Revisiting Early Medieval Chronologies: Radiocarbon dates reveal the origins and history of the Carolingian-age Great Moravian hillforts

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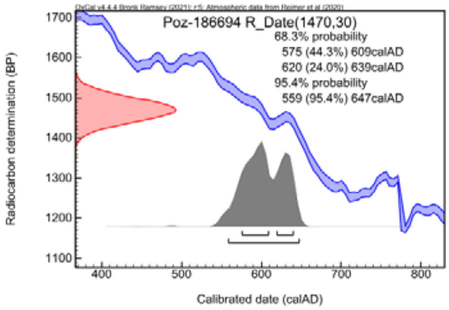
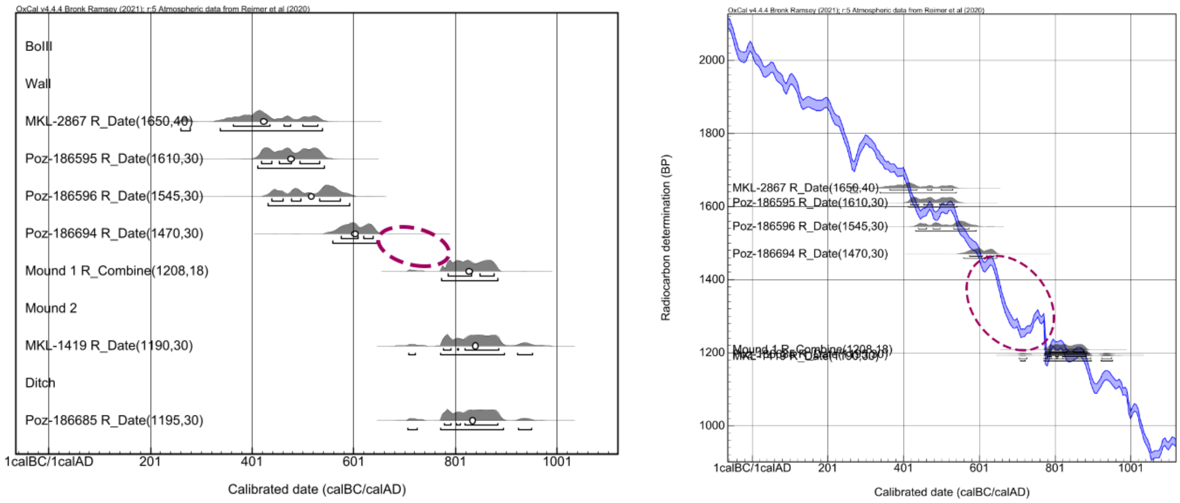
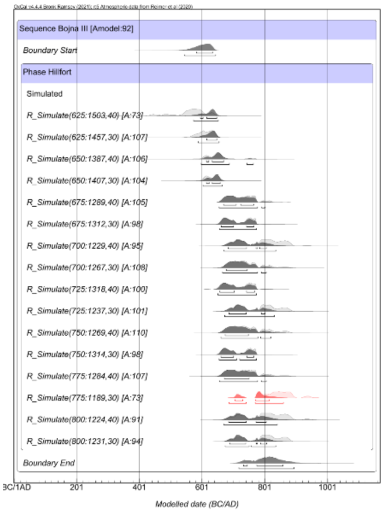
Supplementary material 1 – supplementary figures

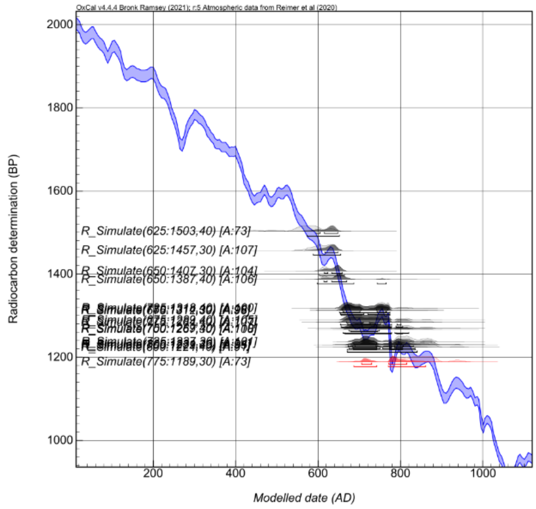


Supplementary Figure S1. Calibration of the radiocarbon date obtained from a sample collected from a concentration of pottery located adjacent to the inner face of the rampart at the Bojná III hillfort. This represents the latest radiocarbon date derived from the rampart and establishes the *terminus post quem* (TPQ) for the construction of the fortifications and the initial occupation of the site.



Supplementary Figure S2. The basic chronological model of the Bojná III hillfort. The "temporal gap" (absence of radiocarbon dates) between dates Poz-186694 and Mound 1 (indicated by the purple ellipse) does not reflect an archaeological hiatus but rather results from the current state of research. This period corresponds to the active use of the Bojná III hillfort.





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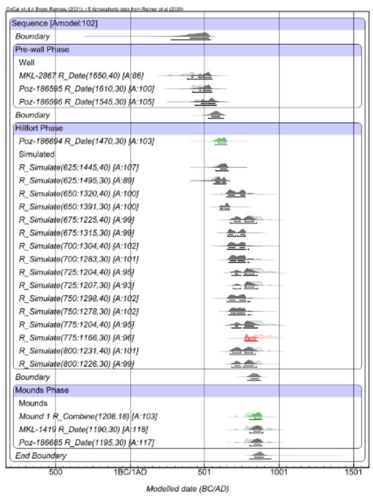
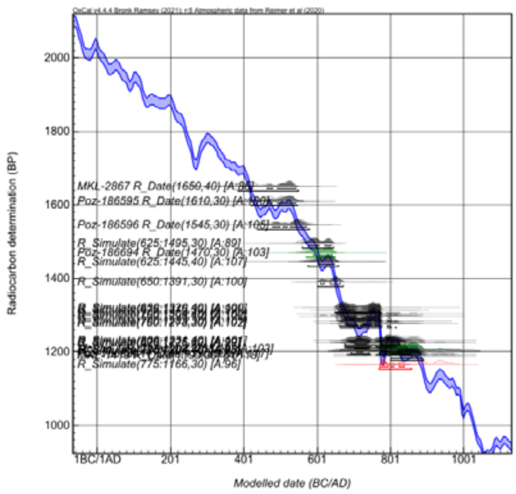
Supplementary Figure S3. Simulation of radiocarbon dates for the settlement phase of the Bojná III hillfort. These dates were used to construct a hypothetical chronological model of the site's development. A potential outlier is marked in red. The simulated date corresponding to AD 775 (1,189 ±30 simulated BP) is noticeably later than the dates associated with the barrow horizon. The simulated date for AD 625 (1, 503 ±40 simulated BP) approximates the age of the youngest samples obtained from the rampart.





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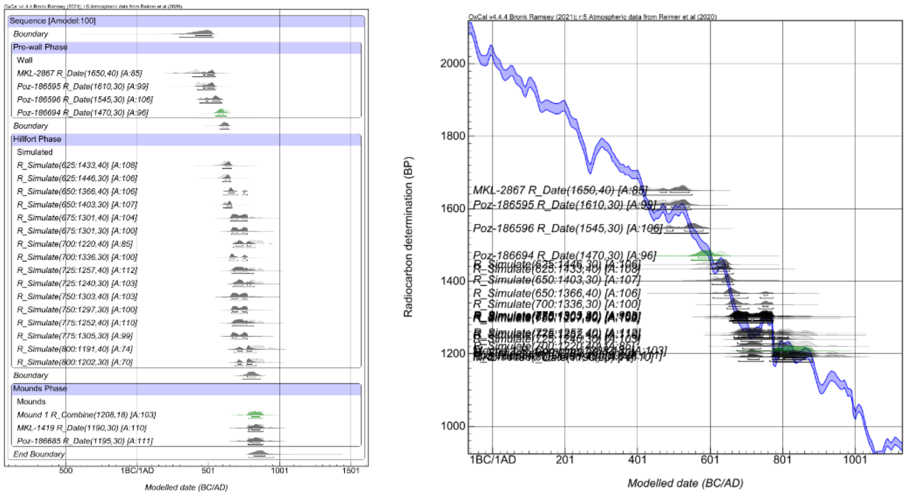

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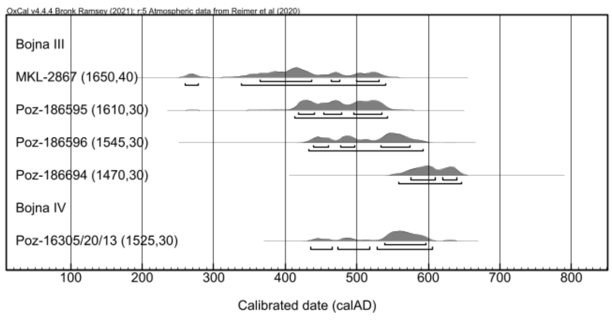
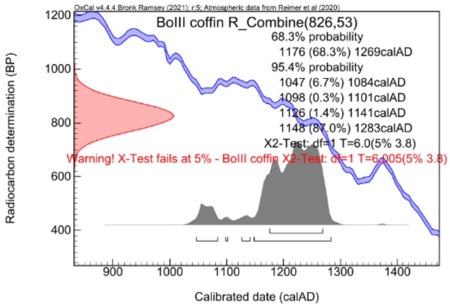
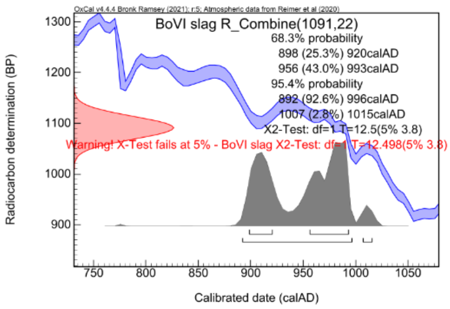
Supplementary Figure S4. Simulated test models of the settlement phase at the Bojná III hillfort. The green markers indicate actual boundary dates obtained from empirical samples. Red denotes dates that are technically accurate but weaken the model (notably AD 775), whose potential presence was already noted in the initial simulation. In the first model, the Poz-186694 sample—derived from charcoal found in association with a pottery concentration—was interpreted as belonging to the settlement phase. In the second model, it was considered an intrusive element related to activity predating the construction of the rampart. Both models are robust and allow for the establishment of a *terminus post quem* for the settlement phase between approximately AD 650 and 800. Dates younger than 1,240 ±30 BP must be approached with caution in future analyses, as they may accurately represent elements from either of the two phases: the settlement phase or the barrow horizon. The simulated dates are not identical across the two models, as the *OxCal* software performs separate simulations for each model.



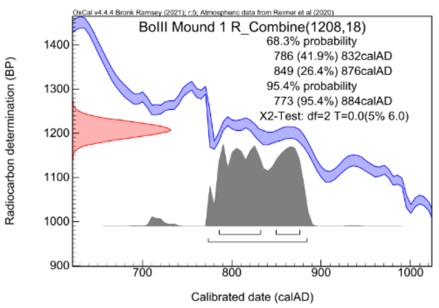
Supplementary Figure S5. Chronological model for the earliest radiocarbon dates from the Bojná III site, incorporating the calibrated date obtained from the rampart fill at the Bojná IV site (Poz-16305/20/13). This date establishes a *terminus post quem* for the construction of the rampart, which closely corresponds to the TPQ for the Bojná III rampart (after AD 600). As both sites form part of the same fortified complex, the inclusion of this individual date in the analysis is justified.



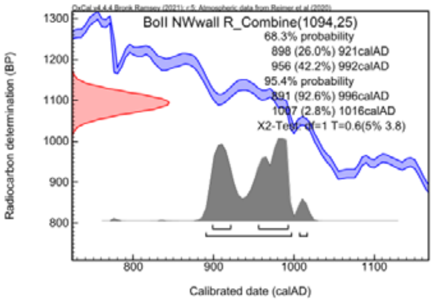
Supplementary Figure S6. Calibration of a combined radiocarbon date (R_Combine) for samples MKL-1430 (970 ±80 BP) and MKL-1701 (710 ±70 BP), both taken from an unburnt wooden plank forming part of a coffin in a female burial beneath Mound 2 at the Bojná III site. The discrepancy between the obtained BP dates is too great, and the combination fails the agreement test. The dating of the unburnt plank was deemed unreliable from the outset, due to inconsistencies with the archaeological context and with the radiocarbon date of sample MKL-1419 (1,190 ±30 BP), which was derived from charcoal from the same burial feature.



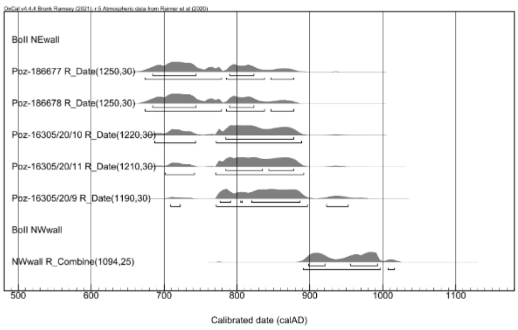
Supplementary Figure S7. Calibration of a combined radiocarbon date (R_Combine) for samples Poz-172271 (1,165 ±30 BP) and Poz-172245 (1,015 ±30 BP), both derived from slag collected from a furnace at the Bojná VI site. The discrepancy between the resulting BP dates is too substantial, and the combination fails the agreement test. Despite apparently reliable individual dates and low analytical uncertainty, the dating was deemed unreliable. Moreover, the radiocarbon determination of an additional sample, Poz-172257 (10,150 ±60 BP), yielded a clearly erroneous result. Therefore, slag cannot be considered a reliable material for radiocarbon dating within the context of this analysis.



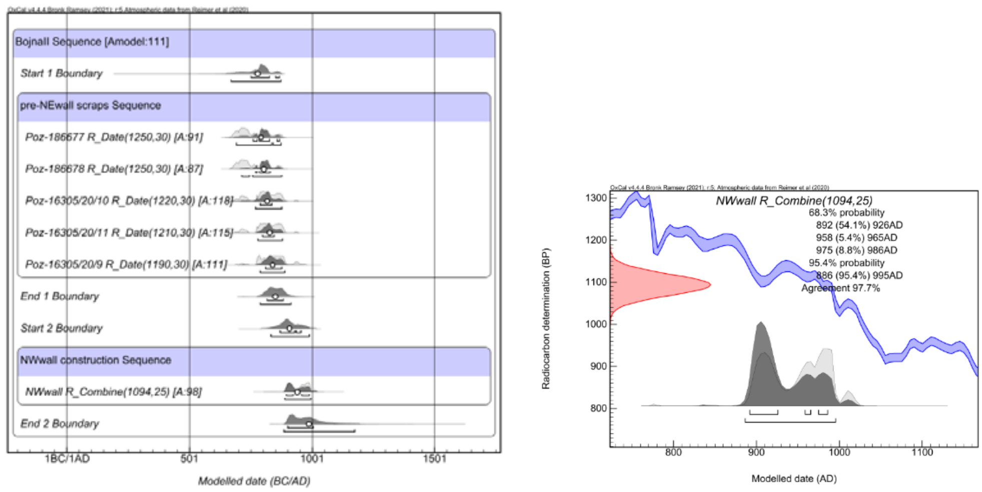
Supplementary Figure S8. Calibration of a combined radiocarbon date (*R_Combine*) for samples MKL-1418 (1,210 ±30 BP), MKL-1421 (1,210 ±30 BP), and Poz-186683 (1,205 ±30 BP), all derived from three charcoal samples collected from a burnt timber layer at the base of Mound 1 at the Bojná III site. The dates show perfect agreement.



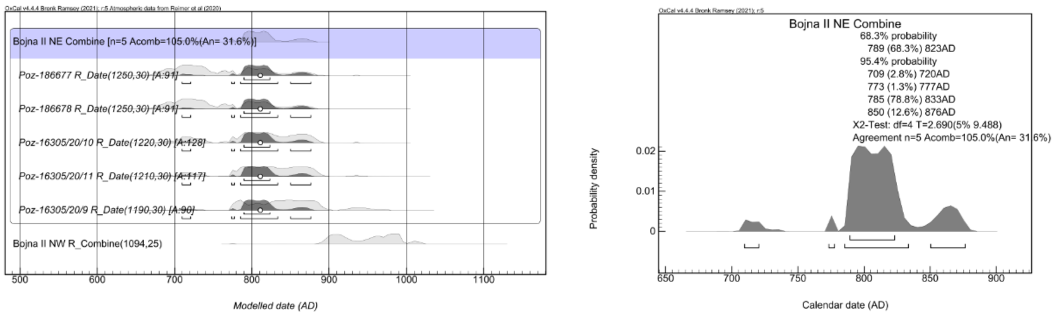
Supplementary Figure S9. Calibration of a combined radiocarbon date (*R_Combine*) for samples MKL-2357 (1,120 ±40 BP) and MKL-2356 (1,080 ±30 BP), both derived from a burnt structural element of the rampart, found at the bottom of the north-western ditch of the rampart at the Bojná II hillfort.



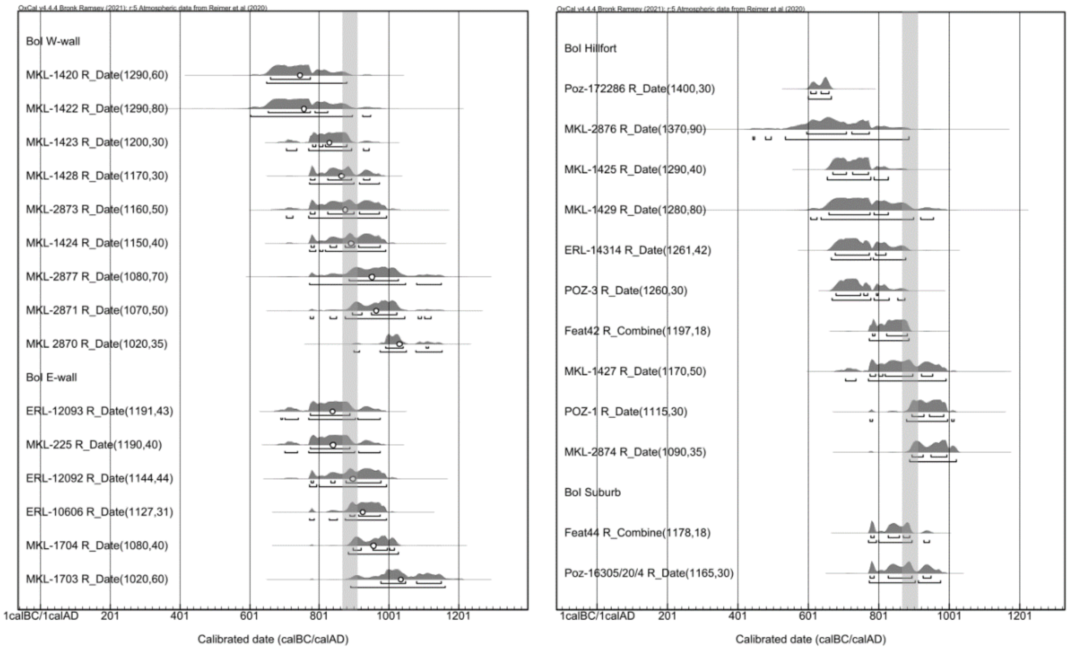
Supplementary Figure S10. Basic chronological model for the Bojná II hillfort. The calibrated date for the north-western rampart was obtained through the combination (*R_Combine*) of radiocarbon dates derived from structural elements found at the bottom of the ditch (Fig. S9).



Supplementary Figure S11. Test model of the chronological phases of the Bojná II hillfort. It constrains the duration of the earlier phase to the 9th century and suggests with increased probability that the rampart was constructed at the turn of the 9th and 10th centuries (b). This supports chronological observations previously derived from the site's archaeological investigation. However, these archaeological observations were not incorporated as modifiers in the model.



Supplementary Figure S12. Test model of the chronological phases of the Bojná II hillfort, assuming the existence of an earlier rampart phase or an earlier construction of the north-eastern section (hypothetical event μ = AD 810). The agreement index (An = 31.6%) indicates some inconsistencies within the model and sits precisely at the threshold of acceptability (for A5 = 31.6%). Although the model does not differ substantially from the initial test model and passes the agreement test, there remains a considerable gap between the earliest and latest radiocarbon dates.



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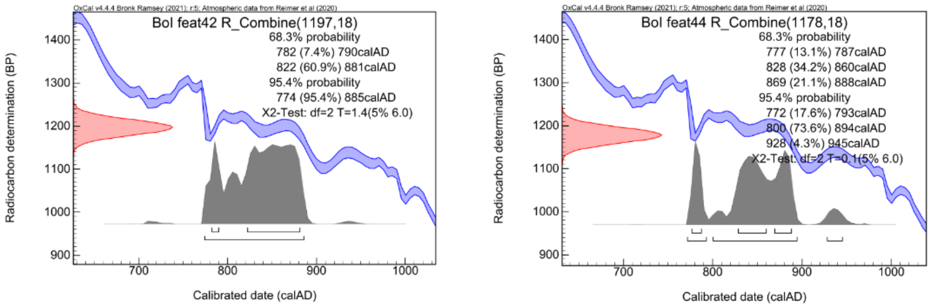
Supplementary Figure S13. Basic chronological model of the Bojná I hillfort. Radiocarbon dates obtained from the rampart (a) and from archaeological features (b) are presented separately. The grey bar indicates the range of dendrochronological dates obtained for the rampart construction (after AD 866 – after AD 908). Combined dates from individual features are detailed below. The clusters group similar date ranges, generally falling between the 6th and 11th centuries, except in the Suburbium area, where the dates are significantly later. This discrepancy may result from a smaller and less diverse sample set.



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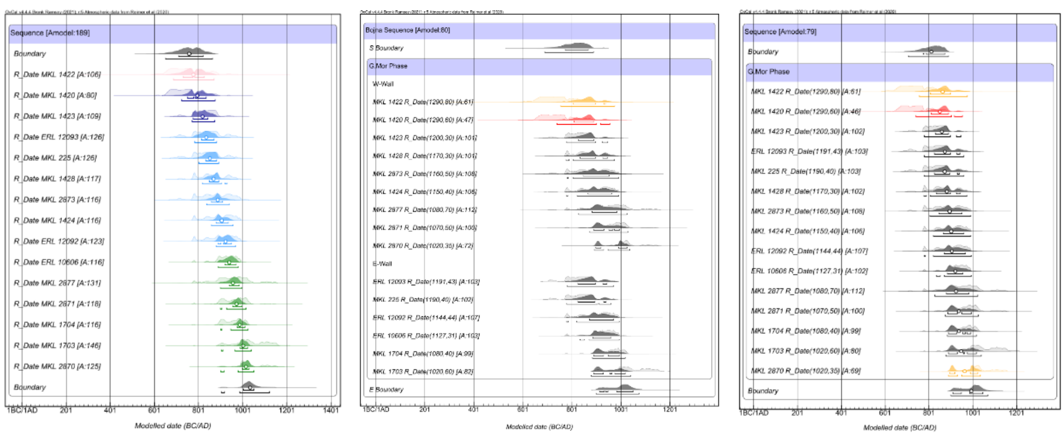
Supplementary Figure S14. a. Calibration of a combined radiocarbon date (R_Combine) for samples Poz-186597 (1,225 ±30 BP), Poz-16305/20/1 (1,185 ±30 BP), and Poz-91031 (1,180 ±30 BP), derived from two charcoal samples collected from Feature 42 (“sunken house no. 8”) at the Bojná I site. The dates Poz-16305/20/1 and Poz-91031 originate from the same sample and exhibit near-perfect agreement. **b.** Calibration of a combined radiocarbon date (R_Combine) for samples Poz-16305/20/8 (1,185 ±30 BP), Poz-16305/20/2 (1,175 ±30 BP), and Poz-16305/20/7 (1,175 ±30 BP), obtained from three charcoal samples collected from Feature 44 (sunken house) at the Bojná I *suburbium*. The dates demonstrate near-perfect consistency.



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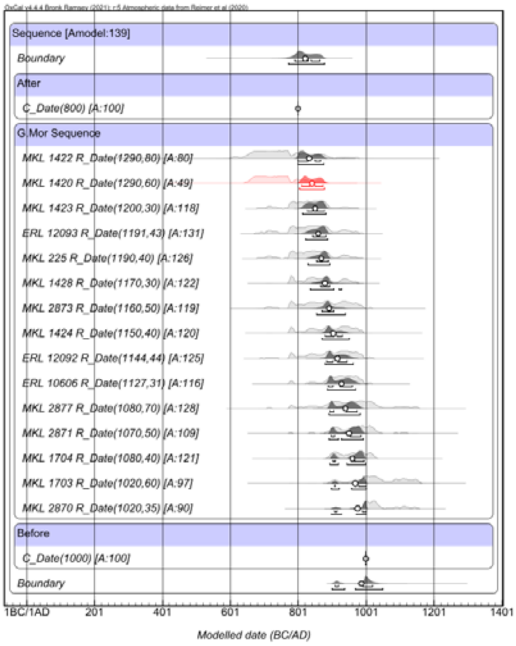
Supplementary Figure S15. Chronological sequences of rampart elements. The first model (a), a non-Bayesian approach, assumes a depositional sequence of rampart construction elements based on their function and position within the structure (pink – elements likely belonging to an earlier phase; dark blue – load-bearing elements; blue – internal structural components; green – external structural components and outer wattlework). The model, as indicated by a high Amodel value (>150), may be overly consistent, likely due to the absence of imposed chronological constraints. As a result, the duration of rampart construction appears unrealistically extended, contradicting archaeological and dendrochronological evidence.

The second model (b) assumes that all dated events belong to a single construction phase (the division into “W” and “E” sections has no impact on the model’s outcome). A clear outlier (MKL-1420), representing a significantly older element, is marked in red (A’c = 47). An additional element, dated similarly and weakening the model but not yet an outlier (A’c < 60%), is marked in orange. Sample MKL-1422, while early, is considered valid: its leading position in the sequence corresponds to its stratigraphic location, although the early date may reflect the use of old wood.

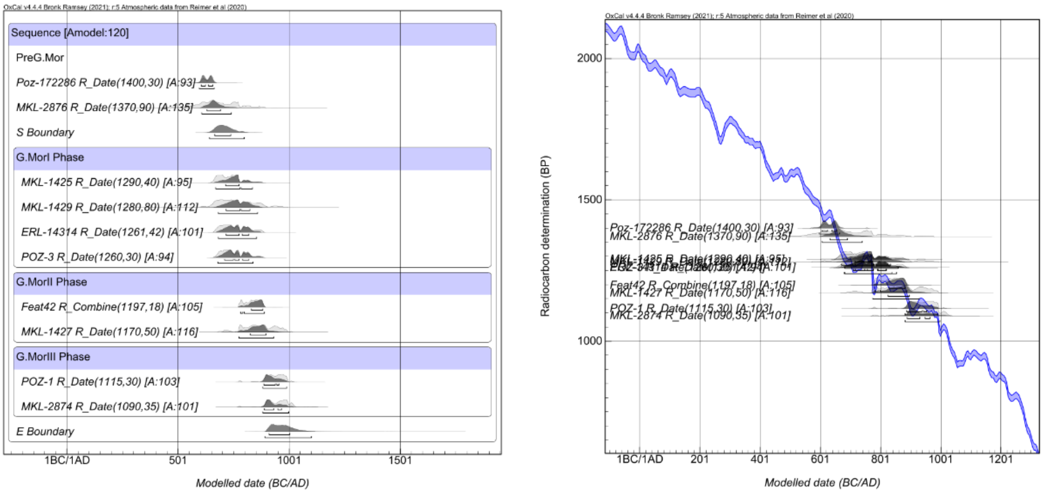
The third model (c) combines the assumptions of both previous models. Both models (b) and (c) yield Amodel values below 100, suggesting that single-phase interpretations are insufficient and that improved, more nuanced modelling (multi-phased) should be pursued.



Supplementary Figure S16. Chronological sequence of samples collected from the rampart of the Bojná I hillfort. The model assumes the construction and use of the rampart between AD 800 and 1000—an assumption overlooked by previous models. Elements that weaken the model are highlighted in red and have been further analysed. Samples MKL-1422 and MKL-1420 may indeed originate from earlier structures, potentially remnants of a preceding phase of fortification. While high dating uncertainty may be a factor, both appear to be genuinely older.

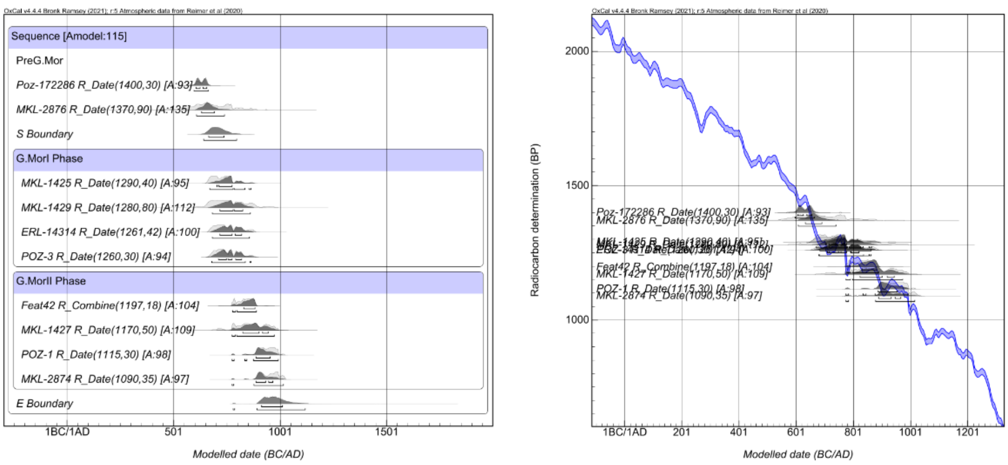
Sample MKL-2870 is classified as a "valid outlier." Its final position in the sequence aligns with its stratigraphic context, yet its date is anomalously recent, potentially reflecting specific properties of the sample. However, its modelled mean date (μ = AD 975) raises significant doubts regarding its young age. A similar observation applies to sample MKL-1703.

The model demonstrates the necessity of phase-based modelling of the rampart material and challenges the validity of arbitrarily excluding dates that suggest pre-AD 800 construction.

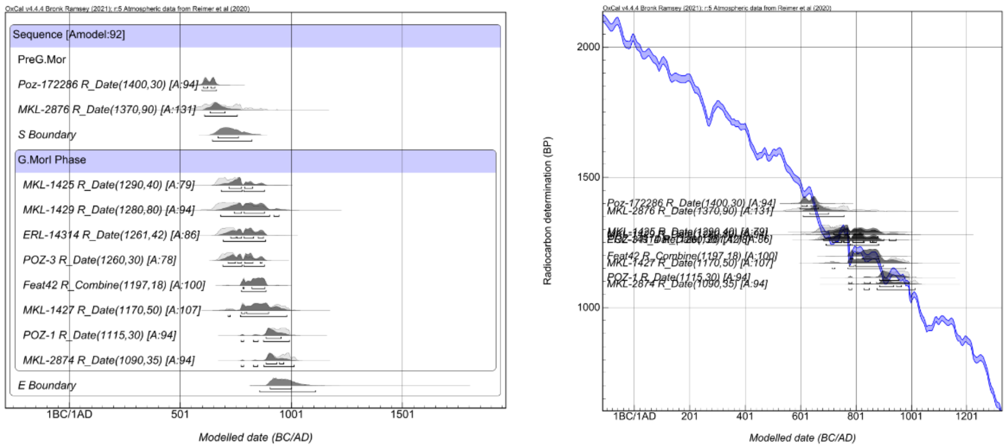


Supplementary Figure S17. Test Model 1 for scattered charcoal samples from archaeological features, assuming three phases of settlement activity at the Bojná I Valy site. The phases were defined based on the identification of distinct gaps within the data clusters. The phase labelled *preG.Mor.* was not temporally constrained. The dates Poz-172286 (1,400 ±30 BP) and MKL-2876 (1,370 ±90 BP), derived from feature fills, were interpreted as incidental contaminants—at best, indicating sporadic human presence and providing a *terminus post quem* for the onset of intensive settlement. Additionally, the MKL-2876 sample originates from a deliberately backfilled feature situated in a subpositional relationship to the hillfort's settlement layer.

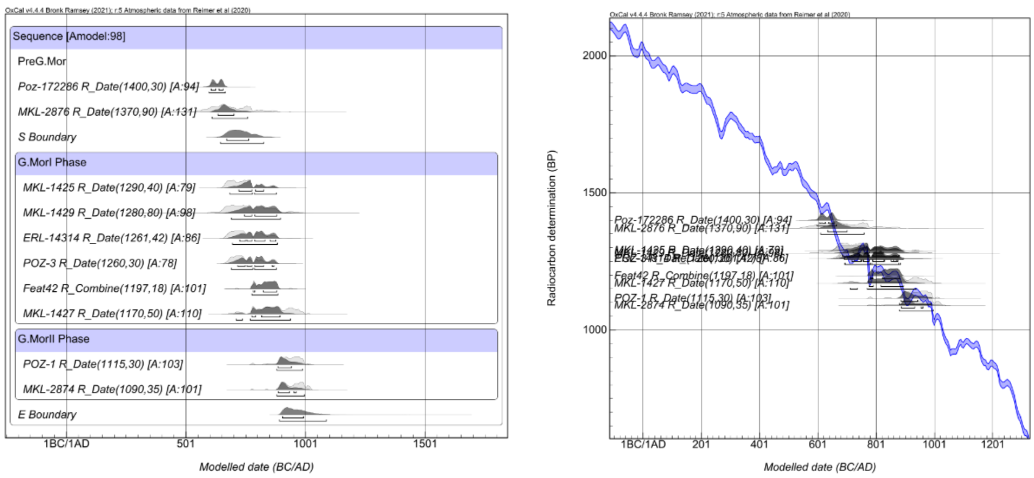
The earliest dates in the sequence are nearly identical to those initiating the sequence of samples obtained from the fortifications. Transitions between the phases are fluent (hence no *Boundary* modifier was used) and were defined arbitrarily. While the phases are hypothetical, they are supported by patterns observed in the artefactual assemblage and archaeological interpretations.



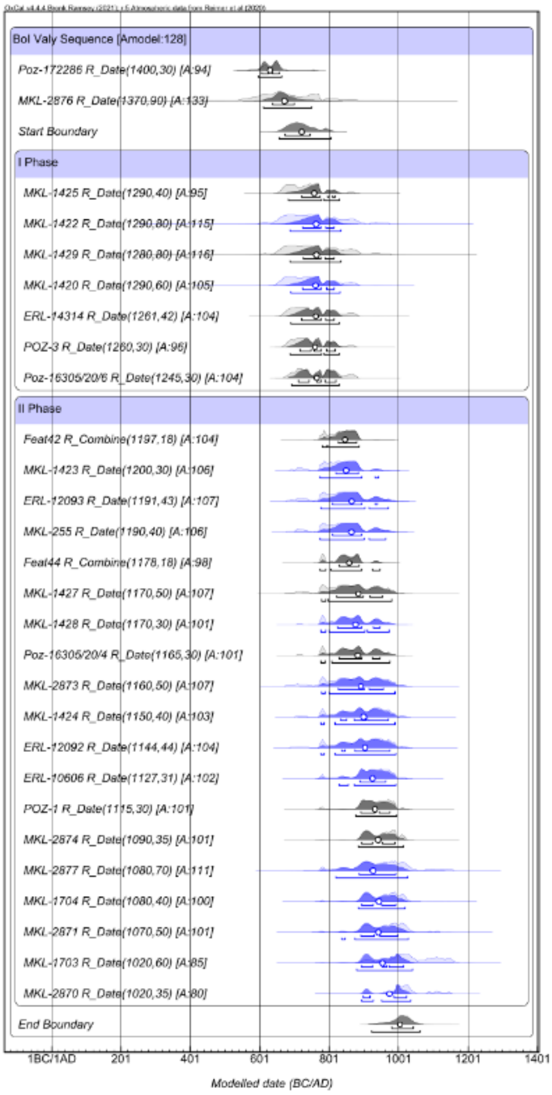
Supplementary Figure S18. Test Model 2 for scattered charcoal samples from archaeological features, assuming two phases of settlement activity at the Bojná I Valy site. All other assumptions are identical to those in Model 1. The model is acceptable; however, it clearly exhibits a tendency to subdivide the G.MorII phase into smaller units—a pattern more distinctly demonstrated in Test Model 1.



Supplementary Figure S19. Test Model 3 for scattered charcoal samples from archaeological features, assuming a single settlement phase at the Bojná I Valy site. All other assumptions follow those outlined in Model 1. This model is the weakest of the three (Amodel: 92) and provides a poor explanation of the settlement chronology. The extended single-phase structure contradicts archaeological observations. Moreover, the model clearly indicates the necessity of defining a phase transition around AD 900.



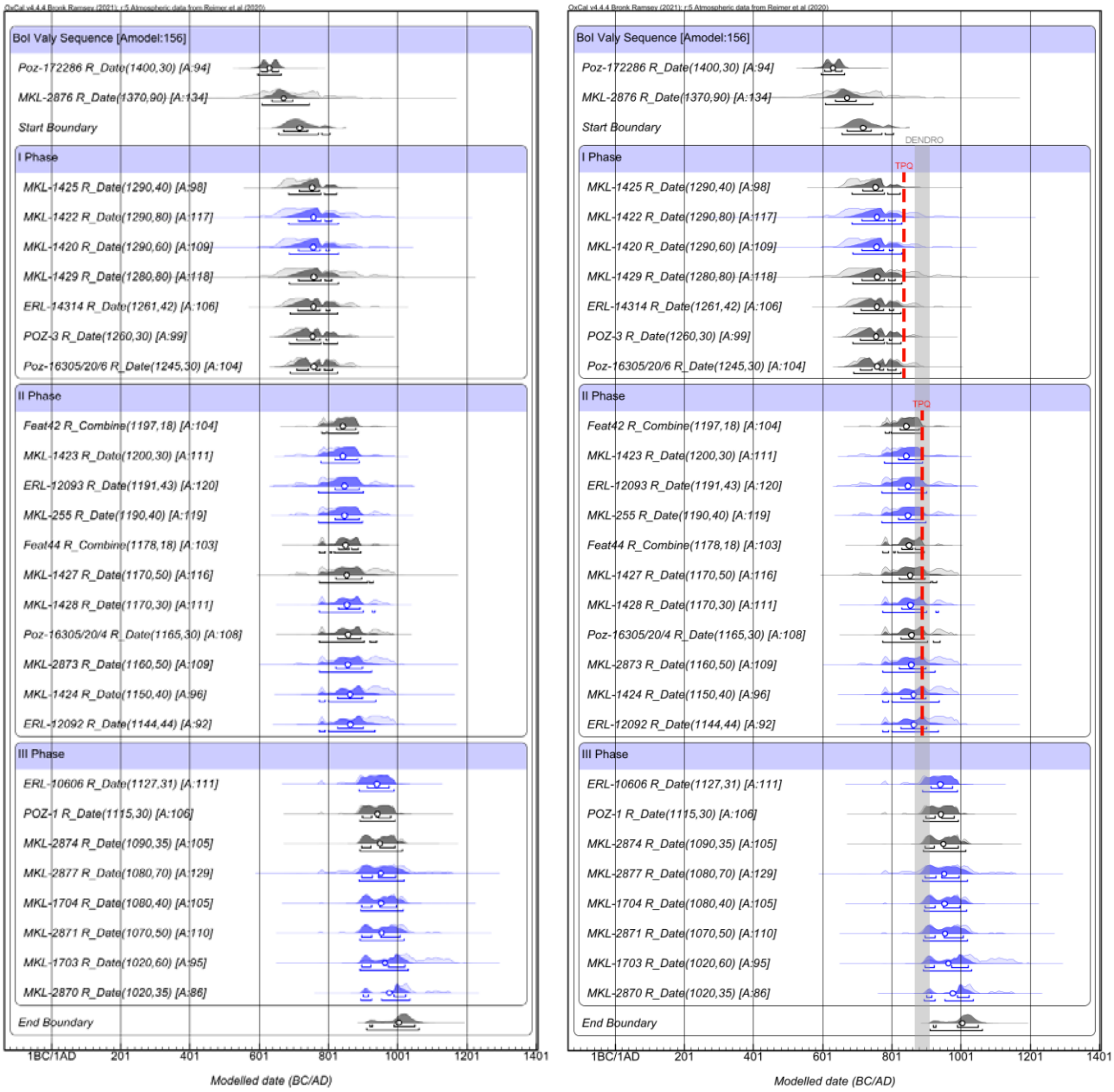
Supplementary Figure S20. Test Model 4 for scattered charcoal samples from archaeological features, assuming a prolonged initial settlement phase preceding a terminal transition at the Bojná I Valy site. All other assumptions are consistent with those in Model 1. While the model is acceptable, it provides a weak explanation for the chronology of early settlement at the site. Any hypothetical occupation predating the turn of the 8th and 9th centuries is not supported by the results of archaeological investigations.



Supplementary Figure S21. Test Model 1 for the complete set of radiocarbon data from the Bojná I site. The starting point for the phases was defined by the *terminus post quem* (TPQ) of the fill of the oldest stratigraphically identified feature (sample MKL-2876). The phase transition was arbitrarily placed at the interval with no radiocarbon dates (1,245 ±30 – 1,200 ±30 BP). Samples derived from rampart construction elements are marked in blue.

The model is valid, but it does not clearly pinpoint the moment of rampart construction (ca. AD 890), and Phase II is overly homogenised, which fails to resolve key research questions. Moreover, Phase I is based primarily on data from feature fills and rampart elements identified as "old wood" (MKL-1422 and MKL-1420), which likely entered the archaeological context later than the Phase I chronology suggests.

In effect, the model reflects the general chronology of the Bojná I hillfort rather than a nuanced reconstruction of its occupational and constructional history.

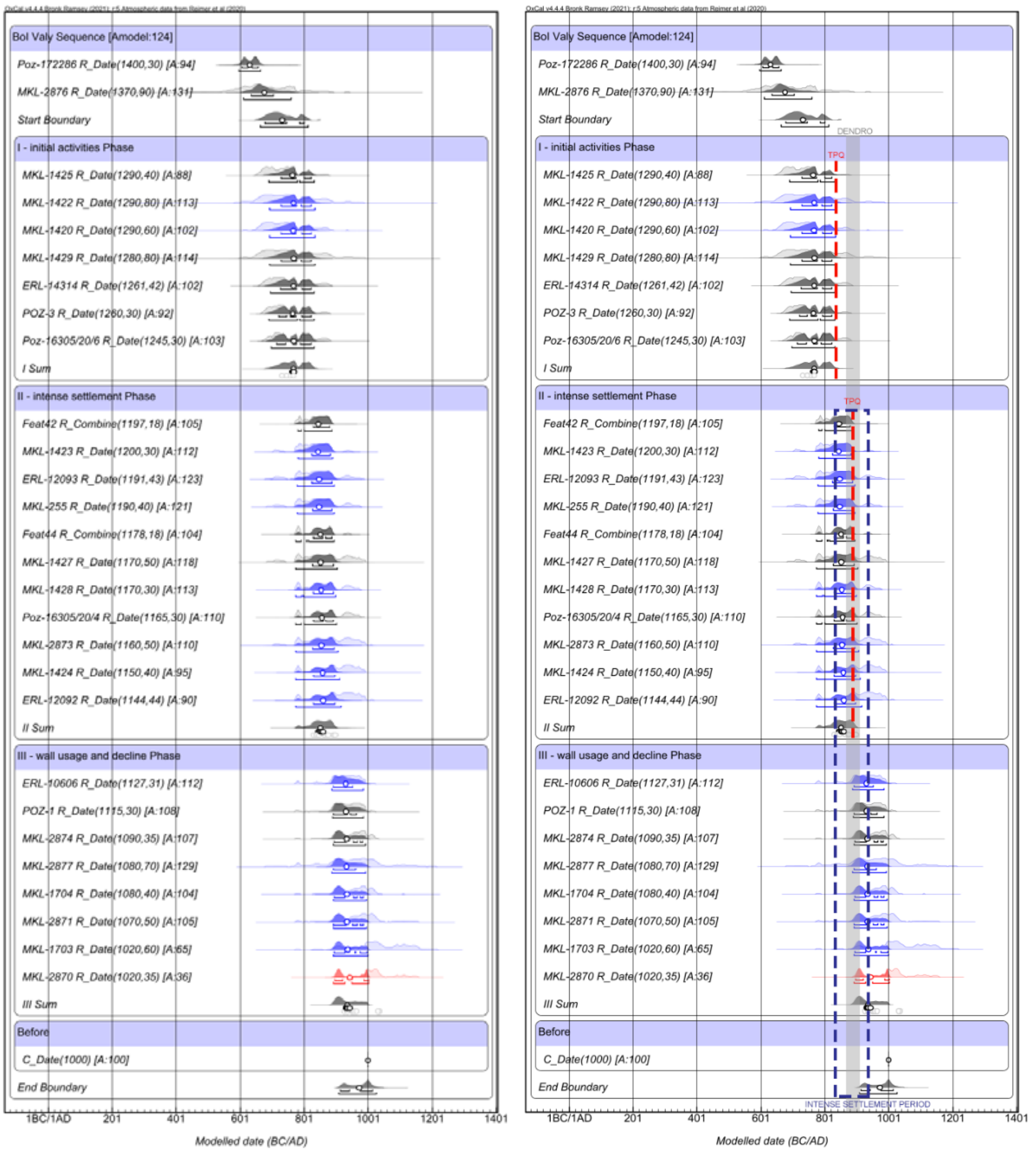


Supplementary Figure S22. Test Model 2 for the complete set of radiocarbon data from the Bojná I site, incorporating the assumptions and interpretative conclusions drawn from Model 1. Samples originating from rampart construction elements are marked in blue. Phase transitions were defined arbitrarily as follows: the transition between Phases I and II corresponds to the absence of radiocarbon dates for the period 1,245 ±30–1,200 ±30 BP, while the transition between Phases II and III is marked by the earliest date obtained from the outer face of the rampart (ERL-10606), which relates to a structural element that must have been constructed during the site's final phase of use.

Phases I and II define *termini post quem* (TPQ) for the use or deposition of the sampled materials (indicated by the red dashed line). Samples ERL-14314 (animal tooth) and POZ-3 (grain) derive from short-lived organisms, and thus are unlikely to be affected by inbuilt age or extended use. Their radiocarbon determinations can therefore be considered approximate reflections of actual chronological events.

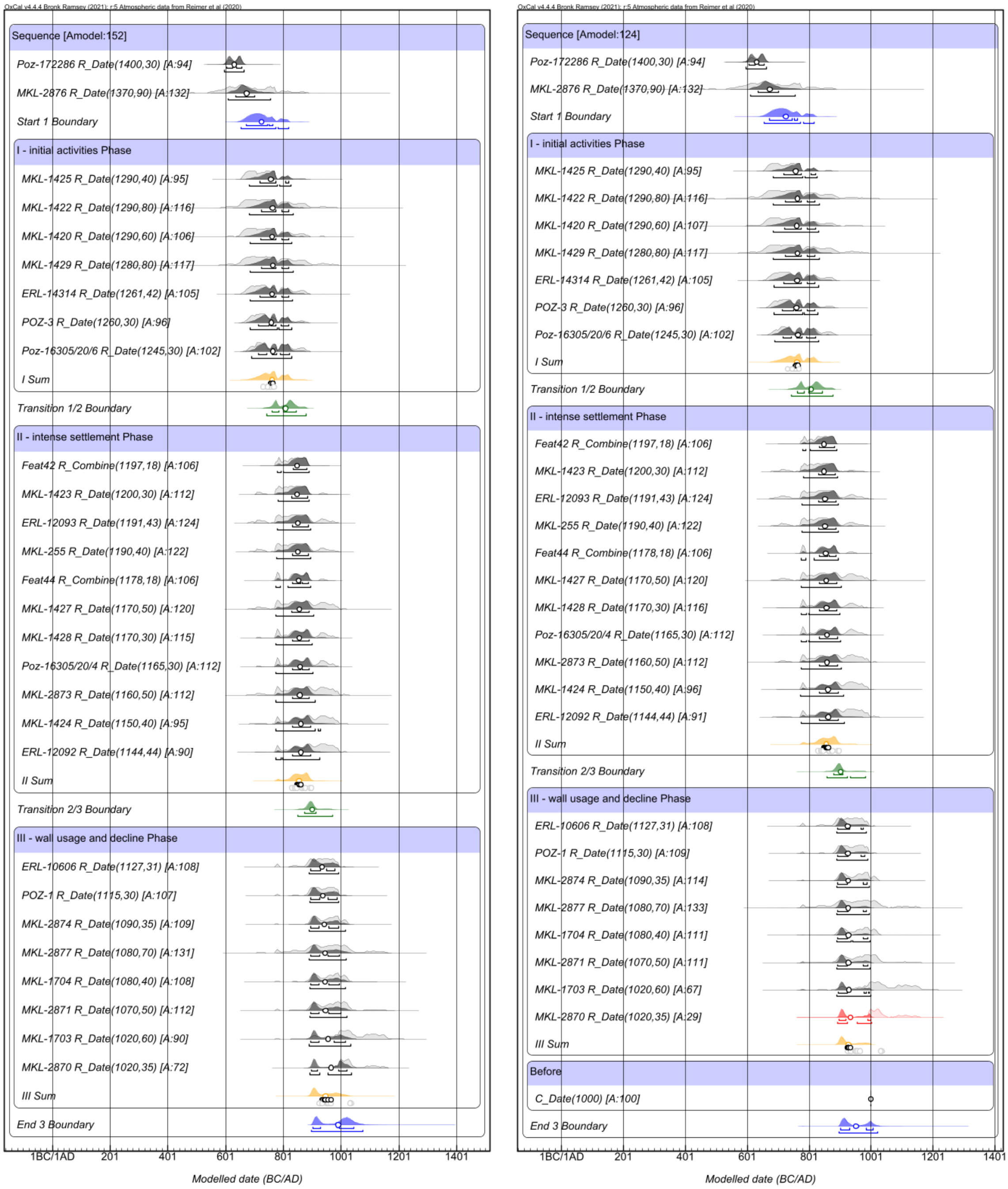
Consequently, elements associated with Phase I—such as objects and "old wood"—were likely deposited during Phase II. Elements attributed to Phase II were either in use (in the case of the rampart) or deposited (as archaeological features) during Phase III. Only Phase III, which is based almost exclusively on construction elements from the external face of the rampart (i.e. made from freshly felled wood), corresponds chronologically to the active use and abandonment of the fortification. This interpretation is further supported by sample MKL-2874, obtained from the upper part of the settlement layer.

The absence of clearly defined phase boundaries (*Boundary*) reflects the archaeological reality—namely, continuous occupation and the lack of evident hiatuses—but is likely the cause of overfitting, as indicated by the high Amodel value (>150). The grey bar represents the dendrochronological dating range of the rampart elements (after AD 866 – after AD 908).



Supplementary Figure S23. Test Model 3 for the complete set of radiocarbon data from the Bojná I site, incorporating the assumptions and interpretations of the previous models. This model additionally assumes that the definitive end of settlement activity at the site occurred before AD 1000. Samples derived from rampart construction elements are marked in blue. A red marker denotes an outlier which weakens the model but represents the youngest securely dated structural element of the rampart.

The transition between Phases II and III corresponds to the period of rampart construction. The modelled mean dates (μ = AD 835–850 and AD 918–932) may represent, respectively, the beginning and end of the intensive settlement phase, indicated by the blue dashed line. All other notations are consistent with those in the figure above.



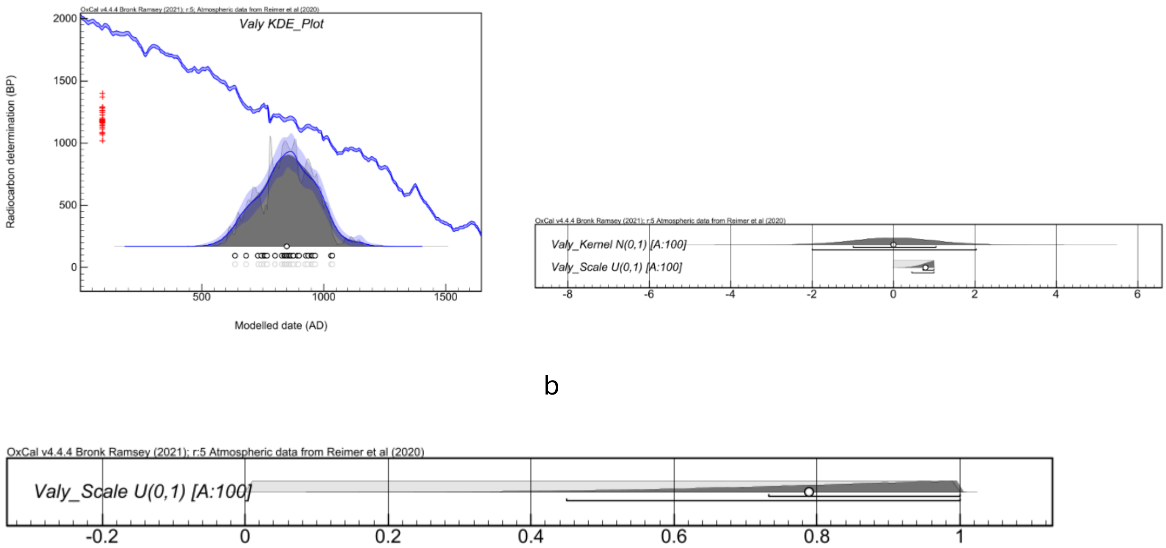
Model A	Model B

Supplementary Figure S24. Models for the complete set of radiocarbon data from the Bojná I site, incorporating the assumptions and interpretations derived from the test models. Both models assume a phased development of the site with gradual transitions between phases, without clear archaeological hiatuses. Model A appears to be overfitted (Amodel > 150), indicating that further constraints could be introduced to improve interpretive clarity. In Model B, an additional assumption was made: the definitive end of settlement activity at the site occurred before AD 1000.

Outliers weakening the model—but representing structural elements of the rampart—are marked in red. Their exclusion results in only minimal changes to the overall model. The "Sum" function, highlighted in yellow, indicates the highest probability for the occurrence of any event within a given group.

The transition between Phases I and II corresponds to the onset of occupation at the site. The transition between Phases II and III closely mirrors the period of rampart construction (μA = AD 900; μB = AD 901). Model B aligns well with archaeological observations and may serve as a useful framework for guiding future field investigations.

In the final model (Fig. 4), the end of rampart use was constrained to no later than AD 950.



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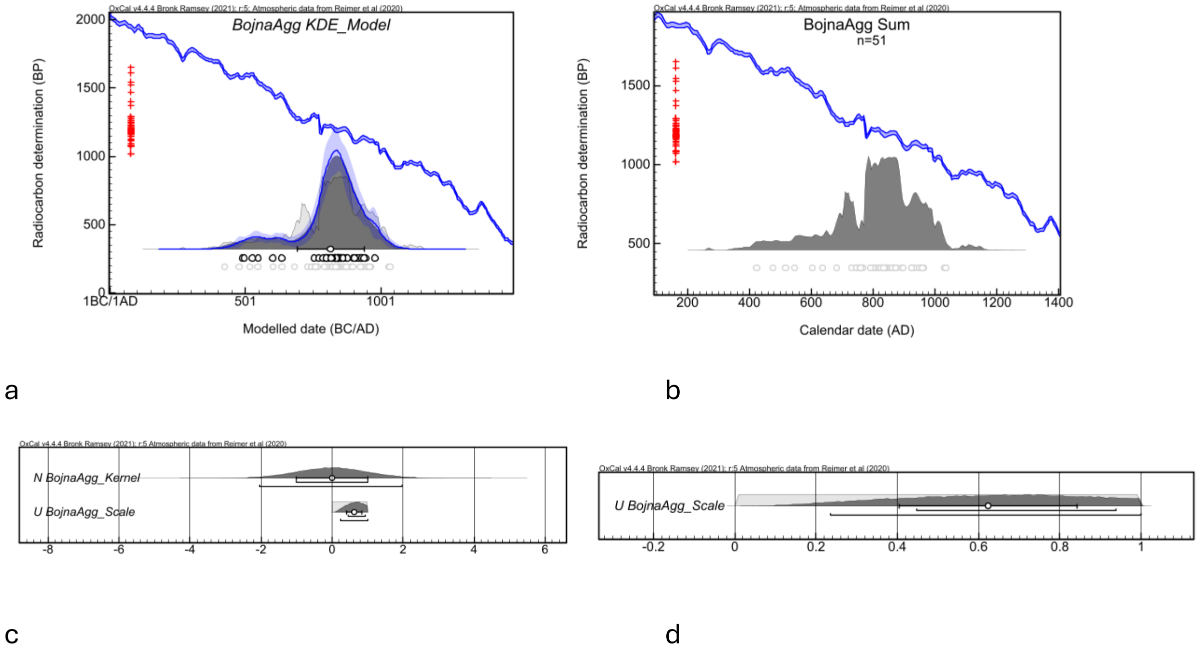
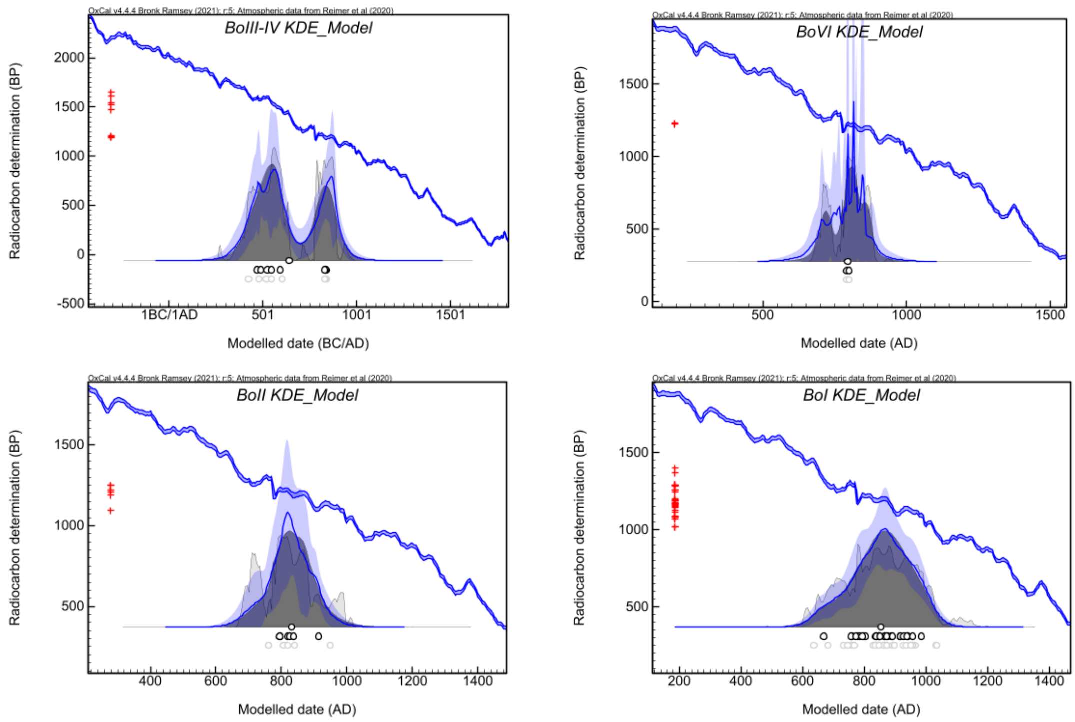
Supplementary Figure S25. KDE_Plot model for the radiocarbon data from the Bojná I hillfort (a).

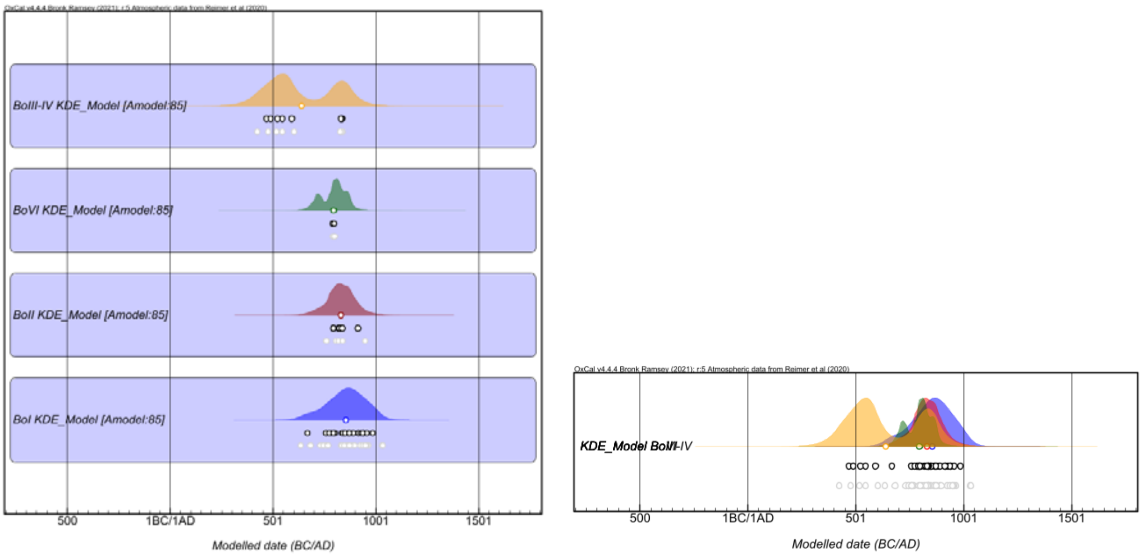
The dark grey distribution represents the sampled KDE estimate. The blue line and surrounding light blue band show the mean ±1σ, based on KDE snapshots generated during the MCMC process, providing an indication of the robustness of any features. For comparison, the light grey distribution above shows the *Sum* distribution.

The near-perfect normal distribution of the data (b) reflects the short chronological span of the dataset and limits the potential for detailed interpretation. Compared to a Bayesian model, the KDE model does not yield satisfactory results. The marginal posterior distribution (i.e. the probability density for a single date after modelling) is extremely narrow and concentrated (≈1), which can dominate the KDE result, producing an artificial "peak" and distorting the overall distribution (c).



Supplementary Figure S26. KDE model for the complete set of radiocarbon data (n = 51) from sites comprising the Bojná agglomeration, as listed in Supplementary Table S1. The peak of the density distribution occurs around AD 840, which can be attributed to the chronological overlap of all sites in this period (see Supplementary Figure S27) and to the overrepresentation of samples from the Bojná I site. Notably, the KDE model does not confirm a secondary peak around calAD 720, which would otherwise be suggested by the summed probability distribution. This absence is consistent with archaeological observations indicating a lack of datable events from this period (see Supplementary Figures S2 and S28).





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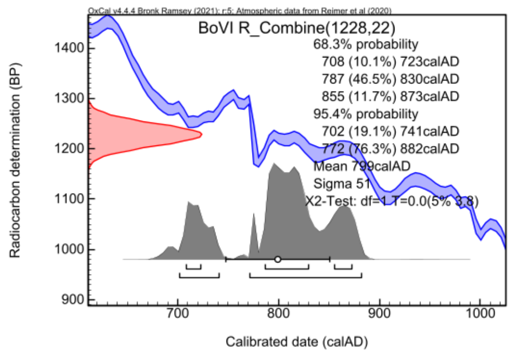
Supplementary Figure S27. KDE models for radiocarbon data from sites within the Bojná agglomeration. Only the model for the Bojná III–IV site reflects the archaeologically observed phasing (Wall and Mounds).



Supplementary Figure S28. Calibration of a combined radiocarbon date (R_Combine) for samples POZ-4 (1225,30 BP) and Poz-172285 (1, 230 ±30 BP), originating from two burial mounds at the Bojná VI site. The averaged date for both burials (calAD 799 ±51, 1σ) is consistent with archaeological observations. The apparent peak in the probability density curve around calAD 720 is most likely an artefact of the calibration curve rather than a reflection of the archaeological reality, as the burial material provides no basis for assigning the interments to the early 8th century.