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AN 11,000-YEAR GERMAN OAK AND PINE DENDROCHRONOLOGY FOR RADIOCARBON CALIBRATION

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INTRODUCTION

Sequences of dendrodated tree rings provide ideal sources for radiocarbon calibration. The wood structure of trees consists of continuous series of annual growth layers, the carbon content of which can be ^{14}C-dated and calibrated to calendar yr. The cellulose and lignin of trees deposited in river gravels or peat-bog sediments below the water table are often very well preserved, even after several millennia. Such tree-trunk deposits are well protected from contamination by younger or older organic materials. Further, the physical and chemical structure of wood allows a strong chemical pretreatment of samples for ^{14}C analysis.

A further advantage of the German oak and pine tree-ring series for ^{14}C calibration is the fact that even single-yr wood samples can be prepared in amounts sufficient for ^{14}C analysis. In this respect, the Hohenheim collection of more than 5000 subfossil, dated cross-sections is a unique source of ^{14}C calibration samples.

The establishment of the German Holocene oak dendrochronology required linking thousands of recent, historic and prehistoric tree-ring records through cross-dating. Aside from the US bristlecone pine, the Irish oak and the Göttingen German oak chronologies, the Hohenheim oak/pine chronologies are the only source for extended dendrochronological ^{14}C calibration measurements. Most of the calibration data presented within this volume are based on our German oak and pine sequences. Thus, a discussion of the validity of this record, focusing on critical links of the chronology, is given here.

Because of the remarkable length of the chronology and the great number of integrated tree-ring patterns, a detailed discussion of all the subsequent linkages would exceed page limitations. Thus, I will demonstrate the reliability of the chronology by presenting the replication of the Holocene master curve. The only valid proof of an absolute dendrochronology is the external replication by significant cross-dating of independently established tree-ring chronologies. In the case of the Hohenheim oak dendrochronology, this can be shown by cross-dating between the Rhine-Main-Danube river oak series, and by comparison with the Irish oak chronology.

Finally, it should be noted that the comparison between the radiocarbon calibration measurements on the German oak and those of US bristlecone pine and Irish oak represent valid corroborative tests; a dendrochronological mismatch between samples at any linkage of each chronology would be detected easily by offsets between the high-precision ^{14}C measurements. In this respect, the absence of anomalies in the ^{14}C intercalibration series, presented in this issue, provides evidence for the accuracy of both European and US dendrochronologies.

THE ESTABLISHMENT OF SUPER-LONG HOLOCENE CHRONOLOGIES

I have described elsewhere the history of dendrochronology with respect to radiocarbon age calibration (Becker 1992). Following the completion of the US bristlecone pine series (Ferguson 1969), research was begun in Ireland and Germany to construct super-long chronologies. After two decades of intensive field collection and laboratory analyses, three European Holocene oak series have been established:

1. Irish oak, Belfast: Present–5289 BC (Pilcher *et al.* 1984)
2. German oak, Göttingen: Present–6255 BC (Leuschner & Delorme 1988)
3. German oak, Hohenheim: Present–8021 BC

The Belfast group collected subfossil oak trunks from peat-bog deposits, whereas the Hohenheim Laboratory focused on subfossil river oaks from gravel deposits. Researchers from the Göttingen Laboratory used both river and bog oaks for their oak record. Two series, the Belfast Irish oak and the Hohenheim German oak chronologies, became important for radiocarbon age calibration.

THE HOHENHEIM GERMAN OAK CHRONOLOGY

The river oaks of the Hohenheim Laboratory were collected in gravel pits along the upper Rhine, Main and Danube Valleys, and from minor tributaries, such as the Neckar, Iller and Isar Rivers. The subfossil trunks are remnants of riparian Holocene oak forests (*Quercus robur*, probably also *Quercus petraea*). The trees were washed into the rivers by undercutting of meander banks and by erosion of larger river channels during floods. The eroded trees drifted into oxbow lakes, or were immediately deposited in river-channel gravels. Tree-trunk horizons of alluvial terraces were preserved below the water table for >10,000 yr (Becker 1982).

Growth ages of the riparian oaks are surprisingly short; 95% of the trees consist only of 150–400 tree rings. This is related to flood frequency on the alluvial plains. Regularly occurring floods, especially those with drifting ice during the spring, often must have destroyed floodplain forests. Evidently, Holocene river oak stands seldom grew longer than 300–400 yr without disturbance. This explains why >5000 subfossil tree trunks were needed for a continuous Holocene river oak chronology.

The connection of the river oak chronology with present oak series was achieved by using living trees and medieval framework timbers. Further, oak samples associated with the Early Medieval, Roman and Celtic periods in southern Germany became available through archaeological excavations. For the prehistoric part of the chronology, samples from the Bronze Age and Neolithic dwelling sites of Switzerland and southern Germany were used (Becker *et al.* 1985).

For several years before its final linkage, the Hohenheim oak chronology consisted of three parts, namely, the absolute master (to 4000 BC), the middle Holocene floating master (4000 BC–7200 BC), and the earliest part (Main 9 chronology, before 7200 BC). The linkages at 4000 BC and 7200 BC, and a period of lower replication at 6200 BC, are described in detail below. For the present stage of the Hohenheim chronology, >95% of the past 9900 yr are replicated by a minimum of 15–25 cross-dated samples, which is sufficient for significant and reliable cross-dating among the individual curves of the master chronology (see Fig.1).

A first maximum of cross-matched curves occurs during Medieval times. This peak of replication results from numerous dendrodatings of historical buildings in southern Germany. Further maxima exist during AD 700–500, and AD 250–300 BC. Both result from the coincidence of an increased number of oak timbers from archaeological sites and a remarkable number of tree deposits from Late Holocene floods; the floods were induced by widespread forest clearing during Roman times and by Early Medieval settlement activities (Becker 1982). The prehistoric peaks of replication at 1900–2100 BC and at 2400–2600 BC are caused exclusively by increased flooding during the Late Neolithic and Early Bronze Age.

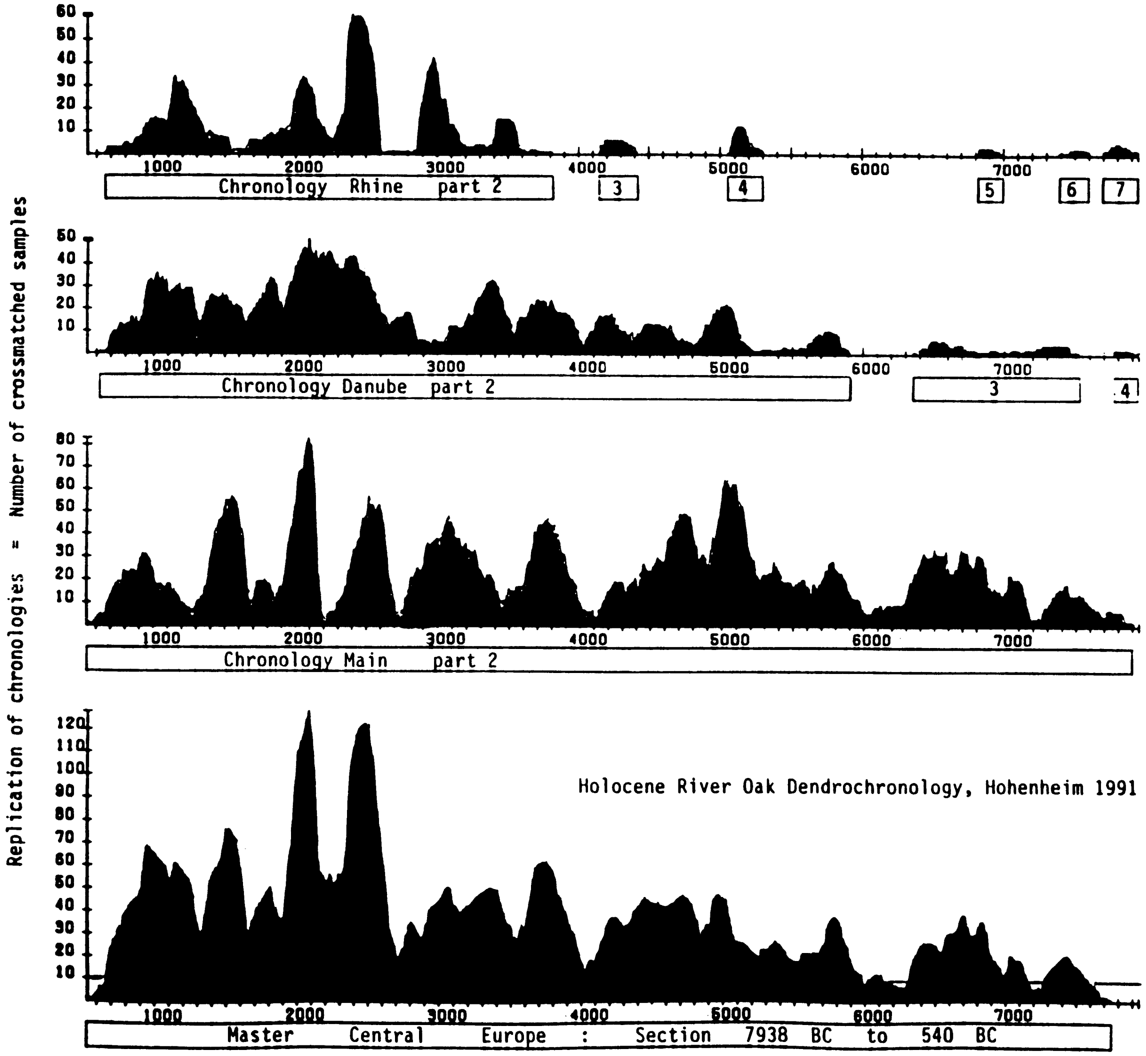

Fig. 1. Replication of the central European oak dendrochronology of the Hohenheim Tree-Ring Laboratory. Shown here is the number of individual samples at each year of the chronologies. The Hohenheim master chronology (bottom) results from matches of the regional series of the Rhine, Main and Danube Rivers, and the series of historical and prehistorical sites in south-central Europe. With the exception of the 6th century BC, the German oak dendrochronology exceeds, at each point, a minimum of 15 cross-dated individual oak samples.

Periods of low replication occur within the Hohenheim oak dendrochronology at 500 BC, 6200 BC and 7200 BC. The only critical linkage of the Hohenheim oak chronology, however, is the "Hallstatt-link" at 500 BC.

The Bridging of the Hallstatt Oak Chronology

The gap in the Hohenheim river oak chronology during the later part of the Hallstatt period exists even after 20 years of intensive field sampling, and is still unexplained. On the one hand, continuous overlapping older oak sequences (and in the oldest part, pines) show a unique continuity of flooding events over the entire Holocene. The exception to this is the lack of evidence for tree accumulation in river gravels in south-central Europe between 540 BC (the latest accumulation date

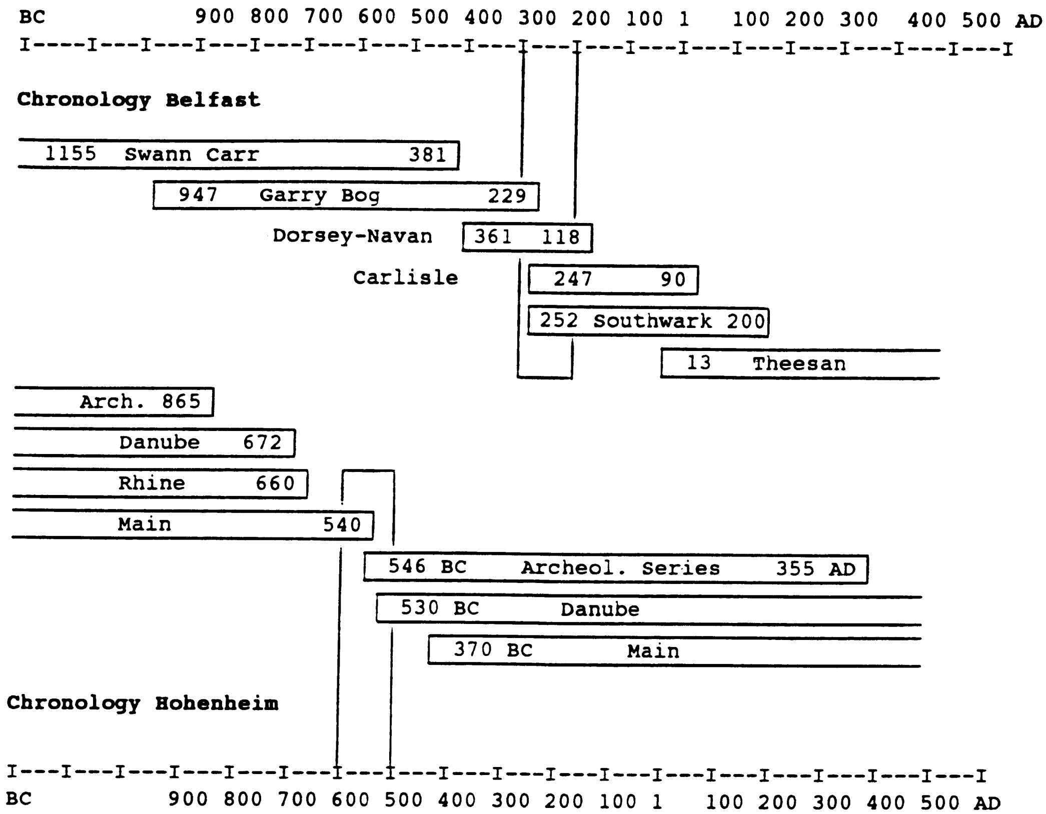

Fig. 2. Linkage of the Hohenheim German oak and the Belfast Irish oak chronologies of the first millennium BC, as published in Pilcher *et al.* (1984). The critical periods at 600–500 BC (German oak) and 300–200 BC (Irish oak) are confirmed by significant cross-datings between both series after their internal linkages (see also Becker *et al.* 1985).

from the Lahn River) and 382 BC (the earliest accumulation date of a series of subfossil trees at the Danube). Because of this lack of evidence, a 10-yr gap in the subfossil river oak series occurs from 540 to 530 BC (see Fig. 2).

Unfortunately, this small gap coincides with a period when finds of archaeological oak samples in southern Germany are also very rare. The early Hallstatt oak samples from archaeological sites end at 684 BC, but the tree-ring curves of the hitherto earliest dendrodated La Tène oak constructions do not start before 546 BC. However, this archaeological series (Thielle, Switzerland) overlaps the prehistoric river oak chronology between 546 and 540 BC. Of course, the resulting six-year link was too short to be detected visually or by cross-dating, but was confirmed in cooperative efforts with the Belfast and Köln laboratories by successful stepwise linkages of German and Irish oak series of the first millennium BC. Figure 2 shows the original overlap among the Hohenheim and Belfast series, and the evidence for the cross-dating by stepwise validation among the master series is indicated by t-test values (see Baillie & Pilcher 1982). The Belfast and Hohenheim chronologies cross-date over 5174–115 BC with a t-value of 7.3.

The Neolithic Linkage at 4000 BC

In 1985, the Hohenheim master chronology was extended to 4089 BC. This was important for determining the absolute chronology of prehistoric lake and bog dwelling sites north of the Alps;

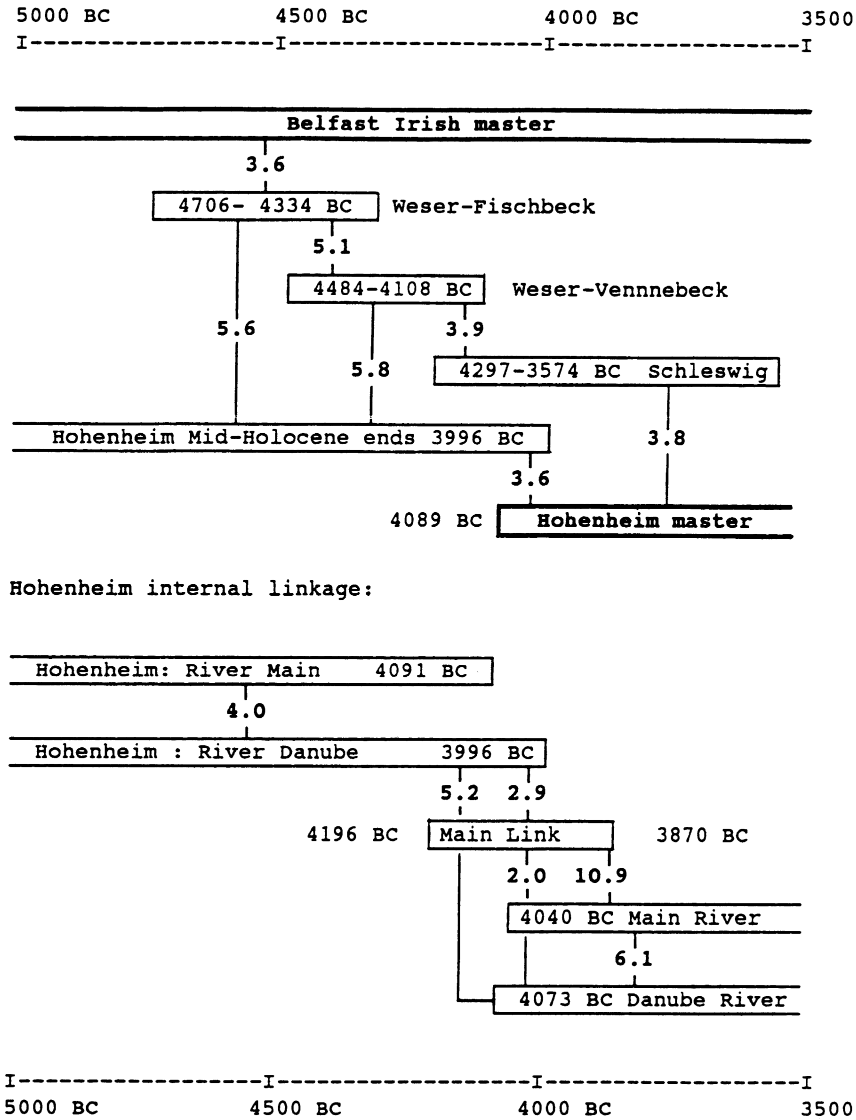

Fig. 3. Linkage of the Hohenheim middle Holocene oak master at 4000 BC. For the first time, the linkage was achieved by stepwise cross-datings among the northern German oaks (Köln) with both the Irish master and the southern German oaks (top). In its actual stage, the Hohenheim master, at 4000 BC, is internally confirmed by a new link of oaks from the Main River, reaching from 4196 to 3870 BC (bottom). The numbers between the blocks show the t-test values of the cross-matches.

it allowed the dendrodating of nearly 100 Neolithic and Bronze Age dwelling settlements of the period 3900–800 BC (Becker *et al.* 1985).

At this stage, a floating mid-Holocene oak sequence also existed, which covered 3242 tree rings (after linkage with the master, this sequence dated from 3996 to 7237 BC). This series was used for calibration measurements by the La Jolla, Seattle and Heidelberg laboratories. Its absolute age was already precisely fixed in 1985 by calibration of its ^{14}C curve with the bristlecone pine ^{14}C curve (Linick, Suess & Becker 1985).

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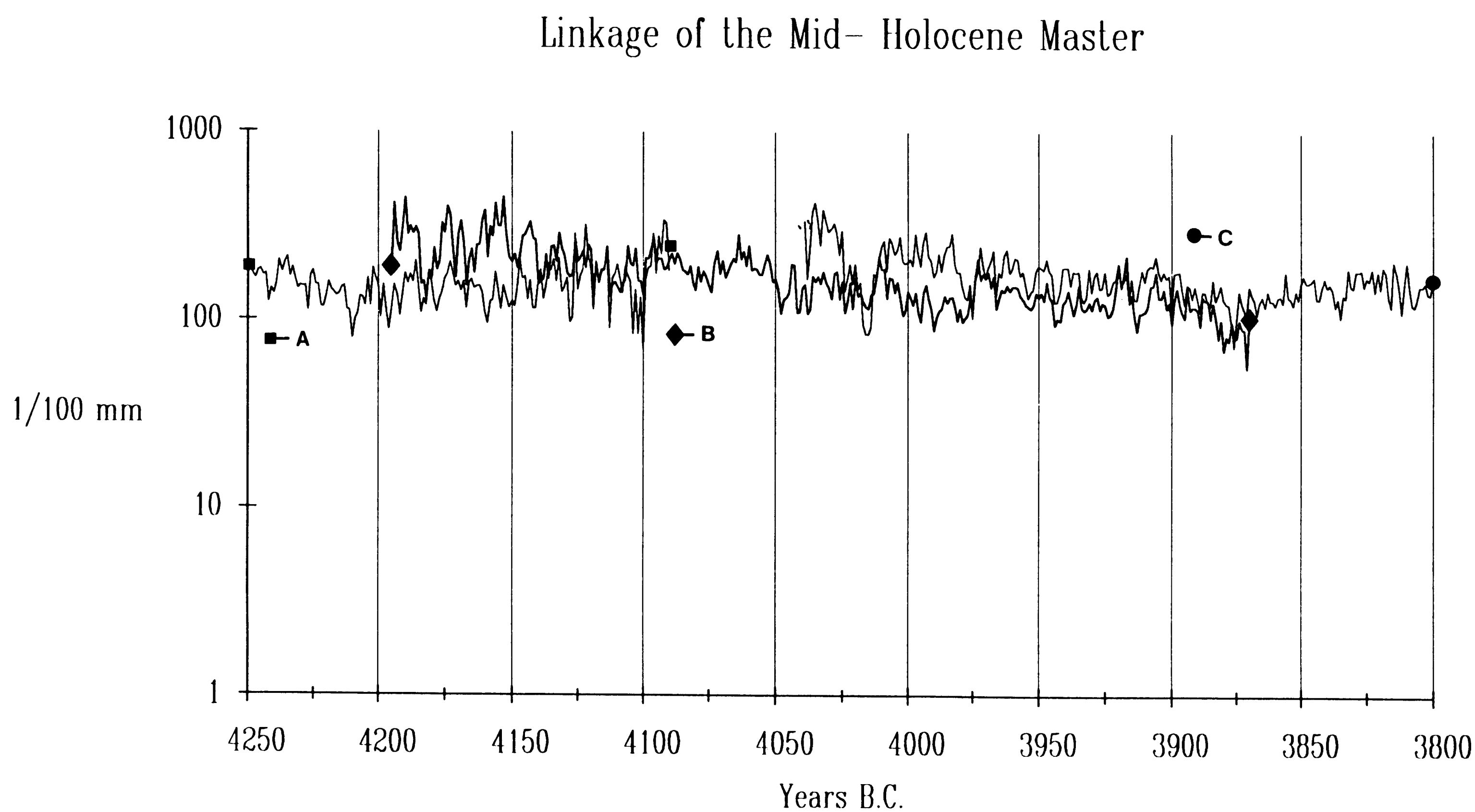

Fig. 4. Linkage of the middle Holocene oak master at 4000 BC. ■–A = end of the middle Holocene master; ◆–B = Link Main River oaks 4196–3870 BC; ●–C = Beginning of the absolute master (see also Fig. 3).

The first linkage of the middle Holocene chronology was again achieved in a cooperative project between the Köln and Hohenheim laboratories. As a result, the absolute German oak chronology was extended continuously back to 7237 BC (Becker & Schmidt 1990). The earliest part of the Köln floating Neolithic master (4706–3574 BC) cross-matches significantly with the Irish master (4706–4334 BC, t = 3.6, see Fig. 3). The Köln oak series was then linked with the end of the middle Holocene Hohenheim master (4706–3996 BC, t = 9.0), and with the beginning of the absolute Hohenheim chronology (4089–3574, t = 3.8). These stepwise cross-matches are confirmed by the final cross-match between the entire Köln Neolithic master, 4706–3574 BC, and the unbroken Hohenheim absolute master; for 1133 yr, the t-test value reaches 9.3.

Since these first successful linkages, the Hohenheim chronology of this part of the curve was further replicated. Figures 3 and 4 show the present status: the middle Holocene Main series (12 trees), ending at 4091 BC, overlaps the Main oak link (4196–3780 BC, 6 trees) with t = 5.2., and the start of the absolute Main sequence cross-matches with this link with t = 10.9. The linkage is also confirmed by the Danube oak series (22 middle Holocene oaks), which also overlaps the Main linkage at both ends. The final chronology, 4200–3900 BC, is now well replicated by at least 25 individual curves.

The Mesolithic Linkage of the Main 9 Chronology at 7200 BC

During the construction of the Hohenheim chronology, a further floating Holocene oak sequence (Main 9 series) was established. It is placed before the middle Holocene master. Before its final linkage, it was already the subject of ^{14}C calibration measurements (by H. E. Suess, La Jolla, B. Kromer, Heidelberg and M. Stuiver, Seattle). This series dates from before the range of the bristlecone pine. For many years, no age determination by ^{14}C calibration was available. After successful cross-match with the master, the sequence was dendrodated from 7751 to 7235 BC. The link was derived from two oaks (7339–7025 BC) which also overlap at the end of the Main 9 series and the beginning of the middle Holocene master, which was slightly enlarged to 7237 BC (see Fig. 5). The link cross-matches Main 9 with t = 5.4, and the beginning of the middle Holocene master with t = 4.4. This extension of the absolute master is also confirmed by two overlapping Danube oak series: 7464–7144 BC and 7195–6743 BC. The validity of this cross-match can be seen from the tree-ring curves of Figure 6.

In 1988, the German Holocene oak chronology was extended by very early oaks of the Main, Rhine and Danube Rivers, which date from the beginning of the Boreal period. This extension of the Boreal oak chronology extends the absolute German oak chronology to 7938 BC. During 1991 field sampling, we found three older oaks from the Main River floodplain, which cross-date with the beginning of the master, and extend the entire absolute master chronology to 8021 BC.

The 6200–6300 BC Linkage

A close look at the replication of the Hohenheim Holocene oak master chronology points to a period of decreased replication between 6200 and 6300 BC. The linkage of the Main oaks of this period can be subdivided into three well-replicated overlapping parts (see Fig. 7). The bridging series of 6402–6057 BC overlaps the end of the older chronology by 122 yr, and the younger chronology, by 131 yr. The corroborative tests yield significant t-values of 7.0 and 6.4, respectively (see also curves of Fig. 8).

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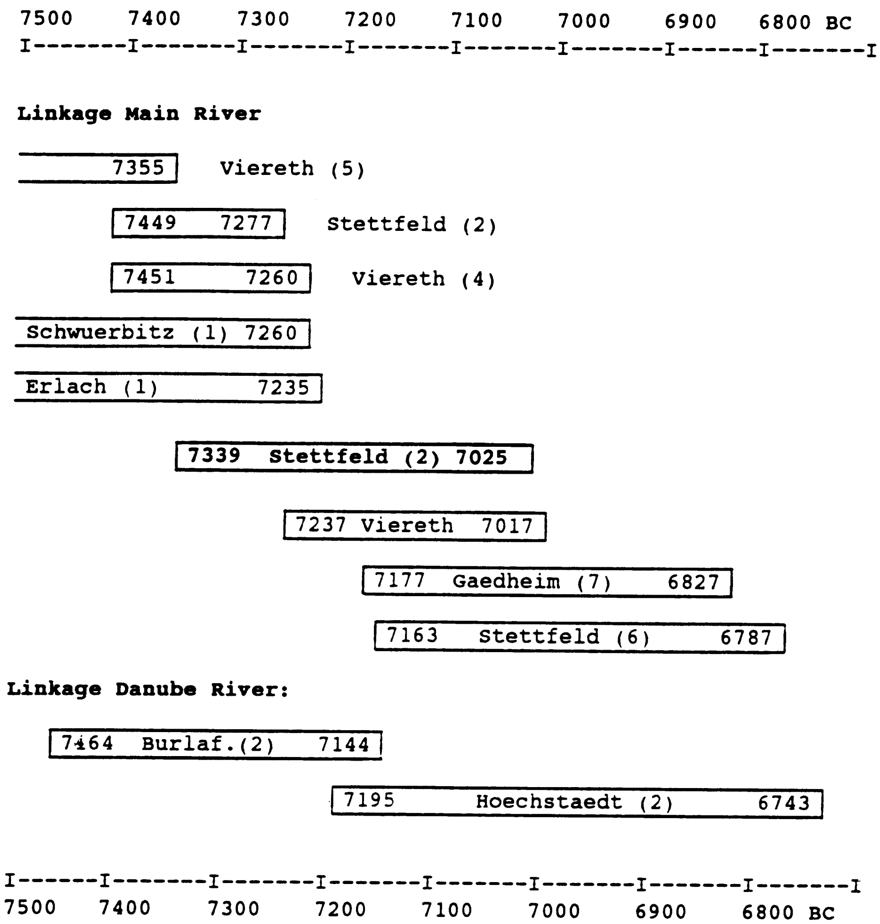

Fig. 5. Linkage of the Main 9 chronology with the absolute master at 7200 BC. Each block represents a site chronology, the numbers in parentheses refer to the replication of the series. The linking series consist of oaks from the Stettfeld site (Main), dating from 7339–7025 BC.

CONFIRMATION OF THE ABSOLUTE HOLOCENE GERMAN OAK CHRONOLOGY BY EXTERNAL REPLICATION

As mentioned above, the validity of a long dendrochronology can be evaluated best by replications between links that have been independently established by samples from different regions or from different sample sources. In the case of the Hohenheim oak chronology, valid cross-matches exist among the river oak chronologies of the Rhine, Main and Danube regions. Further, cross-matches exist between the river oak chronologies and the chronologies from historic to prehistoric oak constructions of south-central Europe. For example, the unbroken 2537-yr oak master curve of modern and Medieval to Iron Age samples (present to 546 BC) is replicated over 2211 yr by the stepwise overlapping river oak chronologies. In its prehistoric section, the 7482-yr unbroken regional series of the Main River (540–8021 BC) is replicated by 3 archaeological oak sample chronologies over 2602 yr, by 8 Rhine River oak series over 3885 yr, and by 5 Danube River oak series over 6440 yr (see Fig. 9).

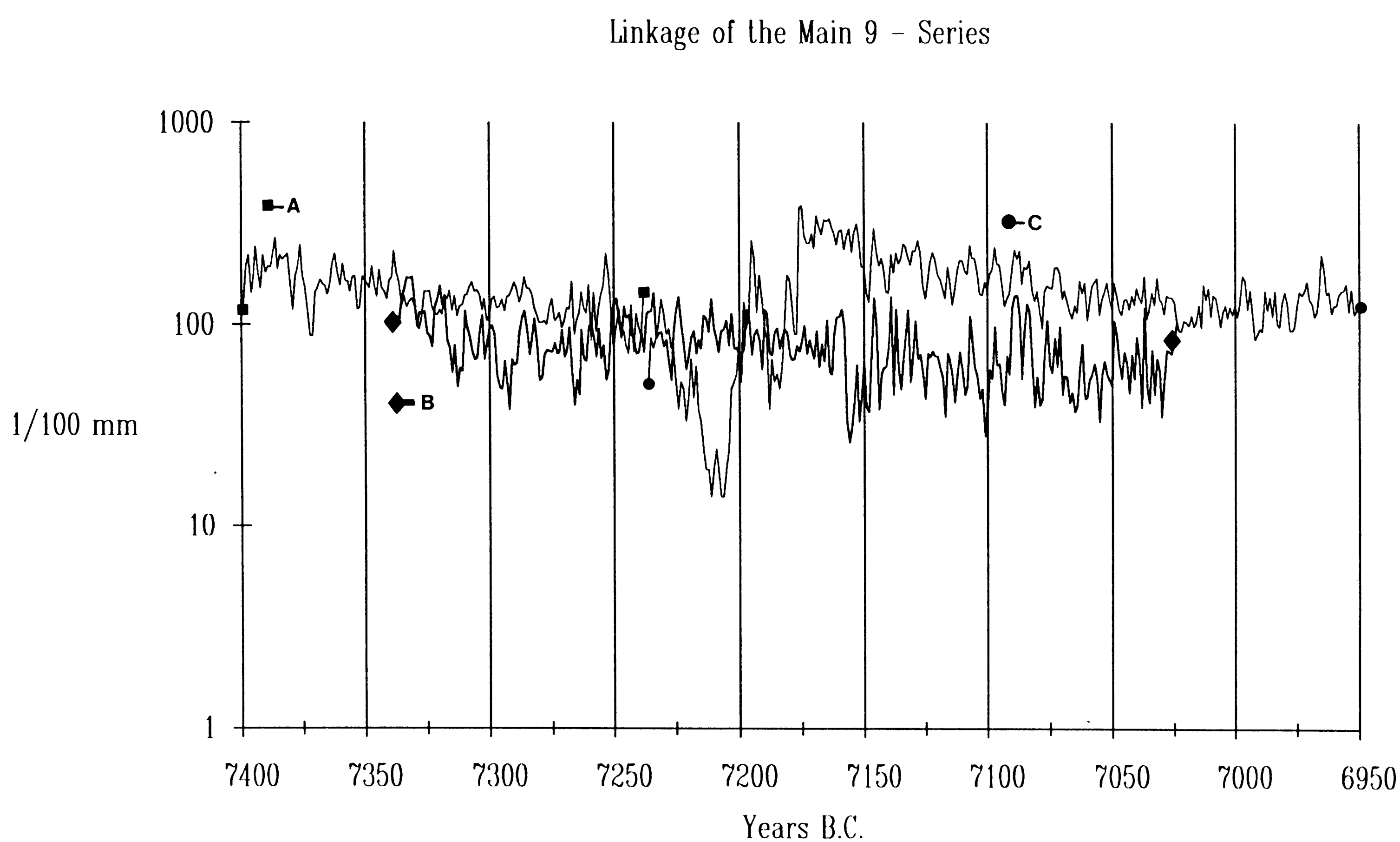

Fig. 6. Linkage of the Main 9 chronology at 7200 BC. ■-A = Main 9 series; ◆-B = Stettfeld link 7339–7025 BC; ●-C = beginning of the absolute master (see also Fig. 5).

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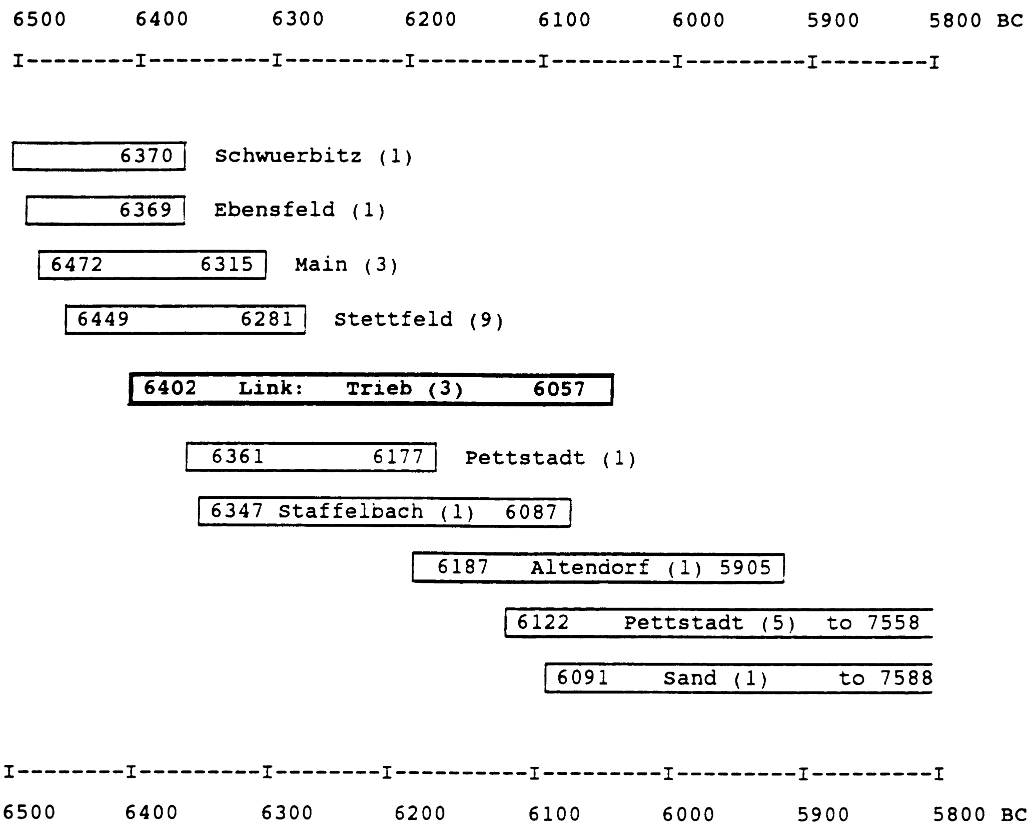

Fig. 7. Linkage at 6200 BC. The linkage consists of three oaks of the Trieb site, dating from 6402–6057 BC, which overlap the older part by 121 yr and the younger part by 131 yr.

THE EARLY HOLOCENE–LATE GLACIAL GERMAN PINE CHRONOLOGY

Along the Danube and Rhine rivers, remnants of well-preserved pine trunks (*Pinus sylvestris*) are frequently dredged from river gravels, along with oaks. When the first ^{14}C dates of H. E. Suess (unpublished data) attributed a surprisingly old age to these pine trees, I started collecting both pines and oaks. This project led to the construction of an unbroken 1768-yr floating late Younger Dryas and early Holocene pine chronology, as well as a 405-yr Allerød pine series.

The subfossil pines are remnants of Late Glacial forests, where both pine and birch (*Betula verrucosa*, *B. pubescens*) covered the central European valley plains. Pines disappeared when oaks entered the river valleys, displacing the light- demanding pine/birch forests. However, before pines vanished from the Holocene Danube and Rhine valleys, a mixed pine/oak forest must have existed. The temporal overlap of pine and oak trunk deposits of that period provided a unique opportunity to extend further the absolute dendrochronology.

First, we have linked 185 subfossil pines to an unbroken floating record of 1605 tree rings. This sequence crosses the boundary between the early Holocene and the Late Glacial, a boundary recently detected in ^{13}C and ^{2}H records of pine tree-ring cellulose (Becker, Kromer & Trimborn 1991). We derived an absolute minimum age of 11,370 dendroyr BP for the beginning of the pine sequence by linking the end of the pine series with oak at the 8800 BP ^{14}C oscillation, which is visible in both series (Kromer & Becker 1992).

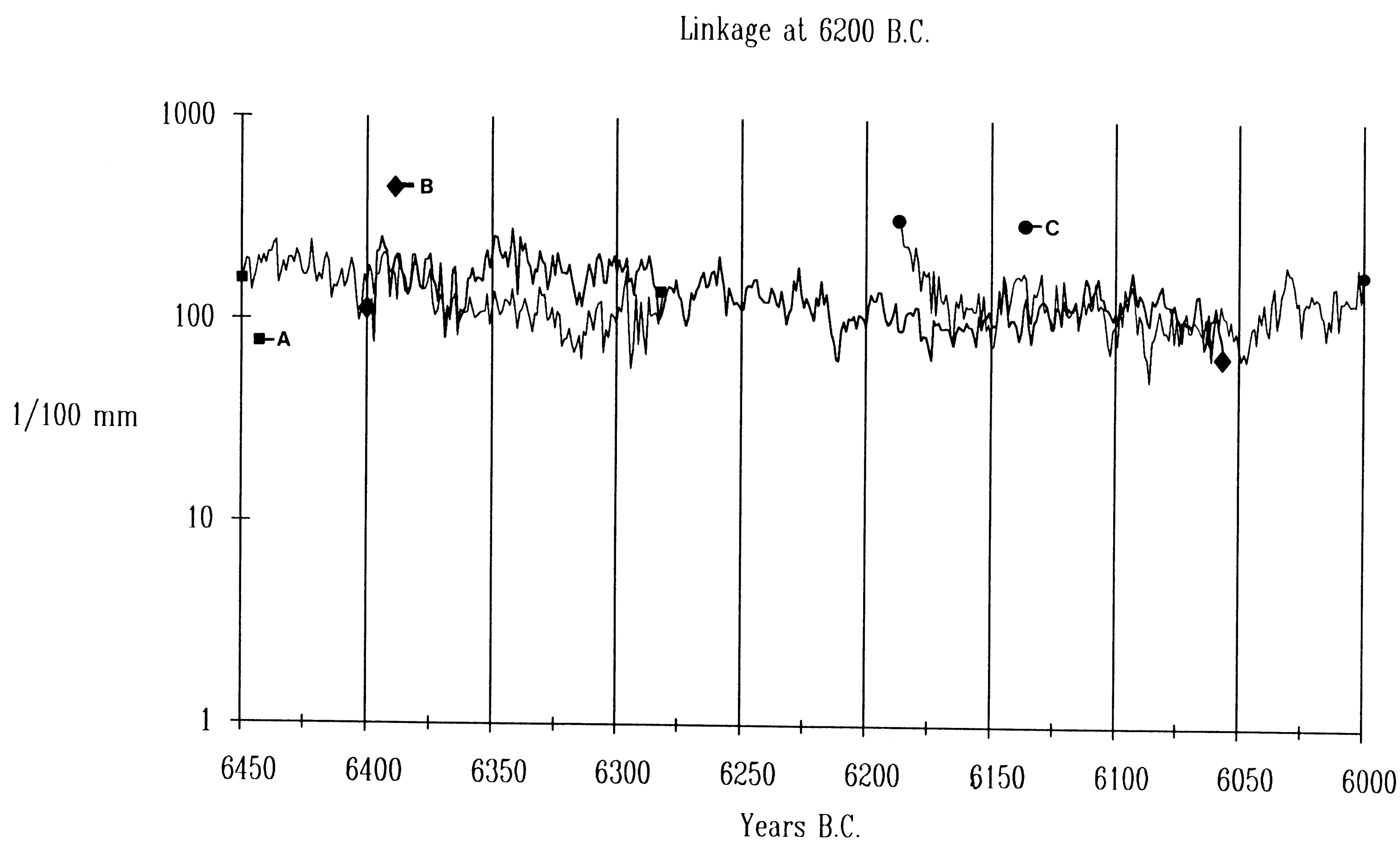

Fig. 8. Tree-ring chronologies of the Hohenheim oak master between 6450 and 6000 BC. The bridging series is ◆–B (Trieb site) (see also Fig. 7).

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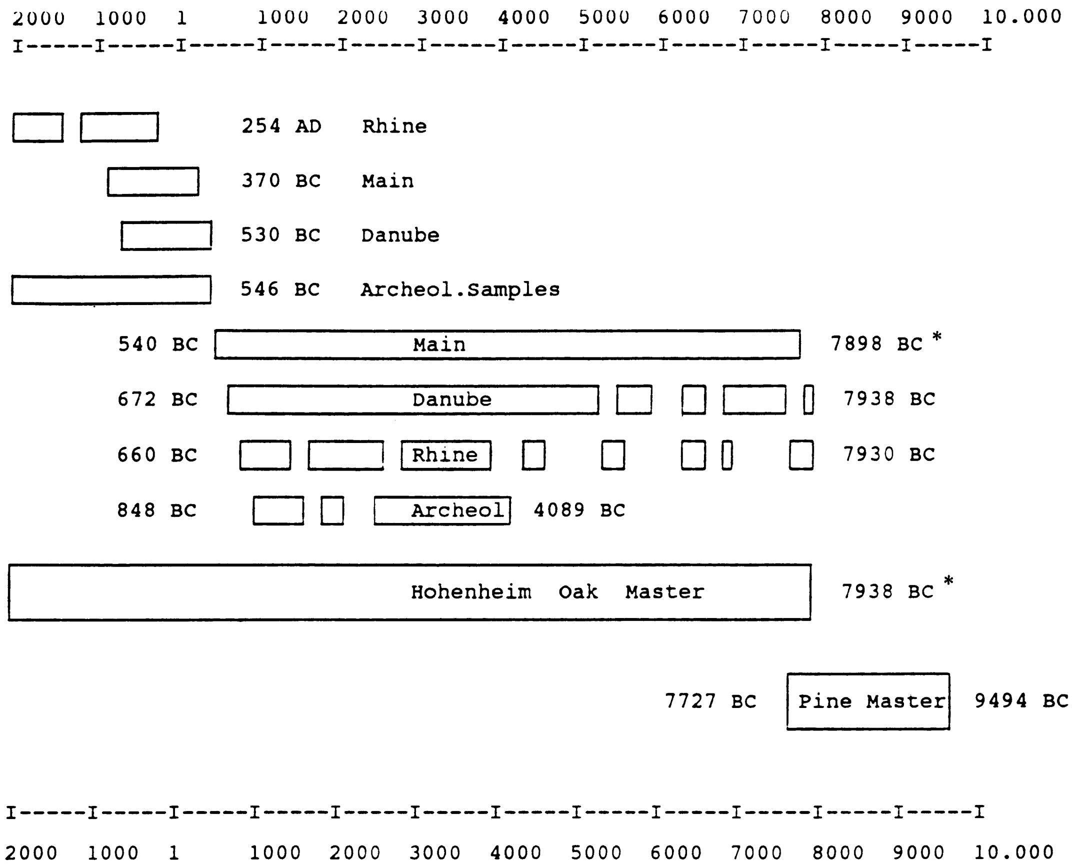

Fig. 9. Compilation of the south central European Holocene/Late Glacial dendrochronology, Hohenheim Laboratory. The blocks represent replicated regional master chronologies. The oak chronology to 546 BC consists of an unbroken series of modern trees, and samples from historic and prehistoric sites. The prehistoric part consists of an unbroken oak record of the Main River valley from 540 to 7898 BC. This chronology is replicated over most sections by archaeological site chronologies, and by series of the Rhine and Danube Rivers. The Danube and Rhine samples extend the master to 7938 BC. The late Preboreal pine chronology overlaps the oak master between 7727 and 8021 BC. A recently detected, but still tentative link of this 1768-yr pine master extends the entire dendrochronology to 9494 BC. The earliest part of the pine series dates from the Younger Dryas and covers the Holocene/Pleistocene boundary (Becker, Kromer & Trimborn 1991). *Recently expanded to 8021 BC, see text.

Very recently, five additional pines covering ^{14}C dates in the 8800 BP range have cross-matched with the end of the pine master chronology, extending the sequence to 1768 tree rings. This series must now overlap the beginning of the oak master near 8800 BP, which meanwhile is extended to 8021 BC. Indeed, a reasonable cross-match between the 8800 BP pine/oak masters is now visible. The overlap between both curves consists of 295 tree rings, but this important linkage is still tentative and must be confirmed by additional ^{14}C measurements. However, this link extends the absolute German oak/pine dendrochronology by an additional 1550 yr, to 9494 BC. The calibration data beyond 7800 BC presented here are derived from this tentative zero point of 9494 BC.

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