Calibration of ^{14}C dates using biological kinship

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Zusammenfassung

Die Kalibrierung von ^{14}C-Datierungen unter Verwendung von biologischer Verwandtschaft

Die Bestimmung des absoluten Alters mithilfe der ^{14}C-Datierung ist ein unverzichtbarer Bestandteil der Archäologie geworden. Als eine der wichtigsten physikalischen Datierungsmethoden wird sie ständig verbessert, sodass heutige AMS-Geräte (Beschleunigermassenspektrometer) weitaus präzisere Datierungen liefern als in der Vergangenheit. Die Präzision einer Datierung ist heute hauptsächlich durch die Kalibrierung eingeschränkt, d. h. die Übersetzung eines ^{14}C-Alters in ein Kalenderdatum. Daher kann ein höchst präzises ^{14}C-Alter wegen der Struktur der relevanten Kalibrierungskurve manchmal mehrere, weitreichende Datierungsspannbreiten hervorbringen. Dennoch können in Fällen, bei denen relative chronologische Information mit ^{14}C-Altersangaben verknüpft werden – wie etwa bei der Datierung von Individuen mit bekannten Familienverwandtschaften – diese relativchronologischen Hinweise zu präziseren Kalibrierungen und ^{14}C-Datierungen führen. In allen diesen Fällen, wo eine bayesianische Modellierung durchgeführt wird, sind die modellierten ^{14}C-Datierungen weitaus genauer als die unkontextualisierten. Eine Verkürzung der kalibrierten Datierungspannen um 40–70 % kann bei gleichzeitiger Beibehaltung ihrer Genauigkeit erreicht werden.

Summary

The determination of absolute dates with the help of ^{14}C dating has become an indispensable part of archaeology. As one of the most important physical dating methods, it is constantly being improved, so that today's modern AMS devices (Accelerator Mass Spectrometer) provide significantly more precise analytical data than in the past. The precision of a date today is mainly limited by the calibration, i.e., the translation of a ^{14}C age into a calendar date. Thus, a single highly precise ^{14}C age can sometimes yield several broad dating spans due to the structure of the relevant calibration curve. However, in cases where relative chronological information can be linked with ^{14}C ages – such as dating individuals with known family relationships – these relative chronological clues can lead to more precise calibrations and ^{14}C dates. In all cases where Bayesian modeling is performed, the modeled ^{14}C dates are significantly more constrained than the individual uncontextualised dates. A narrowing of the calibrated date ranges by 40–70 % can be achieved, while still maintaining accuracy.

Introduction

Radiocarbon dating was conceived and introduced in the 1940s as the first absolute dating technique and has revolutionised our understanding of the past when applied in archaeological research. In many other fields of research such as geochemistry, solar science and climate research, this methodology has also pushed our understanding of system earth to new limits. Since its introduction, radiocarbon dating has been continually developed. Sample preparation procedures have been developed in many laboratories to such an extent that nowadays basically all types of samples of interest for archaeologists can be analysed. The analytical techniques used for radiocarbon dating have virtually entirely moved over from the use of counting techniques to accelerator mass spectrometers (AMS), which deliver very high precision on very small sample sizes of a few grams for bone samples or milligrams for other materials. However, despite this progress, radiocarbon dating has limitations that are not related solely to analytical and laboratory aspects. The main limitation, which is inherent to radiocarbon dating, is the radiocarbon calibration.

The result of a ^{14}C analysis is a conventional radiocarbon age. Instead of providing the researchers with pure ratios of the carbon isotopes ^{14}C, ^{12}C and ^{13}C, which is essentially the outcome of the analysis, conventional radiocarbon ages are calculated and reported by all laboratories. The word »conventional« emphasizes the fact that those radiocarbon ages are calculated using certain conventions that allow us to use such dates, no matter which laboratory has produced them or when they were produced. However, some of these conventions are not fulfilled in nature so that a conventional radiocarbon age does not represent a true calendar date. In order to provide calendar dates, radiocarbon ages must be calibrated, for example using materials such as wood samples, which can be dated with alternative methods such as dendrochronology and thus yield ^{14}C ages. As early as the 1960s the first datasets were compiled of those pairs of

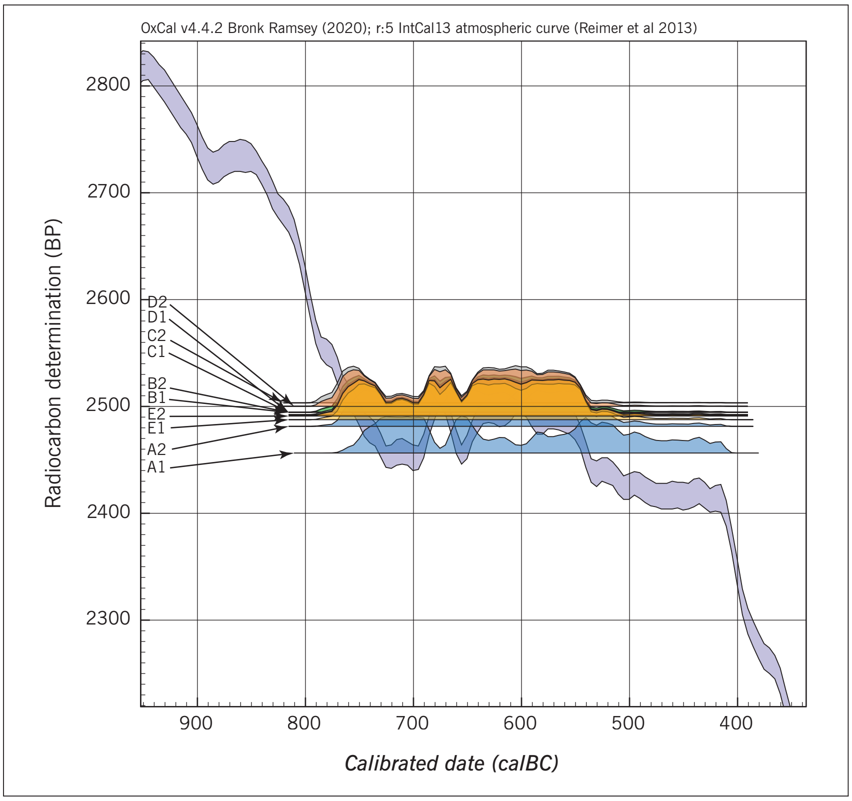

Fig. 1 A plateau-rich calibration curve (Hallstatt plateau). The calibrated ^{14}C dates of all individuals overlap to a degree where no distinction is possible. The labels on the left marked with arrows indicate the individuals as shown in Fig. 6.

Abb. 1 *Eine plateaureiche Kalibrierungskurve (Hallstattplateau). Die kalibrierten ^{14}C-Daten aller Individuen überlappen sich so weit, dass zwischen ihnen keine Unterscheidung möglich ist. Die Beschriftungen auf der linken Seite mit hinzugefügten Pfeilen bezeichnen die Individuen. Vgl. hierzu Abb. 6.*

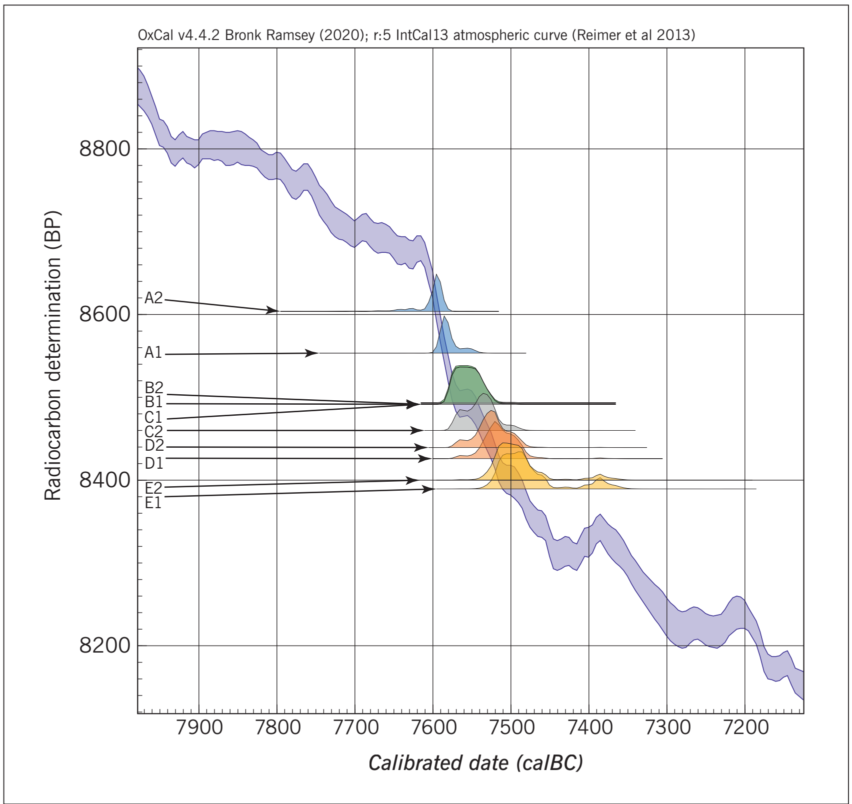

Fig. 2 A steep section of the calibration curve. The calibrated ^{14}C dates of the individuals are much narrower and overlap to a considerably lesser degree compared to a plateau-rich curve.

Abb. 2 *Ein steiler Abschnitt der Kalibrierungskurve. Die kalibrierten ^{14}C-Datierungen der Individuen liegen enger beieinander und überlappen sich weit weniger im Vergleich zu einer plateaureichen Kurve.*

known calendar dates to their conventional radiocarbon ages. Use of such large datasets allows us to assign a measured conventional radiocarbon age to a true calendar date. The most recent iteration of such a dataset applicable to samples from the whole northern hemisphere is the international calibration curve IntCal20 (Reimer et al. 2020), which covers a time period of the last 55 000 years.

The calibration curves shown in Fig. 1–4 show past changes in the ^{14}C content of the atmosphere, which are driven by many factors such as solar activity or changes in the earth's magnetic field. These variations cause the ^{14}C content of the atmosphere to fluctuate over time, which is expressed in the calibration curve as wiggles or fluctuations. A simple one-to-one relationship between a measured

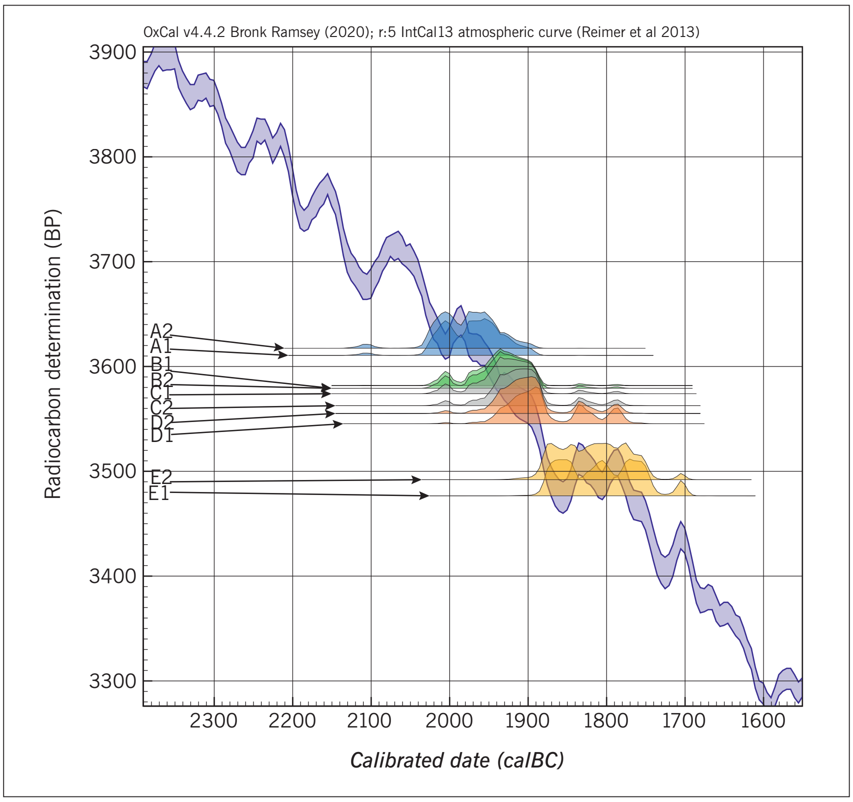

Fig. 3 A section of the calibration curve that contains some plateaus but also has steep sections. This reflects a combination of the cases with a plateau-rich or steep calibration curve. While generations 1 and 5 could be distinguished by their ^{14}C dates, the dating ranges of generations in between show considerable overlap.

Abb. 3 *Ein Abschnitt der Kalibrierungskurve, der einige Plateaus aufweist, aber auch über einen steilen Abschnitt verfügt. Dies spiegelt eine Kombination von den Fällen wider, die eine plateaureiche oder eine steile Kalibrierungskurve besitzen. Während Generation 1 und 5 anhand ihrer* ^{14}C*-Datierungen unterschieden werden konnten, überlappen sich die Datierungsspannen der dazwischen liegenden Generationen deutlich.*

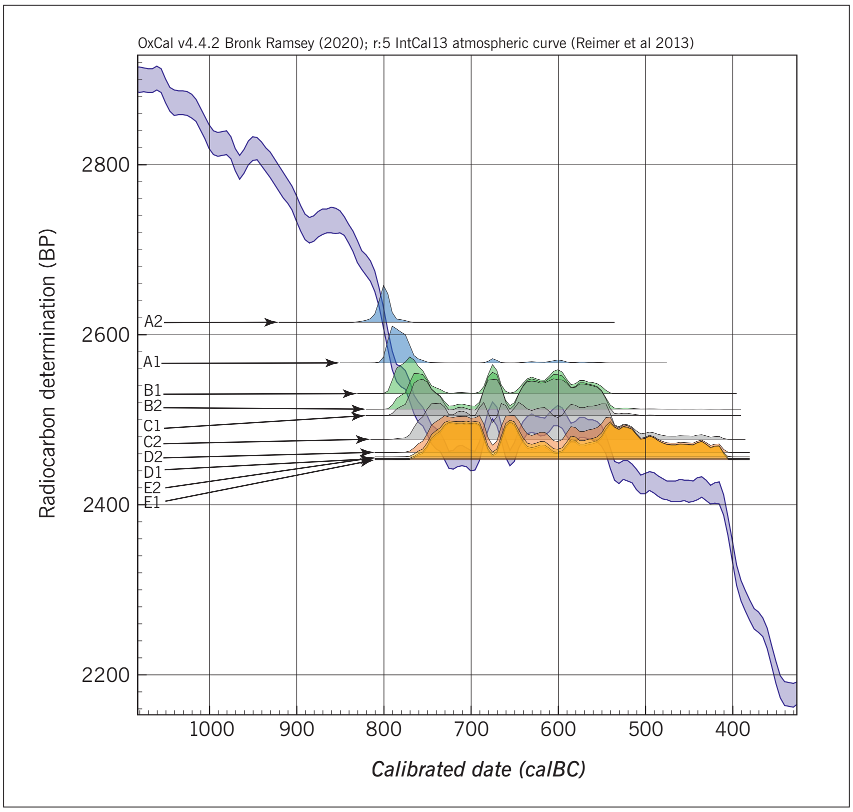

Fig. 4 A plateau-rich calibration curve (Hallstatt plateau). Compared to Fig. 1, one of the individuals (A2) is located on the steep section of the curve, right before the plateau, while all other individuals are located inside the plateau.

Abb. 4 *Eine plateaureiche Kalibrierungskurve (Hallstattplateau). Im Vergleich zu Abb. 1 ist ein Individuum (A2) auf einem steilen Abschnitt der Kurve kurz vor dem Plateau platziert, während alle anderen Individuen sich innerhalb des Plateaus befinden.*

conventional ^{14}C age to one calendar date is not given. Several calendar dates can have the same ^{14}C age. Conversely, a measured ^{14}C age typically results in multiple possible calendar dates (ranges of dates) depending on the shape of the calibration curve. A very flat section of the curve (plateau) would result in calibrated ^{14}C dates that span a very broad range (e.g., Fig. 1).

Figure 5 shows the precision of calibrated ^{14}C dates that can be achieved when calibrating conventional ^{14}C ages with an analytical precision of 20 years – a value that is achievable in laboratories today for samples spanning the past few thousand years.

Even though the measured ^{14}C age is relatively precise, the calibrated ranges can span several hundreds of years when plateaus are present in the calibration curve.

Methods and Discussion

How can we overcome this limitation and still achieve precise (and accurate) ^{14}C dates, even though the calibration curve would not provide the necessary means? In the early 1760s T. Bayes (1701–1761) formulated the Bayes' theorem, which is an approach where existing knowledge about a parameter is updated with new information from observed data. When applied to ^{14}C dating, any chronological information (of relative or absolute nature) can be combined with conventional ^{14}C ages in order to constrain better the calibrated dates. As a simple example, archaeologists may provide stratigraphic information about two subsequent burials in superposition. Even though ^{14}C dates might not be able to resolve the actual dates of the buried individuals, due to the shape of the calibration curve, the stratigraphic information shows that the individuals must have been buried one after the other. Thus, this information can be used to constrain the calibrated ages by Bayesian modeling. However, grave-pit intersections are not observed very often, so that other non-stratigraphic information is needed.

The origin of the relative chronological information used for Bayesian modeling is not limited to archeological information. Today, geneticists are able to uncover family relationships in burial sites by ancient DNA analysis (e.g., Mittnik et al. 2019). These pedigrees offer a rich set of relative chronological information in the same way as stratigraphic data, albeit not in space, but by forming a »temporal stratigraphy«.

What Bayesian modeling can offer, e.g., the effects of the shape of the calibration curve when modeling, and what information is most effective in order to constrain the calibrated ^{14}C dates, has been discussed in detail in Massy et al. (2022). Here, we will give an overview about the topic and focus on the main findings of the article. While modeling of actual pedigrees is also discussed by Massy et al. (2022), here we focus specifically on the modeling of artificial pedigrees.

In order to test the applicability and effectiveness of combining pedigree information with radiocarbon dates, artificial pedigrees were constructed as shown in Fig. 6. Five generations with two individuals each were used, where the years-of-birth (YoB) and ages-at-death (AaD) are prescribed. Hence, the years-of-death (YoD) are also known.

Those prescribed pedigrees with their YoBs and AaDs (hence, YoDs) are in many ways simplified versions of the ones that archaeologists and geneticists find in nature. However, the main advantages of Bayesian modeling can be tested more clearly and transparently. The scaffold of a family tree was then assigned various sets of YoBs covering time periods in which very different shapes of the calibration curve are present – a section where a plateau-rich curve (the »Hallstatt plateau«; Fig. 1), or a steep calibration curve

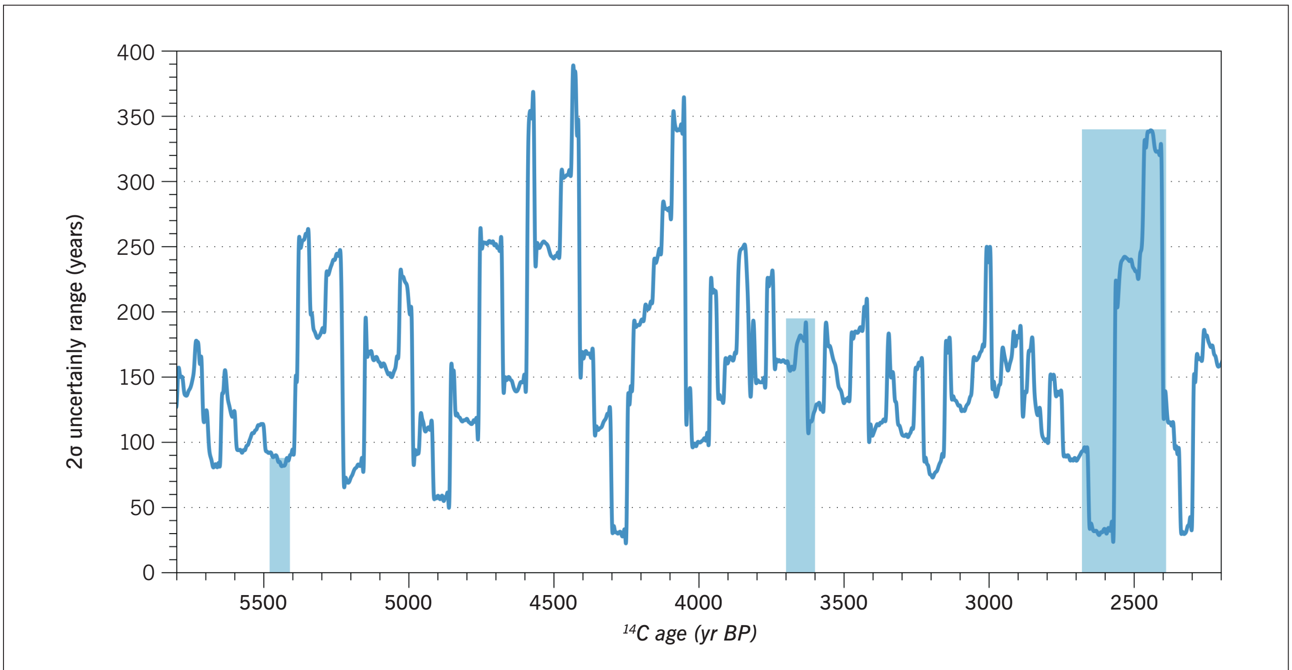

Fig. 5 Age uncertainty ranges (2σ) of calibrated ^{14}C dates depending on the measured conventional ^{14}C age (assuming 20 years of analytical precision). When a conventional ^{14}C age falls within a plateau-rich calibration curve (e.g., around 2450 or 4450 BP), the calibration delivers dates that span a very broad range. Conversely, when a steep calibration curve is present (e.g., 2300 or 4250 BP) the calibrated dates are more precise and narrower in their range. Shaded areas show the sections where the effect of Bayesian modeling was studied here.

Abb. 5 *Datierungsungenauigkeiten (2σ) von kalibrierten ^{14}C-Datierungen, abhängig von dem gemessenen konventionellen Alter (unter Annahme einer Präzision von 20 Jahren). Wenn ein konventionelles ^{14}C-Alter innerhalb eines plateaureichen Abschnitts der Kalibrationskurve fällt (z. B. um 2450 oder 4450 v. heute), dann liefert die Kalibrierung Datierungen mit einem großen Schwankungsbereich. Umgekehrt sind die kalibrierten Daten präziser und kürzer, wenn eine steile Kalibrationskurve vorliegt (z. B. 2300 oder 4250 v. heute). Eingefärbte Bereiche zeigen die in der hier vorgestellten Studie diskutierten Effekte der bayesianischen Modellierungen.*

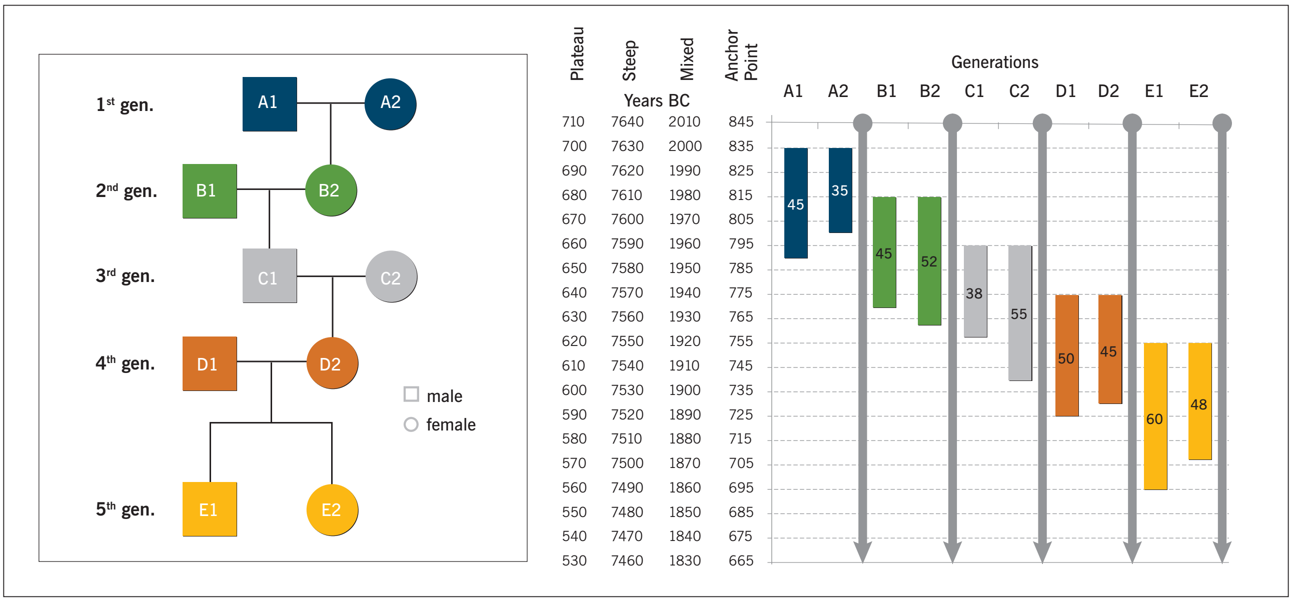

Fig. 6 Artificially constructed pedigree used for Bayesian modeling. Five generations with two individuals each were used in which the dates-of-birth (YoB) and ages-at-death (AaD) are prescribed. Several sets of YoB's are used to reflect periods with different shapes of the calibration curve.

Abb. 6 *Künstlich konstruierter Stammbaum, der für die bayesianische Modellierung benutzt wird. Es wurden fünf Generationen mit jeweils zwei Individuen verwendet, bei denen das Geburtsjahr (YoB) und das Alter zum Todeszeitpunkt (AaD) vorgegeben sind. Mehrere Reihen von Geburtsjahren (YoB's) wurden genutzt, um Zeitperioden mit verschiedenem Verlauf der Kalibrierungskurve zu berücksichtigen.*

dominates (Fig. 2), and a more mixed-feature curve (Fig. 3) that neither shows large plateaus nor very steep sections. Modeling[1] was performed with two sets of prior information:

1. Sequencing of the generations (using the OxCal command »sequence«), as given by the layout of the artificial pedigree but maintaining the individuals within a generation in no particular order (encapsulating those ^{14}C data using the OxCal command »phase«). The generations were placed in sequence with the prescribed information that individuals forming generation 2 died after those of generation 1 and so on.
2. Adding a time interval between the generations (using OxCals command »interval«) in order to constrain the fact that individuals of different generations died in a defined period of time after each other. This interval reflects the reproductive age of individuals in the past. The information can be precisely prescribed for the constructed pedigree as the difference between the mean YoDs between two generations.

The conventional ^{14}C ages that reflect the prescribed YoDs for the individuals are taken from the respective value in the calibration curve IntCal13. The results of the calibrations are shown as 2σ ranges.

In general, when using actual ^{14}C samples from archaeological contexts, the ^{14}C ages need to be corrected for the Human Bone Collagen Offset (HBCO). This takes into account that a ^{14}C age of human collagen does not allow definition of the date of YoD. Bone collagen is a mixture of collagen build-up over the course of the lifetime of an individual (Barta/Štolc 2007). More details on the effect of the HBCO correction can be found in Massy et al. (2022).

Plateau calibration curve

The Hallstatt plateau was used to investigate the benefits of combining ^{14}C ages with pedigree information. Figure 1 shows this section of the calibration curve, which mainly consists of one large plateau spanning almost 400 years.

One conventional ^{14}C age of around 2450 years BP (similar to individual A1) always results in calibrated dates ranging from approximately 800 to 400 cal BC. Resolving the dates of individuals who died during this period of time without prior information is not possible. However, using known family relationships between individuals can substantially improve the precision of the dates.

Figure 7 shows the unmodeled ages (light gray) for each individual when the pedigree information is not considered. All of these calibrated dates are basically identical and cannot be distinguished from each other. The modeled ages are displayed (in their respective colors) when family relationships are incorporated. In Fig. 7a only the sequence of the generations is considered. This sequence results in a substantial shortening of the calibrated ranges. While individual D2 (generation 4) has an unmodeled calibrated range of approximately 780–520 cal BC (260 years) the modeled range is reduced to 680–540 cal BC (140 years) – a reduction of 46 %. Adding an interval to the Bayesian model between the generations, so that the generations are

1 Using the software OxCal, see Bronk Ramsey (2009).

separated by a certain (prescribed) amount of time (Fig. 7b), can reduce the calibrated ranges even further. Looking at individual D2 again, the modeled dates now range from 625–525 cal BC (100 years). A reduction of 61 % compared to the unmodeled results. Similar improvements are seen for all the individuals in the pedigree. Besides narrowing the calibrated ranges, and thus improving the precision of the dates, the results remain accurate. The prescribed YoDs of all individuals (red triangles in Fig. 7) fall within the modeled date ranges.

Steep calibration curve

In stark contrast to the plateau-rich calibration curve, a steep gradient provides short time spans of calibrated ^{14}C dates, even when no other chronological information is considered (Fig. 2 and 8).

The range of calibrated dates are much narrower and even without modeling there is some chronological separation between the generations and lesser overlap compared to the plateau-rich setting. However, subsequent generations could not be fully resolved, even in the presence of a steep gradient within the curve.

Sequencing of the radiocarbon dates from the generations (Fig. 8a) and adding an interval between the generations (Fig. 8b) narrows the modeled calibrated dates adding more separation between the generations. Using individual D2 as an example again, Bayesian modeling narrows the unmodeled calibrated date from spanning approximately 90 years down to 45 years (when sequenced only) and down to 40 years (when adding an interval between the generations), representing a reduction in time-span of 50 % and 55 %. While adding an interval between the generations improves the precision of the calibration only slightly compared to sequencing only, the accuracy is improved considerably. The prescribed YoDs (red triangles) are located more

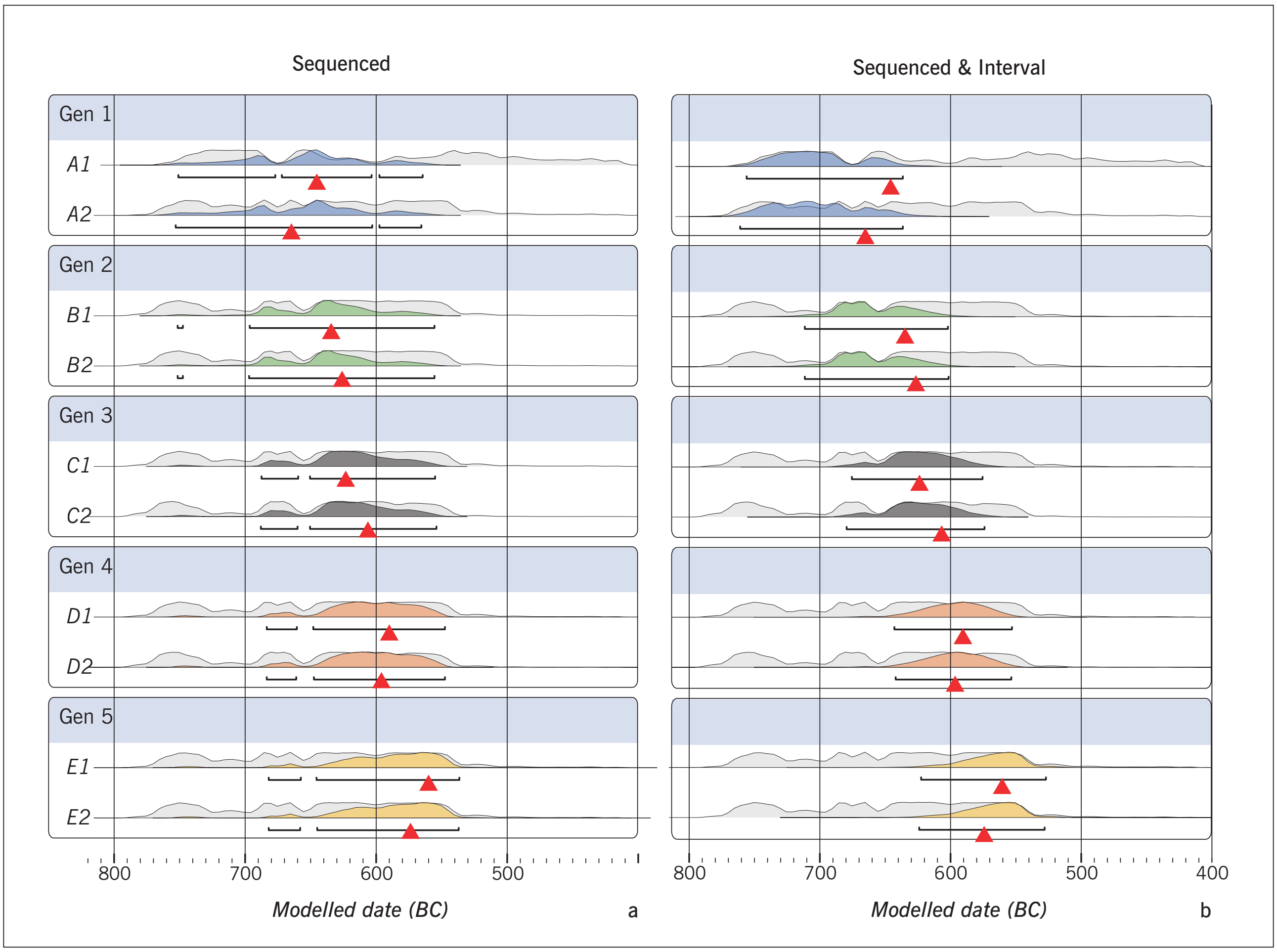

Fig. 7a–b Calibrated dates for the individuals forming the pedigree on a plateau-rich calibration curve. Unmodeled dates without considering the pedigree information are shown in light gray. All of the calibrated dates are basically identical and could not be distinguished from each other. The modeled dates are displayed in their respective colors where the family relationships are used with U-shaped brackets showing the 2σ calibrated date ranges after modeling. a Only the sequence of the generations is considered; b an interval is added between the sequenced generations, which narrows the date ranges even further.

Abb. 7a–b *Kalibrierte Datierungen der Individuen des Stammbaumes, die auf einer plateaureichen Kalibrierungskurve liegen. Nicht modellierte Datierungen, bei denen die Stammbauminformationen nicht berücksichtigt wurden, sind grau unterlegt. Alle kalibrierten Datierungen sind identisch und konnten nicht voneinander unterschieden werden. Die modellierten Datierungen sind in ihren jeweiligen Farben den benutzten Familienverwandtschaften zugeordnet und die U-förmigen Klammern zeigen die 2σ kalibrierten Datierungsbereiche nach der Modellierung. a Nur die Generationenabfolge ist berücksichtigt; b ein Zeitintervall ist zwischen den aufeinanderfolgenden Generationen eingefügt, was die Datierungsspannbreiten noch weiter verkleinert.*

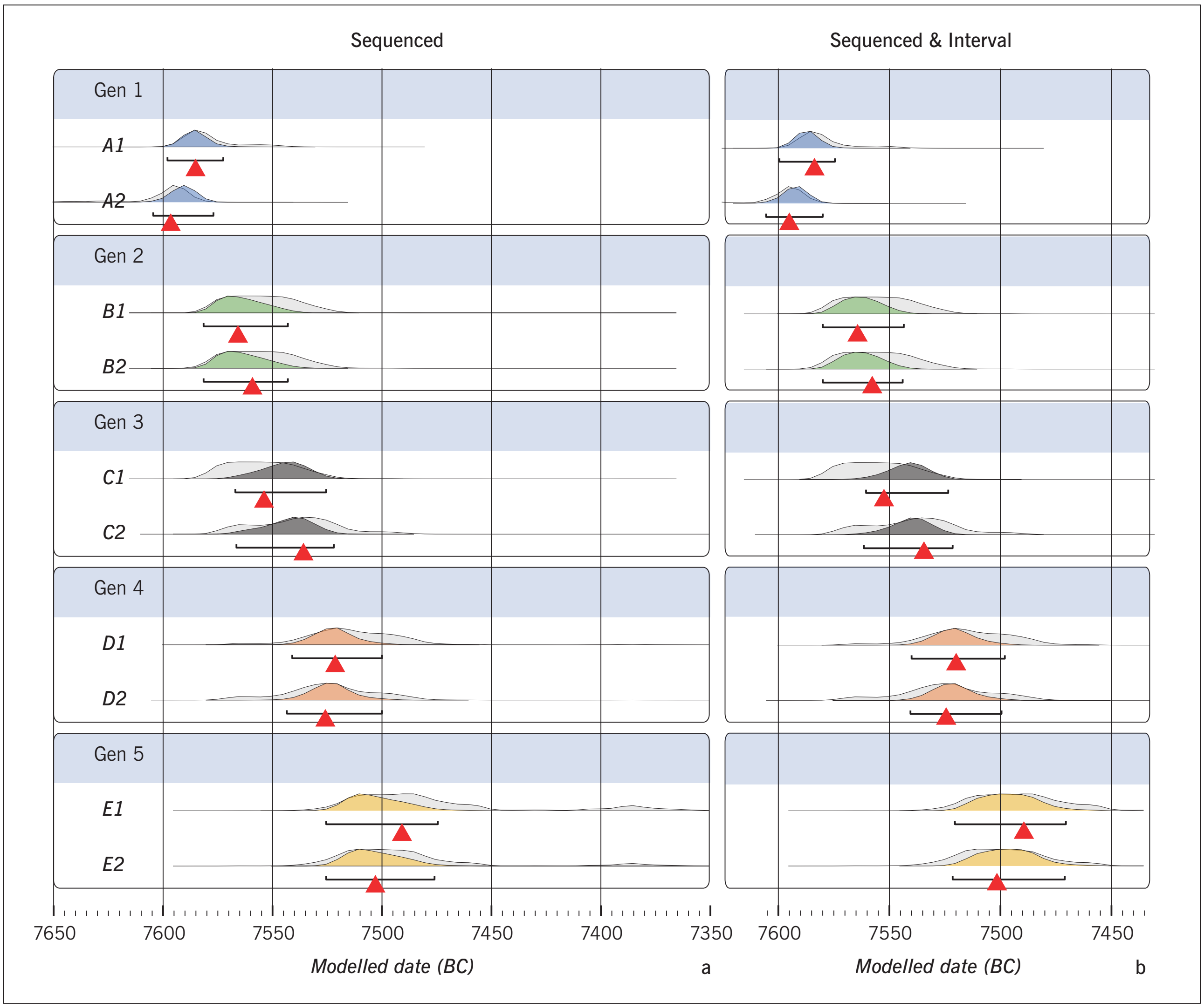

Fig. 8a–b Calibrated dates for the individuals forming the pedigree on a steep calibration curve. Unmodeled dates not considering the pedigree information are shown in light gray. Even when unmodeled, the calibrated age ranges are much narrower compared to the plateau-rich calibration curve. The modeled dates are displayed in their respective colors where the family relationships are used with U-shaped brackets showing the 2σ calibrated date ranges after modeling. a Only the sequence of the generations is considered; b an interval is added between the sequenced generations, which narrows the date ranges slightly further.

Abb. 8a–b Kalibrierte Datierungen der Individuen des Stammbaumes, die auf einem steilen Abschnitt der Kalibrierungskurve liegen. Nicht modellierte Datierungen, bei denen die Stammbauminformationen nicht berücksichtigt wurden, sind grau unterlegt. Sogar unmodelliert sind die kalibrierten Datierungsschwankungen weit kürzer im Vergleich zu der plateaureichen Kalibrierungskurve. Die modellierten Datierungen sind in ihren jeweiligen Farben den benutzten Familienverwandtschaften zugeordnet und die U-förmigen Klammern zeigen die 2σ kalibrierten Datierungsbereiche nach der Modellierung. a Nur die Generationenabfolge ist berücksichtigt; b ein Zeitintervall ist zwischen den aufeinanderfolgenden Generationen eingefügt, was die Datierungsspannbreiten noch weiter verkleinert.

towards the center of the calibrated ranges when compared to the sequencing-only dates.

Mixed calibration curve

The results of the tests using the mixed calibration curve with plateaus intersected by steeper sections are a combination of the plateau and steep-gradient data (Fig. 3 and 9). Unmodeled calibrated ranges are relatively broad. Individual D2 calibrates to approximately 1970–1780 cal BC (190 years), while individuals forming the first generation can be separated from the 5th generation by their ^{14}C dates; however, subsequent generations in between cannot be separated.

Combining the pedigree information with the ^{14}C data improves the precision of the calibrated ranges yet further. The improvement between sequencing the generations only and adding an interval between them is only marginal. Both setups, however, narrow the calibrated range of D2 down to 60 years – a substantial improvement of 68 %.

Anchor point example

In this example (Fig. 4 and 10), the YoD's of the artificial pedigree are moved slightly to older dates compared to the Hallstatt-plateau example. Now, the YoD of one of the individuals (A2) falls within the steep section of the calibration

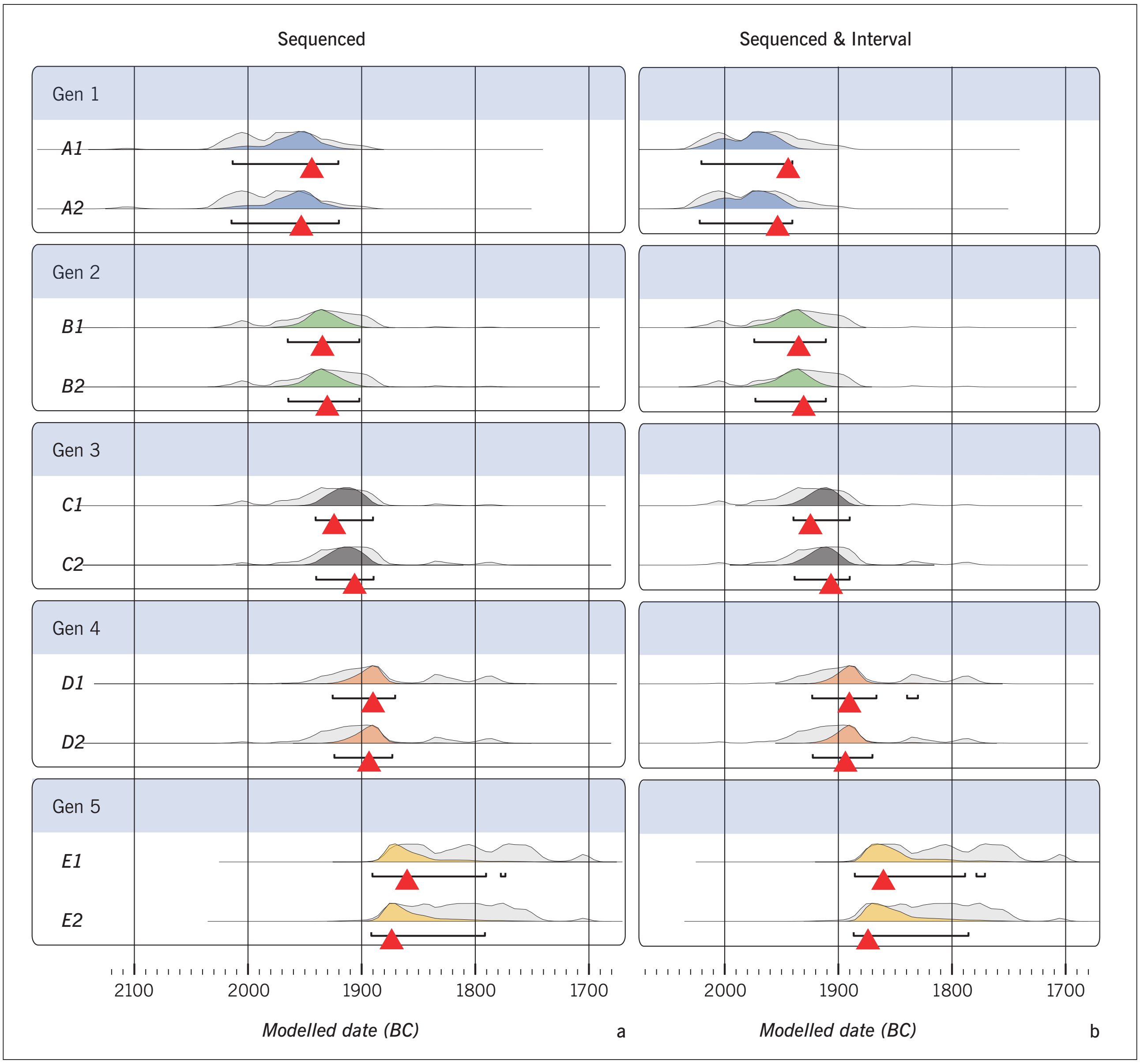

Fig. 9a–b Calibrated dates for the individuals forming the pedigree on a section of the calibration curve with some plateaus but also steep sections. Unmodeled dates not considering the pedigree information are shown in light gray. While generation 1 and 5 could be distinguished by their ^{14}C dates, subsequent generations close to each other show considerable overlap. The modeled dates are displayed in their respective colors where the family relationships are used with U-shaped brackets showing the 2σ calibrated date ranges after modeling. a Only the sequence of the generations is considered; b an interval is added between the sequenced generations, which narrows the date ranges moderately.

***Abb. 9a–b** Kalibrierte Datierungen der Individuen des Stammbaumes, die auf einigen Plateaus aber auch steilen Abschnitten der Kalibrierungskurve liegen. Nicht modellierte Datierungen, bei denen die Stammbauminformationen nicht berücksichtigt wurden, sind grau unterlegt. Während die Generationen 1 und 5 durch ihre ^{14}C-Datierungen unterschieden werden konnten, liegen darauffolgende Generationen eng beieinander oder überlappen. Die modellierten Datierungen sind in ihren jeweiligen Farben den benutzten Familienverwandtschaften zugeordnet und die U-förmigen Klammern zeigen die 2σ kalibrierten Datierungsbereiche nach der Modellierung. a Nur die Generationenabfolge ist berücksichtigt; b ein Zeitintervall ist zwischen den aufeinanderfolgenden Generationen eingefügt, was die Datierungsspannbreiten noch weiter verkleinert.*

curve, immediately before the Hallstatt plateau; this forms an anchor point on the steep section of the curve.

While A2 can be calibrated to a very narrow unmodeled date range of approximately 50 years, all other individuals fall within the plateau. Their calibrated ranges span at least 200 years, or even approximately 350 years when the full range of the plateau is considered. Using individual D2 again as an example, the modeled date when generations are sequenced only is narrowed to a range spanning 210 years instead of 360 years (unmodeled), representing a reduction of 42 %. By adding an interval between the generations, the reduction is 220 years. In this setup, adding the interval pushes the calibrated dates further into the plateau, which consequently widens the calibrated ranges as opposed to narrowing them further, as in the other examples. Please see Massy et al. (2022, Fig. 18) for more information on how to constrain further the calibrated date ranges.

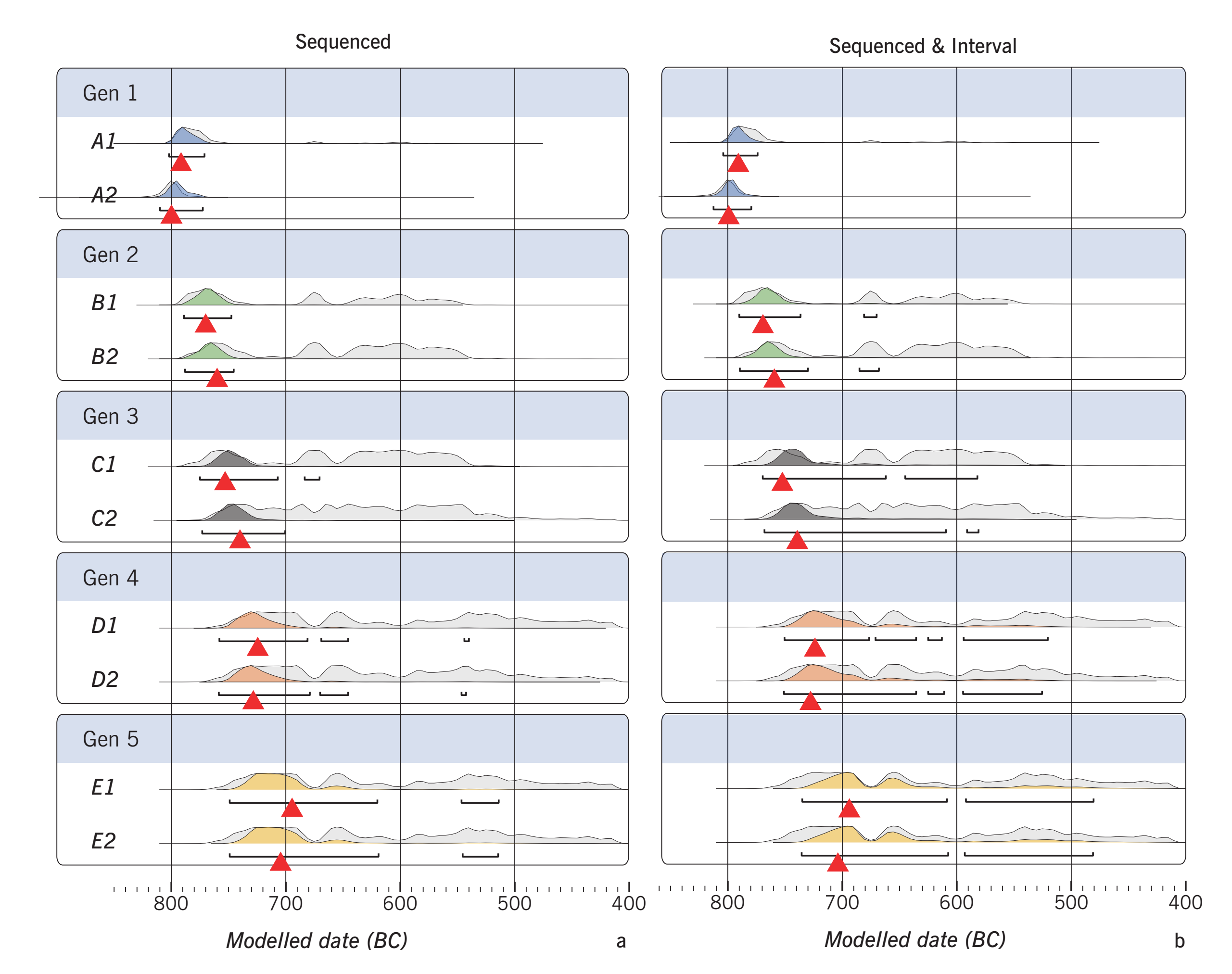

Fig. 10a–b Calibrated dates for the individuals forming the pedigree on a section of the calibration curve with a wide plateau (Hallstatt plateau). One individual (A2), however, is located on the steep section of the curve. Unmodeled dates not considering the pedigree information are shown in light gray. The modeled dates are displayed in their respective colors where the family relationships are used with U-shaped brackets showing the 2σ calibrated date ranges after modeling. a Only the sequence of the generations is considered; b an interval is added between the sequenced generations. Here, adding an interval pushed some of the ^{14}C ages further into the plateau, leading to slightly broader age ranges.

***Abb. 10a–b** Kalibrierte Datierungen der Individuen des Stammbaumes, die auf einem Abschnitt der Kalibrierungskurve mit einem breiten Plateau (Hallstattplateau) liegen. Ein Individuum (A2) befindet sich auf dem steilen Abschnitt der Kurve vor dem Plateau. Nichtmodellierte Datierungen, bei denen die Stammbauminformationen nicht berücksichtigt wurden, sind grau unterlegt. Die modellierten Datierungen sind in ihren jeweiligen Farben den benutzten Familienverwandtschaften zugeordnet und die U-förmigen Klammern zeigen die 2σ kalibrierten Datierungsbereiche nach der Modellierung. a Nur die Generationenabfolge ist berücksichtigt; b ein Zeitintervall ist zwischen den aufeinanderfolgenden Generationen eingefügt, was dazu führt, dass einige ^{14}C-Alter weiter ins Plateau gerückt sind und es so zu etwas breiteren Altersschwankungen kommt.*

Conclusion

In all of the examples shown, combining ^{14}C ages with chronological information taken from pedigrees improves the precision of the calibrated ^{14}C dates. Generally, the range of calibrated dates is always narrower when modeled. An improvement of 40–70 % can be attained, depending on the shape of the calibration curve and the actual location of the ^{14}C data on the curve. Sequencing the generations alone in many cases already provides substantial improvements. Moreover, adding an interval between the generations does not always reduce the calibrated ranges in situations when the ^{14}C ages are moved into a more plateau-like section. As shown in Massy et al. (2022), even if individuals of only 2 generations can be identified, Bayesian modeling already provides more precise dates. The more generations that are included, the more the ^{14}C dates can be constrained. Generations that are bracketed by others benefit most from modeling because their dates can be constrained by the earlier and later generations. The shape of the calibration curve, however, is still restrictive. In plateau-like calibration curves the modeled ^{14}C dates still span relatively broad periods of time. In all cases, Bayesian modeling narrows the calibrated ranges and still conserves the prescribed YoDs. Thus, the precision is improved while maintaining accuracy.

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Source of Figures

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