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Radiocarbon dating and Hallstatt chronology: a Bayesian chronological model for the burial sequence at Dietfurt an der Altmühl ‘Tennisplatz’, Bavaria, Germany

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Abstract
This study is first attempt to refine Early Iron Age absolute chronology, specifically the timing of the Hallstatt C-D transition in southern Germany, using Bayesian chronological modelling of radiocarbon (14C) dates. The Hallstatt period (c.800–450 BC) marks the transition from prehistory to proto-history in Central Europe. The relative chronological framework for Hallstatt burials developed by the mid-twentieth century is still used today, but absolute dating is limited by the scarcity of dendrochronological dates and the perception that 14C dating in the Hallstatt period (HaC-HaD) is futile, due to the calibration plateau between c.750 and 400 cal BC. We present new AMS 14C dates on 16 HaC-HaD burials from a stratified sequence at Dietfurt an der Altmühl ‘Tennisplatz’ (Bavaria, Germany). This sequence is situated entirely on the ‘Hallstatt plateau’, but by combining 14C dating with osteological, stratigraphic, and typological information, we demonstrate that the plateau is no longer the ‘catastrophe’ for archaeological chronology once envisaged. Taking into account dendrochronological dating elsewhere, we show that at Dietfurt, the HaC-HaD transition almost certainly occurred before 650 cal BC, and most likely between 685 and 655 cal BC (68.3% probability), several decades earlier than usually assumed. We confirm the accuracy and robustness of this estimate by sensitivity testing. We suggest that it is now possible, and essential, to exploit the increased precision offered by AMS measurement and the IntCal20 14C calibration curve to re-evaluate absolute chronologies in Early Iron Age Europe and equivalent periods in other regions.

Keywords Iron Age · Hallstatt C-D transition · Radiocarbon dating · Hallstatt plateau · Bayesian chronological modelling

Introduction

In current narratives, the Hallstatt period (c.800–450 BC) marks the transition from prehistory to proto-history in Central Europe, as it coincided with Greek colonisation of the western Mediterranean, the appearance of the Etruscans and other state-like societies in the Italian peninsula, and the development of trade links between Central Europe and the Mediterranean world. Especially the later Hallstatt period is characterised by central places like the ‘Heuneburg’ and the appearance of lavishly furnished, so-called princely burials (Fernández-Götz and Krausse 2013).

The term ‘Hallstatt period’ was first coined in the nineteenth century, with reference to the famous Hallstatt cemetery, and by the middle of the twentieth century, a framework of relative chronology was developed which is more or less still valid today (Jacob-Friesen 1980). This includes the division into an earlier Late Bronze Age period with phases HaA and HaB and a later Early Iron Age period with phases HaC and HaD that are divided further into sub-phases (HaC1, HaC2, HaD1, HaD2, HaD3). The absolute chronology of the later Hallstatt period has traditionally been constrained by occasional finds of artefacts imported from the Mediterranean region (Sacchetti 2016; Guggisberg 2007). Since the 1990s, absolute dating has also increasingly relied on dendrochronological results (Billamboz 2008). Radiocarbon (14C) dating has seldom been applied, not least because of
the longstanding perception that between c.750 and 400 cal BC, coinciding with HaC and HaD, the $^{14}$C calibration curve is too flat to justify $^{14}$C dating. The only Hallstatt site which has been subject to intensive $^{14}$C dating is the Hallstatt salt mine complex (Stadler 1999; Grabner et al. 2021), at least partly because the archaeological periodisation of grave goods from Hallstatt burials is inapplicable to the types of artefacts found in the salt mines. Unfortunately, this also implies that the absolute chronologies (dendrochronology and $^{14}$C) available for the salt mines cannot be used to test or refine the traditional periodisation of Hallstatt grave-good assemblages. $^{14}$C dating has been used elsewhere to check whether features may be associated with Hallstatt occupation, but not to check the archaeological chronology itself (e.g. Müller-Scheeßel et al. 2020a, b).

This paper investigates the chronology of a $^{14}$C dated stratigraphic burial sequence from the Hallstatt cemetery Dietfurt an der Altmühl ‘Tennisplatz’ in Bavaria, Germany (Fig. 1). The aim is to provide a probabilistic estimate of the date of the Hallstatt C-D (HaC-HaD) transition at Dietfurt and to discuss it in view of other absolute dates for HaC and HaD contexts in Germany, and traditional chronologies for the Early Iron Age in Central Europe.

**The Hallstatt calibration plateau**

The $^{14}$C ages of Northern Hemisphere tree-rings dated dendrochronologically to the period c.750–420 BC fall within such a narrow range (c.2520–2420 BP) that they are practically indistinguishable, given typical measurement uncertainties (Fig. 2). This phenomenon, first demonstrated in the early 1980s (Pearson et al. 1983; Stuiver and Becker 1986) and immediately described as ‘the 1st millennium BC radiocarbon disaster’ (Baillie and Pilcher 1983), became known to European archaeologists as the Hallstatt plateau.
in $^{14}$C calibration curves (Wijma et al. 1996; Stäuble and Hiller 1997). As $^{14}$C calibration is a global phenomenon, the 1st-millennium BC plateau has also hindered chronological research in, e.g. southeast Asia (Higham and Higham 2009), pre-Columbian Peru (Unkel et al. 2012), and Bronze Age China (Yu et al. 2021).

Three developments in $^{14}$C science suggest that the Hallstatt plateau is no longer the ‘catastrophe’ for archaeological chronology envisaged by Baillie and Pilcher (1983). One is the steady improvement in $^{14}$C measurement precision, with 1-sigma uncertainties on routine archaeological samples now often better than ±25 (e.g. Aerts-Bijma et al. 2020). Another is the modification of the algorithm used to calculate the internationally recognised calibration curves, leading to less smoothing in periods with more high-resolution calibration data, and allowing the curve to be calculated at annual resolution (Heaton et al. 2020). A third is the inclusion in the most recent calibration curve, IntCal20 (Reimer 2020), of high-resolution calibration data spanning 856–626 BC, covering the first half of the Hallstatt plateau (Fahrni et al. 2020; Park et al. 2017). The new calibration data, from dendro-dated German oak and Californian bristlecone pine, are at single-year resolution, whereas earlier iterations of the calibration curve were based mainly on $^{14}$C measurements of decadal blocks. The new data also confirm that there was a Miyake-type event (Miyake et al. 2012) in c.660 BC, whereby the atmospheric $^{14}$C level suddenly increased by about 10‰ (O’Hare et al. 2019), which would potentially serve to anchor wiggle-matched tree-ring sequences (e.g. Wacker et al. 2014). Despite these developments, even relatively precise $^{14}$C ages for short-lived samples produce calibrated date ranges spanning the whole plateau, or at best, give multimodal distributions offering alternative solutions in different centuries (Fig. 2). Using Bayesian chronological modelling, however, it is possible to resolve sample dates much more precisely.

**Bayesian chronological modelling**

Bayesian chronological modelling offers a coherent statistical framework for interpreting chronometric data, such as $^{14}$C ages and dendrochronological dates (Buck et al. 1996). It evaluates probability distributions of calibrated dates in view of ‘prior information’ that can either take the form of informative priors, i.e. the temporal relationships between samples, such as relative dating based on depositional sequences or typology, or uninformative priors that impose a statistical distribution on the dated events (Bayliss 2009; Hamilton and Krus 2018). A Bayesian chronological model evaluates all prior information and in view of this estimates the statistically most likely date ranges (posterior density estimates) of the $^{14}$C samples and other events of interest. This can improve the precision of individual site chronologies and estimate dates of events that cannot be dated directly, such as when burial activity started at a cemetery, or the timing of a typological transition. Model output should be reproducible and its sensitivity to various model components can be tested.

Bayesian chronological modelling has only recently been applied on a larger scale to studies coinciding with the Hallstatt plateau (Hamilton et al. 2015). Applications tend to target
sites or assemblages with informative prior information based on stratigraphy (Waddington et al. 2019), artefact typology (Rose 2020), or floating tree-ring series (Jacobsson et al. 2018; Manning et al. 2018). Such approaches are robust yet rarely applied, and Early Iron Age chronologies in Europe are still mainly based on ‘archaeological dating’, i.e. typo-chronology.

The cemetery at Dietfurt an der Altmühl ‘Tennisplatz’

The burial ground of Dietfurt an der Altmühl is one of the largest Hallstatt cemeteries in southern Germany to have been excavated and published. Due to construction works, excavations took place at the ‘Tennisplatz’ site in 1963, 1964, and 1980–1983 (Röhrig 1994). In the 1990s and 2000s, further burials were excavated only 100 m away at the ‘Tankstelle’ site, but both sites are believed to belong to the same cemetery (Augstein 2015: 28). If true, this cemetery would have covered an area of at least 3 ha, with probably more than 1,000 buried individuals.

The earliest burial at Dietfurt ‘Tennisplatz’ dates to the Urnfield period (c.1200–800 BC), and the cemetery remained in use until the Later Hallstatt period (c.800–450 BC). Funerary practices were very variable and the most impressive burials are chamber graves, probably made of wood and packed with stones. Chambers were nearly always enclosed by rings of stones. Because additional chamber graves were often built in close proximity, later rings of stones did not form full circles. In some instances, further grave chambers were placed on top of older chambers, and in other instances, and particularly in the later phases, burials were interred in existing chamber graves. In terms of burial rites, the earlier graves contain mostly cremated remains, whereas the later burials are inhumations.

Many of the chamber graves had been partly disturbed by ploughing or erosion prior to excavation, but in the southern part of the cemetery, the construction of seven chamber graves can be ordered chronologically by the intersection of surviving rings of stones (Fig. 3). The horizontal and vertical stratigraphy applied in the present paper was first proposed by Röhrig (1994), and the horizontal stratigraphy for graves 11, 117, 119, 110A, 113, 124, 123, and 122A was later critically re-examined and supported by Nikulka (1998: 143f. with Fig. 35f.). Multiple individuals buried in the same chamber grave are not necessarily regarded as contemporaneous burials, because the graves were constructed as stone chambers, probably with a wooden inner frame and a wooden ceiling, which was re-opened to accommodate later burials (Hughes 1993/1994). The new burial would be placed beside the earlier burial, pushing this to the side. An undisturbed individual is thus interpreted as the latest interment, whereas an individual with disordered bones is interpreted as its predecessor. The burial chamber will have lost structural integrity and collapsed within a century, leading us to assume that any secondary interments must have happened 5–100 years after the primary interment. A similar situation with consecutive burials is known from the Dürrnberg cemeteries in Austria (Wendling 2020).

Based on typological attributions of grave goods (Table 1), the HaC-HaD transition at Dietfurt took place between the primary burials in grave 11 and grave 9 of this sequence (following Röhrig 1994: 111; Nikulka 1998: 143). Neither the stratigraphic sequence of burial chambers nor the recovery of rich assemblages of typologically diagnostic grave goods is unique in this region (Nikulka 1998: 134–145), but the combination of both these attributes with the survival of well-preserved human bone makes Dietfurt an der Altmühl ‘Tennisplatz’ the ideal site for dating the HaC-HaD transition. At the ‘Tankstelle’ part of the Dietfurt cemetery, for example, the stratigraphic sequence of burial chamber construction was already almost completely lost when the site was excavated (Augstein 2015).

Research questions

There is a striking gap — spanning most of the seventh century BC — between the latest dendrochronological dates from HaC contexts and the first dates from HaD sites.
| Original grave no. (Röhrig, 1994) | Grave no. | Context | Individual | Age | Sex | Burial goods | Relative date |
|----------------------------------|-----------|---------|------------|-----|-----|-------------|--------------|
| Grave 9                          | Grave 110 | Stratum 110A | Primary burial | ? | M? | Late HaC or Early HaD type bronze arm ring; only seven ceramic vessels securely attributable, including one stepped bowl; six more vessels possibly also belonging to the grave; rouletting and scratched lines, possibly also stamped radial-eye pattern and black painting present | Early HaD |
|                                  |           | Stratum 110B | Double burial, sk. 1 | 20–26 yr | M | Fibula with loop (type S4 \textit{Schlangenfibel}), plain belt plate | Early HaD |
|                                  |           |          | Double burial, sk. 2 | 47–52 yr | M | Six ceramic vessels attributable to sk. 1 or 2, mainly bowls, partly ornamented with broad graphite lines, scratched lines, and rouletting | Early HaD |
|                                  |           | Stratum 110C | Sk. 4 | 7–12 yr | ? | One ceramic bowl with red painting | Early HaD |
|                                  |           |          | Sk. 5 | Adult? (20–39 yr) | M? | | |
| Grave 10                         | Grave 124 | Double burial, sk. 1 | 20–26 yr | M | Ceramics not attributable to one of the three individuals; 21 vessels of different sizes including three stepped bowls, ornamented partly with rouletting, stamped radial-eye pattern, and broad graphite lines | Early HaD |
|                                  |           | Double burial, sk. 2 | 33–39 yr | M | | |
|                                  |           | Cremation burial | ? | ? | | |
| Grave 11                         | Grave 119 | Primary burial | 20–26 yr | M | 24 ceramic vessels of different sizes including one stepped bowl, ornamented partly with black and red paint, rouletting, and stamped radial-eye pattern | Late HaC |
| Grave 12                         | Grave 123 | Primary burial | 20–26 yr | F | Neck ring, two spiral fibulas, melon ring; nine ceramic vessels of different sizes, sparsely ornamented with rouletting and stamped radial-eye pattern | Early HaD |
| Grave 14                         | Grave 117 | Primary burial | 27–32 yr | M | Rein ring (German: \textit{Zügelring}), bridle with imitated torsion as part of the horse harness; belt hook; 30 ceramic vessels of different sizes including three stepped bowls; ornamented partly with rouletting and stamped radial-eye pattern; one vessel ornamented in Weillohe style | Late HaC |
in Germany (Fig. 4). The latest-dated HaC context may be Mainz Römerpassage, where Bauer (2008) suggested a construction date of c.680–650 BC. With a last-surviving oak heartwood tree-ring dating to 704 BC, however, and allowing for a minimum of 10 missing sapwood rings, this timber may have been felled as early as 694 BC. Reim (1990) proposed a slightly later dendro date for the HaC burial at Dautmergen (671 ± 10 BC, revised to 677 ± 10 BC by Friedrich and Hennig 1996). The felling date range was, however, not for the burial chamber itself, but for a surrounding ring of posts. Even if Reim’s assumption that the structures were contemporaneous is correct, the first sapwood ring was dated to 692 BC, which hardly affects the gap between HaC and HaD dendro dates (Fig. 4).

The earliest dated HaD burial is grave 1 at Villingen-Schwenningen ‘Magdalenenberg’ in Baden Württemberg, attributed to sub-phase HaD1 (Trachsel 2004; Parzinger 1989), with a felling date of 616 BC (Friedrich and Hennig 1996). Researchers have generally accepted a date of c.616 BC for the HaC-HaD transition, based on the Magdalenenberg dendro date and archaeological cross-dating (Parzinger 1989: 123–125). A transition date of 616 BC conveniently divides the later Hallstatt period equally in two halves, each lasting about 160 years. There is no real reason to exclude an earlier date, however. Indeed, Trachsel (2004) proposed a mid-seventh century date for the transition, but his view has not been widely accepted. Dietfurt an der Altmühl ‘Tennisplatz’ represents the first opportunity to reduce this uncertainty using a tightly constrained sequence of 14C dates on burials.

The merits of precise chronologies are self-evident. Population estimates based on, e.g. the number of graves attributed to each period need to be scaled to the length of the relevant time periods, and whether these periods are e.g. 120 years or 160 years long can significantly influence the resulting estimates (e.g. Müller-Scheeßel 2007). The present study is concerned with Hallstatt chronology in Germany, but providing an absolute date for the HaC-HaD transition at Dietfurt an der Altmühl enables further investigations into differences in tempo and spatial directions of key cultural transformations across larger geographical regions (for an overview of changes during this period, see Stöllner (2012)). We may imagine a gradual transition, with short time lags between the start of HaD at different sites, of which Dietfurt may not be the earliest or the latest. Allowing for some geographic variation in the transition date, we can estimate broad date ranges for the start and end of the HaC-HaD transition, based only on dendrochronological dates on oak (Fig. 4). The Dietfurt HaC-HaD transition should fall between these ranges.

### Material and methods

#### Sample selection

Contexts to be dated were selected by Nils Müller-Scheeßel on the basis of the stratigraphic sequence and typological attributions of grave goods (Table 1), in order to bracket the HaC-HaD transition. The only material suitable for

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14C dating was bone, mostly from articulated inhumations, and occasionally from cremated human bone, or unburnt animal bones interpreted as food offerings accompanying the burial. Human remains from Dietfurt an der Altmühl ‘Tennisplatz’ were analysed by Claassen (1989), provided in Röhrig (1994), following standard anthropological methods (Ferembach et al. 1979; Nemeskéri et al. 1960; Wahl 1982). There are some discrepancies between the anthropology report and the archaeological grave descriptions, e.g. an individual aged 7–12 years at death was identified anthropologically from grave 9, but was not mentioned in the archaeological description of the grave (Röhrig 1994). We rely on the anthropological report, because anthropological analysis was carried out after the archaeological analyses, and any additional finds by the anthropologist were unfortunately not incorporated in the grave descriptions. During the selection of samples for the present study, anthropologist Anja Staskiewicz carried out a cursory check of sex and age attributions. Skeletal elements were sampled from each individual, primarily smaller bones from hands and feet, or fragments of long bones and pelvic bones, and were sent for AMS 14C dating and EA-IRMS analysis for dietary stable isotopes (δ13C, δ15N).1 The human remains of the primary individual from grave 9 could not be located and a sample of animal bone from the same burial level was selected instead. There is some uncertainty as to which individuals were sampled from the youngest level of grave 9, but the sampled bones must be from two different individuals, an adult probably aged 20–39 years at death (sk. 5) and a child probably aged 7–12 years at death (sk. 4). A sample of un-cremated bone was selected for grave 17 sk. 3, although according to Röhrig (1994), this should be a cremation burial. The sample can be attributed to the Dietfurt cemetery, but not to a specific individual.

The chronological order of dated burials is shown in Fig. 5. Before the HaC-HaD transition, grave 28 sk. 2 preceded grave 14, which was followed by grave 11. The HaC-HaD transition was followed by the primary burial in grave 9, which in turn was followed by the primary burials in graves 10, 12, and 17. The three dated burials from grave 10 (sk. 1, sk. 2, CB) appear to be contemporaneous; the inhumations are both undisturbed and laid alongside each other. The cremated bone (CB) was deposited in the area of the left lower leg of sk. 1. Secondary burials in grave 9 form an internal sequence: sk. 1 and 2 predate sk. 4 and sk. 5. Likewise, there is an internal sequence in grave 17, with sk. 2 predating sk. 1. Two dated samples are not securely stratified in this sequence: the bone originally attributed to grave 17 sk. 3, and a bone attributed to grave 28 sk. 1, which must be later than grave 28 sk. 2, whose 14C age is an outlier in our chronological model (see below).

1 Part of the collagen extracted from six bones at the Leibniz-Labor, Kiel, for AMS 14C dating was sent for EA-IRMS analysis at the Scottish Universities Environmental Research Centre (SUERC), East Kilbride. Separate bone samples from 8 of the 16 dated individuals were extracted for EA-IRMS analysis at GeoZentrum Nordbayern, Erlangen.
Laboratory analyses

For AMS $^{14}$C dating, collagen was extracted at the Leibniz Labor, Kiel, following standard protocols (Grootes et al. 2004). At room temperature, crushed bones were treated with dichloromethane-methanol (2:1) to remove fats and waxes, washed in distilled water and demineralised in 1% HCl, treated with 1% NaOH to dissolve secondary organic compounds, and re-acidified in 1% HCl. Samples were then dissolved to gelatine overnight in demineralised water (at 85 °C, pH = 3), filtrated to remove insoluble particles, and freeze-dried following Longin (1971). Extracts were then combusted to CO$_2$ with CuO and silver wool at 900 °C, allowing %C to be determined from gas pressure readings, and reduced to graphite for measurement on an HVE 3MV Tandetron 4130 accelerator mass spectrometer (AMS). Measured $^{14}$C/$^{12}$C ratios were corrected for fractionation using the simultaneously AMS-measured $^{13}$C/$^{12}$C isotope ratios to calculate conventional $^{14}$C ages (Stuiver and Polach 1977). The reported $^{14}$C age errors incorporate uncertainties in measurement, standard normalisation, instrumental background, blank correction, and additional uncertainty arising from sample pretreatment, based on long-term experience with laboratory standard and known-age samples of similar materials.

EA-IRMS analyses were conducted by GeoZentrum Nordbayern, Erlangen, and Scottish Universities Environmental Research Centre (SUERC), East Kilbride. At GeoZentrum Nordbayern, collagen was extracted from a bone fragment (minimum 250 mg), following a standard protocol (Becker and Grupe 2012). Well-preserved collagen samples were measured using a Flash EA 2000 elemental analyser connected online to a Thermo Finnigan Delta V Plus mass spectrometer, and $\delta^{13}$C and $\delta^{15}$N values were determined with a precision of 0.1‰ and 0.2‰, respectively. At SUERC, $\delta^{13}$C and $\delta^{15}$N were measured on a Delta V Advantage continuous-flow isotope ratio mass spectrometer coupled via a ConFloIV to an IsoLink elemental analyser (Thermo Scientific, Bremen), as described in Sayle et al. (2019), using IAEA reference materials USGS40 and USGS41a to normalise $\delta^{13}$C and $\delta^{15}$N values. Results are reported as per mil (‰) relative to the internationally accepted standards VPDB and AIR. Normalisation was checked using the marine collagen USGS88 and the well characterised Elemental Microanalysis IRMS fish gelatin.
standard B2215. $\delta^{13}C$ and $\delta^{15}N$ values were determined with a precision of 0.1‰ and 0.15‰, respectively.

Results

We report 16 new AMS $^{14}C$ dates measured on samples representing 16 individuals and supporting IRMS measurements of dietary stable isotopes ($^{15}N$, $^{13}C$) for 14 of these (Table 2). Collagen yields from the bones extracted for AMS dating were good (8–20%). A single apatite sample yielded 0.21% carbon, which is within the expected range for cremated bone (Rose et al. 2020). Collagen EA-IRMS results fall within expected ranges with mean $\delta^{13}C$ values ($−19.4\pm0.8‰$) and mean $\delta^{15}N$ values ($9.6\pm1.1‰$). All EA-IRMS samples gave satisfactory atomic C/N ratios, well within the commonly quoted range of 2.9–3.6 (DeNiro 1985). The EA-IRMS results are further discussed in Supplementary Information. The calibrated $^{14}C$ ages of the 16 dated burials span the entire calibration plateau c.750–400 cal BC (Bronk Ramsey 2009a; Reimer 2020). Individual calibrations dated burials span the entire calibration plateau c.750–400 cal BC.

Chronological modelling

These calibrated dates, and the prior information based on the burial sequence (cf. Figure 5), are incorporated in a Bayesian chronological model (Fig. 6). The exact code in OxCal v4’s Chronological Query Language (Bronk Ramsey 2009a) is provided in Supplementary Information. The $^{14}C$ age of bone collagen corresponds to the average date when atmospheric CO$_2$ was sequestered as organic carbon in the living organism, which may be offset from the date of death, depending on turnover rates in bone remodelling. This results in an increasing risk of significant intrinsic ages in bones from older individuals (e.g. Calcagnile et al. 2013). To allow for this risk, we apply a bespoke Intrinsic_age Outlier_Model (OM), based on the default Charcoal OM provided in OxCal (Bronk Ramsey 2009b; Dee and Bronk Ramsey 2014). The OM assumes that offsets follow an exponential probability density function, i.e. most samples will date close to the burial date, but a diminishing number of dates will be increasingly older (Nicholls and Jones 2001). As the age at death of most individuals has been estimated from anatomic evidence, we have scaled the prior probability of intrinsic-age offsets to age-at-death estimates. Although different mechanisms are involved, intrinsic-age offsets in cremated bone may have a similar statistical distribution (Rose et al. 2020). Sensitivity testing

To validate the preferred model output (Fig. 6), we tested the sensitivity of output to various model components. Initial modelling showed three burial sequences have higher posterior probabilities of being outliers: grave 9 sk. 5 (KIA-52053), the cremation burial (KIA-52056) from grave 10, and the secondary burial grave 28 sk. 1 (KIA-52063). The $^{14}C$ age of KIA-52053 is slightly too high for any date after 750 BC, but according to the burial sequence, it must date to HaD, so it is assumed that this is a measurement outlier (although it is impossible to exclude that in this case, there was a small dietary reservoir effect; see Supplementary Information). The three $^{14}C$ ages for grave 10 (KIA-52054—6) are statistically consistent, according to the method of Ward and Wilson (1978) ($T=0.8$, $T'(5%)=6.0$, $\nu=2$) and based on skeletal evidence, the two inhumations are exactly contemporaneous. As the grave 10 skeletons were undisturbed, the cremation is unlikely to be a later insertion; given its calibrated date, therefore, it is almost certainly contemporaneous with the inhumations. KIA-52063 (2388 ± 25 BP) is regarded as reliable, based on collagen yield and % carbon, but from the published records, it cannot be excluded that the dated bone was intrusive from a later phase of burial activity. However, KIA-52063 is almost compatible with single-year data points in IntCal20 in the early 650 s BC (659 BC: 2445 ± 11 BP; 658: 2442 ± 11; 657 BC: 2441 ± 11 BP; 656 BC: 2442 ± 11 BP; 655: 2444 ± 11 BP) (Reimer 2020), and with $^{14}C$ measurements on tree-rings from Oberhaid, c.130 km NW of Dietfurt an der Altmühl, included in IntCal20 (Fahrni et al. 2020; Park et al. 2017) (2407 ± 14 and 2416 ± 14 BP in 660 BC). As a secondary burial, it does not constrain the dates of primary burials in stratigraphically later graves, so regarding KIA-52063 as a measurement outlier from an individual who died in the early 650 s cal BC would have no measurable impact on the estimated date of the HaC-HaD transition at Dietfurt. In our model, we assume that the dated bone was intrusive and that it cannot be older than the primary burial, grave 28 sk. 2.

Satisfactory indices of agreement ($A_{model}=73$, $A_{overall}=71$, Table 3) (Bronk Ramsey 2009a) show that the calibrated dates are compatible with the archaeological prior information incorporated in our preferred chronological model. The Intrinsic_age OM posterior distribution implies offsets of between 1 and 13 calendar years (95.4% probability), which is within the expected range of intrinsic age in human bone. The model suggests that all the dated individuals (except perhaps grave 28 sk.1) were buried in the seventh century cal BC (Fig. 6, Table 3), and strongly favours an earlier seventh century date for the HaC-HaD transition (Fig. 7).
Table 2  AMS (\(^{14}\)C) and EA-IRMS (\(\%\)C, \(\%\)N, \(\delta^{15}\)N, \(\delta^{13}\)C) results from Dietfurt an der Altmühl ‘Tennisplatz’. Unless indicated otherwise, each sample consisted of an unburnt human bone, from which collagen was extracted for dating or stable isotope analysis.

| Sample ID | AMS lab no | AMS sample                  | % collagen | \(\delta^{13}\)C (AMS) | \(^{14}\)C age (BP) | IRMS lab no | IRMS sample   | \(\delta^{15}\)N (‰AIR) | \(\delta^{13}\)C (‰VPDB) | \(\%\)C (IRMS) | \(\%\)N (IRMS) | C/N |
|-----------|------------|-----------------------------|------------|--------------------------|---------------------|-------------|--------------|--------------------------|--------------------------|----------------|--------------|-----|
| Grave 9 primary burial\(^1\) | KIA-52065   | Animal bone                 | 11.8       | −22.5                    | 2476±18             | GuSi1 1930   | Animal bone\(^2\) | 6.6                      | −21.5                    | 41.7           | 15.3         | 3.2 |
| Grave 9 sk. 1 | KIA-52050   | Radius diaphysis            | 8.9        | −19.0                    | 2490±35             | Dt1          | Pubic bone    | 9.7                      | −19.9                    | 26.7           | 9.4          | 3.3 |
| Grave 9 sk. 2 | KIA-52051   | Metacarpal                  | 13.0       | −18.3                    | 2478±25             | Dt2          | Iliac bone    | 9.3                      | −18.9                    | 34.7           | 13.9         | 2.9 |
| Grave 9 sk. 4 | KIA-52052   | Iliac bone                  | 12.8       | −19.8                    | 2511±24             | GuSi1 1925   | Iliac bone\(^2\) | 9.6                      | −20.3                    | 42.5           | 15.0         | 3.3 |
| Grave 9 sk. 5 | KIA-52053   | Metacarpal                  | 11.3       | −20.7                    | 2556±25             | GuSi1 1926   | Metacarpal\(^2\) | 10.8                     | −19.1                    | 42.2           | 15.3         | 3.2 |
| Grave 10 sk. 1 | KIA-52054   | Phalanx from hand           | 17.5       | −19.6                    | 2426±26             | Dt5          | Metacarpal    | 8.9                      | −19.9                    | 27.3           | 10.3         | 3.1 |
| Grave 10 sk. 2 | KIA-52055   | Metatarsal                  | 18.2       | −18.4                    | 2440±22             | GuSi1 1927   | Metatarsal\(^2\) | 11.0                     | −18.8                    | 42.9           | 15.5         | 3.2 |
| Grave 10 CB | KIA-52056   | Long bone diaphysis         | -          | −18.9                    | 2410±26             | -            | -            | -                        | -                        | -              | -            | -   |
| Grave 11    | KIA-52057   | Metacarpal                  | 19.5       | −18.7                    | 2489±27             | Dt7          | Tarsal bone   | 10.3                     | −19.1                    | 37.3           | 13.7         | 3.2 |
| Grave 12    | KIA-52058   | Phalanx from hand           | 8.4        | −18.6                    | 2517±30             | GuSi1 1928   | Phalanx from hand\(^2\) | 10.8                     | −19.1                    | 41.4           | 15.1         | 3.2 |
| Grave 14    | KIA-52059   | Phalanx from foot           | 18.7       | −18.5                    | 2477±25             | Dt9          | Metatarsal    | 8.8                      | −19.1                    | 33.9           | 13.1         | 3.0 |
| Grave 17 sk.1 | KIA-52060   | Phalanx from hand           | 18.4       | −18.9                    | 2530±25             | GuSi1 1929   | Phalanx from hand\(^2\) | 10.7                     | −19.0                    | 41.5           | 15.2         | 3.2 |
| Grave 17 sk. 2 | KIA-52061   | Metatarsal                  | 14.4       | −18.9                    | 2485±28             | Dt11         | Metatarsal    | 9.7                      | −19.1                    | 26.8           | 9.9          | 3.2 |
| Grave 17 sk. 3 | KIA-52062   | Phalanx from foot\(^3\)    | 17.9       | −18.1                    | 2539±22             | -            | -            | -                        | -                        | -              | -            | -   |
| Grave 28 sk. 1 | KIA-52063   | Metacarpal                  | 24.0       | −17.6                    | 2388±25             | Dt12         | Metacarpal    | 9.7                      | −18.6                    | 40.1           | 15.4         | 3.0 |
| Grave 28 Sk. 2 | KIA-52064   | Metacarpal                  | 17.3       | −19.7                    | 2484±22             | Dt13         | Distal ulna   | 9.1                      | −18.8                    | 34.4           | 13.1         | 3.1 |

\(^1\)Human bone not located but substituted with animal bone from the same stratum

\(^2\)Sample split for AMS and EA-IRMS analyses

\(^3\)Un-cremated bone from uncertain context was sampled and dated for the present study
Sensitivity testing is particularly important here due to the relatively small number of individuals and contexts dated, and the tight constraints imposed by the stratigraphic sequence. $^{14}$C measurement scatter or misinterpretation of archaeological findings could be more influential than if each phase was represented by a significant number of independent dates. Extensive sensitivity testing successfully demonstrates the preferred model output to be accurate and reproducible, however. Full details are given in Supplementary Information.

Sensitivity testing covered the following aspects:

- Prior information. We tested the influence of prior information on the model output by using the real $^{14}$C ages but including different prior information. Given the stratigraphic and artefactual evidence, the chronological order of dated primary burials is not in doubt, but the relative dates of some of the dated secondary burials may be questioned, as may our assumption that additional burials must have taken place within 5–100 years of
the primary burial. Easing the sequencing constraints on secondary burials or removing the time gap constraints between reburials has no visible impact on model output. Omitting the date of the undocumented grave 17 sk. 3 sample (KIA-52062) has no visible impact on model output. Including or omitting any of the three possible 14C outliers (KIA-52053, 52,056, 52,063) affects overall indices of agreement, but does not affect the conclusion that the HaC-HaD transition fell in the earlier seventh century BC. Our model assumes that the Dietfurt HaC-HaD transition is an event within the overall HaC-HaD transition process, whose chronology is also constrained by dendrochronological dating at other sites (Fig. 4). Without this assumption, the Dietfurt 14C evidence would also permit a later 8th-century transition date, although an earlier 7th-century date would remain more probable.

- Reproducibility. Given the relatively small number of dated burials and the flatness of the calibration curve in this period, stochastic variation (14C measurement scatter) might be an important determinant of model output. This can be tested by repeatedly simulating 14C ages with similar precision to the real measurements. If the simulated samples are assigned calendar dates equivalent to the median posterior dates in the preferred model output, the output appears to be reproducible: the HaC-HaD transition distribution has a similar shape and peak to that of the preferred model (Fig. 8) and overall agreement remains satisfactory.

- Calendar date. We can easily simulate the model output on a different section of the calibration curve, by adding a constant to the sample median dates from the preferred model, and using these calendar dates to simulate new 14C ages. In particular, given the calibration plateau and absence of dendrochronological dates between c.680 and 616 BC, it is important to replicate the model shifted up to 75 years later. This should also shift the estimated date of the HaC-HaD transition later; if not, the relatively early estimate given by the Dietfurt preferred model may be unreliable. Figure 8 shows that shifting the entire chronology 25 years, 50 years, or 75 years later always provides later estimated dates for the HaC-HaD transition, which means that the relatively early estimated date for the HaC-HaD transition at Dietfurt should be accurate. Had the real transition date at Dietfurt been even 25 years later than indicated by the preferred model output (Fig. 7), the model would be able to show it.

Table 3 Posterior density estimates from preferred chronological model of Dietfurt an der Altmühl ‘Tennisplatz’ (Fig. 6)

| Model parameter                                      | AMS lab no | Probability ranges cal BC | Agreement index | Outlier probabilities |
|------------------------------------------------------|------------|---------------------------|-----------------|-----------------------|
|                                                      |            | 68.3% 95.4%               | Prior Posterior |
| Boundary start of dated burial sequence              | -          | 722–669 772–665           | - - -           |
| Date Dietfurt_HaC_D_transition                       | -          | 685–655 728–651           | - - -           |
| Boundary end of dated burial sequence                | -          | 672–569 678–543           | - - -           |
| Grave 9 primary burial 1                             | KIA-52065  | 671–650 724–647           | 93 0 0          |
| Grave 9 sk. 1                                        | KIA-52050  | 664–617 703–603           | 112 20 20       |
| Grave 9 sk. 2                                        | KIA-52051  | 664–621 706–604           | 110 50 50       |
| Grave 9 sk. 4                                        | KIA-52052  | 636–592 686–573           | 115 0 0         |
| Grave 9 sk. 5                                        | KIA-52053  | 678–593 684–575           | 37 20 19        |
| Grave 10 sk. 1                                       | KIA-52054  | 660–650 716–643           | 83 20 21        |
| Grave 10 sk. 2                                       | KIA-52055  | 660–650 716–643           | 118 20 20       |
| Grave 10 CB                                          | KIA-52056  | 660–650 716–643           | 50 100 100      |
| Grave 11                                             | KIA-52057  | 695–661 741–657           | 99 20 20        |
| Grave 12                                             | KIA-52058  | 652–623 706–604           | 91 20 18        |
| Grave 14                                             | KIA-52059  | 705–663 748–661           | 108 20 20       |
| Grave 17 sk. 1                                       | KIA-52060  | 676–590 683–567           | 103 20 20       |
| Grave 17 sk. 2                                       | KIA-52061  | 644–607 695–583           | 115 20 20       |
| Grave 17 sk. 3                                       | KIA-52062  | 684–596 766–574           | 84 20 19        |
| Grave 28 sk. 1                                       | KIA-52063  | 477–401 539–398           | 104 10 10       |
| Grave 28 Sk. 2                                       | KIA-52064  | 710–665 756–663           | 100 10 10       |

1 Human bone not located but substituted with animal bone from the same stratum
2 Un-cremated bone from uncertain context was sampled and dated for the present study
Discussion

The chronology of Hallstatt burials at Dietfurt an der Altmühl ‘Tennisplatz’

The chronological model’s estimated start and end dates (Fig. 6) are unlikely to be representative of the full time span of burial activity at Dietfurt ‘Tennisplatz’, as all the sampled burials were in a small and specific part of the site, where burial activity began in the late 8th or early seventh century cal BC and ended in the late 7th or early sixth century cal BC (Fig. 6, Table 3, Boundaries start of dated burial sequence and end of dated burial sequence). The model provides absolute dates for artefact types typically used as leading types, which bears significance far beyond Dietfurt. The dates of grave 14, grave 9 sk. 1, and grave 12 are of particular interest, as they contain well-defined metal objects with a widespread regional (grave 12) or even supra-regional distribution (grave 14; 9 sk. 1). In each case, the burial date provides a terminus ante quem for the start of production of the artefact types in question (Fig. 9). Grave 14 contained, among other items, a rein ring (German: Zügelring) and a bridle with imitated torsion as part of the horse harness. Trachsel (2004) (353 cat. BAY 021/04) placed this grave in his sub-phase ‘HaC2 early’; our model dates the burial to 705–663 cal BC (68.3% probability). Grave 9 sk. 1 was buried with a fibula with loop (type S4 ‘Schlangenfibel’) and a plain belt plate, which following the first chronological subdivision by Zürn (1942) are leading types for sub-phase HaD1 north of the Alps. Our model dates the burial to 664–617 cal BC (68.3% probability). Grave 12 contained a neck ring, a
spiral fibula, and a melon ring, which are also considered leading types for sub-phase HaD1, only instead in northern Bavaria. Our model dates this burial to 652–623 cal BC (68.3% probability).

Most importantly, the model shows that the HaC-HaD transition at Dietfurt probably occurred in the second quarter of the seventh century (685–655 cal BC at 68.3% probability), and almost certainly before 650 cal BC (> 98% probability), several decades earlier than is usually assumed. However, Kern et al. (2021) have dated an HaC2 tumulus in Hungary by wiggle-matching a floating oak dendrochronology, obtaining an estimated felling date of (not before) 735–695 cal BC (95% probability), which is also significantly earlier than expected. Archaeological periodisation can have important consequences for interpretations of changes in the past, especially if the periodisation is relatively fine-grained as the Hallstatt chronology. This paper demonstrates that the HaC-HaD occurred 40–70 years earlier at Dietfurt an der Altmühl than the traditional transition date of 616 BC, which naturally raise questions regarding the implications of such a significant change. Will the chronological framework have to be shifted by several decades or do the results rather demonstrate considerable temporal differences in the adoption of cultural development in southern Germany? Shifting the chronological framework will significantly shorten HaC to about a century and in turn extend HaD to about two centuries, whereas HaC and HaD are currently divided equally in two halves, each lasting about 160 years parts. This will potentially have great influence on population estimates when the number of graves or settlements are scaled to the length of the relevant time period (Müller-Scheefel 2007). Extending the HaD period might also extend Ha D2 that is traditionally supposed to last only 25 years, which results in a suspicious peak in settlement intensity around Heuneburg in southern Germany (Nakoinz 2017). Further investigation of the Hallstatt chronology is however needed, with particular attention not only to the timing of events and cultural developments north and south of the Alps but also to other chronologies that might be used for cross-referencing, such as the Mediterranean chronologies.

### Implications for Bayesian chronological modelling on the Hallstatt plateau

Is it possible to produce accurate, precise, and reproducible chronologies on the Hallstatt plateau? As suggested by Meadows et al. (2020), we often cannot rule out bimodal or multimodal solutions for individual dates, despite detailed stratigraphic sequence, without long-lived samples such as tree-ring wiggle-matches (Manning et al. 2018) or other constraints on date differences between contexts, such as archaeogenetic kinship (Meadows et al. 2020). Such constraints are seldom available, but it should be remembered that the inclusion of single-year calibration data in IntCal20 permits wiggle-matching of shorter tree-ring sequences than can be dated dendrochronologically (e.g. 30–40 years) (Jacobsson et al. 2018). Also, a wiggle-matched terminus post quem date (for a timber with missing outer rings) may still eliminate some of the potential burial dates suggested by multimodal calibrations. An import from the Mediterranean world, whose production date is constrained by semi-historical evidence (Sacchetti 2016), can likewise provide a terminus post quem in a Bayesian model.

Informative prior information constraining the temporal order of $^{14}C$ samples is more common. In the Dietfurt case study, there is a construction sequence of burial chambers, and depositional sequences within burial chambers. It was therefore unnecessary to use grave-good seriation to reveal the sequence of burials, but seriation of Hallstatt grave assemblages does appear to provide accurate burial sequences (Müller-Scheefel 2009). For adult humans, it is also possible to date two (or more) $^{14}C$ samples: a bone which is remodelled continuously throughout life and a tooth or petrous bone which has a negligible collagen turnover rate, and therefore dates to childhood. This provides both a strict date sequence for the two samples, and an approximate date difference between them, depending on the estimated age at death (Chmielewski et al. 2020).

One further tool for refining archaeological chronologies in this period may be the Miyake event in c.660 BC (O’Hare et al. 2019). Short-lived samples dating to this event, such as animal bones and archaeobotanical remains, might be

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**Fig. 9** Estimated burial dates of graves from Dietfurt an der Altmühl containing well-defined metal objects with a widespread regional or supra-regional distribution (see text). The probability density functions of the simple calibrated dates are shown in outline and the posterior density estimates as estimated by chronological model (Fig. 6, Table 3) are shown in solid.

| KIA-52050 grave 9 sk.1 | KIA-52058 grave 12 | KIA-52059 grave 14 |
|------------------------|---------------------|---------------------|
| 900                    | 800                 | 700                 |
| 600                    | 500                 | 400                 |

| Modeled date (BC) | 900 | 800 | 700 | 600 | 500 | 400 |
|------------------|-----|-----|-----|-----|-----|-----|
| KIA-52050 grave 9 sk.1 |     |     |     |     |     |     |
| KIA-52058 grave 12 |     |     |     |     |     |     |
| KIA-52059 grave 14 |     |     |     |     |     |     |
incorrectly dated to the fifth century cal BC (although probably not adult human bones, as slow remodelling means that the $^{14}$C age of bone integrates atmospheric $^{14}$C levels over several years or even decades (Calcagnile et al. 2013)). Finding this event in a floating tree-ring sequence could provide the equivalent of dendrochronological precision for a $^{14}$C wiggle-match; finding it in e.g. the tooth of an adult human whose bones were also dated would date this individual almost as precisely. The benefits of the IntCal20, in comparison to IntCal13, would be greater if the burial sequence from Dietfurt was dated on annual samples, rather than predominantly on adult bone. The higher resolution of IntCal20 does, however, enable a better fit between the calibration data and the calibrated $^{14}$C dates.

**Conclusion**

Although model estimates of the dates of many burials remain bimodal or multimodal, due to a lack of long-lived dating material such as timber suitable for $^{14}$C wiggle-matching, our model shows unequivocally that the Hallstatt C-D transition at Dietfurt an der Altmühl ‘Tennisplatz’ took place at least several decades earlier than expected on the basis of traditional archaeological chronologies. If we combine the Dietfurt $^{14}$C evidence with dendrochronological dating at other sites in the region, the HaC-HaD transition at Dietfurt is likely to have occurred between 685 and 655 cal BC (68.3% probability). This estimate overlaps with the latest dendrochronological felling date ranges (normally attributed to Hallstatt C assemblages, from sites in west and southwest Germany, suggesting that if the HaC-HaD transition occurred gradually, it may have started in the southeast and spread westwards. A significant gap (c.40–65 years) would remain between the Dietfurt transition date and the earliest Hallstatt D dendro date, from Magdalenenberg in southwest Germany, which may be due to a gap in research, a genuine time-lag, or a combination of these factors. We also have to take into account that individuals might be buried with items they received in their youth. Trachsel (2004: 149ff) specifically discussed this possibility in relation to the 40+ aged individual in the central chamber of the ‘Magdalenenberg’.

This study is probably the first to attempt to refine the Early Iron Age chronology of southern Germany using Bayesian chronological modelling of $^{14}$C dates. It shows that in the right circumstances, the improved precision of calibrated dates, provided by better laboratory measurement precision and the inclusion of single-year calibration data in IntCal20, combined with detailed stratigraphy, allows us to test longstanding beliefs about the timing and pace of changes in material culture. The Dietfurt case study demonstrates that we are on the cusp of an important stage in research, when it will become possible to re-examine the mechanisms of change in proto-historic Europe using realistic chronologies based on scientific methods.

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Christian Hamann: writing — original draft, writing — review and editing

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