., Lebl, T., 2011a. Alkali extraction of archaeological and geological charcoal: evidence for diagenetic degradation and formation of humic acids. Journal of Archaeological Science 38, 69–78.

Ascough, P.L., Bird, M.I., Francis, S.M., Thornton, B., Midwood, A.J., Scott, A.C., Apperley, D., 2011b. Variability in oxidative degradation of charcoal: Influence of production conditions and environmental exposure. Geochimica et Cosmochimica Acta 75, 2361–2378.

Bennett, K.D., 1994. Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences. The Holocene 4, 337–348.

Bird, M.I., 2006. Radiocarbon dating of charcoal. In: Elias, S.A. (Ed.), The Encyclopaedia of Quaternary Science. Elsevier, Amsterdam, pp. 2950–2958.

Bird, M.I., Ascough, P.L., 2012. Isotopes in pyrogenic carbon: a review. Organic Geochemistry 42, 1529–1539.

Bird, M.I., Ayliffe, L.K., Fifield, K., Cresswell, R., Turney, C., 1999. Radiocarbon dating of ‘old’ charcoal using a wet oxidation-stepped combustion procedure. Radiocarbon 41, 127–140.

Bird, I.M., Levchenko, V., Ascough, P.L., Meredith, W., Wurster, C.M., Williams, A., Tilston, E.L., Snape, C. E., Apperley, D.C., 2014. The efficiency of charcoal decontamination for radiocarbon dating by three pre-treatments – ABOX, ABA and hypy. Quaternary Geochronology 22, 25–32.

Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6, 457–474.

Braadbart, F., Poole, I., 2008. Morphological, chemical and physical changes during charcoalification of wood and its relevance to archaeological contexts. Journal of Archaeological Science 35, 2434–2445.

Braadbaart, F., Poole, I., van Brussel, A.A., 2009. Preservation potential of charcoal in alkaline environments: an experimental approach and implications for the archaeological record. Journal of Archaeological Science 36, 1672–1679.

Brennan, R., Quade, J., 1997. Reliable Late-Pleistocene stratigraphic ages and shorter groundwater travel times from ^{14}C in fossil snails from the southern Great Basin. Quaternary Research 47, 329–336.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Chappell, J., Head, M.J., Magee, J., 1996. Beyond the radiocarbon limit in Australian archaeology and Quaternary research. Antiquity 70, 543–752.

Cohen-Ofri, I., Weiner, L., Boaretto, E., Mintz, G., Weiner, S., 2006. Modern and fossil charcoal: aspects of structure and diagenesis. Journal of Archaeological Science 33, 428–439.

Douka, K., Higham, T., Sinitsyn, A., 2010. The influence of pre-treatment chemistry on the radiocarbon dating of Campanian ignimbrite-aged charcoal from Kostenki 14 (Russia). Quaternary Research 73, 583–587.

Evin, J., Marechal, J., Pachiaudi, C., 1980. Conditions involved in dating terrestrial shells. Radiocarbon 22, 545–555.

Gavin, D.G., 2003. Forest soil disturbance intervals inferred from soil charcoal radiocarbon dates. Canadian Journal of Forest Research 33, 2514–2518.

Gillespie, R., Hammond, A.P., Goh, K.M., Tonkin, P.J., Lowe, D.C., Sparks, R.J., Wallace, G., 1992. AMS radiocarbon dating of a Late Quaternary tephra site at Graham's Terrace, New Zealand. Radiocarbon 34, 21–28.

Gocke, M., Kuzyakov, Y., Wiesenberg, G.L., 2010. Rhizoliths in loess—evidence for post-sedimentary incorporation of root-derived organic matter in terrestrial sediments as assessed from molecular proxies. Organic Geochemistry 41, 1198–1206.

Gocke, M., Pustovoytov, K., Kuhn, P., Wiesenberg, G., Löscher, M., Kuzyakov, Y., 2011. Carbonate rhizoliths in loess and their implications for paleoenvironmental reconstruction revealed by isotopic composition: $\delta^{13}C$, ^{14}C. Chemical Geology 283, 251–260.

Goldberg, E.D., 1985. Black Carbon in the Environment. John Wiley, New York.

Goodfriend, G.A., 1987. Radiocarbon age anomalies in shell carbonate of land snails from semi-arid areas. Radiocarbon 29, 159–167.

Goodfriend, G.A., Hood, D.G., 1983. Carbon isotope analysis of land snail shells: implications for carbon sources and radiocarbon dating. Radiocarbon 25, 810–830.

Goodfriend, G.A., Stipp, J.J., 1983. Limestone and the problem of radiocarbon dating of land-snail shell carbonate. Geology 11, 575–577.

Head MJ, Jacobsen G, Tuniz C. 1996. Assessement of the AAA pretreatment technique for charcoal and other organic materials used for 14C AMS studies. Radiocarbon 38, 46.

Hatté, C., Morvan, J., Noury, C., Paterne, M., 2001a. Is classical acid-alkali-acid treatment responsible for contamination? An alternative proposition. Radiocarbon 43, 177–182.

Hatté, C., Pessenda, L.C.R., Lang, A., Paterne, M., 2001b. Development of an accurate and reliable ^{14}C chronology for loess sequences: Application to the loess sequence of Nussloch (Rhine valley, Germany). Radiocarbon 43, 611–618.

Jull, A.J.T., Burr, G.S., Beck, J.W., Hodgins, G.W.L., Biddulph, D.L., Gann, J., Hatheway, A.L., Lange, T.E., Lifton, N.A., 2006. Application of accelerator mass spectrometry to environmental and paleoclimate studies at the University of Arizona. Radioactivity in the Environment 8, 3–23.

Kadereit, A., Kind, C-J., Wagner, G.A., 2013. The chronological position of the Lohne Soil in the Nussloch loess section — re-evaluation for a European loess-marker horizon. Quaternary Science Reviews 59, 67–86.

McGeehin, J.P., Burr, G.S., Jull, A.J.T., Reines, D., Gosse, J., Davis, P.T., Muhs, D., Southon, J.R., 2001. Stepped-combustion ^{14}C dating of sediment: a comparison with established techniques. Radiocarbon 43, 255–261.

Moine, O., Rousseau, D.-D., Antoine, P., 2008. The impact of Dansgaard-Oeschger cycles on the loessic environment and malacofauna of Nussloch (Germany) during the upper Weichselian. Quaternary Research 70, 91–104.

Molnár, M., Janovics, R., Major, I., Orsovszki, J., Gönczi, R., Veres, M., Leonard, A.G., Castle, S.M., Lange, T.E., Wacker, L., Hajdas, I., Jull, A.J.T., 2013a. Status report of the new AMS 14C sample preparation lab of the Hertelendy Laboratory of Environmental Studies (Debrecen, Hungary). Radiocarbon 55, 665–676.

Molnár, M., Rinyu, L., Veres, M., Seiler, M., Wacker, L., Synal, H-A., 2013b. ENVIRONMICADAS: a mini 14C AMS with enhanced gas ion source interface in the Hertelendi Laboratory of Environmental Studies (HEKAL), Hungary. Radiocarbon 55, 338–344.

Olson, E.A., Broecker, W.S., 1958. Sample contamination and reliability of radiocarbon dates. Transactions of the New York Academy of Science Series II 20, 593–604.

Pigati, J.S., McGeehin, J.P., Muhs, D.R., Bettis III, E.A., 2013. Radiocarbon dating late Quaternary loess deposits using small terrestrial gastropod shells. Quaternary Science Reviews 76, 114–128.

Pigati, J.S., Quade, J., Shanahan, T.M., Haynes Jr., C.V., 2004. Radiocarbon dating of minute gastropods and new constraints on the timing of spring-discharge deposits in southern Arizona, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 204, 33–45.

Pigati, J.S., Rech, J.A., Nekola, J.C., 2010. Radiocarbon dating of small terrestrial gastropod shells in North America. Quaternary Geochronology 5, 519–532.

Porter, S. C., An, Z. S., 1995. Correlation between climate events in the North Atlantic and China during the last glaciation, Nature 375, 305–308.

Preston, C.M., Schmidt, M.W.I., 2006. Black, pyrogenic carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. Biogeoscience 3, 397–420.

Pustovoytov, K., Terhorst, B., 2004. An isotopic study of a late Quaternary loess–paleosol sequence in SW Germany. Revista Mexicana de Ciencias Geologicas 21, 88–93.

Rebollo, N.R., Cohen-Ofri, I., Popovitz-Biro, R., Bar-Yosef, O., Meignen, L., Goldberg, P., Weiner, S., Boaretto, E., 2008. Structural characterisation of charcoal exposed to high and low pH; implications for ^{14}C sample preparation and charcoal preservation. Radiocarbon 50, 289–307.

Rebollo, N.R., Weiner, S., Brock, F., Meignen, L., Goldberg, P., Belfer-Cohen, A., Bar-Yosef, O., Boaretto, E., 2011. New radiocarbon dating of the transition from the Middle to the upper Paleolithic in Kebara cave, Israel. Journal of Archaeological Science 38, 2424–2433.

Rech, J.A., Pigati, J.S., Lehmann, S.B., McGimpsey, C.N., Grimley, D.A., Nekola, J.C., 2011. Assessing open-system behavior of carbon-14 in terrestrial gastropod shells. Radiocarbon 53, 325–335.

Reimer, P.J., Bard,E., Bayliss, A., Warren Beck, J., Blackwell, P.G., Bronk Ramsey, Ch., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, Ch., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, Ch.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon 55, 1869–1887.

Rousseau, D. D., Sima, A., Antoine, P., Hatté, C., Lang, A., Zoeller, L., 2007. Link between European and North Atlantic abrupt climate changes over the last glaciation, Geophysical Research Letters 34, L22713, doi:10.1029/2007gl031716.

Rubin, M., Likins, R.C., Berry, E.G., 1963. On the validity of radiocarbon dates from snail shells. Journal of Geology 71, 84–89.

Schmidt M.W.I., Noack A.G., 2000. Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. Global Biogeochemical Cycles 14, 777–793.

Southon, J.R., Magana, A.L., 2010. A comparison of cellulose extraction and ABA pretreatment methods for AMS 14C dating of ancient wood. Radiocarbon 52, 1371–1379.

Stevens, T., Lu, H., Thomas, D.S.G., Armitage, S.J., 2008. Optical dating of abrupt shifts in the late Pleistocene East Asian monsoon. Geology 36, 415–418.

Stevens, T., Thomas, D.S.G., Armitage, S.J., Lunn, H.R., and Lu, H., 2007. Reinterpreting climate proxy records from late Quaternary Chinese loess: A detailed OSL investigation. Earth-Science Reviews 80, 111–136.

Sun, Y., Clemens, S.C., Morrill, C., Lin, X., Wang, X., An, Z., 2012. Influence of Atlantic meridional overturning circulation on the East Asian winter monsoon. Nature Geoscience 5, 46–49.

Sümegi, P., Hertelendi, E., 1998. Reconstruction of microenvironmental changes in the Kopasz Hill loess area at Tokaj (Hungary) between 15 and 70 ka BP. Radiocarbon 40, 855–863.

Sümegi, P., Krolopp, E., 2002. Quartermalacological analyses for modelling of the Upper Weichselian paleoenvironmental changes in the Carpathian basin. Quaternary International 91, 53–63.

Synal, H-A., Stocker, M., Suter, M., 2007. MICADAS: a new compact radiocarbon AMS system. Nuclear Instruments and Methods in Physics Research B 259, 7–13.

Tamers, M.A., 1970. Validity of radiocarbon dates on terrestrial snail shells. American Antiquity 35, 94–100.

Trumbore, S.E., 2000. Radiocarbon geochronology. In: Noller, J.S., Sowers, J.M., Lettis, W.R. (Eds.), Quaternary Geochronology: Methods and Applications. American Geophysical Union, Washington, D.C, pp. 41–60.

Újvári, G., Molnár, M., Novothny, Á., Páll-Gergely, B., Kovács, J., Várhegyi, A., 2014. AMS ^{14}C and OSL/IRSL dating of the Dunaszekcső loess sequence (Hungary): chronology for 20 to 150 ka and implications for establishing reliable age-depth models for the last 40 ka. Quaternary Science Reviews 106, 140–154.

de Vries, H., Barendsen, G.W., 1954. Measurements of age by the carbon-14 technique. Nature 174, 1138–1141.

Wacker, L., Bonani, G., Friedrich, M., Hajdas, I., Kromer, B., Némec, M., Ruff, M., Suter, M., Synal, H.A., Vockenhuber, C., 2010. MICADAS: Routine and high-precision radiocarbon dating. Radiocarbon 52, 252–262.

Welter-Schultes, F.W., 2012. European non-marine molluscs, a guide for species identification. Planet Poster Editions, Göttingen, ISBN-13: 9783933922755, p. 757.

Wild, E.M., Steier, P., Fischer, P., Höflmayer, F., 2013. ^{14}C dating of humic acids from Bronze and Iron Age plant remains from the eastern Mediterranean. Radiocarbon 55, 599–607.

Wood, R.E., Douka, K., Boscato, P., Haesaerts, P., Sinitsyn, A., Higham, T.F.G., 2012. Testing the ABOx-SC method: dating known age charcoals associated with the Campanian Ignimbrite. Quaternary Geochronology 9, 16–26.

Xu, B., Gu, Z., Han, J., Hao, Q., Lu, Y., Wang, L., Wu, N., Peng, Y., 2011. Radiocarbon age anomalies of land snail shells in the Chinese Loess Plateau. Quaternary Geochronology 6, 383–389.

Yates, T., 1986. Studies of non-marine mollusks for the selection of shell samples for radiocarbon dating. Radiocarbon 28, 457–463.

Zhou, W., Head, W.J., Wang, F., Donahue, D.J., Jull, A.J.T., 1999. The reliability of AMS radiocarbon dating of shells from China. Radiocarbon 41, 17–24.

Figure captions

Figure 1. Location of the Dunaszekcső loess sequence in the Carpathian Basin.

Figure 2. Some mollusc species included in this study. a) Clausiliidae sp. (sample Dsz-Ch1), b) *Cochlicopa lubrica* (Dsz-RC20), c) *Discus ruderatus* (Dsz-RC7), d) *Euconulus fulvus* (Dsz-RC8), e) *Nesovitrea hammonis* (Dsz-RC9), f) *Orcula dolium* (Dsz-RC3), g) Succineidae sp. (most probably *Succinella oblonga*) (Dsz-RC12), h) *Trochulus hispidus* (Dsz-1R), i) *Vallonia costata* (Dsz-RC6), j) *Vitrea crystallina* (Dsz-RC4). Scale bars represent 2.5 mm.

Figure 3. Comparison of conventional AMS radiocarbon ages of charcoal fragments and mollusc shells obtained during the first and second runs from samples Dsz-Ch1 and 2 (depths 8.20, and 8.25 m). Note that the youngest, obviously anomalous shell age (DeA-2918) from sample Dsz-Ch1 is not displayed in this figure.

Figure 4. Comparison of conventional AMS radiocarbon ages of charcoal fragments between depths of 10.10 to 8.50 m. Note that ABA-OSC_{1000} ages are from profile 1 (first run), while ABA-$TSC_{400/800}$ ages are from profile 2 (second run).

Figure 5. Bayesian age-depth model for the 8.65-2.50 m part of the Dunaszekcső loess record and calibrated mollusc shell and charcoal ^{14}C ages (mean age ± 2σ). Two post-IR $IRSL_{225}$ ages are also shown for comparison (errors are 2σ; data from Újvári et al., 2014). Parameters of the age-depth model as described in the ‘Materials and methods’ section. Note that ^{14}C ages from profile 2 were excluded from modeling.

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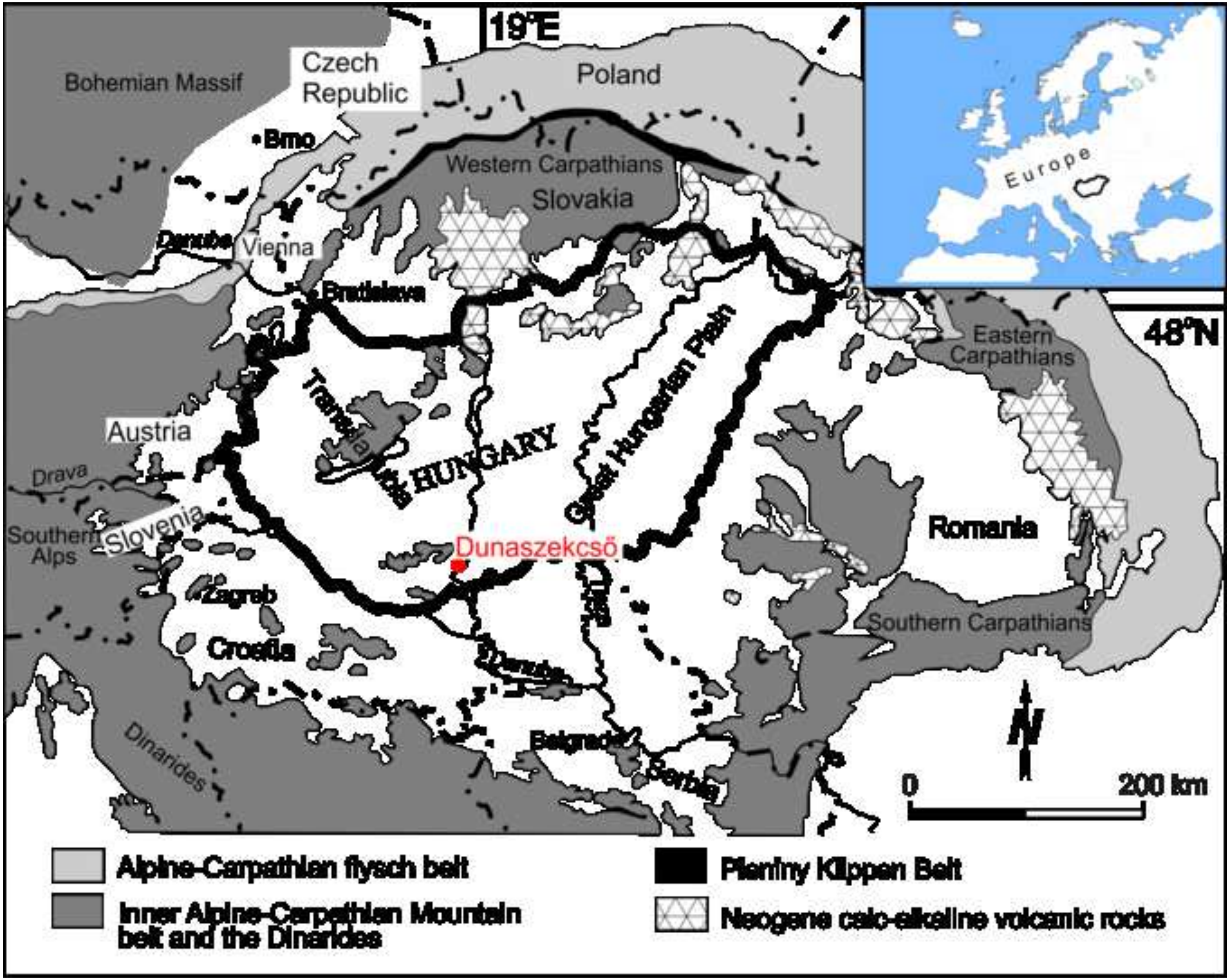

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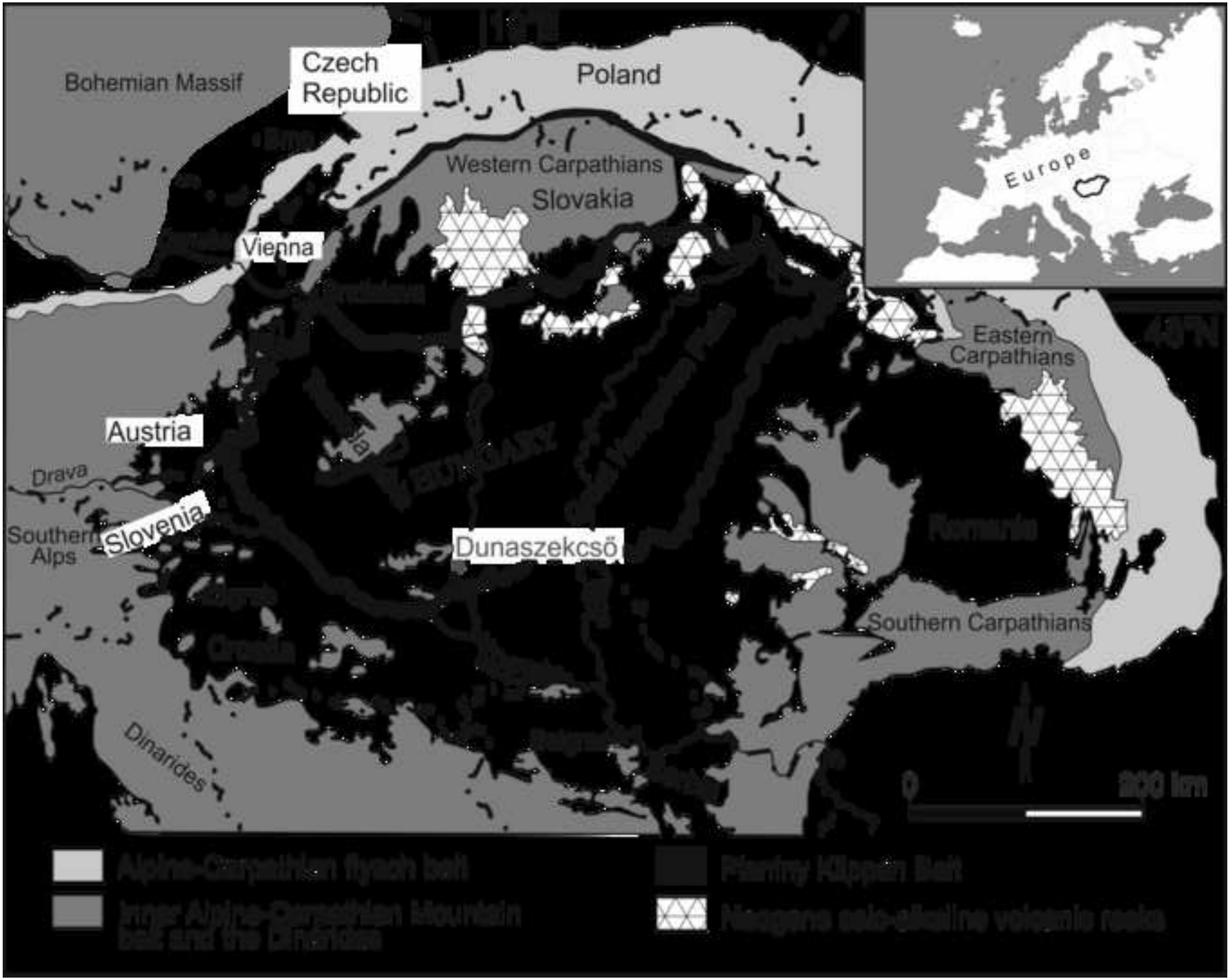

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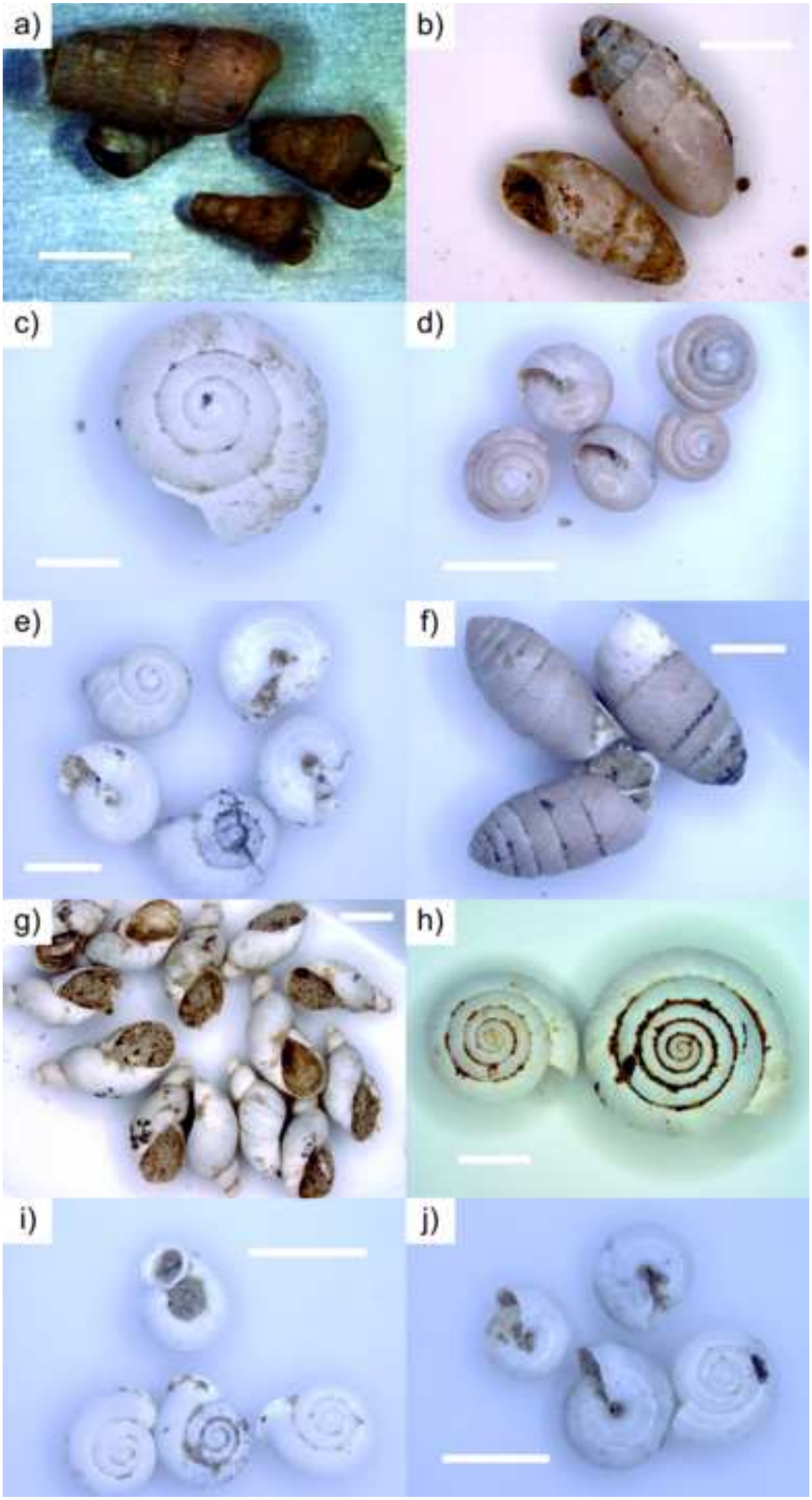

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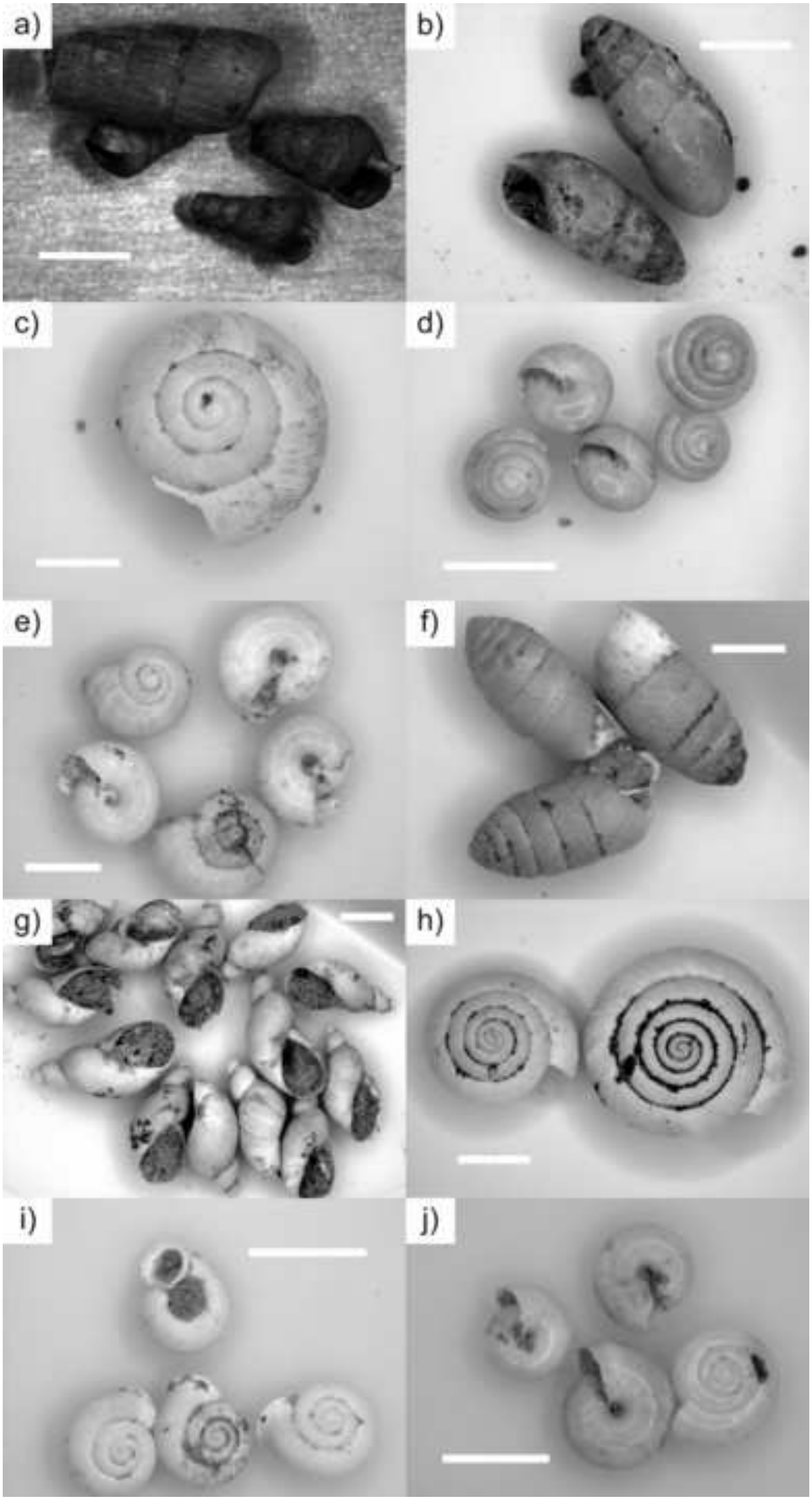

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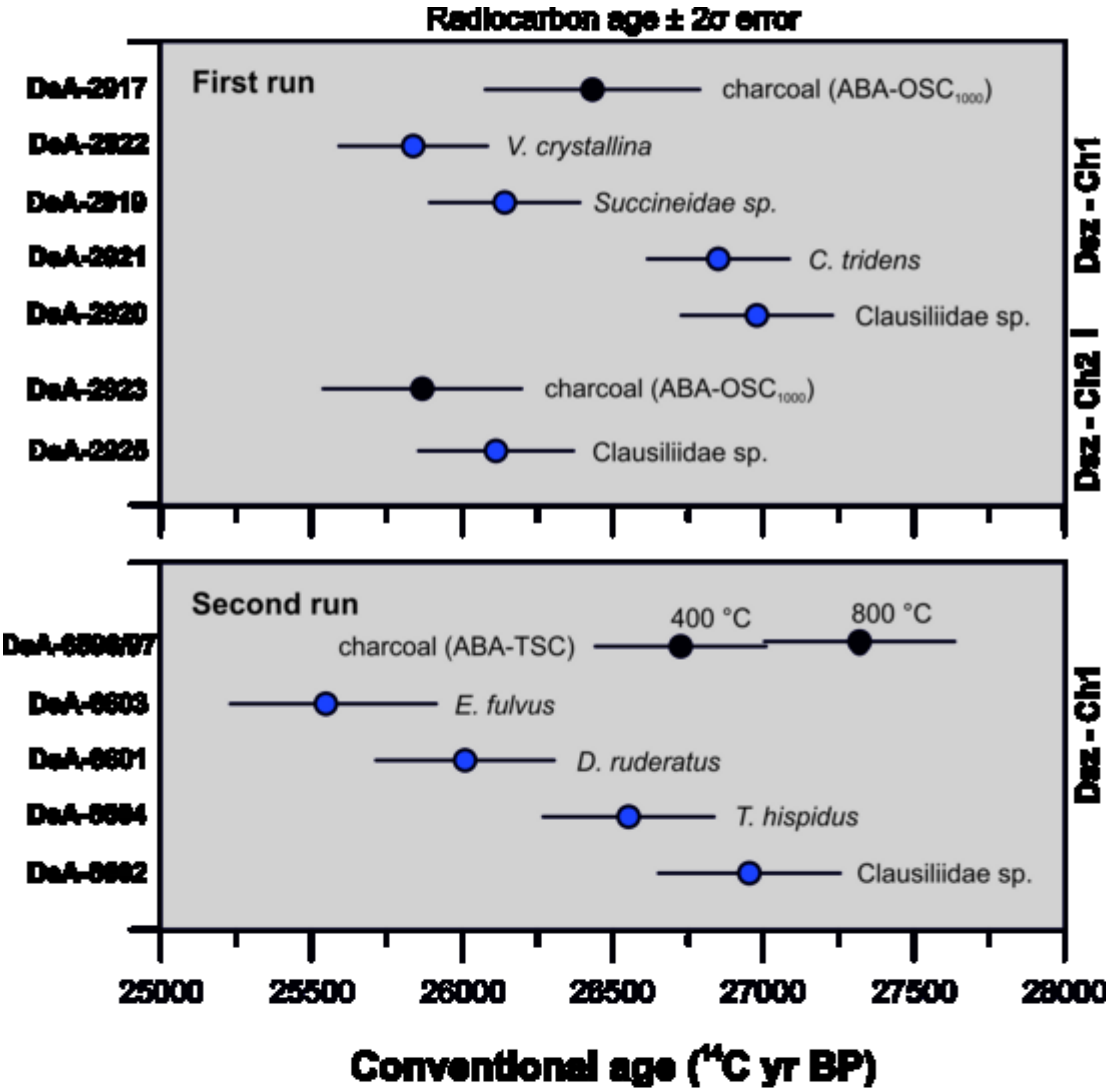

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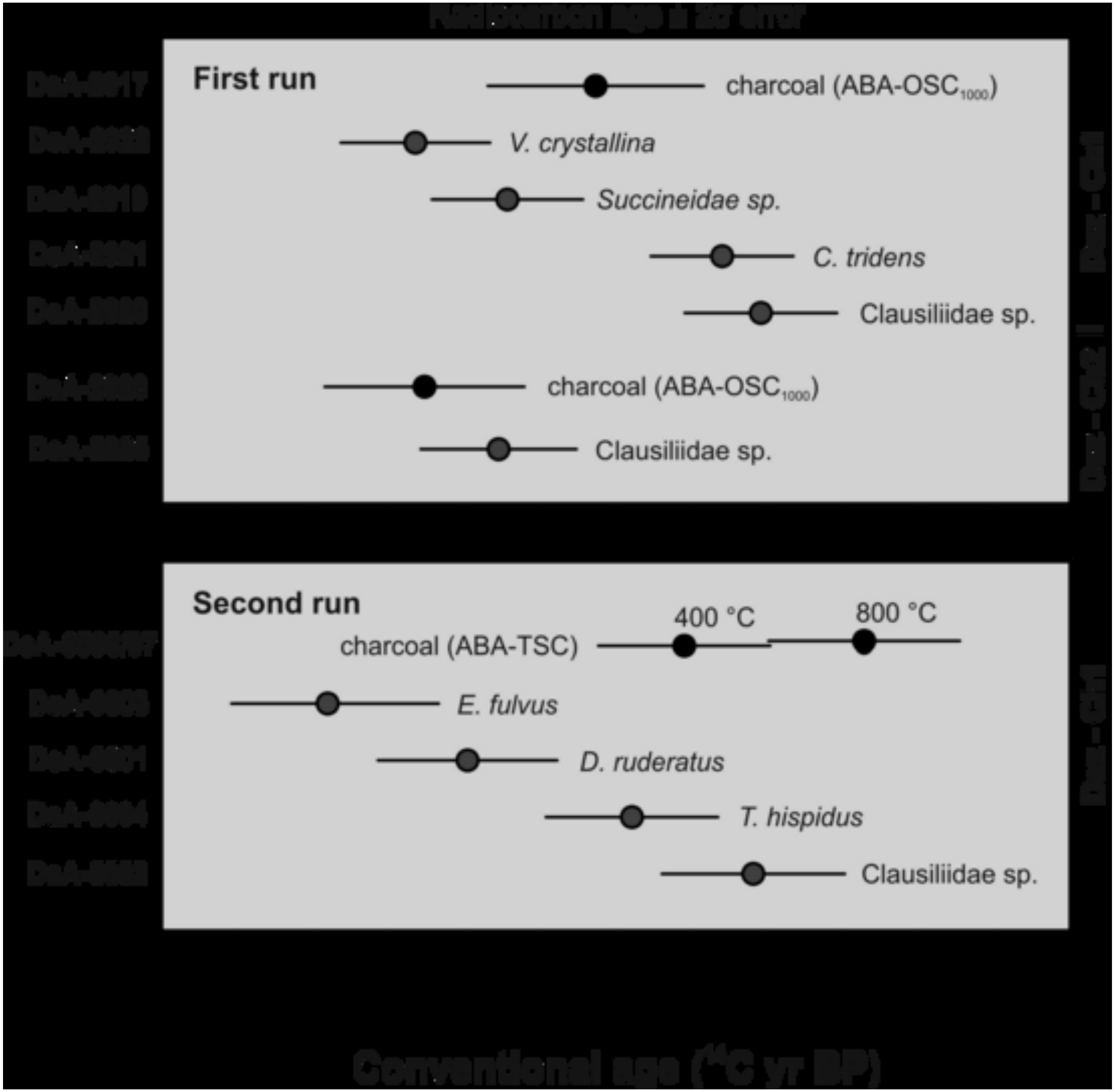

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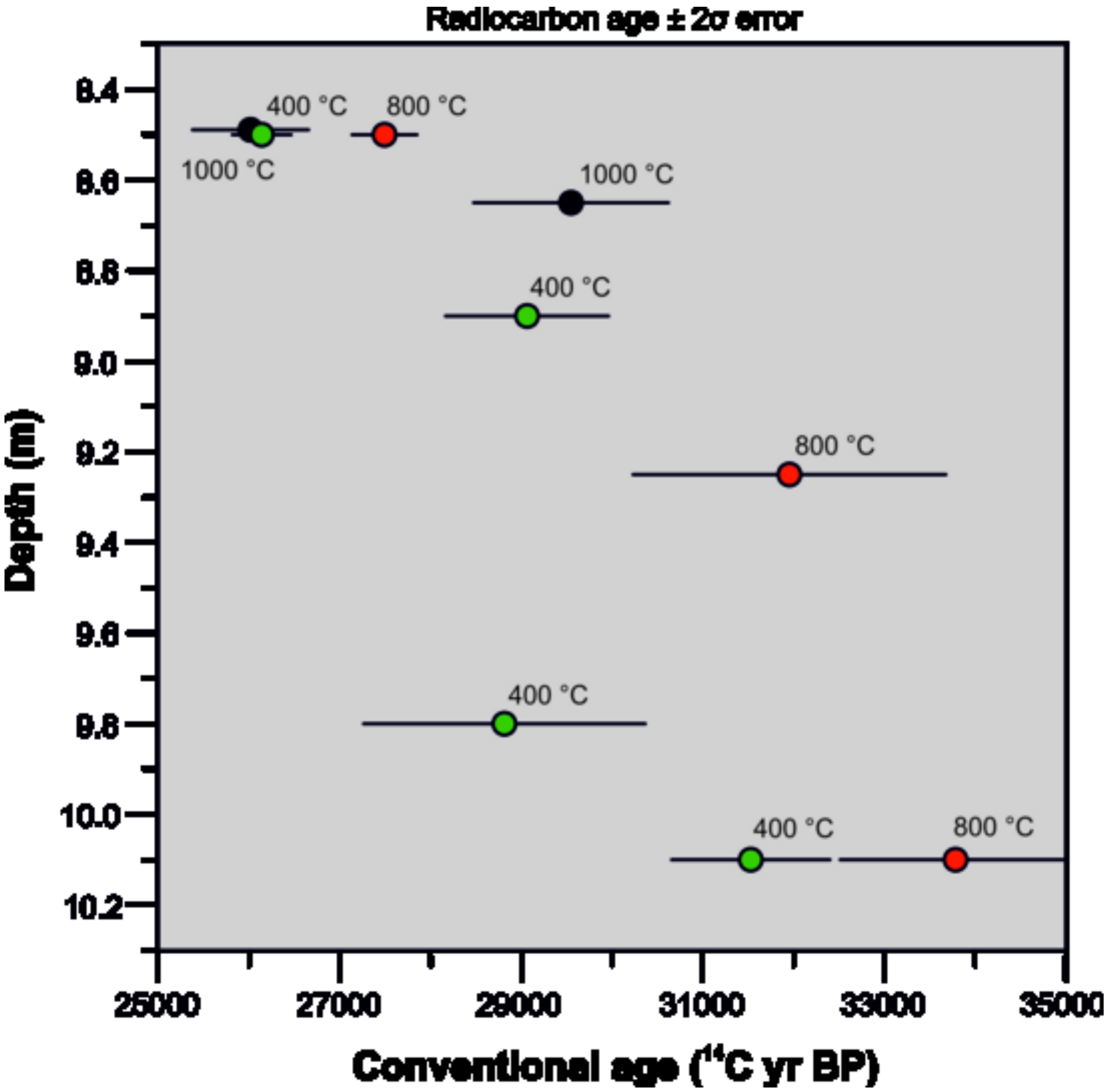

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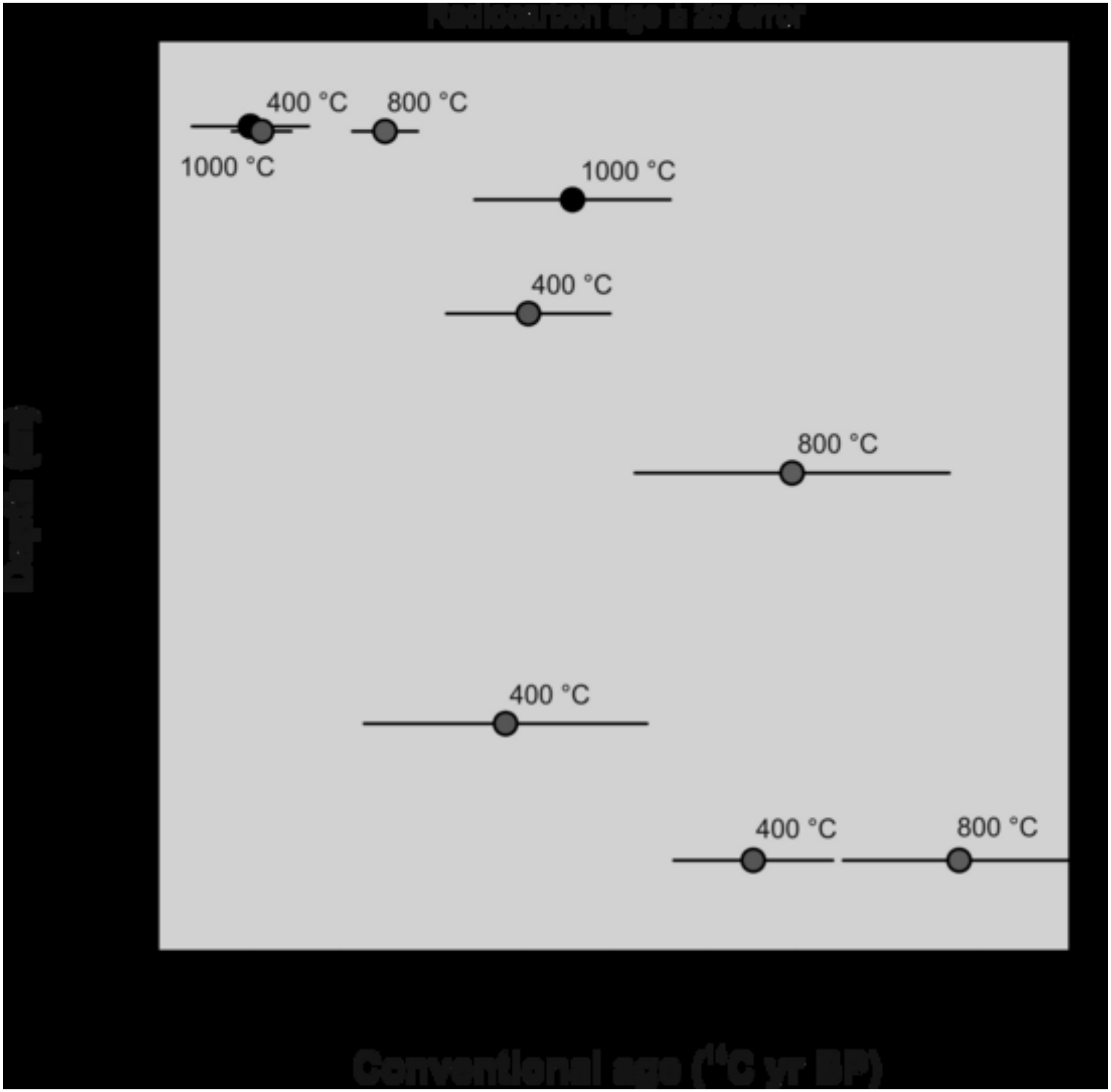

Figure5_color

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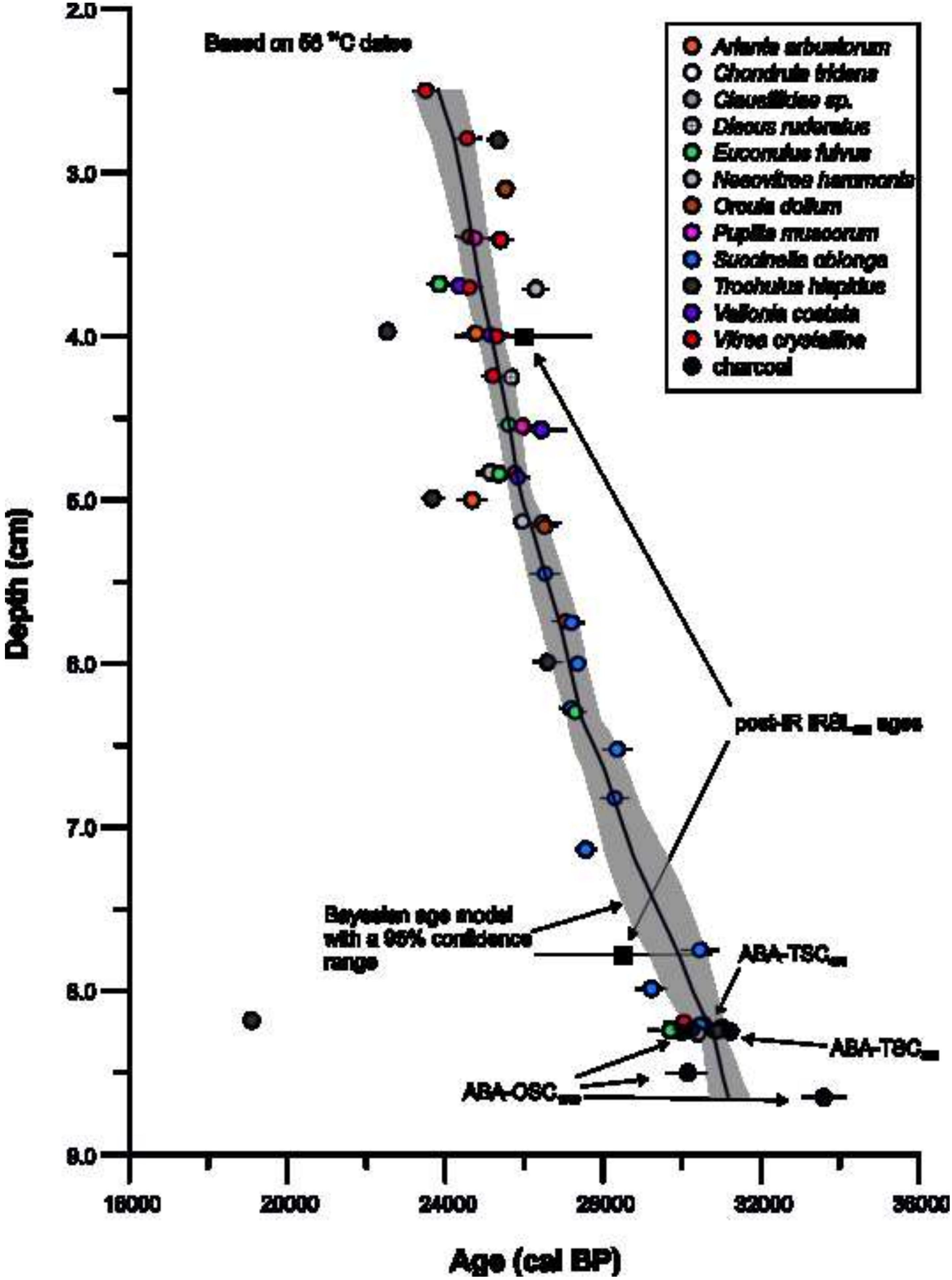

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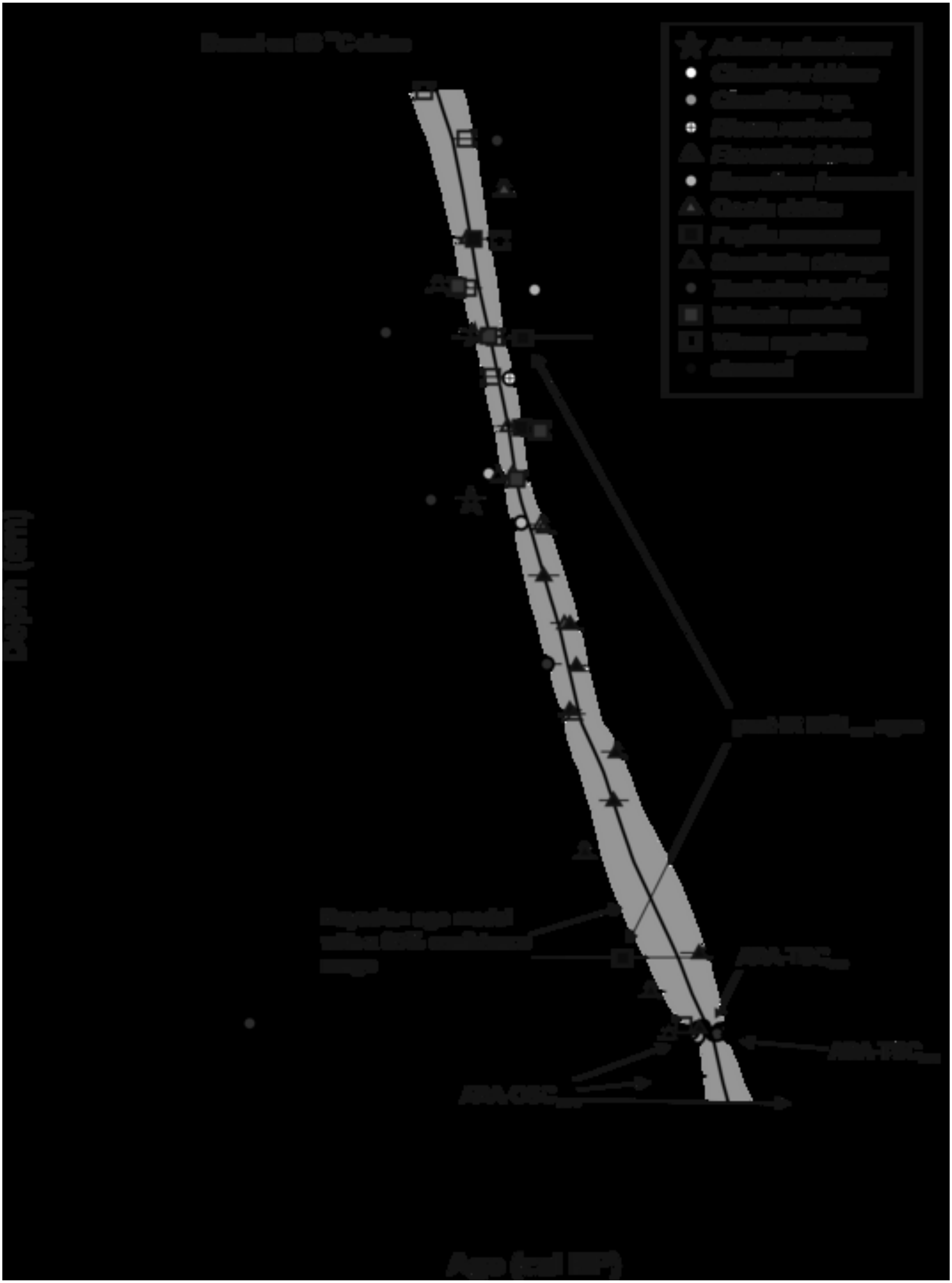

Table 1. AMS ^{14}C data of charcoal fragments and mollusc shells from the Dunaszekcső loess record

Depth (m)	Sample code	AMS lab code	Dated material	C (mg)	Remark	^{14}C age (yr BP)	1σ	Calibrated age range (2σ, cal BP)		Mean age (cal BP)	2σ	Age difference (^{14}C yr)[a]	Error	Age anomaly (^{14}C yr)[b]	Error	Age anomaly (^{14}C yr)[c]	Error	Used for age model	Source
								Min	Max										
Profile 1																			
2.50	Dsz-RC1	DeA-4700	shell (V. crystallina)	0.84		19515	81	23180	23800	23510	300							yes	This study
2.80	Dsz-RC2	DeA-4699	shell (V. crystallina)	0.90		20409	86	24240	24930	24550	340							yes	This study
2.80	Dsz-RC2	DeA-4698	shell (T. hispidus)	1.50		20995	76	25110	25580	25350	240							yes	This study
3.10	Dsz-RC3	DeA-4696	shell (O. dolium)	2.43		21182	67	25290	25730	25530	220							yes	This study
3.40	Dsz-RC4	DeA-4693	shell (O. dolium)	1.88		20457	67	24330	24940	24610	320							yes	This study
3.40	Dsz-RC4	DeA-4694	shell (P. muscorum)	0.35		20555	116	24380	25160	24760	400							yes	This study
3.40	Dsz-RC4	DeA-4695	shell (V. crystallina)	0.41		21066	112	25130	25690	25410	280							yes	This study
3.70	Dsz-RC5	DeA-4689	shell (E. fulvus)	0.61		19813	96	23560	24120	23850	280							yes	This study
3.70	Dsz-RC5	DeA-4691	shell (V. costata)	1.07		20283	76	24090	24590	24360	240							yes	This study
3.70	Dsz-RC5	DeA-4692	shell (V. crystallina)	1.05		20457	78	24310	24970	24620	340							yes	This study
3.70	Dsz-RC5	DeA-4690	shell (N. hammonis)	0.79		22086	102	26020	26590	26300	300							yes	This study
4.00	Dsz-1R	DeA-2068	shell (T. hispidus)			18678	68	22370	22740	22540	180							yes	This study
4.00	Dsz-1R	DeA-2067	shell (A. arbustorum)			20585	75	24470	25120	24790	340							yes	This study
4.00	Dsz-RC6	DeA-4688	shell (V. costata)	0.29		20851	133	24640	25540	25140	440							yes	This study
4.00	Dsz-RC6	DeA-4687	shell (V. crystallina)	1.35		20946	76	25060	25540	25300	240							yes	This study
4.25	Dsz-RC7	DeA-4635	shell (V. crystallina)	1.21		20889	80	24960	25510	25220	280							yes	This study
4.25	Dsz-RC7	DeA-4634	shell (D. ruderatus)	1.68		21328	72	25480	25860	25670	180							yes	This study
4.55	Dsz-RC8	DeA-4631	shell (E. fulvus)	0.86		21271	97	25350	25850	25610	240							yes	This study
4.55	Dsz-RC8	DeA-4632	shell (P. muscorum)	0.48		21695	147	25680	26230	25950	260							yes	This study
4.55	Dsz-RC8	DeA-4633	shell (V. costata)	0.20		22137	261	25910	27080	26440	620							yes	This study
4.85	Dsz-RC9	DeA-4629	shell (N. hammonis)	1.44		20828	73	24820	25450	25140	300							yes	This study
4.85	Dsz-RC9	DeA-4628	shell (E. fulvus)	0.20		21075	233	24750	25890	25370	560							yes	This study
4.85	Dsz-RC9	DeA-4627	shell (O. dolium)	1.74		21469	72	25610	25950	25780	160							yes	This study
4.85	Dsz-RC9	DeA-4630	shell (V. costata)	0.44		21540	150	25560	26090	25830	260							yes	This study
5.00	Dsz-3R	DeA-2071	shell (T. hispidus)			19656	76	23420	23950	23680	260							yes	This study
5.00	Dsz-3R	DeA-2070	shell (A. arbustorum)			20504	79	24370	25030	24690	340							yes	This study

5.15	Dsz-RC10	DeA-4626	shell (N. hammonis)	0.96		21719	95	25780	26140	25960	180							yes	This study
5.15	Dsz-RC10	DeA-4625	shell (E. fulvus)	0.34		22191	176	26030	26980	26450	480							yes	This study
5.15	Dsz-RC10	DeA-4624	shell (O. dolium)	2.84		22272	65	26200	26820	26500	300							yes	This study
5.45	Dsz-RC11	DeA-3743	shell (Succineidae sp.)	1.90		22280	104	26170	26950	26530	380							yes	This study
5.75	Dsz-RC12	DeA-3745	shell (O. dolium)	2.74		22708	101	26670	27360	27050	340							yes	This study
5.75	Dsz-RC12	DeA-3744	shell (Succineidae sp.)	1.77		22841	112	26890	27480	27200	280							yes	This study
6.00	Dsz-5R	DeA-2930	shell (T. hispidus)			22332	80	26270	26990	26610	360							yes	This study
6.00	Dsz-5R	DeA-2931	shell (Succineidae sp.)			23036	88	27140	27560	27360	200							yes	This study
6.25	Dsz-RC13	DeA-3746	shell (Succineidae sp.)	2.34		22848	110	26920	27480	27210	280							yes	This study
6.25	Dsz-RC13	DeA-3747	shell (E. fulvus)	0.97		22943	130	27010	27550	27280	280							yes	This study
6.50	Dsz-RC14	DeA-3748	shell (Succineidae sp.)	1.85		24311	135	27990	28690	28350	360							yes	This study
6.80	Dsz-RC15	DeA-3749	shell (Succineidae sp.)	1.24		24262	138	27940	28650	28300	360							yes	This study
7.10	Dsz-RC16	DeA-3750	shell (Succineidae sp.)	0.56		23349	163	27310	27810	27560	240							yes	This study
7.75	Dsz-RC18	DeA-3751	shell (Succineidae sp.)	1.32		26159	157	29930	30860	30450	460							yes	This study
8.00	Dsz-RC19	DeA-3752	shell (Succineidae sp.)	2.16		25187	141	28850	29600	29230	380							yes	This study
8.20	Dsz-Ch1	DeA-2918	shell (T. hispidus)			15844	56	18920	19290	19100	180			-10590	190	-11480	170	no	This study
8.20	Dsz-Ch1	DeA-2922	shell (V. crystallina)			25838	123	29600	30530	30060	480			-600	220	-1480	210	yes	Újvári et al. (2014)
8.20	Dsz-Ch1	DeA-2917	charcoal		ABA-OSC$_{1000}$	26433	178	30340	31030	30710	180	-890	240					yes	This study
8.20	Dsz-Ch1	DeA-2919	shell (Succineidae sp.)			26142	125	29990	30830	30460	400			-290	220	-1180	210	yes	Újvári et al. (2014)
8.20	Dsz-Ch1	DeA-2921	shell (Ch. tridens)			26851	118	30780	31170	30980	200			420	220	-470	200	yes	Újvári et al. (2014)
8.20	Dsz-Ch1	DeA-2920	shell (Clausiliidae sp.)			26979	126	30830	31240	31040	200			550	220	-340	210	yes	Újvári et al. (2014)
8.20	Dsz-Ch1	DeA-6596	charcoal	1.73	ABA-TSC$_{400}$	26726	142	30690	31130	30910	220	-590	220					yes	This study
8.20	Dsz-Ch1	DeA-6597	charcoal	0.81	ABA-TSC$_{800}$	27320	158	30990	31450	31220	220							yes	This study
8.20	Dsz-Ch1	DeA-6601	shell (D. ruderatus)			26010	148	29770	30730	30270	500					-1310	220	yes	This study
8.20	Dsz-Ch1	DeA-6602	shell (Clausiliidae sp.)			26954	151	30800	31240	31030	220					-370	220	yes	This study
8.20	Dsz-Ch1	DeA-6603	shell (E. fulvus)			25548	171	29210	30290	29710	540					-1770	240	yes	This study
8.20	Dsz-Ch1	DeA-6604	shell (T. hispidus)			26553	142	30560	31060	30810	240					-770	220	yes	This study
8.25	Dsz-Ch2	DeA-2923	charcoal		ABA-OSC$_{1000}$	25868	165	29580	30630	30100	270							yes	This study
8.25	Dsz-Ch2	DeA-2925	shell (Clausiliidae sp.)			26113	129	29930	30800	30420	420			250	210			yes	Újvári et al. (2014)
8.50	Dsz-RC20	DeA-3810	charcoal	0.52	ABA-OSC$_{1000}$	26015	320	29500	30890	30220	370							yes	This study
8.65	Dsz-RC21	DeA-3811	charcoal	0.89	ABA-OSC$_{1000}$	29547	537	32450	34760	33640	560							yes	This study

Profile 2														
8.50	Dsz/2sz-RC22	DeA-5943	charcoal	1.39	ABA-TSC$_{400}$	26139	162	29880	30850	30420	480	-1350	250	This study
8.50	Dsz/2sz-RC22	DeA-5944	charcoal	1.46	ABA-TSC$_{800}$	27492	179	31050	31590	31320	280			This study
8.90	Dsz/2sz-RC23	DeA-5945	charcoal	0.38	ABA-TSC$_{400}$	29063	449	31900	34060	33110	1080			This study
9.25	Dsz/2sz-RC24	DeA-5946	charcoal	0.22	ABA-TSC$_{800}$	31954	862	34430	38400	36220	2100			This study
9.80	Dsz/2sz-RC25	DeA-5947	charcoal	0.17	ABA-TSC$_{400}$	28813	776	31290	34370	32850	1640			This study
10.10	Dsz/2sz-RC26	DeA-5948	charcoal	0.57	ABA-TSC$_{400}$	31528	436	34630	36330	35470	900	-2260	780	This study
10.10	Dsz/2sz-RC26	DeA-5949	charcoal	0.45	ABA-TSC$_{800}$	33785	636	36470	39700	38110	1660			This study

All the ^{14}C dates are calibrated by OxCAL Online (version 4.2) using the IntCal13 calibration curve

[a] Calculated as ABA-OSC$_{1000}$ – ABA-TSC$_{800}$ or ABA-TSC$_{400}$ – ABA-TSC$_{800}$, rounded to the closest ten (or up in case of errors), errors propagated as

$$\sqrt{\sigma^2_{ABA-OSC1000\ or\ ABA-TSC400} + \sigma^2_{ABA-TSC800}}$$

[b] Calculated as ^{14}C age$_{shell}$ - ^{14}C age$_{charcoal\ (ABA\text{-}OSC1000)}$, rounded to the closest ten (or up in case of errors), errors propagated as

$$\sqrt{\sigma^2_{14C-age-shell} + \sigma^2_{14C-age-charcoal}}$$

[c] Calculated as ^{14}C age$_{shell}$ - ^{14}C age$_{charcoal\ (ABA\text{-}TSC800)}$, rounded to the closest ten (or up in case of errors), errors propagated as in b)

For definitions of the ABA-OSC$_{1000}$ and ABA-TSC$_{400/800}$ protocols see the 'Methods' section