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INTCAL09 AND MARINE09 RADIOCARBON AGE CALIBRATION CURVES, 0–50,000 YEARS CAL BP

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ABSTRACT. The IntCal04 and Marine04 radiocarbon calibration curves have been updated from 12 cal kBP (cal kBP is here defined as thousands of calibrated years before AD 1950), and extended to 50 cal kBP, utilizing newly available data sets that meet the IntCal Working Group criteria for pristine corals and other carbonates and for quantification of uncertainty in both the ^{14}C and calendar timescales as established in 2002. No change was made to the curves from 0–12 cal kBP. The curves were constructed using a Markov chain Monte Carlo (MCMC) implementation of the random walk model used for IntCal04 and Marine04. The new curves were ratified at the 20th International Radiocarbon Conference in June 2009 and are available in the Supplemental Material at www.radiocarbon.org.

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INTRODUCTION

Radiocarbon calibration is essential for comparing ^{14}C ages with records dated by other means, such as uranium series, ice-core annual layers, tree rings, and historical records, or for investigating rates of change within a single record. This is because the calculation of a conventional ^{14}C age assumes that the ^{14}C content of the atmospheric has been constant (Stuiver and Polach 1977). However, past atmospheric ^{14}C variations were observed soon after the development of the method (de Vries 1958, 1959) and ^{14}C measurements of known-age tree-ring samples were being suggested as a way to correct (or calibrate) ^{14}C ages (Suess 1965; Stuiver and Suess 1966; Walton and Baxter 1968). Since then, numerous calibration curves have been constructed based on absolutely dated tree-ring chronologies and other archives (Klein et al. 1982; Stuiver 1982; Pearson and Stuiver 1986, 1993; Stuiver and Becker 1986, 1993; Stuiver et al. 1998). But beyond the end of the absolutely dated tree-ring chronologies, ^{14}C calibration has been difficult and contentious (Bronk Ramsey et al. 2006; Mellars 2006a,b; Turney et al. 2006; Blockley and Housley 2009).

In recent years, there has been a proliferation of curves used for calibration (Reimer et al. 2004; Fairbanks et al. 2005; Hughen et al. 2006; Weninger and Jöris 2008); furthermore, the CalPal software (Jöris and Weninger 1998; Weninger and Jöris 2004) provides a "build your own" calendar-age curve construction capability. While no one "owns time" (van Andel 2005), it is also true that not all reconstructed timescales are equal, and a quality controlled, statistically robust consensus calibration curve is very useful (as van Andel agrees) since it allows studies by different researchers to be compared directly and timescales to be constructed consistently. The International Calibration (IntCal) curves are intended to provide a comprehensive summary of the current state of knowledge of past variation in ^{14}C, where consensus can be reached. The IntCal Working Group (IWG) includes members who have detailed knowledge of the primary data that go into the calibration curves and appropriate statistical approaches that can be used to summarize the data and associated uncertainties. Whether authors choose to use IntCal09 or alternative curves (including single data sets), it is important that they clearly state exactly which curve or data set has been used (as opposed to the computer software package alone), and the reasons for any choices made, since this makes direct comparison between different studies easier. However, regardless of whether IntCal09 or an alternative curve is used, we urge all authors to include or cite their original uncalibrated ^{14}C data to permit proper comparison and possible re-evaluation of calibrated ages reported in different studies.

In the strictest sense, a *bona fide* calibration archive must have obtained carbon directly from the reservoir of interest (e.g. the atmosphere) and the calendar age must be known absolutely (e.g. dendrochronologically dated). However, there are at present few such archives of purely atmospheric ^{14}C prior to the European tree-ring chronologies spanning the last 12,594 yr (Friedrich et al. 2004b; Schaub et al. 2008a,b).

Dendrochronologically dated records provide a direct measure of atmospheric ^{14}C content on an absolute timescale. At present, however, those records linked to the present day are restricted to the past 12.59 cal kBP (Friedrich et al. 2004b). Importantly, however, the European tree-ring floating chronologies are likely to be linked in the near future, providing a calibration record back to about 14 cal kBP (Friedrich et al. 2004a; Schaub et al. 2008a,b), while an important wiggle-matched Southern Hemisphere data set is available spanning the early Younger Dryas (YD) period from work on Huon pine (Hua et al. 2009). Beyond this range, the floating New Zealand kauri tree-ring chronologies show considerable promise to extend across the full ^{14}C range (Hogg et al. 2006; Palmer et al. 2006; Turney et al. 2007), while subfossil finds in North America may also one day offer scope for pre-Holocene time series (e.g. Griggs and Kromer 2008; Stambaugh and Guyette 2009).

In an attempt to go beyond the currently limited range of dendrochronologically dated records, recourse has been made to dating terrestrial macrofossils from continuous varved lake sediments, potentially providing important contributions to calibration data sets. Unfortunately, early work on some key records (e.g. Swedish varves, Lake of the Clouds, and Lake Suigetsu) encountered problems with missing varves and/or hiatuses in the sediment cores (Stuiver 1971; Kitagawa and van der Plicht 1998, 2000; Wohlfarth and Possnert 2000). Significant progress is being made on some of these important records. For instance, "missing" varves in the Lake Suigetsu sequence are now being identified in the Lake Suigetsu 2006 Project by overlapping multiple cores and improved varve counting techniques, but further work remains before a continuous ^{14}C calibration record is generated (Bronk Ramsey et al. 2008; Staff et al. 2009).

Numerous other records including marine archives (corals and planktonic foraminifera) and highly resolved speleothems come close to being *bona fide* calibration archives. Yet, marine archives and speleothems reflect ^{14}C in local dissolved inorganic carbon (DIC) instead of in atmospheric CO_2. Since DIC ^{14}C is determined by exchange with atmospheric CO_2 and admixture of ^{14}C-depleted carbon from the deep ocean (corals, foraminifera) and soil carbonates (speleothems), atmospheric ^{14}C values have to be calculated from these archives by considering carbon reservoir exchange and removing admixtures. U-Th dating can provide accurate and independent timescales for corals and speleothems and foraminifera in varved sediments can sometimes be dated accurately by varve counting, but all have reservoir (or dead carbon fraction) correction issues. Marine archives, such as corals and planktonic foraminifera, can provide a regional record of the surface ocean ^{14}C, but short-term fluctuations in atmospheric ^{14}C are attenuated and may be overprinted by ocean circulation changes, which complicates the reconstruction of atmospheric ^{14}C values (Stuiver et al. 1986). Speleothems have a similar amplitude attenuation as a result of ^{14}C-free carbon (from the host or bedrock) and potentially old soil carbon being incorporated into the speleothem carbonate, which causes an apparent ^{14}C age offset on the order of several thousand years (Genty et al. 1998). This addition, which may vary with time, is termed the "dead carbon fraction" (DCF) or dead carbon proportion (dcp). DCF has been estimated from comparison to pre-bomb atmospheric ^{14}C, overlap with tree rings or other calibration data, and modeled using δ^{13}C. A number of studies have found the variability in DCF to contribute about 250–300 yr to the ^{14}C uncertainty for the intervals compared (Genty et al. 1999; Beck et al. 2001; Weyhenmeyer et al. 2003). The question of variability of the DCF over time has caused the IWG to be cautious about incorporation of these records. However, the 2 Bahamas speleothem ^{14}C records (GB89-24-1 and GB89-25-3) agree very well in the 40–44 ka period using DCF values of 1450 ± 235 ^{14}C yr and 2075 ± 270 ^{14}C yr calculated from the 11–15 ka overlaps with tree rings and IntCal04, respectively, giving some confidence in the relatively constant nature of the DCF in this case (Hoffmann et al. 2010). These records, which were not published in time for the IntCal09 curve construction, are likely to be included in future calibration curves.

Additional marine and terrestrial data sets are available that have timescales transferred through climatic correlation with an independently dated record (such as δ^{18}O of ice cores or U-Th dated speleothems) and/or tie-points, such as independently dated tephra. Although transferred timescales are not ideal, high-resolution records of this type can provide important contributions to the calibration curve, provided there is a physical mechanism linking the proxy climate signals in the records (ideally with the event synchronicity independently tested [cf. Blaauw et al. 2009; Austin and Abbott, in press) and all known sources of uncertainty are taken into consideration. IntCal09 includes the non-varved Cariaco Basin (Hughen et al. 2006) and the Iberian Margin (Bard et al. 2004b,c; Shackleton et al. 2004) marine sediment records, as well as independently dated coral records, with an assumed constant reservoir age pending quantification of their actual—possibly large—reservoir age changes over time.

At the time of the release of the Marine04 and IntCal04 calibration curves in 2004 (Hughen et al. 2004b; Reimer et al. 2004), the IWG deemed the discrepancy among even the most robust data sets too large to make a reliable ^{14}C calibration curve beyond 26 cal kBP. The degree of discrepancy of a number of data sets was highlighted by the offsets from the modeled NotCal curve, which was not intended for use in calibration (van der Plicht et al. 2004; cf. Mellars 2006b). Major discrepancies between the data sets used in NotCal appear to have been resolved, especially with the new Bahamas speleothem record (Hoffmann et al. 2010) and preliminary data from the Lake Suigetsu 2006 project (Bronk Ramsey et al. 2008; Staff et al. 2009). These records, although not available in time to be included in the IntCal09 curve construction, provide confidence that the selected data sets allow a reconstruction of atmospheric ^{14}C concentrations suitable for ^{14}C calibration beyond 26 cal kBP. However, anomalously large changes in ^{14}C ages have been observed in other records (Voelker et al. 2000; Giaccio et al. 2006; Sarnthein et al. 2007), possibly related to changes in oceanic circulation (Heinrich events) or Earth magnetic field intensity (Laschamp and Mono Lake events), which could indicate that the shape of the present calibration may still change and become more structured when more calibration data become available. With this caveat, the IWG has generated a new calibration curve back to 50 cal kBP, which was recommended and ratified at the 20th International Radiocarbon Conference.

DATA SET SELECTION CRITERIA

In 2002, the IWG stated a "preference for future marine records to be developed from oceanographically 'simple' regions to minimize reservoir age uncertainty" (Reimer et al. 2002). Since then, a great deal more has been learned about marine reservoir variability and changes over time, particularly at high latitudes (Björck et al. 2003; Eíriksson et al. 2004; Sarnthein et al. 2007; Ascough et al. 2009), restricted basins (Sarnthein et al. 2007), upwelling regions (Fontugne et al. 2004; Soares and Dias 2006; Taylor et al. 2007), and other regions of complex oceanography (Paterne et al. 2004; Druffel et al. 2008; McGregor et al. 2008; Burr et al. 2009). The criterion for minimal past reservoir variability is difficult to uphold. The appropriate quantification of the reservoir uncertainty is therefore extremely important. In some cases, portions of data sets have been omitted in IntCal09 for this reason as discussed in the following section.

One of the criteria used to help establish whether corals have undergone post-depositional alteration and exchange of ^{14}C, U, and Th with the environment is the $\delta^{234}U_{initial}$ value. In 2002, the IWG criterion was that the $\delta^{234}U_{initial}$ of fossil corals should be within ±5‰ of the accepted modern seawater value. This was based on the understanding at the time, that δ^{234}U in seawater was constant over the last 30 ka. Several recent studies have reported precise δ^{234}U values of ~147‰ for modern and recent corals (Cheng et al. 2000; Delanghe et al. 2002; Robinson et al. 2004a) In addition, however, there is evidence of seawater $\delta^{234}U_{initial}$ 7–10‰ lower during the last glacial period (Esat and Yokoyama 2006; Robinson et al. 2004b). Thus, using the modern seawater δ^{234}U value as a screening criterion is likely to exclude pristine corals. The corals currently in the IntCal database have satisfied the criteria established in 2002, i.e. they have a site-specific reservoir age with a "reasonable" error (<±200 ^{14}C yr if younger than 12,540 cal BP based on a tree-ring comparison [Table 1], unknown beyond 12.54 cal ka); <1% calcite as determined by X-ray diffraction; precise U-Th ages (uncertainties on the order or less than that of the ^{14}C age of the same sample), which fall in stratigraphic order; and concordant protactinium ages where feasible. Comparing $\delta^{234}U_{initial}$ of these corals in the IntCal database, we found the initial δ^{234}U values were clustered in 2 groups with an obvi-

Table 1 New and previously published data-set- and site-specific marine reservoir age corrections. The age range and number of points *N* in the overlap with the tree-ring data set that was used to calculate the offsets are also given. References to the data sets are given for those locations where there are 2 separate records. All others are given in the Appendix.

Location	Overlap cal BP	Reservoir correction (^{14}C yr)	*N*	Previously published reservoir correction (^{14}C yr)
Barbados (Bard et al. 1998, 2004a)	770–12,245	420 ± 100	9	400[a]
Barbados (Fairbanks et al. 2005)	7290–12,304	320 ± 110	22	365 ± 60 (*n* = 21)[b]
Cariaco Basin—varved sediment	10,502–12,540	430 ± 50	194	420[c]
Kirimati	8825–12,299	335 ± 100	25	350 ± 55[b] (*n* = 4)
Iberian Margin		n/a	n/a	500 ± 100[d,e]
Mururoa	No overlap	Same as Tahiti		
Papua New Guinea	1780–12,369	495 ± 155	15	407[f]
Tahiti	8570–12,005	235 ± 110	14	300[a]
Vanuatu Tasmaloum (Burr et al. 1998)	11,830–12,300	475 ± 65	27	494[g]
Vanuatu Tasmaloum (Cutler et al. 2004)	11,045–12,246	480 ± 100	5	500[g,h]
Vanuatu Urelapa	6150–11,697	350 ± 105	14	400[h]
Vanuatu Araki	Data not available	n/a	n/a	365 ± 140 (*n* = 9)[b]

[a]Bard et al. 1998; [b]Fairbanks et al. 2005; [c]Hughen et al. 1996; [d]Bard et al. 2004a; [e]Shackleton et al. 2004; [f]Edwards et al. 1993; [g]Burr et al. 1998; [h]Cutler et al. 2004.

ous increase from the Last Glacial Maximum (LGM) to the deglacial and Holocene samples (Figure 1). The average $\delta^{234}U_{initial}$ for corals younger than 17 ka is 145.6 ± 2.4‰ and for corals older than 17.0 ka it is 141.7 ± 2.6‰. Using an envelope of 2 standard deviations (s.d.) around the mean $\delta^{234}U_{initial}$ of the corals older than 17 ka as the selection criterion would have resulted in 4 Barbados coral samples and 1 New Guinea coral sample being excluded. One of these Barbados corals had also been analyzed for $^{231}Pa/^{235}U$, resulting in concordant U-Th and protactinium ages that suggests a closed system with minimal or no diagenesis (Mortlock et al. 2005). Because the actual variability during the glacial period is unknown, we have taken a pragmatically wide envelope of 3 standard deviations around the mean of the corals older than 17 ka as the screening criteria, i.e. 141.7 ± 7.8‰. The $\delta^{234}U_{initial}$ values for the corals younger than 17 cal kBP trended towards higher values for the more recent corals. We therefore chose to use the value for modern and recent corals of 147 ± 7‰ (3 s.d.). The new criteria did not cause any coral data to be excluded that had been included in Marine04, but there was not enough new coral data to determine if these criteria filtered the records effectively. Note also that U-Th ages and $\delta^{234}U_{initial}$ values were recalculated, where necessary, using the currently accepted ^{234}U and ^{230}Th half-lives (Cheng et al. 2000).

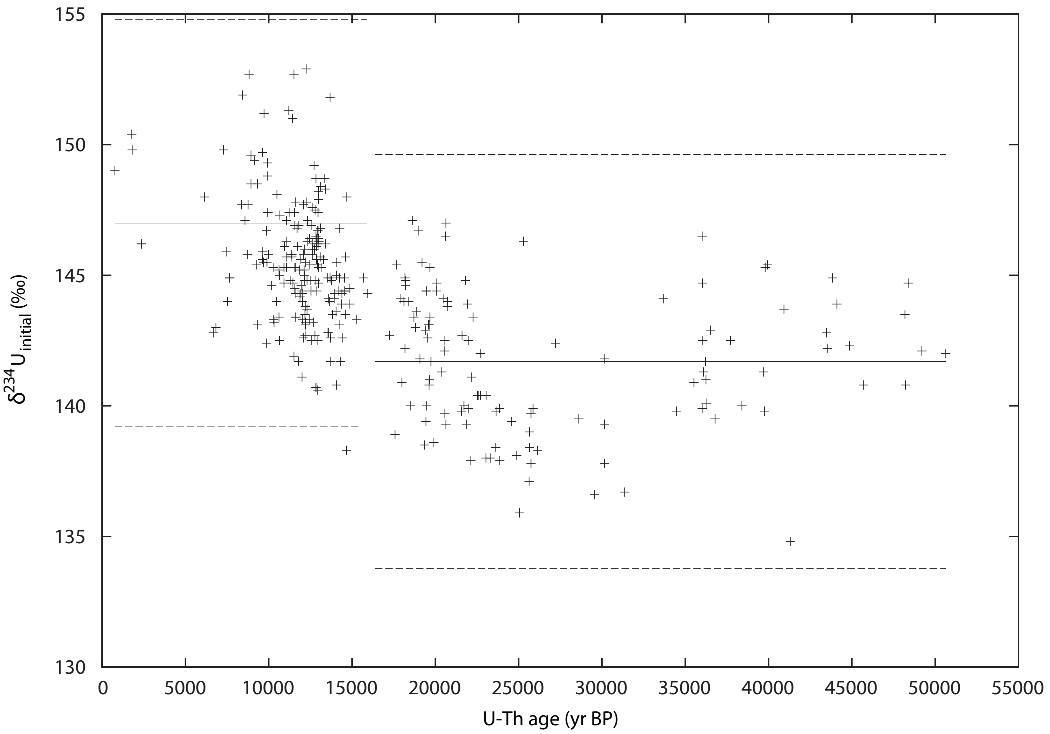


Figure 1 $\delta^{234}U_{initial}$ of coral samples in the IntCal09 database with the mean values (dashed lines) and 3 standard deviations (dot-dashed lines) shown for the 2 periods.

OTHER NEW DEVELOPMENTS

There is growing evidence that the western subtropical Atlantic reservoir age was much less than the modern ~420-yr offset during the early Younger Dryas (~12,550–12,900 cal BP) (Kromer et al. 2004; Muscheler et al. 2008; Singarayer et al. 2008). This is consistent with model results showing the response of the ocean surface age to a reduction or shutdown of North Atlantic Deep Water formation (Meissner 2007; Ritz et al. 2008; Singarayer et al. 2008). Most recently, Hua et al. (2009) used a ^{14}C wiggle-match between the absolutely dated tree rings and the Huon pine chronology with a Southern Hemisphere offset of 40 ^{14}C yr to derive a timescale for the floating European chronologies (Schaub et al. 2008a). Using this derived timescale for the floating tree rings, the subtropical Atlantic coral (Fairbanks et al. 2005) and foraminifera data (Hughen et al. 2004a) with an assumed constant reservoir age are too young in the period ~12,550–12,900 cal BP, whereas the Pacific corals agree with the wiggle-matched tree-ring data. While we could, in theory, calculate a time-dependent reservoir correction for the marine data, it was decided instead to exclude the western subtropical Atlantic marine data for the early Younger Dryas period ~12,550–12,900 cal BP. Similar shifts in reservoir ages may have occurred during Heinrich events and the cold, stadial phases of the Dansgaard-Oeschger events (Bond and Lotti 1995; Clark et al. 2002). Indeed, the Bahamas speleothem record (Beck et al. 2001) and reservoir-corrected Cariaco data appear to disagree in the interval 16–17 ka BP, within Heinrich event 1, although other effects such as DCF changes (Bahamas) or problems with the correlation to Hulu (Cariaco) could also contribute to this offset. A reservoir age discrepancy within Heinrich event 1 is also suggested by foraminifera data from the Iberian and Pakistan Margin cores (Bard et al. 2004c, 2009). Thus, it is prudent to treat calibration during Heinrich and Dansgaard-Oeschger events with caution until further information becomes available.

INTCAL09 DATA SETS

A full list of the IntCal09 data sets and references is given in the Appendix. New data and changes to some of the data sets are discussed below.

Tree-Ring Data Sets (0–12.55 cal kBP)

The tree-ring data sets are unchanged from the IntCal04 data for the period from 0–12,550 cal BP. Laboratory error multipliers were applied as described in the IntCal04 publication (Reimer et al. 2004). The Stuttgart-Hohenheim absolute pine chronology has been extended with pines from Switzerland to 12,594 cal BP (Friedrich et al. 2004b; Schaub et al. 2008a,b). New ^{14}C measurements on those trees back to 12,556 (Hua et al. 2009) have been included in the IntCal09 curve. When adjoining the absolute tree-ring extension to the database, a data-handling error in the calendar age of 19 yr was discovered for 2 of the 3 oldest German pines in the IntCal 2004 tree-ring data set. The corrected data are included in the IntCal09 curve. The tree-ring data sets will be augmented in the next revision of the IntCal calibration curve with measurements of Irish oak from AD 395–485 and AD 735–805 (McCormac et al. 2008) and German oak from the 2nd and 1st millennia BC (Kromer et al. 2009), as well as other potentially suitable data sets.

Marine Data Sets (12.55–50 cal kBP)

Coral data sets are the same as used in IntCal04 with a few exceptions. Western subtropical Atlantic data (i.e. Barbados) in the early YD have been omitted due to uncertain reservoir ages, as discussed previously. New data are included from Araki and Kiritimati in the Pacific and Barbados in the Atlantic (Fairbanks et al. 2005). Three measurements from the Cutler et al. (2004) New Guinea record in the period from 24–29 ka cal BP have been omitted as outliers because they have ^{14}C ages between 1140 and 2160 yr younger than any of the other calibration data that fall within their calendar age uncertainty (2 s.d.). These corals are thought to have been affected by a freshwater lens. Foraminifera from the Cariaco Basin varved sediments (Hughen et al. 2004a) were used as in IntCal04 with the exception of measurements from 12,552–12,944 cal BP, which are likely to be affected by marine surface reservoir age changes associated with the onset of the Younger Dryas as previously discussed. The timescale for the non-varved sediments of Cariaco Basin is derived from correlation with the Hulu Cave speleothems δ^{18}O (Wang et al. 2001). The total uncertainty was based on the combined uncertainties associated with the Hulu Cave U-Th ages, the sampling resolution of the records, and the time-varying correlation coefficients between the speleothem δ^{18}O and the Cariaco Basin gray scale as described in Hughen et al. (2006). The Hulu Cave timescale for the non-varved sediments of Cariaco Basin is unlikely to be the final word in the chronology because the Hulu record itself is in the process of further refinement and the possibility remains of correlating the Cariaco data to other records.

The first set of ^{14}C measurements of foraminifera from the Iberian Margin core MD952042, taken 75 km off the coast of Portugal in a water depth of 3146 m, was reported in Bard et al. (2004b,c), and a set of 12 ages was later published by Shackleton et al. (2004). A compilation of the previous data sets with additional measurements was published late in 2004 (Bard et al. 2004a) and some additional results added since are included in the IntCal09 database for a total of 43 measurements. The chronology for the core was originally tuned to the δ^{18}O records from the Greenland ice cores (GISP2 [Grootes et al. 1993] and GRIP [Dansgaard et al. 1993]) and more recently to the Hulu Cave speleothem timescale following the same method for uncertainty estimates as for the Cariaco Basin non-varved sediments. MD952042 is far from the high-latitude zones where marine reservoir ages may be large and variable (Bard et al. 2004a) and a chemical oceanography transect measured at the same latitude indicate that the site of core MD952042 presently lies outside the coastal upwelling anomaly characterized by low sea-surface temperature and high surface chlorophyll concentrations (Coste et al. 1986; Bard et al. 2004a). Yet, high reservoir ages and variability have been noted from known-age mollusks and contemporaneous marine-terrestrial pairs from archaeological excavations from the Portugal coast through the Holocene (Monge Soares 1993; Soares and Dias 2006), biological productivity proxies measured in cores from this zone show large variability during the last glacial period (Abrantes 2000; Pailler and Bard 2002) and Salguerio et al. (in press) document large changes in oceanography (summer export productivity) for MD952042 during the last 150 ka. Skinner (2008) notes, in a stratigraphic comparison of the Cariaco Basin and Iberian Margin records tuned to various absolute chronologies (GICC05, SFCP04, and Hulu Cave), an increase of the reservoir age for the Iberian Margin data (+400 ^{14}C yr for ages beyond 22 cal kBP), but assumes a constant reservoir age for the Cariaco Basin record. However, such an assumption leads to circular reasoning and we prefer not to use one record to correct the other. For IntCal09, we use the previously published reservoir age value (500 ± 100 ^{14}C yr, Bard et al. 2004a; Shackleton et al. 2004), but recognize that the uncertainty may be an underestimate because glacial oceanographic variability is not adequately considered. However, it should be stressed that for IntCal09, both marine records were tuned independently to the very same target curve of the Hulu Cave δ^{18}O record and examination of the IntCal09 data sets (Figure 2) shows that the Iberian Margin data generally agree within 2 standard deviations with the Cariaco data and other calibration data. The only notable discrepancy occurs between 15–17.5 cal kBP, corresponding to the Heinrich 1 climatic event. This systematic difference could be suppressed by assuming a larger reservoir age for the Iberian Margin. However, such *ad hoc* corrections may not apply since available data measured on other archives (the few corals in Figure 2 and Bahamas speleothem by Hoffmann et al. [2010]) support the Iberian Margin record. Like the Cariaco record, the present MD952042 chronology must be considered a work in progress awaiting refinement by correlation with more independent data from other archives (corals, speleothems, and marine cores from other oceans).

For most of the other data sets, regional reservoir corrections were calculated from the weighted mean offset of the marine data set with the tree-ring portion of the data where possible (Table 1). Because laboratory error multipliers for ^{14}C measurements were not available for all the marine data sets, the reservoir corrections and uncertainties were calculated on a per data set basis. For the Araki corals, the data overlapping with the tree rings are not published, so the reservoir correction calculated by Fairbanks et al. (2005) of 365 ± 140 ^{14}C yr ($n = 9$) was used. No overlapping data are available for the non-varved Cariaco Basin, so the reservoir correction calculated for the varved data was used but the uncertainty was set to ±100 ^{14}C yr. As stated above, these tree-ring-based uncertainty estimates may not reflect the effects of glacial and deglacial oceanographic changes.

INTCAL09 CURVE CONSTRUCTION

For IntCal09, the underlying calibration curve is modeled using the same random walk prior as in IntCal04 (Buck and Blackwell 2004). This takes the form of independent increments from one calendar year to the next drawn from a Gaussian distribution. The collected data are then assumed to represent observations of this random walk subject to possible error in both the calendar dating and the ^{14}C determination. We update our random walk prior in light of this calibration data to generate a posterior distribution for the curve. However, as opposed to IntCal04 where the posterior of this random walk was calculated point-wise, for IntCal09 a Markov chain Monte Carlo (MCMC) approach was used to generate posterior realizations of the complete calibration curve simultaneously.

Details of the MCMC approach used can be found in the accompanying paper by Heaton, Blackwell, and Buck (this issue). Intuitively, the method, which extends that proposed in Blackwell and Buck (2008b), aims to establish which realizations of the set of all possible random walks from the prior are supported by the observed data. It offers significant advantages over the point-wise approach taken for IntCal04 due to its additional flexibility and its ability to represent complete realizations of plausible calibration curves. In particular, we are able to calculate covariances between the values of the curve at differing points and incorporate exactly any known ordering constraints within the data. Neither of these was possible using the methodology of IntCal04. We also hope that in the future our MCMC approach will enable more accurate modeling of the complex structures within the data that, to date, we have not been able to incorporate fully.

As explained above, providing complete realizations from the posterior of the calibration curve enables us to record much greater information about its properties, including possible covariance between values at neighboring points. Blackwell and Buck (2008b) show that this additional information can be of importance when performing calibration, particularly when comparing calibrated dates of multiple samples; the magnitude of the effect is further discussed in Millard (2008) and Blackwell and Buck (2008a). To take advantage of this information, one should calibrate with the set of realizations of the complete walk and not simply record the values of the curve on a fixed grid assuming them to be independent. However, the former approach is not yet feasible for most end-users, as current publicly available calibration packages can only use calibration curve estimates that take the form of posterior means and variances at such grid values. They are not able to incorporate further information on, say, covariance. As a consequence, for the purposes of IntCal09, the posterior realizations were determined on a preselected grid where point-wise means and variances were then calculated. This produced the form of output required for current calibration packages, but possible covariance information between grid points was lost. The IntCal09 calibration curve was calculated at intervals of 10 yr for the range 12–15 cal kBP, 20 yr for 15–25 cal kBP, 50 yr for 25–40 cal kBP, and 100 yr for 40–50 cal kBP from the tree-ring data set and the reservoir-age-corrected marine data set (constant correction: minus 405 ^{14}C yr).

THE INTCAL09 CURVE

The IntCal09 data and curves from 12–50 cal kBP are shown in Figure 2 (p 1120–1138). The credible interval band plotted should not be interpreted as aiming to incorporate a certain percentage of the observed data points, but rather to plot a region where it is probable that the true value of the calibration curve lies. The data points have been modeled as noisy observations of this true value and one should instead consider the proportion of the data error bars (accounting for the combined calendar date and ^{14}C uncertainties) that overlap the band. Furthermore, when comparing the plotted curve with the calibration data, the reader should be aware that the curve is required to take a value such that all the observed data are feasible observations. As such, there may be sections where the majority of the data lie above the curve with a smaller number lying below it, or vice versa. In such instances, a curve which took values through the majority of the data may make the smaller group of data extremely improbable to observe and hence the data as a whole very unlikely. Instead, a curve with values that lie between the 2 groups may act as a compromise whereby none of the observed data is so highly unlikely and, as a consequence, the likelihood of the complete set of data can be increased. Such situations can be particularly expected to occur if observations possess calendar error that is not independent between observations in that data set or there is a disparity in the size of errors between the groups above and below the curve.

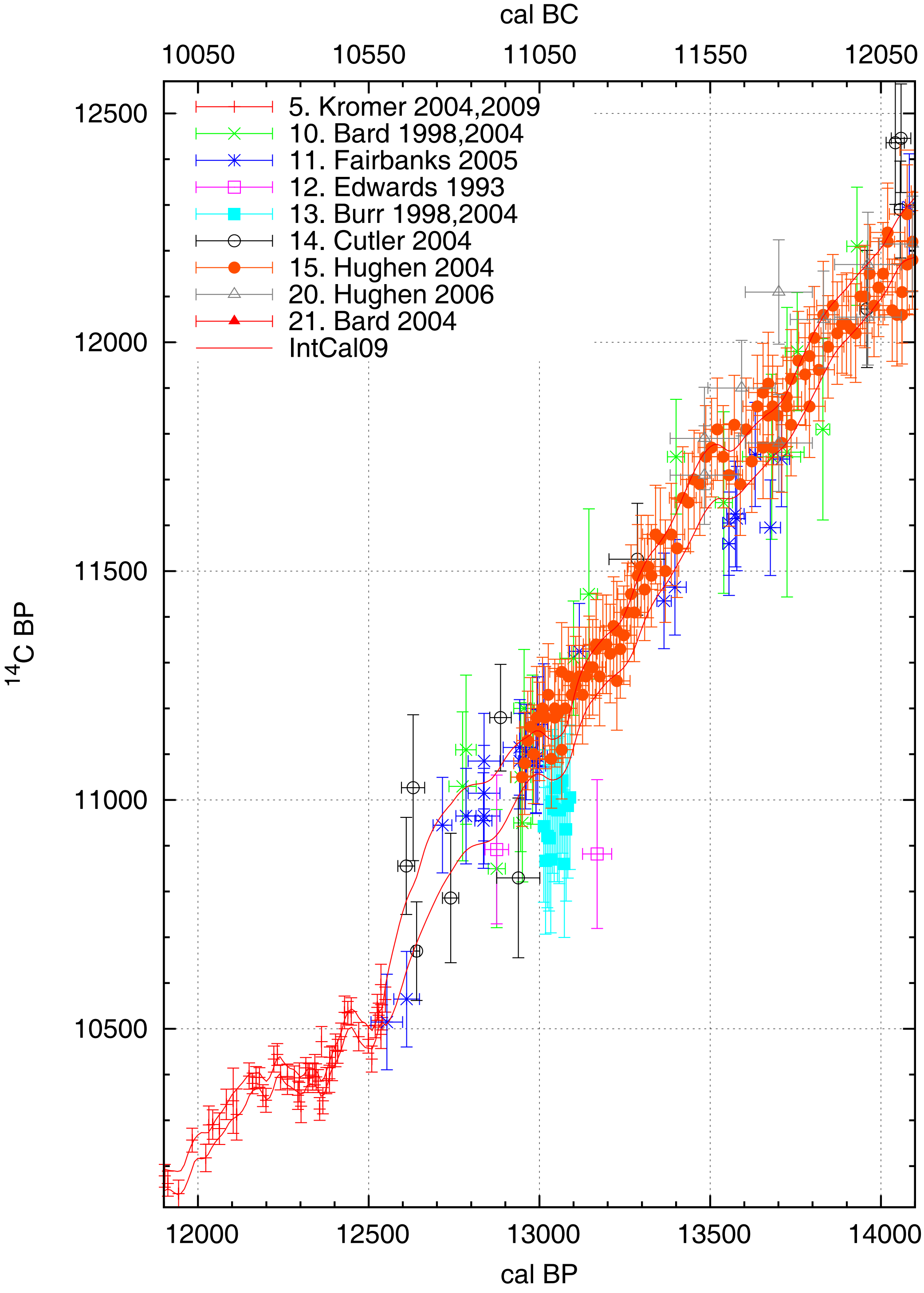
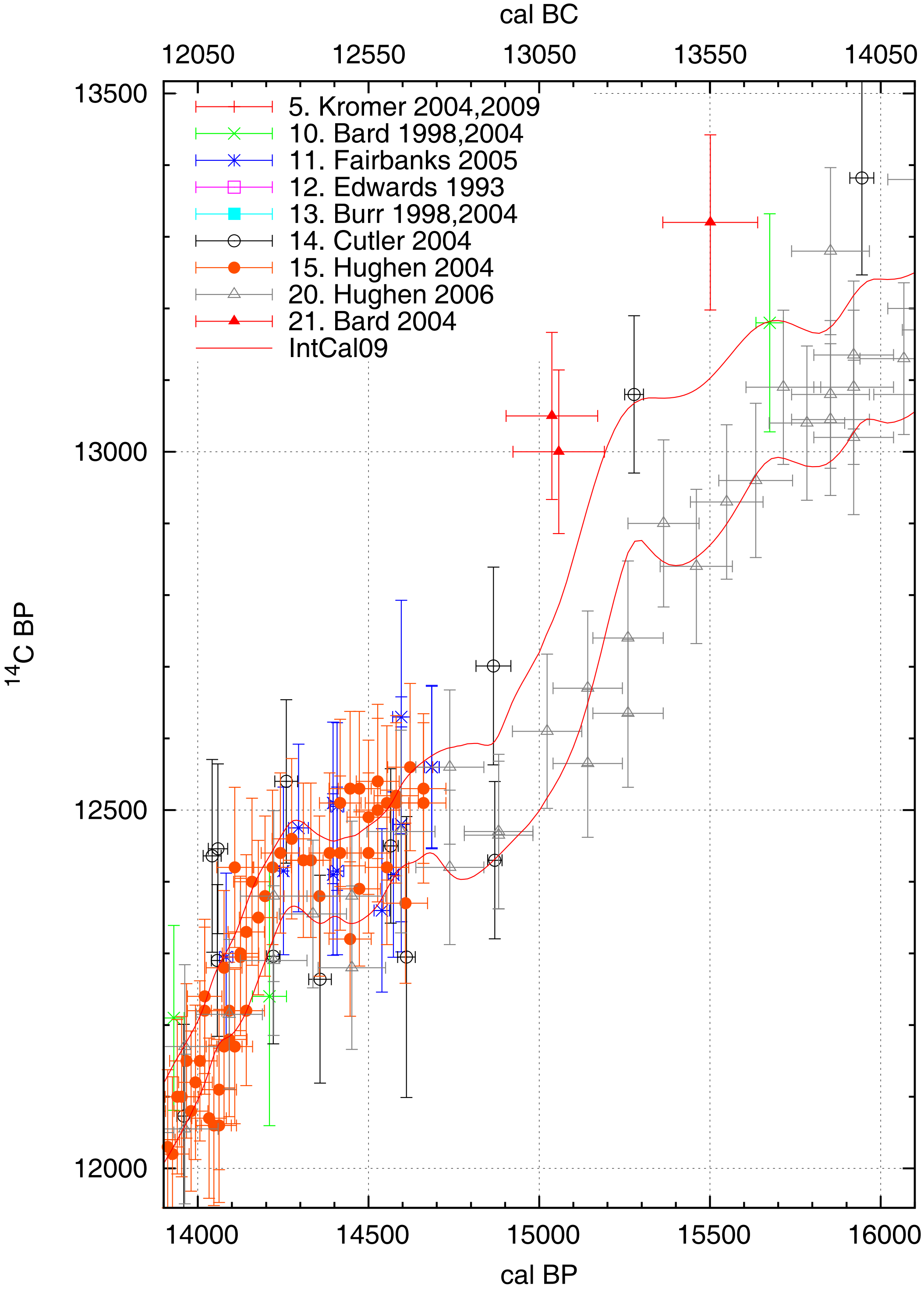


Figure 2 IntCal09 terrestrial calibration curve (1-standard deviation envelope) and data with 1-standard deviation uncertainty in the ^{14}C and calendar ages. Complete references to the data sets are given in the Appendix.



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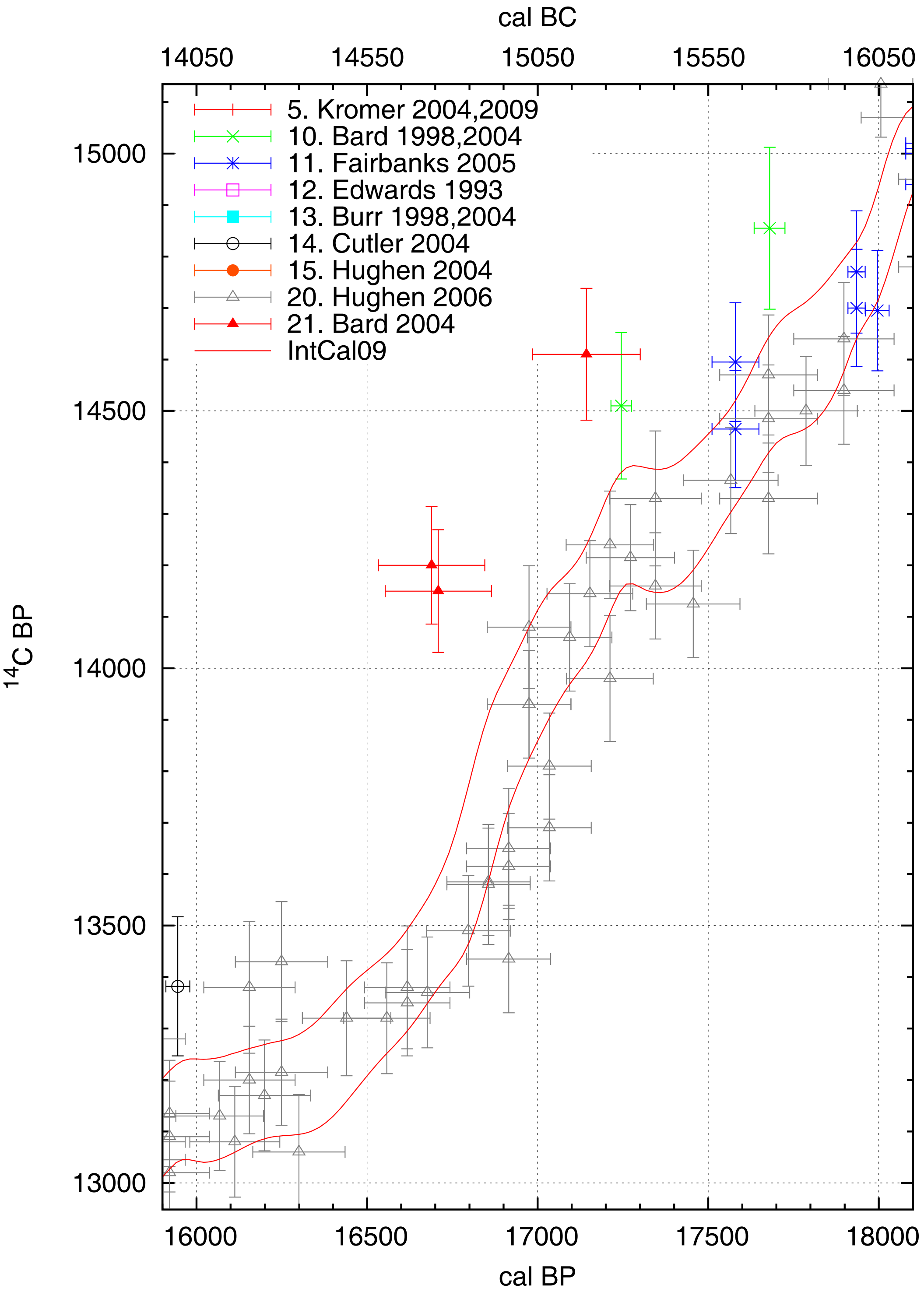

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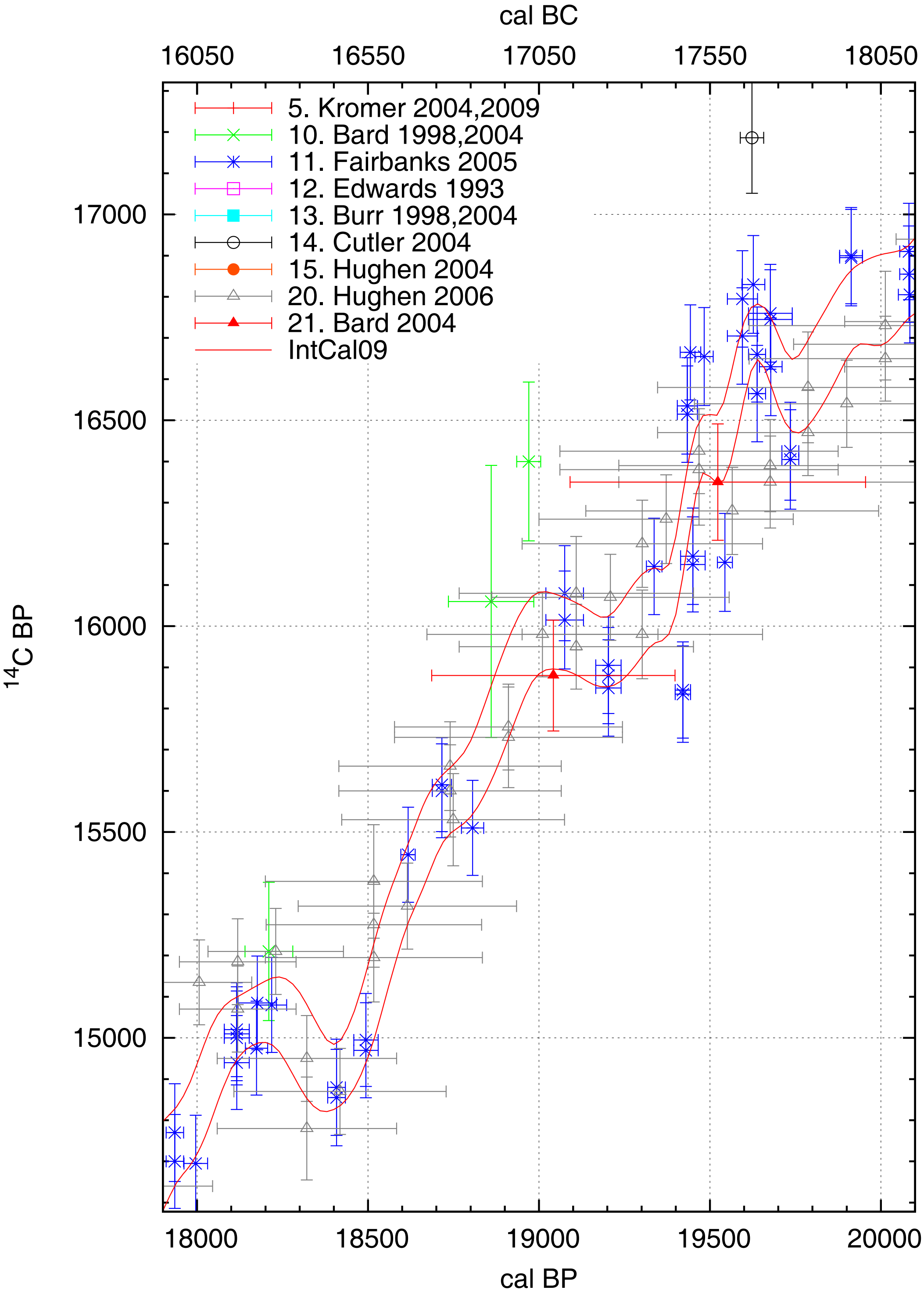

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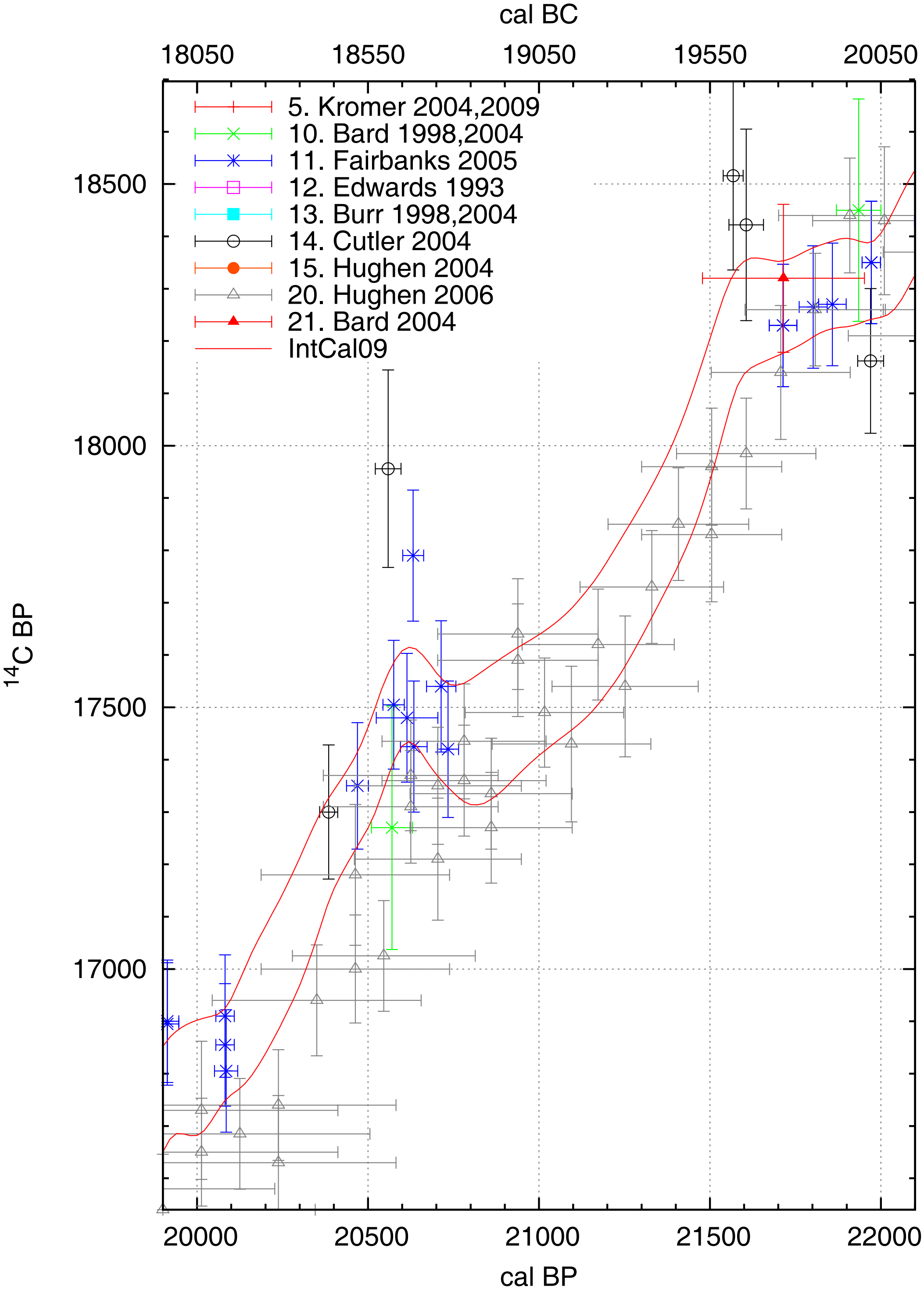

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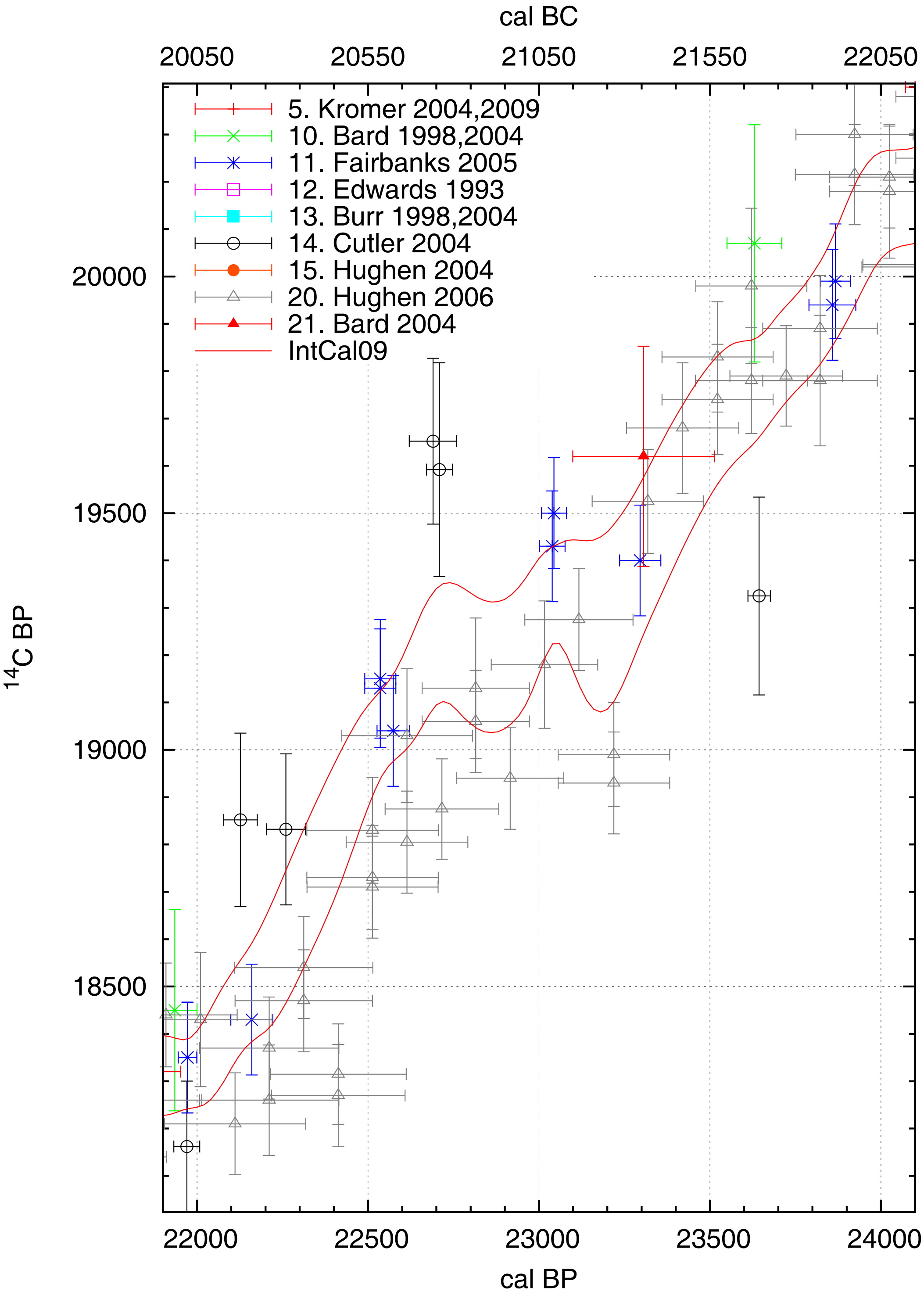

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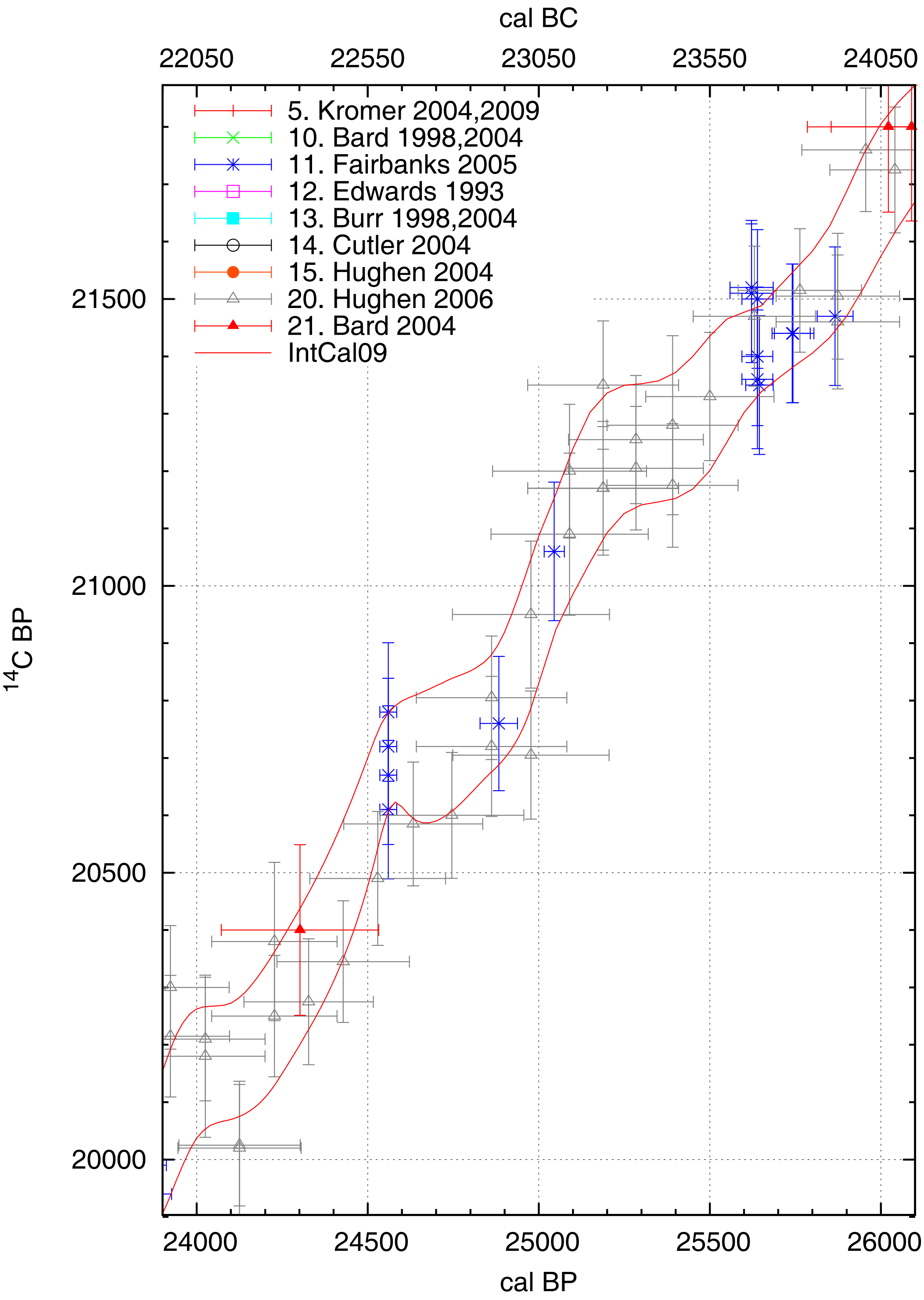

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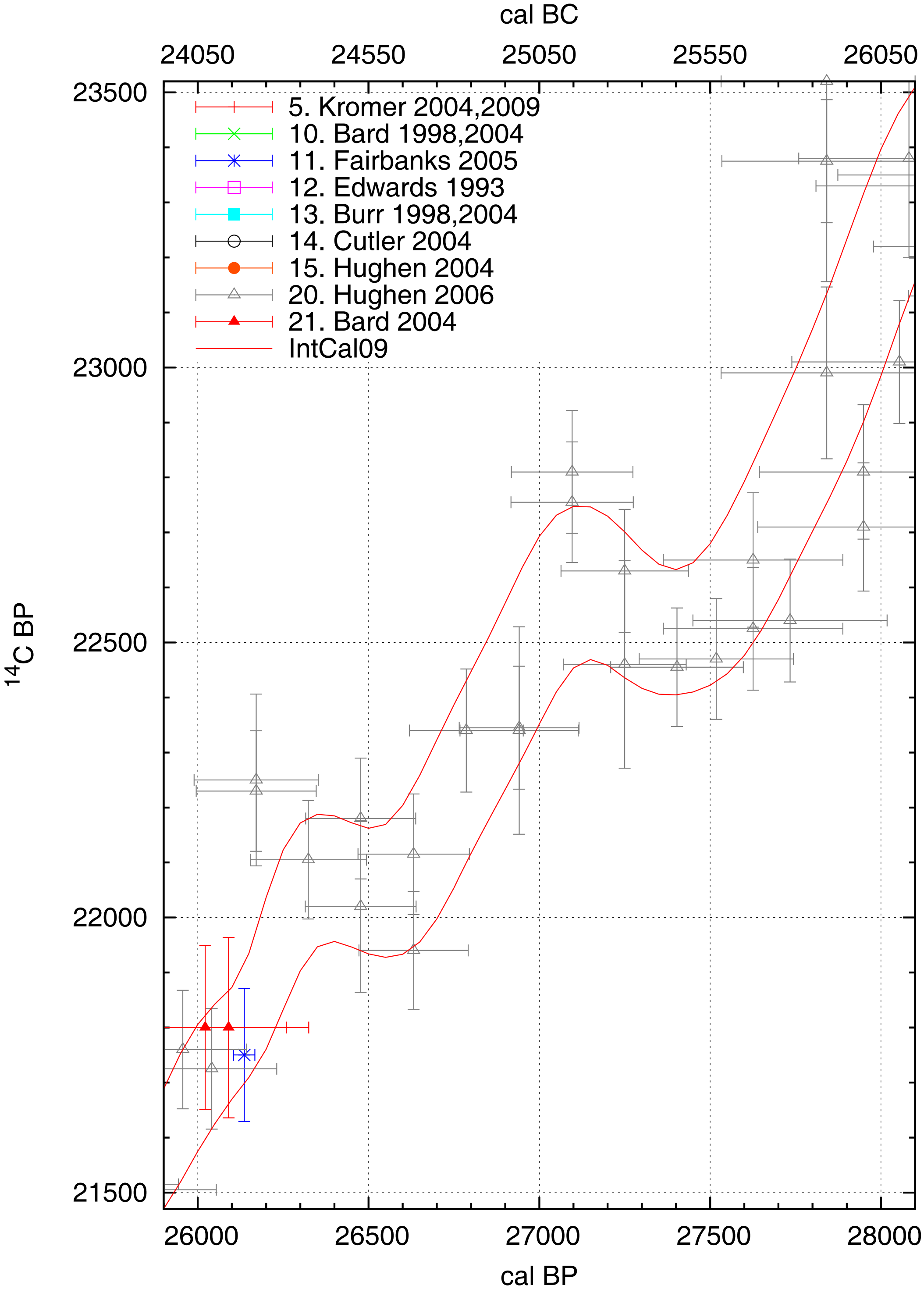

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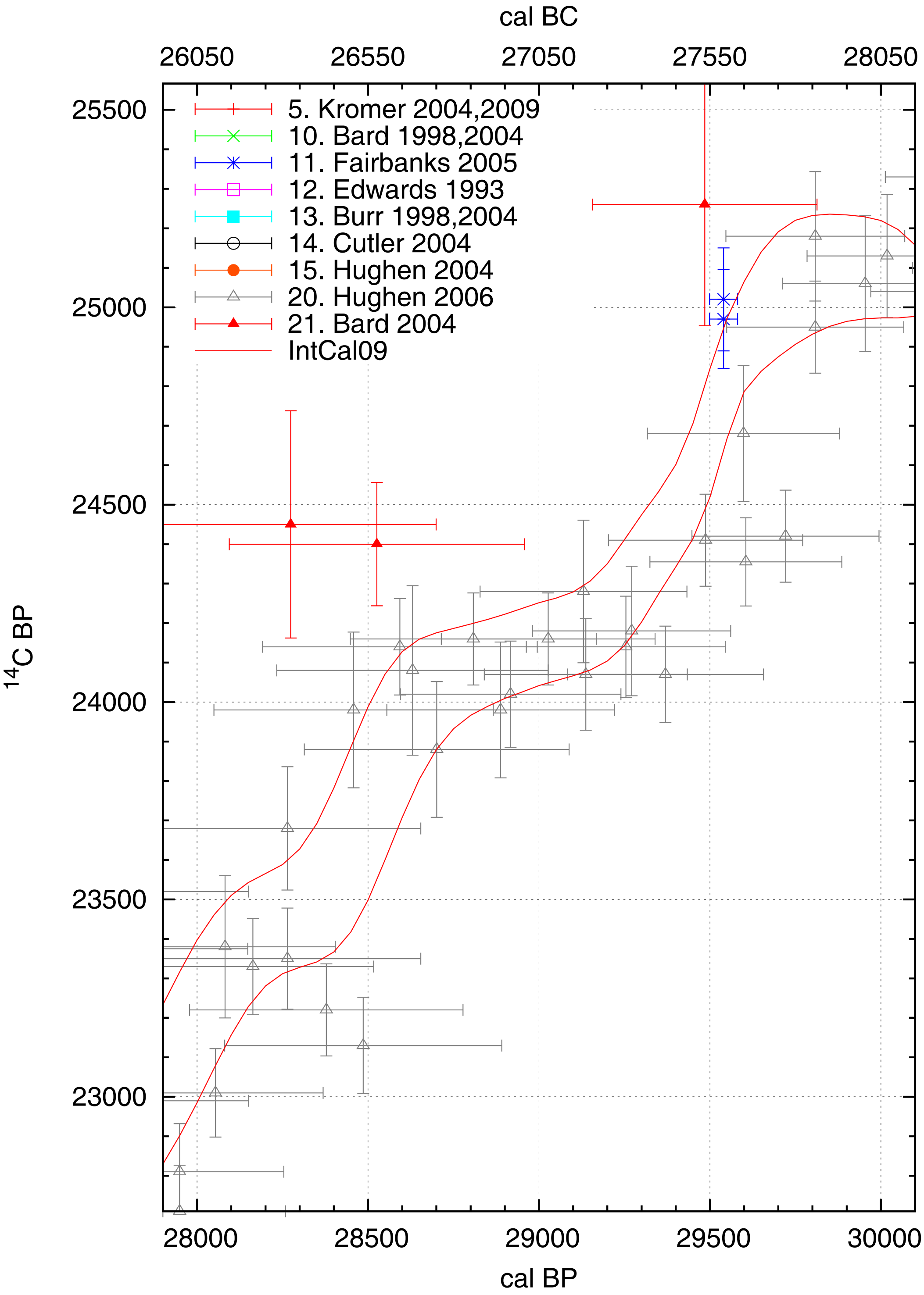

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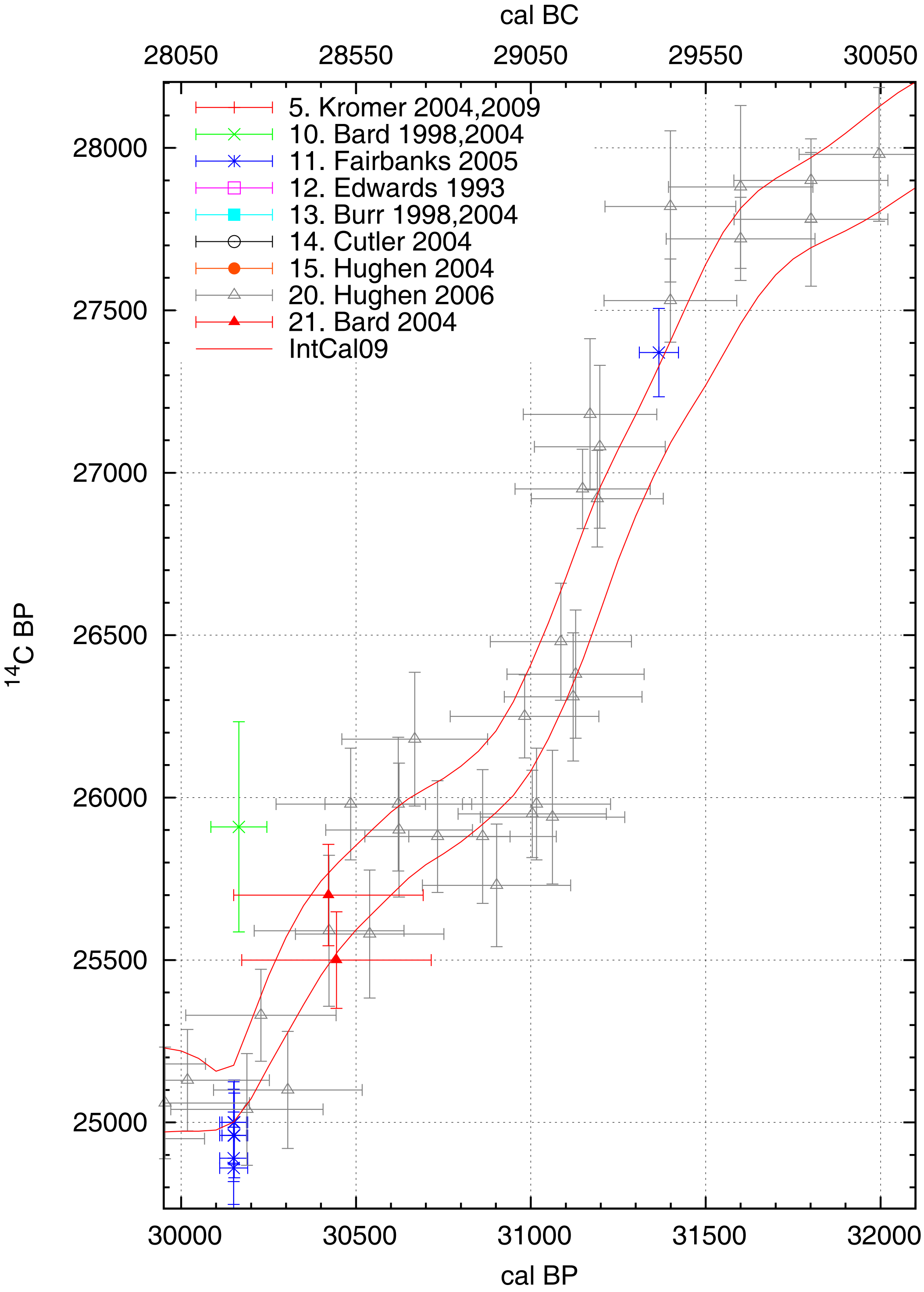

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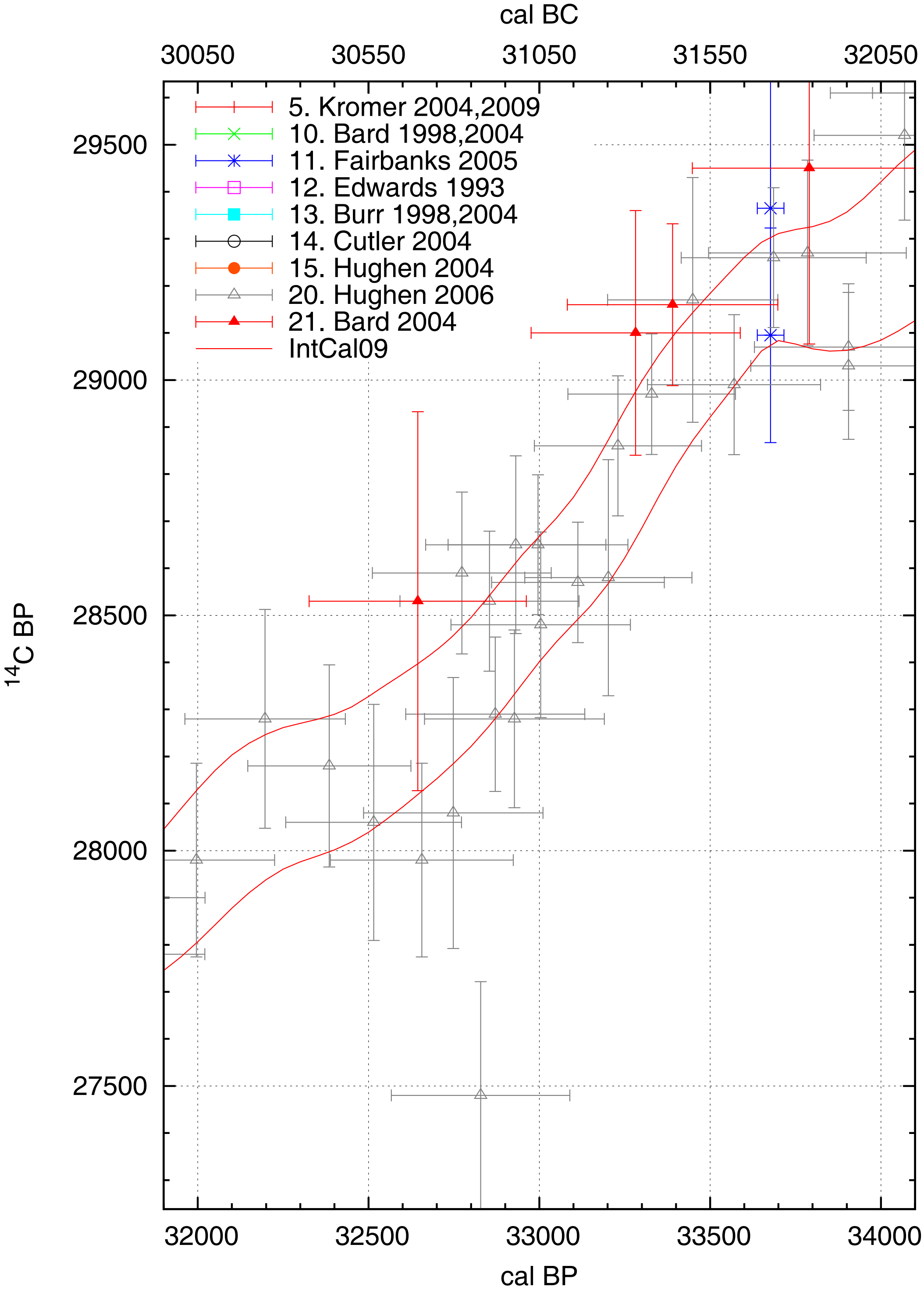

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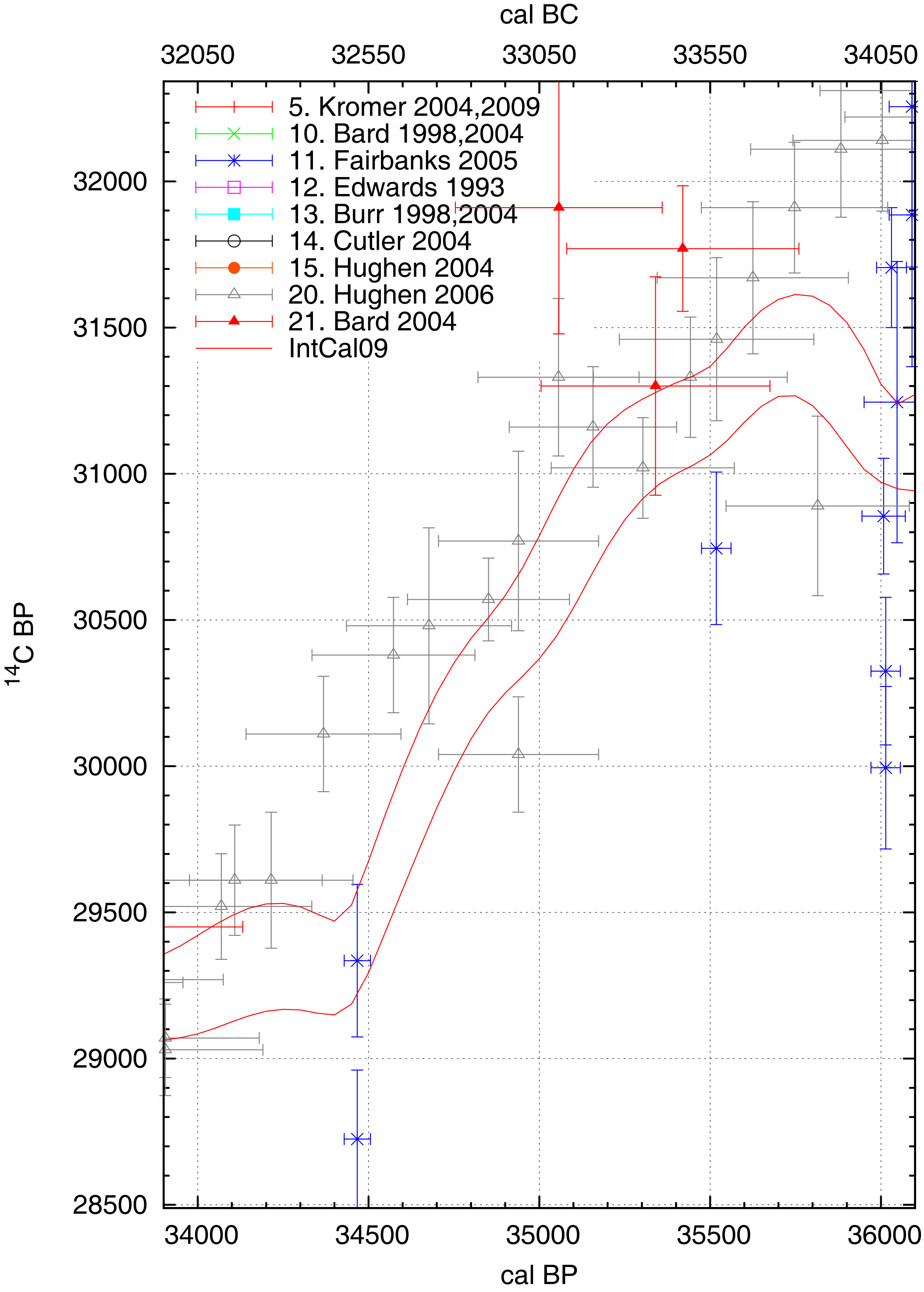

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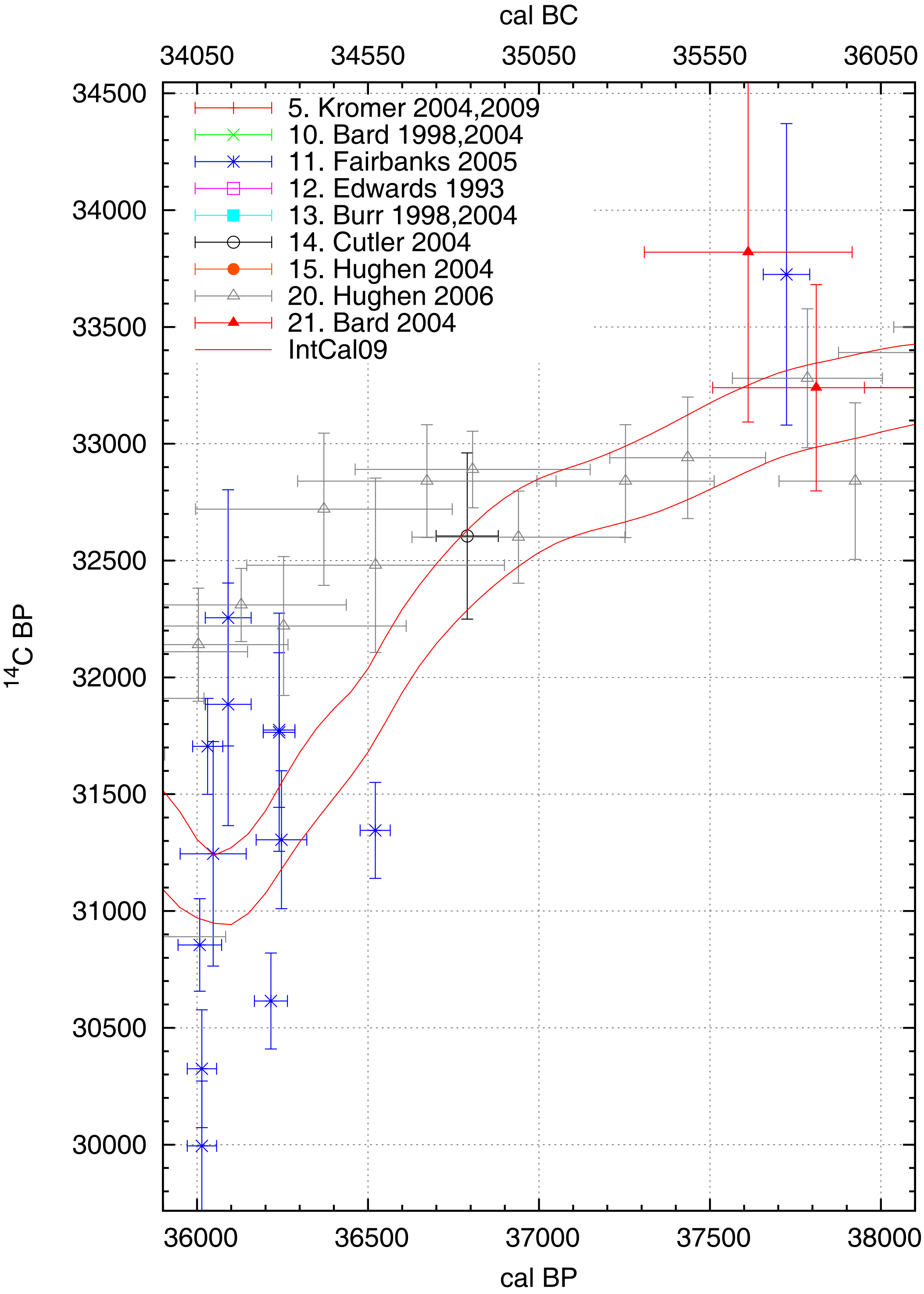

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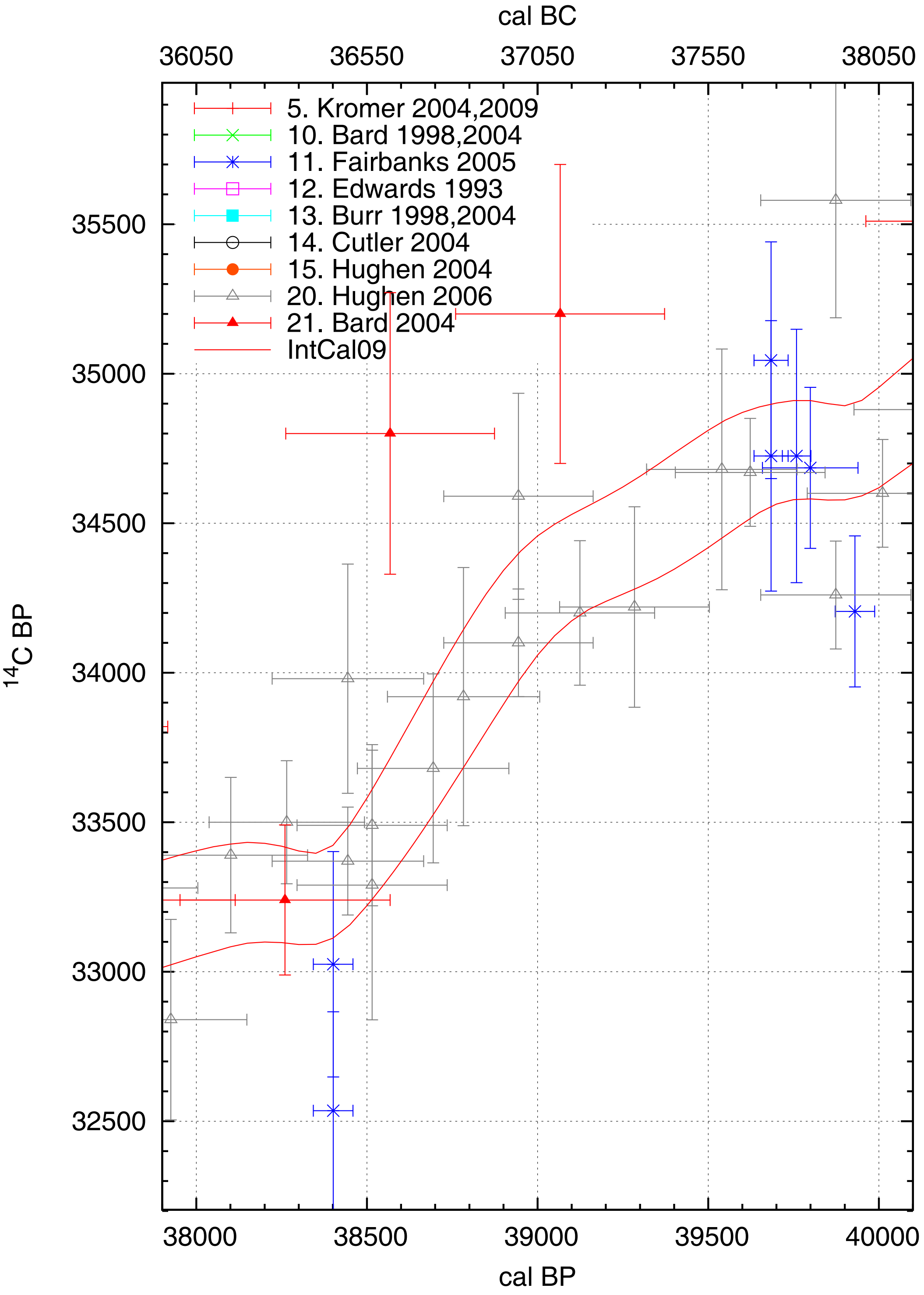

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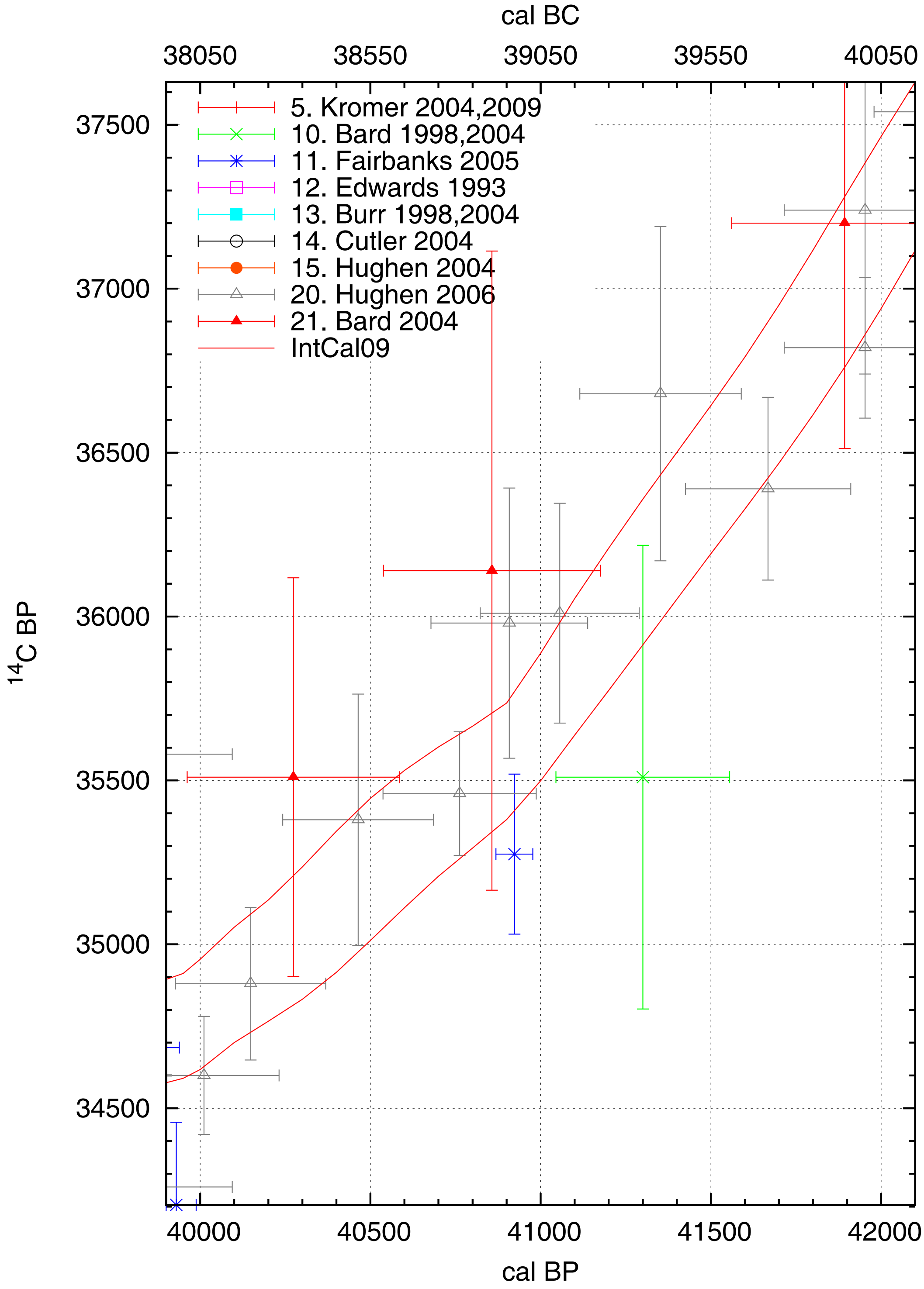

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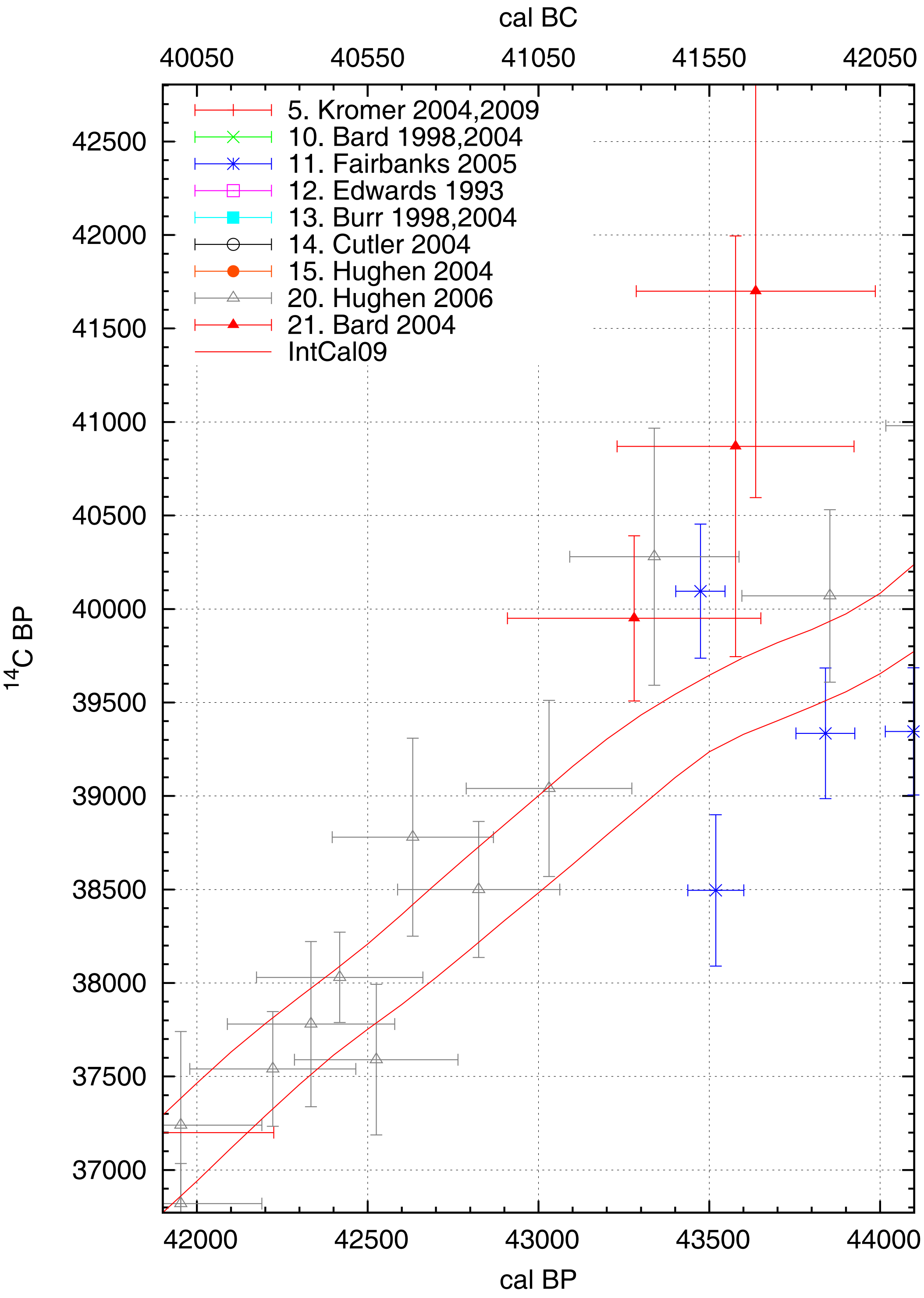

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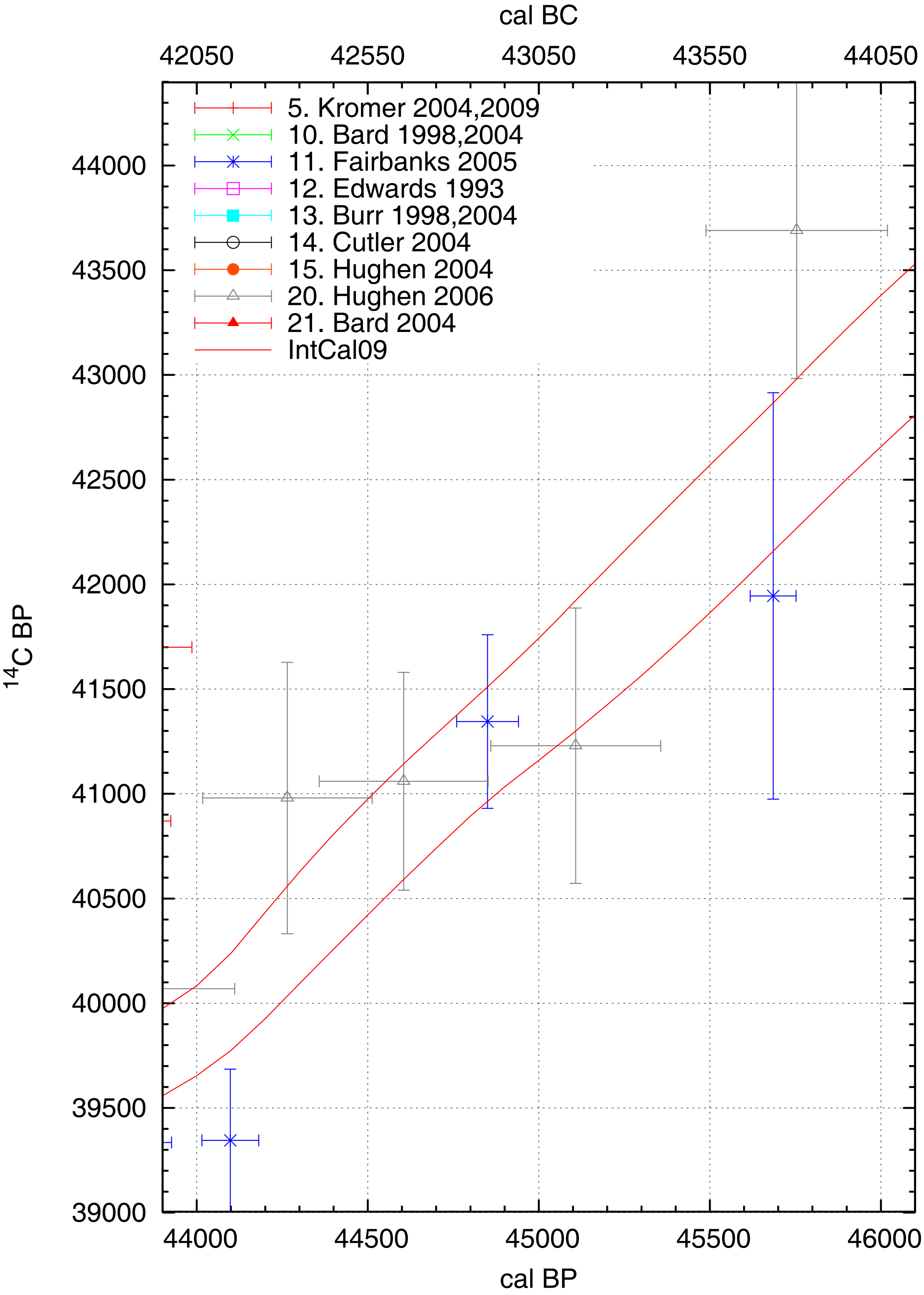

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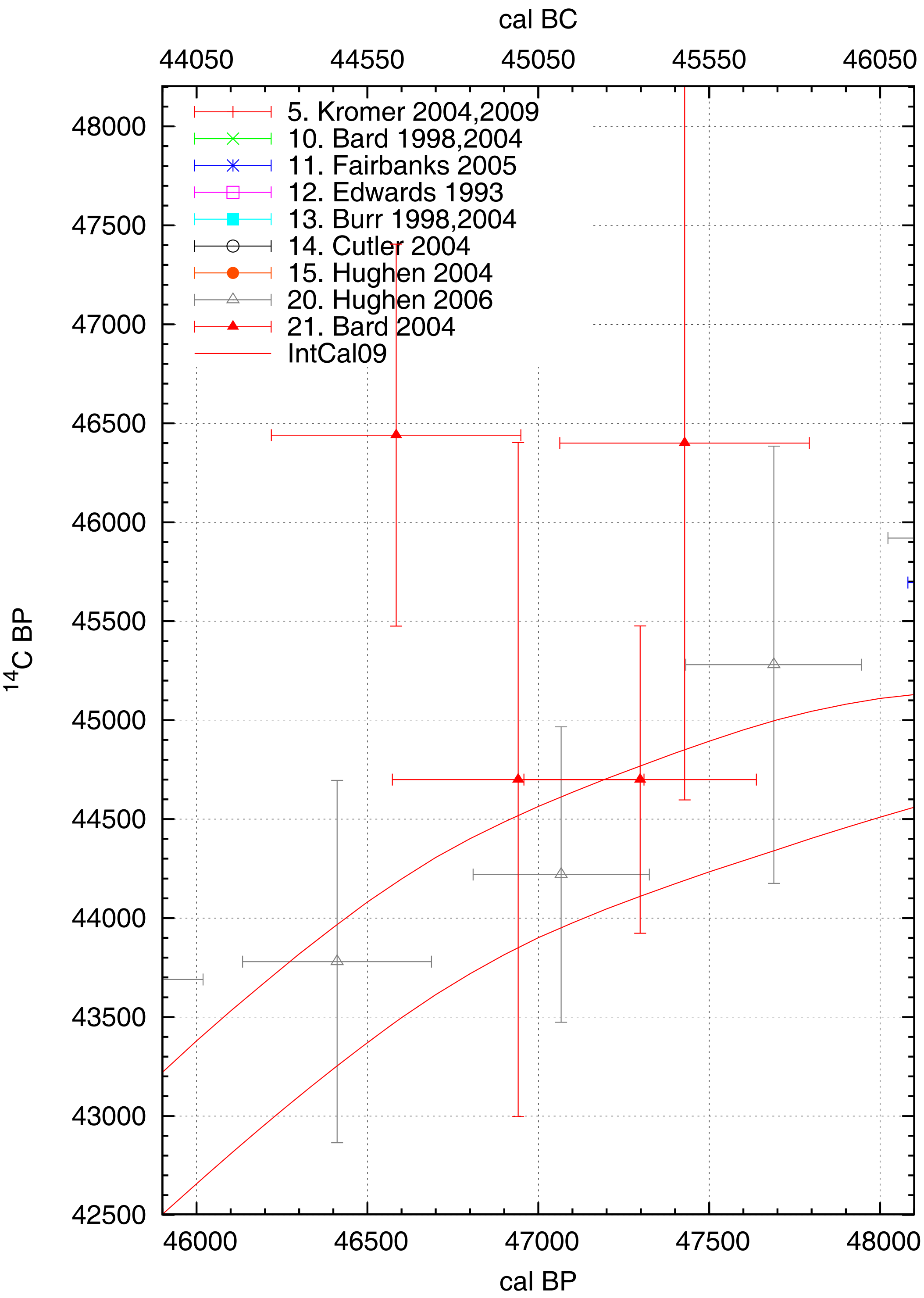

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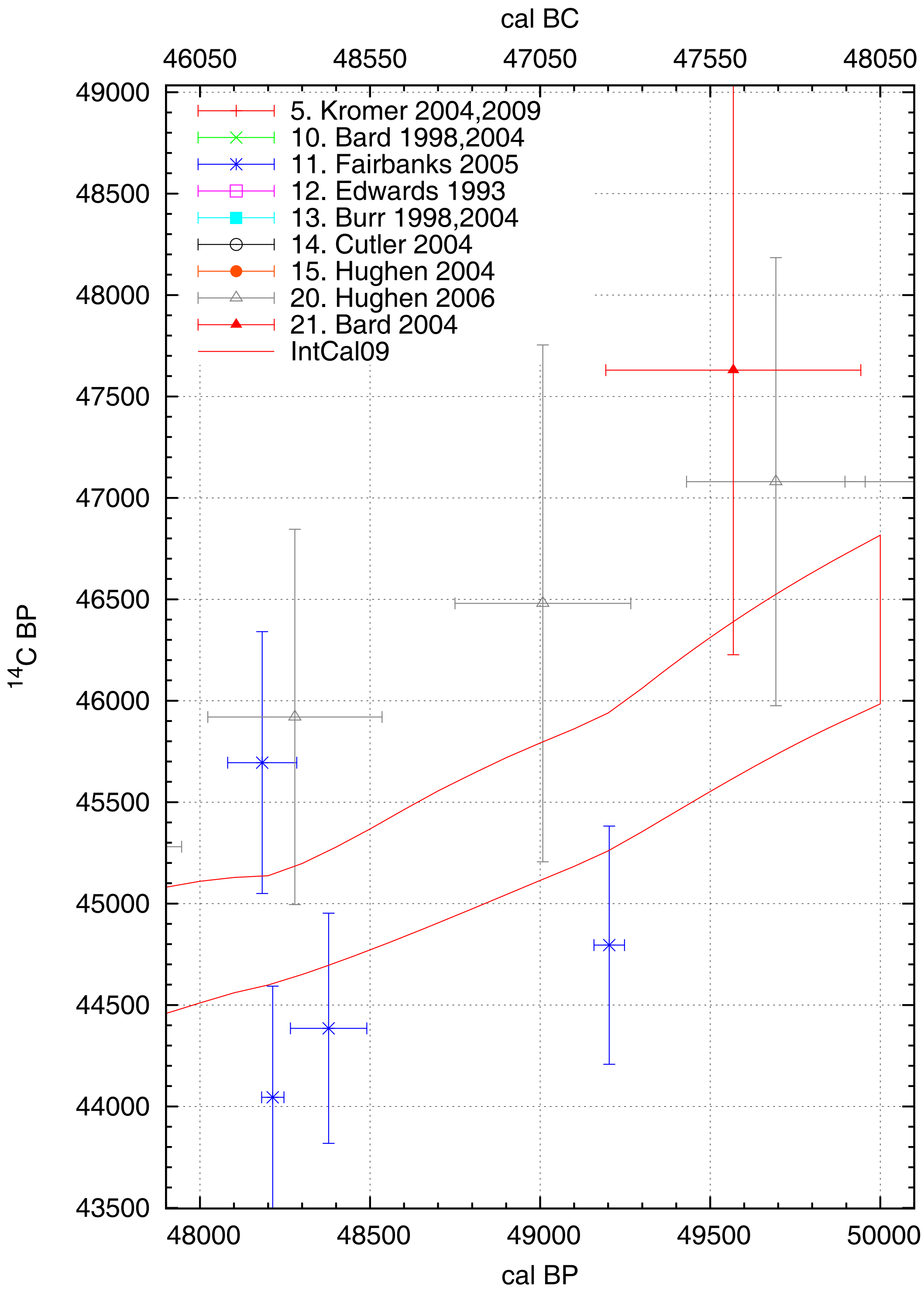

Figure 2 *(Continued)*.

The difference between IntCal04 and IntCal09 varies between –552 and +409 yr from 12–26 cal kBP (Figure 3). The IntCal04 curve did not extend beyond 26 cal kBP. From 0–12 cal kBP, the IntCal09 curve is taken directly from IntCal04 (Reimer et al. 2004) as calculated using the RWM described in Buck and Blackwell (2004). The relatively large differences between IntCal04 and IntCal09 between 16–18 ka and 21–22 ka are due primarily to the addition of the non-varved Cariaco Basin data (Hughen et al. 2006) where there was previously little or no data available. The entire IntCal09 curve and age-corrected $\Delta^{14}C$ and uncertainty calculated from it are shown in Figure 4.

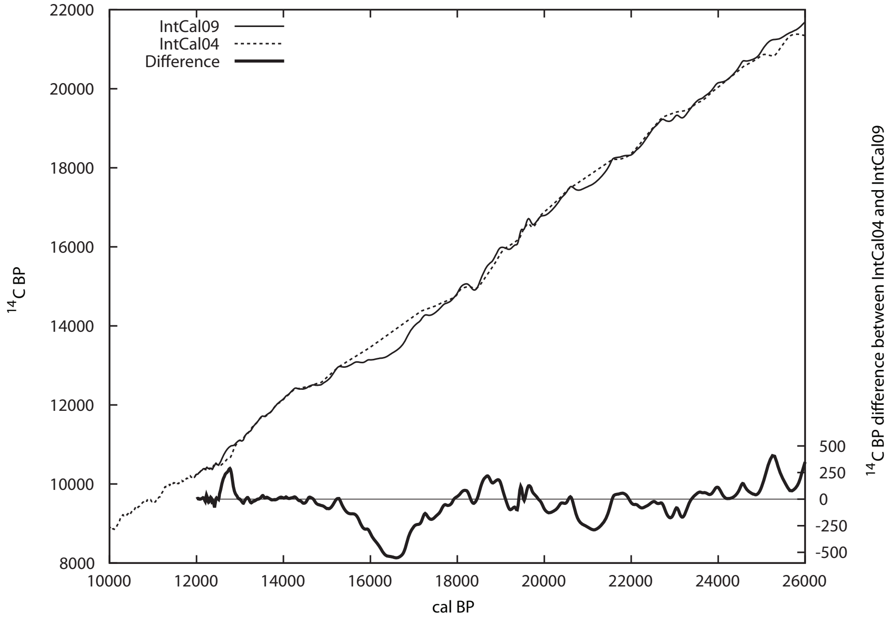

Figure 3 IntCal09 and IntCal04 calibration curves with differences from 12–26 cal kBP

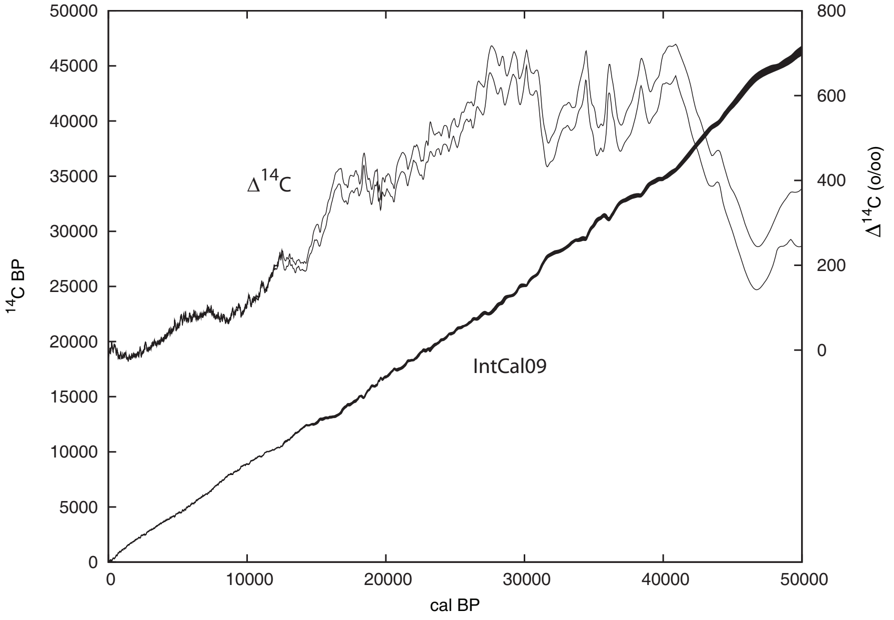

Figure 4 IntCal09 calibration curve and age-corrected $\Delta^{14}C$ (‰) with 1-standard deviation envelopes

THE MARINE09 CURVE

Because of the large variability of marine reservoir corrections in some regions of the world's oceans, it might be questioned whether a marine calibration curve should be provided at all prior to the Holocene. Indeed, in the high-latitude North Atlantic, "tuning" to the Greenland ice cores and using tephra and paleomagnetic tie-points may provide a more meaningful timescale than calibrated ^{14}C ages (Austin et al. 2004; Davies et al. 2008; Singer et al. 2009). The IWG have decided, however, to construct a "general" marine calibration curve assuming constant reservoir corrections, but to impart a strong warning that the user must decide whether large reservoir age changes are likely to affect their chronology and provide their own estimates of reservoir age changes and uncertainties.

The marine ^{14}C curve for the period of 0–12.5 cal kBP is taken from the Marine04 curve, which is calculated with the ocean-atmosphere box diffusion model (Oeschger et al. 1975; Stuiver and Braziunas 1993) as described in Hughen et al. (2004b). More complex models are available for calculating the surface ocean ^{14}C age (Butzin et al. 2005; Franke et al. 2008), but they require estimation of many parameters and at present do not agree with measurements of known-age marine samples from coastal regions (www.calib.org/marine). For the purpose of providing a global estimate to be used with regional reservoir corrections in calibration, a simple model has some merits. We have recently investigated the performance of the model for capturing the changes in atmospheric ^{14}C levels using the nuclear weapons testing spike in atmospheric ^{14}C levels. A comparison of the model with the current parameters used in Marine04 against a number of marine coral records is shown in Figure 5. Changes in the pre-industrial atmospheric pCO$_2$ level within the magnitude of variations

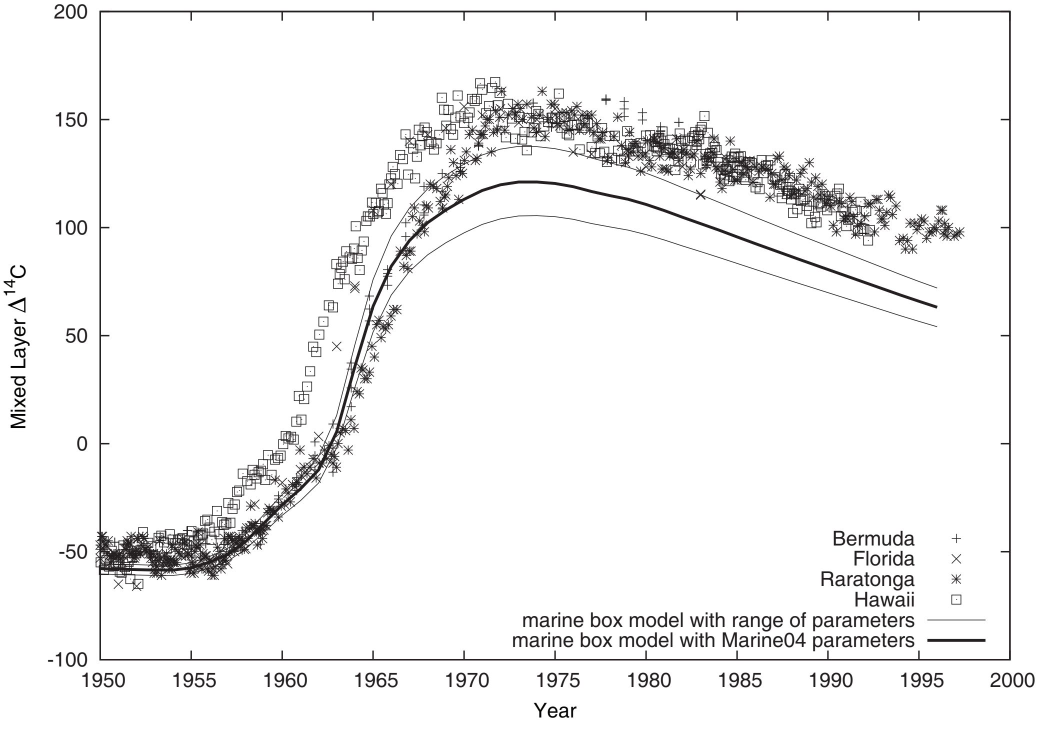

Figure 5 Comparison of the model marine mixed-layer age-corrected Δ^{14}C from the ocean-atmosphere box model with the range of parameters used in Marine04 with coral Δ^{14}C from Rarotonga (Guilderson et al. 2000), Hawaii (Roark et al. 2009), Florida and Bermuda (Druffel 1989).

found in the Taylor Dome Antarctic ice cores for the Holocene (Indermuhle et al. 1999) made no significant difference to the model output. The full output of the box model, which includes production rate and mixed layer, thermocline and deep ocean $\Delta^{14}C$, is available in the supplemental information. From 12.5–50 cal kBP, Marine09 is simply the atmospheric IntCal09 curve, which was derived from marine records, plus the questionable constant reservoir correction of 405 yr.

CONCLUSIONS AND FUTURE WORK

Curves and data sets included in IntCal09 and Marine09 are available in the supplemental material on the *Radiocarbon* Web site at www.radiocarbon.org. The BCal, CALIB, and OxCal software packages have been modified to use the new curves and are available at http://bcal.shef.ac.uk/, www.calib.org, and http://c14.arch.ox.ac.uk, respectively.

The new calibration curves, ratified by the 20th International Radiocarbon Conference, are replacements for IntCal04 and Marine04 and should provide improved ^{14}C calibration from 12–50 cal kBP. We realize that the assumption of a constant reservoir offset for the marine data is an oversimplification, but at present this is the only feasible option. It is also important to recognize that portions of the IntCal09 and Marine09 curves from 14.5–50 cal kBP rely heavily on the non-varved Cariaco Basin data set. The calibration framework is an ongoing, incrementally improving process over time as data are acquired and improved, so it must be realized that these new curves are not definitive but will be a significant improvement for samples older than ~12 cal kBP. More importantly, it provides a widely agreed curve, which is urgently needed for many fields of study.

A further update of IntCal09 and Marine09 is aimed for 2011 that will include new tree-ring, foraminifera, and coral measurements, among others. All of the data selection criteria will be revisited prior to the next IntCal calibration curve update. Further consideration of the marine model and parameters will be undertaken for the next calibration curve release. Other data sets will be considered by the IntCal Working Group and the IntCal Oversight Committee. An update of the Southern Hemisphere calibration curve SHCal04 (McCormac et al. 2004) is also underway. An online searchable database is under construction for all the IntCal calibration data sets and it is expected that the calibration curve construction software will be made available at the next calibration curve release.

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APPENDIX

A summary of the ^{14}C data sets used for IntCal09 and Marine09 is given below with references to the original data sets. These are cataloged by the institute where the ^{14}C measurements were made in some cases and in others by the first author on the publications. Data set number is a historical construct and makes no reflection on the date of publication. Lab codes can be found on the *Radiocarbon* Web site at www.radiocarbon.org.

TREE RINGS

University of Washington

Tree rings from Pacific Northwest Douglas fir, Californian Sequoia, Alaskan Sitka Spruce, and from the German oak and Irish oak chronologies.

Lab code: QL

Data set number: 1

Stuiver M, Braziunas T. 1993. Sun, ocean, climate and atmospheric $^{14}CO_2$: an evaluation of causal and spectral relationships. *The Holocene* 3(4):289–305.

Stuiver M, Reimer PJ, Braziunas TF. 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon* 40(3):1127–1151.

Note: IntCal04 (Reimer et al. 2004) included updates to the calendar age of the German pine measurements and some reinstated tree rings from German oaks affected by beetles, which previously could not be dendrodated (cf. Friedrich et al. 2004).

Queen’s University Belfast

Tree rings from Irish oak and German oak chronologies.

Lab code: UB

Data set number: 2

Pearson GW, Pilcher JR, Baillie MGL, Corbett DM, Qua F. 1986. High-precision ^{14}C measurement of Irish oaks to show the natural ^{14}C variations from AD 1840 to 5210 BC. *Radiocarbon* 28(2B):911–934.

McCormac FG, Hogg AG, Higham TFG, Lynch-Stieglitz J, Broecker WS, Baillie MGL, Palmer J, Xiong L, Pilcher JR, Brown D, Hoper ST. 1998. Temporal variation in the interhemispheric ^{14}C offset. *Geophysical Research Letters* 25(9):1321–1324.

Hogg AG, McCormac FG, Higham TFG, Reimer PJ, Baillie MGL, Palmer JG. 2002. High-precision radiocarbon measurements of contemporaneous tree-ring dated wood from the British Isles and New Zealand: AD 1850–950. *Radiocarbon* 44(3):633–640.

McCormac FG, Bayliss A, Baillie MGL, Brown DM. 2004. Radiocarbon calibration in the Anglo-Saxon period: AD 495–725. *Radiocarbon* 46(3):1123–1125.

Pearson GW, Becker B, Qua F. 1993. High-precision ^{14}C measurement of German and Irish oaks to show the natural ^{14}C variations from 7890 to 5000 BC. *Radiocarbon* 35(1):93–104.

University of Waikato

Tree rings from Irish oak chronology.

Lab code: Wk

Data set number: 3

McCormac FG, Hogg AG, Higham TFG, Lynch-Stieglitz J, Broecker WS, Baillie MGL, Palmer J, Xiong L, Pilcher JR, Brown D, Hoper ST. 1998. Temporal variation in the interhemispheric ^{14}C offset. *Geophysical Research Letters* 25(9):1321–1324.

Hogg AG, McCormac FG, Higham TFG, Reimer PJ, Baillie MGL, Palmer JG. 2002. High-precision radiocarbon measurements of contemporaneous tree-ring dated wood from the British Isles and New Zealand: AD 1850–950. *Radiocarbon* 44(3):633–640.

University of Groningen

Tree rings from German oak chronology.

Lab Code: GrN

Data set number: 4

de Jong AFM, Becker B, Mook WG. 1986. High-precision calibration of the radiocarbon time scale, 3930–3230 cal BC. *Radiocarbon* 28(2B):939–941.

de Jong AFM, Becker B, Mook WG. 1989. Corrected calibration of the radiocarbon time scale, 3904–3203 cal BC. *Radiocarbon* 31(2):201–210.

Vogel JC, van der Plicht J. 1993. Calibration curve for short-lived samples, 1900–3900 BC. *Radiocarbon* 35(1):87–91.

Heidelberger Akademie der Wissenschaften

Tree rings from German oak and pine chronology.

Lab code: Hd

Data set number: 5

Kromer B, Becker B. 1993. German oak and pine ^{14}C calibration, 7200–9439 BC. *Radiocarbon* 35(1): 125–135.

Kromer B, Spurk M. 1998. Revision and tentative extension of the tree-ring based ^{14}C calibration, 9200–11,855 cal BP. *Radiocarbon* 40(3):1117–1125.

Kromer B, Manning SW, Kuniholm PI, Newton MW, Spurk M, Levin I. 2001. Regional $^{14}CO_2$ offsets in the troposphere: magnitude, mechanisms, and consequences. *Science* 294(5551):2529–2532.

Hua Q, Barbetti M, Fink D, Kaiser KF, Friedrich M, Kromer B, Levchenko VA, Zoppi U, Smith AM, Bertuch F. 2009. Atmospheric ^{14}C variations derived from tree rings during the early Younger Dryas. *Quaternary Science Reviews* 28(25–26):2982–90.

Note: IntCal04 (Reimer et al. 2004) included updates to the calendar age of the German pine measurements and some reinstated tree rings from German oaks affected by beetles, which previously could not be dendrodated (cf. Friedrich et al. 2004) as well as previously unpublished data (some of which from the East Mediterranean Radiocarbon Comparison Project is included in Kromer et al. 2009).

CSIR, Pretoria

Lab code: Pta

Tree rings from German oak chronology.

Data set number: 6

Vogel JC, van der Plicht J. 1993. Calibration curve for short-lived samples, 1900–3900 BC. *Radiocarbon* 35(1):87–91.

Center for Accelerator Mass Spectrometry

Tree rings from Irish oak chronology.

Lab code: CAMS

Data set number: 7

Three decadal measurements of Belfast Irish oak processed to cellulose at Queen's University Belfast were included in the IntCal04 data set. Results are from multiple AMS targets with the error taken as the larger of the standard deviation in the mean and square root of the variance.

CORALS AND FORAMINIFERA

E. Bard et al.

Corals from Barbados, Tahiti, Mururoa, and New Guinea

Lab code: GifA

Data set number: 10

Bard E, Hamelin B, Fairbanks RG, Zindler A. 1990. Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature* 345(6274):405–410.

Bard E, Arnold M, Hamelin B, Tisnerat-Laborde N, Cabioch G. 1998. Radiocarbon calibration by means of mass spectrometric $^{230}Th/^{234}U$ and ^{14}C ages of corals: an updated database including samples from Barbados, Mururoa and Tahiti. *Radiocarbon* 40(3):1085–1092.

Bard E, Ménot-Combes G, Rostek F. 2004. Present status of radiocarbon calibration and comparison records based on Polynesian corals and Iberian Margin sediments. *Radiocarbon* 46(3):1189–1202.

R.G. Fairbanks et al.

Corals from Araki, Barbados, and Kirimati.

Lab codes: CAMS, Gif, and KIA

Data set number: 11

Fairbanks RG, Mortlock RA, Chiu T-C, Cao L, Kaplan A, Guilderson TP, Fairbanks TW, Bloom AL, Grootes PM, Nadeau M-J. 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired ^{230}Th/ ^{234}U/^{238}U and ^{14}C dates on pristine corals. *Quaternary Science Reviews* 24(16–17):1781–1796.

R. L. Edwards et al.

Corals from Huon Peninsula, Papua New Guinea.

Lab codes: AA and WHOI

Data set number: 12

Edwards RL, Beck JW, Burr GS, Donahue DJ, Chappell JMA, Bloom AL, Druffel ERM, Taylor FW. 1993. A large drop in atmospheric ^{14}C/^{12}C and reduced melting in the Younger Dryas, documented with ^{230}Th ages of corals. *Science* 260(5110):962–968.

G.S. Burr et al.

Corals from Vanuatu and Papua New Guinea.

Lab code: AA

Data set number: 13

Burr GS, Beck JW, Taylor FW, Récy J, Edwards RL, Cabioch G, Corrège T, Donahue DJ, O'Malley JM. 1998. A high-resolution radiocarbon calibration between 11,700 and 12,400 calendar years BP derived from ^{230}Th ages of corals from Espiritu Santo Island, Vanuatu. *Radiocarbon* 40(3):1093–1105.

Burr GS, Galang C, Taylor FW, Gallup CD, Edwards RL, Cutler KB, Quirk B. 2004. Radiocarbon results from a 13-kyr BP coral from the Huon Peninsula, Papua New Guinea. *Radiocarbon* 46(3):1211–1224

K. B. Cutler et al.

Corals from Vanuatu and Papua New Guinea

Lab code: not given

Data set number: 14

Cutler KB, Gray SC, Burr GS, Edwards RL, Taylor FW, Cabioch G, Beck JW, Cheng H, Moore J. 2004. Radiocarbon calibration to 50 kyr BP with paired ^{14}C and ^{230}Th dating of corals from Vanuatu and Papua New Guinea. *Radiocarbon* 46(3):1127–1160.

K. A. Hughen et al.

Foraminifera from Cariaco Basin varved sediments.

Lab code: CAMS

Data set number: 15

Hughen KA, Southon JR, Bertrand CJH, Frantz B, Zermeño P. 2004. Cariaco Basin calibration update: revisions to calendar and ^{14}C chronologies for core PL07-58PC. *Radiocarbon* 46(3):1161–1187.

Hughen KA, Lehman S, Southon J, Overpeck J, Marchal O, Herring C, Turnbull J. 2004. ^{14}C activity and global carbon cycle changes over the past 50,000 years. *Science* 303(5655):202–207.

Hughen KA, Southon JR, Lehman SJ, Overpeck JT. 2000. Synchronous radiocarbon and climate shifts during the last deglaciation. *Science* 290(5498):1951–1954.

Cariaco Basin-Hulu Timescale

Foraminifera from Cariaco Basin non-varved sediments.

Lab codes: CAMS, NSRL, and UCIAMS

Data set number: 20

Hughen K, Southon J, Lehman S, Bertrand C, Turnbull J. 2006. Marine-derived ^{14}C calibration and activity record for the past 50,000 years updated from the Cariaco Basin. *Quaternary Science Reviews* 25(23–24):3216–3227.

Iberian Margin-Hulu Timescale

Foraminifera from Iberian Margin non-varved sediments.

Lab codes: KIA, GifA, and OS

Data set number: 21

Bard E, Rostek F, Ménot-Combes G. 2004. A better radiocarbon clock. *Science* 303(5655):178–179.

Bard E, Rostek F, Ménot-Combes G. 2004. Radiocarbon calibration beyond 20,000 ^{14}C yr B.P. by means of planktonic foraminifera of the Iberian Margin. *Quaternary Research* 61(2):204–214.

Shackleton NJ, Fairbanks RG, Chiu T-C, Parrenin F. 2004. Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for Δ^{14}C. *Quaternary Science Reviews* 23(14–15):1513–1522.

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