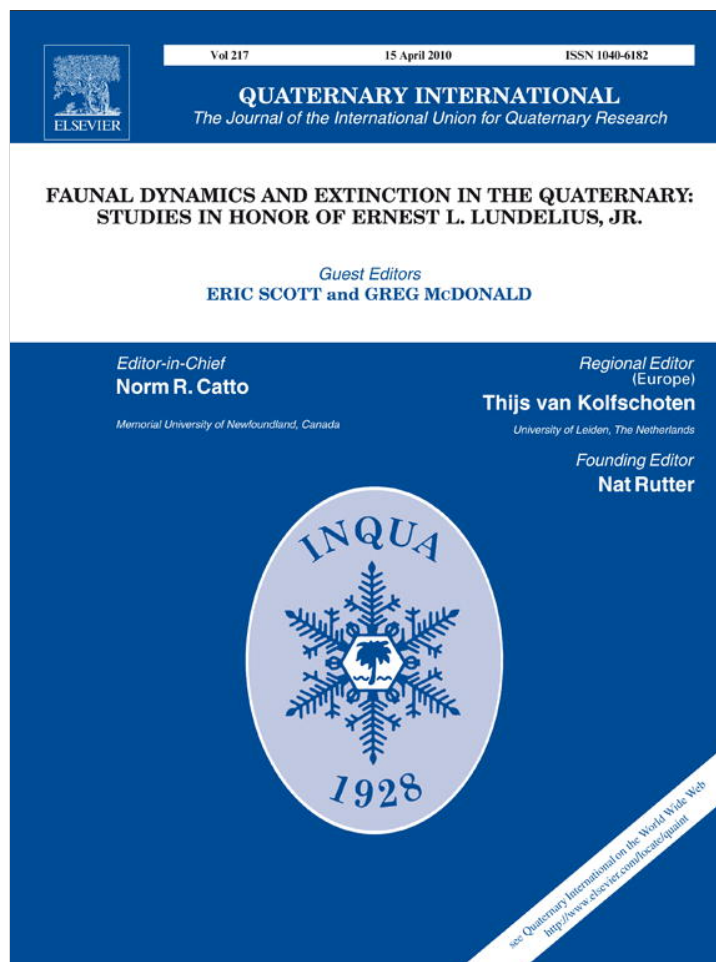


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## Timing of Quaternary megafaunal extinction in South America in relation to human arrival and climate change

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### ABSTRACT

South America lost more genera in the Quaternary megafaunal extinction than any other continent, but how it fits into the worldwide extinction has been unclear largely due to the lack of chronological resolution. This work evaluated 138 published radiocarbon dates for megafauna and 402 published dates for early (>8000 BP) South American archaeological sites. A total of 93 megafauna dates for 15 genera, and 110 archaeological dates on early human appearance, are robust enough to assess correspondence between last-appearance records of megafauna, first-appearance records of humans, and the Younger Dryas to Holocene climatic transition in six different regions of South America.

Interesting patterns come to light, but are based on few dates, particularly in northern South America. No taxon other than *Mylodon* has >7 robust dates, and many taxa have less than 3 dates. Accordingly, an assessment of how likely it is that only a few dates will yield the youngest date in an underlying frequency distribution of dates was conducted, by applying probability and bootstrapping analyses to 27 dates on *Mylodon* from southern Patagonia, 26 of them from a single site. It was found that 15 dates out of a sample of 27 will commonly yield a date within 200 years of the youngest date in the sample. For that reason, and because even for a taxon with many dates it is likely that the youngest dated specimen pre-dates the actual time of extinction, most of the last-appearance dates are interpreted as recording the last time taxa were abundant on the landscape, rather than extinction *per se*.

With those caveats in mind, on a continental scale most megafauna have last appearances after human arrival, but seem to last at least 1000 years after first human presence. Some taxa apparently survived >6000 years after humans entered South America and >1000 years after the end-Pleistocene climatic changes. Last-appearance patterns for megafauna differ from region to region, but in Patagonia, the Argentine and Uruguayan Pampas, and Brazil, extinctions seem more common after humans arrive and during intensified climatic change between 11.2 and 13.5 ka. This pattern suggests that a synergy of human impacts and rapid climate change—analogue to what is happening today—may enhance extinction probability. Nevertheless, even in these regions, some megafauna persisted for thousands of years after human arrival and after the climate warmed. These results highlight the need for future intensive dating efforts on South American megafauna and archaeological remains.

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### 1. Introduction

The Quaternary megafaunal extinction is the most recent of Earth's major extinction events and culled nearly two-thirds of the world's largest animals, that is, those with body mass greater than about 44 kg. In the northern hemisphere it coincided with the end of

the last glacial retreat. On a global scale, the extinctions followed first appearance of humans or expanding human populations in many regions (MacPhee, 1999; Barnosky et al., 2004; Koch and Barnosky, 2006; Brook et al., 2007). As a result, the Quaternary megafaunal extinction has been invoked as an analog for what might be expected under the current conditions of extremely rapid global warming combined with unprecedented human population growth: a synergy between direct human impacts, indirect human impacts, and climatic impacts that accelerates extinction in a wide variety of species (Barnosky et al., 2004; Koch and Barnosky, 2006; Brook et al.,

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2008; Barnosky, 2009; Brook and Barnosky, in review). If that synergy was fatal in the past, today it may be even more so, as global climate warms at much faster than normal rates, to higher than normal magnitudes, and as human population grows from an already unprecedented high of nearly 7 billion to 9 billion near the year 2050 (Nakicenovic et al., 2001).

The most potent argument that coincident global climate change and increasing human population leads to rapid extinction comes from North America, where Clovis hunters first entered the continent at almost exactly the same time that climate rapidly changed, manifested first by a short period of Younger Dryas cooling commencing 13,500 years ago (ka BP), then interglacial warming. Extinction was more rapid and severe under those conditions than on continents where climate change and human arrival were decoupled. For comparison, in North America 34 megafauna genera (72%) went extinct, with at least 15 of those disappearing during the time the Clovis culture and the Younger Dryas climatic event overlapped, 13.5–11.5 ka BP (most of the other North American genera are not well constrained by radiocarbon dates) (Barnosky et al., 2004; Koch and Barnosky, 2006). In northern Eurasia, where colonization by *Homo sapiens* (and their close relatives) occurred long before the onset of terminal Pleistocene climatic changes, the extinction was much milder (only 9 genera, or 35%) and took place over a much longer time, from 48.5 to 7 ka, mainly concentrated in one early and one late pulse, both of which corresponded to times of climate change (Barnosky et al., 2004; Koch and Barnosky, 2006). In Australia, extinction ensued without climatic change but followed the first arrival of humans some 50,000 years ago, and there is growing evidence that the extinction was less sudden than in North America, with the known last records of a total of 14 mammalian megafauna genera (88%) falling between 50 and 32 ka (many perhaps clustered around 45 ka) (Roberts et al., 2001; Barnosky et al., 2004; Brook and Bowman, 2004; Wroe et al., 2004; Trueman et al., 2005; Wroe et al., 2006; Koch and Barnosky, 2006; Wroe and Field, 2006; Brook et al., 2007).

Other than North America, South America is the only continent where initial human arrival and terminal Pleistocene climatic change were reasonably close in time; hence, if a human–climate synergy accelerates extinction, it should parallel North America in seeing the most severe, fastest extinction. It has long been known that South America's extinction was particularly severe (Martin, 1984; Cione et al., 2003); the continent lost more genera of megafauna (52, or 83%) than any other, and most of the losses seem to be at the end of the Pleistocene. Whether it was as fast as in North America, and exactly when in the late Pleistocene most taxa went extinct, have been open questions. This is not for lack of excellent studies on many paleontological and archaeological sites in South America (see references in Appendices 1, 2 and Supplementary Online Material), which have contributed much new, important information over the past decade (Borrero, 2008).

Here, that information is synthesized in order to test the idea that synergy between rapid climate change and human impacts results in more severe extinction on continents than either cause alone, essentially using South America as an independent natural experiment. If human impacts were significant in causing extinctions by either direct (e.g., hunting) or indirect effects (e.g., habitat fragmentation or alteration, or competition for resources), the last records for taxa should be after humans first arrived on the continent, with proximity in timing roughly proportional to the magnitude of human impact, and that the geographic pattern of extinction should correspond to the sequence of human colonization of different regions. If climate alone drove extinction, taxa

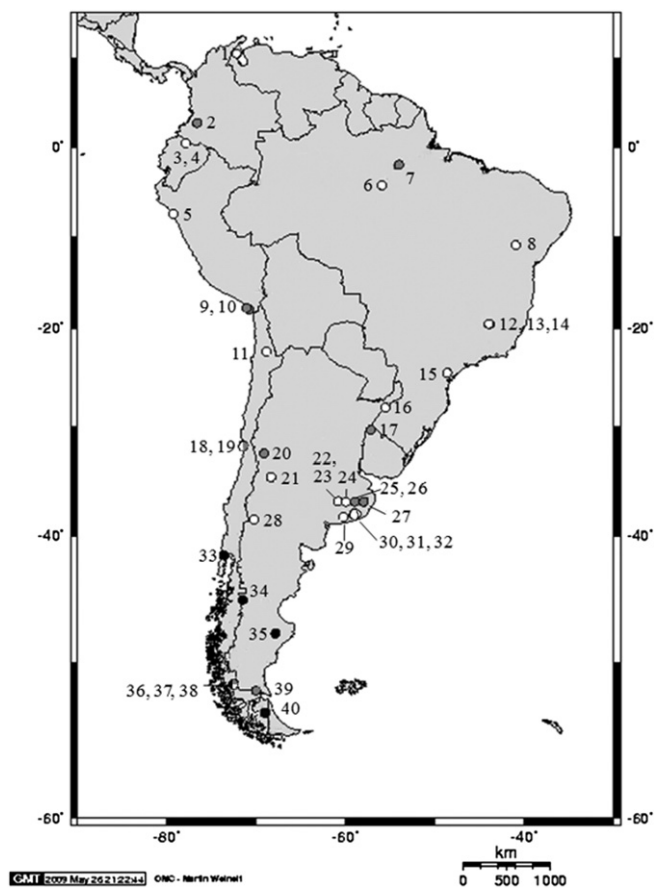
should disappear during the most pronounced climate changes, but not necessarily coincident with first human appearance. If synergy between the two caused the extinction, then extinction should begin after humans first arrive, but accelerate dramatically with addition of climatic pressures. The authors recognize that a full explanation of causes of extinctions requires information over and above simply establishing correlations between timing of extinction and timing of purported causes, for example, specific life history traits of affected species, and direct evidence of human impacts (Grayson, 1984, 2007; Grayson and Meltzer, 2002; Grayson and Meltzer, 2003). Nevertheless, establishing the requisite chronology of events is the essential initial step, on which this paper focuses.

## 2. Methods

To construct the chronology, relevant information was first extracted from peer-reviewed literature published in English, Spanish, and Portuguese that reported radiocarbon dates for (i) genera and species of Quaternary megafauna that are now extinct; (ii) archaeological sites older than 8000 BP; and (iii) palynological, glaciological, and other studies that dated the Younger Dryas and Pleistocene–Holocene climatic transitions in South America. In all, synthesis of information from the sources cited in Appendices 1, 2, and Supplementary Online Material yielded a dataset of 40 sites (21 with megafauna only, 12 archaeological, 7 with both megafauna and archaeological remains) distributed through much of South America (Fig. 1). These sites yielded 138 radiocarbon dates for megafauna and 402 dates for human presence before 8000 BP (see Supplementary Online Material).

Second, after eliminating dates that were obviously problematic (for example, dates that reporting authors flagged as untrustworthy), evaluation was conducted of the strength of the evidence that each radiocarbon date provided for actually determining the age of what it was purported to date. Each date was assigned a numeric ranking that combined scores for the kind of material dated, the association of the dated material with the taxon or event that was being dated, the method of dating (AMS or standard), and in the case of archaeological sites, the kind of evidence (artifacts versus hearths, for example) that was used to indicate human presence. The ranking scale was based on a modified version of the Mead–Meltzer scale (Mead and Meltzer, 1984), updated to reflect more recent advances in radiocarbon dating and to incorporate archaeological evidence (Table 1).

Only the highest-ranked dates were accepted for establishing the chronology. For megafauna, only dates from the bone, hide, hair, or dung of the extinct taxon in question were accepted: this avoids any problems that might be introduced by stratigraphic mixing or dating notoriously unreliable materials like shells, marls, or terrestrial carbonates. The dates considered most robust ranked 12 on the scale, which is the maximum possible for megafauna and requires an AMS date. As an example, a date on collagen from a sloth bone dated by AMS techniques would be assigned a score 5 for the material (collagen), 5 for the stratigraphic association (the specimen itself), and 2 for the dating method (AMS), which sum to give a rank-12 date (Table 1). The same specimen dated by standard techniques would have a dating method score of 1, which would drop its overall rank to 11; the implications of accepting such rank-11 dates are discussed below. In theory it is also possible to obtain a rank-11 date from charcoal at the same stratigraphic level as a bone; however, the stratigraphic detail reported in most publications does not allow distinguishing whether a given charcoal date was in fact at the same stratigraphic level, rather than above or below a megafaunal specimen. Unless otherwise



**Fig. 1.** Distribution of localities with robustly dated megafaunal (white), archaeological (gray), and both (black) material in South America. (1) Inciarte, Venezuela. (2) San Isidro, Colombia. (3) Quebrada Cuesaca, Ecuador. (4) Quebrada Pistud, Ecuador. (5) Pampa de Fosiles, Peru. (6) Itaituba Quarry, Brazil. (7) Pedra Pintada, Brazil. (8) Gruta de Brejões, Brazil. (9) Quebrada Tacahuay, Peru. (10) Quebrada de los Burros, Peru. (11) Betecas 1, Chile. (12) Gruta Cuvieri, Brazil. (13) Lapa de Escrivânia, Brazil. (14) Lapa dos Tatus, Brazil. (15) Ponta de Flecha Cave, Brazil. (16) Touro Passos/Lageado dos Fosseis, Brazil. (17) Pay Paso 1, Uruguay. (18) Los Vilos, Chile. (19) Quebrada Santa Julia, Chile. (20) Agua de la Cueva, Argentina. (21) Gruta del Indio, Argentina. (22) Campo Laborde, Argentina. (23) La Moderna, Argentina. (24) Salto de Piedra, Argentina. (25) Cerro La China, Argentina. (26) Cerro El Sombrero, Argentina. (27) Cueva Tixi, Argentina. (28) Cuchillo Cura, Argentina. (29) Arroyo Seco, Argentina. (30) Paso Otero 5, Argentina. (31) Zanjón Seco, Argentina. (32) Campo de Arce Rio, Argentina. (33) Monte Verde, Chile. (34) Baño Nuevo, Chile. (35) Piedra Museo, Argentina. (36) Cueva del Medio (Ultima Esperanza area), Chile. (37) Cueva del Milodón, (*Mylodon* Cave) Chile. (38) Lago Sofía 1 (Ultima Esperanza area), Chile. (39) Fell Cave, Chile. (40) Tres Arroyos, Chile.

specified in the original publication, reported dates for bone are assumed to be on bone collagen. For brevity in the text and appendices, dates on bone collagen are referred to simply as “bone” dates.

Archaeological sites included the additional scoring category of ‘Association of Date with Archaeological Material’ (Table 1). This refers to the strength of the evidence that the dated material was in direct archaeological context, whereas the category ‘Stratigraphic Association’ refers simply to the strength of physical-stratigraphic association of the dated material, irrespective of archaeological context. The addition of the archaeological association score means that ranks for archaeological dates are systematically higher (with a maximum of 17) than for strictly megafaunal dates (for which the maximum rank is 12). Archaeological dates are considered robust if they ranked at least 13 on the 17-point archaeological-date scale. A ranking of at least 13 required that the date had to be on charcoal, wood, bone, hide, hair, or dung, and in strong stratigraphic

**Table 1**  
Numerical ranking scale for assessing the strength of radiocarbon dates.

	Score
<b>Material</b>	
Collagen	5
Dung	5
Hide	5
Hair	5
Apatite	3
Whole bone	1
Charcoal	6
Wood (logs, twigs, leaves)	5
Peat	3
Organic mud (gyttja)	3
Soil	3
Shell	2
Terrestrial carbonate (marl)	1
<b>Stratigraphic association of specimen of interest with dated material</b>	
Date on the specimen itself	5
Date from same stratum as the specimen	3
Date on material above the specimen	2
Date on material below the specimen	2
“Associated” date	1
<b>Association of dated material with archaeological evidence</b>	
Date from human remains	5
Living floor/assemblage	4
Clear hearth	3
Single artifact	3
Probable hearth	2
Clear butchering	2
Equivocal evidence	1
<b>Dating method</b>	
AMS	2
Standard or unknown	1

association with obvious signs of human activity, such as within a well-developed hearth or from an undisputed living floor that contained abundant and obvious artifacts. As examples, an AMS date on charcoal embedded in an undisputed living floor that contained many artifacts would have an overall rank of 17: scored 6 for the material (charcoal), 5 for the stratigraphic association (object itself), 4 for the archaeological association (living floor), and 2 for the dating method. Likewise, AMS-dated collagen from a human bone would have a rank of 17 (5 for material, 5 for stratigraphic association, 5 for archaeological association, 2 for method). A standard date on a piece of wood that was found directly below a stone artifact would have a rank of 11: score of 5 for material, 2 for stratigraphic association (below the specimen), 3 for archaeological association (directly below an artifact), 1 for dating method (standard).

Dates below rank-11 for megafauna or rank-13 for archaeological dates were not accepted, because such lower-ranked dates imply lack of certainty in stratigraphic association or dating of materials that are known to be often problematic.

All radiocarbon ages were calibrated by using the program OxCal (<http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html>). Because the calibration curves specific to South America (ShCal04) extend back only 11 ka (McCormac et al., 2004), the IntCal04 calibration was used (all ages in the text and figures are from this calibration). The uncalibrated radiocarbon ages are reported in the [Supplementary Online Material](#); using them instead of calibrated ages does not change any of the conclusions.

An attempt was made to assess how adding more dates per taxon increased the likelihood of obtaining younger dates in two ways: (1) bootstrapping and (2) calculating probabilities of getting the youngest date from an underlying distribution of known dates. For both, the 27 dates on *Mylodon* from southern Patagonia were

used to represent an underlying distribution of dates. Twenty-six of the dates were from Cueva del Milodón, Chile (loc. 37 in Fig. 1), and one was from Ultima Esperanza (NUTA, Appendix 1; locs. 36 and 38 in Fig. 1). For bootstrapping analyses, EstimateS (Colwell, 2005) was used, substituting temporal bin for species, and sampling the southern Patagonia *Mylodon* distribution with replacement for 200 iterations. For the probability analyses, R-scripts written by Nicholas J. Matzke (University of California Department of Integrative Biology) were used to determine the probability of obtaining the youngest date from a known distribution of dates. For these analyses, the southern Patagonia *Mylodon* distribution of radiocarbon dates was sampled 1000 times without replacement, and the number of times an age was drawn from the youngest bin in the frequency distribution after sampling 1 date, 2 dates, and so on up to 27 dates was computed, as well as the youngest average age that resulted with each number of samples. Frequency distributions and linear regressions were computed in Microsoft Excel ver. 12.1.7 (2008).

### 3. Results and discussion

Of the 138 megafauna dates reported in peer-reviewed publications, there were 46 dates of rank-12 and 47 dates of rank-11, for a total of 93 dates deemed robust (Appendix 1). Of the 402 archaeological dates, one date ranked 17, one ranked 16, 43 ranked 15, 40 ranked 14, and 25 ranked 13, for a total of 110 dates considered robust (Appendix 2).

#### 3.1. Using only megafauna dates of rank-12

The megafauna dates provide a basis for estimating the last-occurrence data for 15 of the 52 genera that went extinct (Appendix 1). At face value, using only dates ranked 12, the last occurrences fall into three groups: those earlier than 18 ka (*Holmesina*, *Glyptodon*, *Haplomastodon*); those between 18 and 11 ka (*Cuvieronius*, *Mylodon*, *Glossotherium*, *Nothrotherium*, *Eremotherium*, *Toxodon*, *Hippidion*, *Equus*); and those between 11.5 and 8 ka (*Smilodon*, *Catonyx*, *Megatherium*, *Doedicurus*) (Fig. 2).

However, all three of the taxa with last occurrences older than 18 ka have very few dates (Fig. 3). For *Holmesina*, median ages from 43.587 to 47.987 ka were obtained from three specimens, each of which had a different pre-treatment, from Inciarte, Venezuela. Two specimens of *Glyptodon* from the same site (a tar deposit) had median ages of 25.546 and 27.997 ka. One date on *Haplomastodon* is from a single specimen from Quebrada Cuesaca in Ecuador; the other is from an alluvial deposit on the Rio Tapajos, Brazil. Given that the probability is extremely low that so few specimens, especially from a single site, record the actual first or last appearance of a taxon (Signor and Lipps, 1982) (and see Section 3.3), it seems likely that dating additional specimens would extend the range of these “early extinctions” significantly forward. It is suspected this will be the case with additional direct dating of bones of especially *Haplomastodon* and *Glyptodon*, as the former has been reported in association with strata dated to about 12.5 ka at Taima-Taima, Venezuela (Surovell et al., 2005) and the latter is associated with charcoal that yielded median ages of 9.596–10.514 ka at Pay Paso 1, Uruguay (Suárez, 2003). Because bones were not dated directly, dates for the Pay Paso *Glyptodon* rank only 9 on the scale. Not enough data was reported for the Taima-Taima *Haplomastodon* date to rank it, and the authors (Surovell et al., 2005) considered the date questionable.

Likewise, most of the megafauna with rank-12 last-occurrence dates that fall between 18 and 11.5 ka are known by very few rank-12 dates: *Cuvieronius* (2 dates from Monte Verde, Chile); *Glossotherium* (3 dates, 1 from Quebrada Pistud, Ecuador, and 2 from

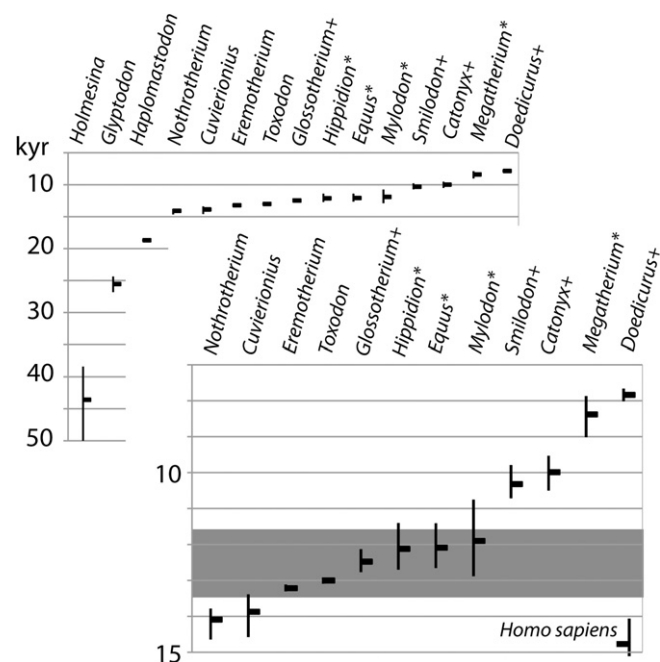


Fig. 2. Last-appearance dates for megafauna and first-appearance date for humans for all of South America using only rank-12 (most taxa) and rank-11 (*Mylodon*, *Catonyx*, *Equus*) megafauna dates. Horizontal bars show median calibrated radiocarbon date, vertical bars show 95.4% confidence interval for the date. Upper set of dates shows the complete suite from 50 ka to 5 ka; lower inset expands the timescale to show detail from 15 to 7 ka. The human first-appearance date is from Monte Verde, Chile, and has a rank of 13. Dates indicated by an \* are those taxa that have at least five dates; those marked by a + are those regarded as last-appearance dates the authors are willing to accept for now, with the understanding that additional dating might be expected to reveal even younger dates. Dark gray bar shows the terminal Pleistocene cold spell roughly equivalent to the Younger Dryas.

Arroyo Seco 2, Argentina); *Mylodon* (1 date from Baño Nuevo Cave, Chile); *Toxodon* (2 from Ribeira do Iguape, Brazil). (Figs. 3–6, citations in Appendices 1 and 2). It would not be surprising if future dating efforts reveal rank-12 dates that are younger than the presently known last appearances for these genera. *Equus* and *Hippidion*, in contrast, are known by 6 and 7 rank-12 dates each (for *Equus*, 3 from Arroyo Seco 2 and 3 from Lapa da Escrivânia 5, Lagoa Santa, Brazil; for *Hippidion*, 2 from Cueva del Medio, 2 from Cueva Lago Sofia 1, 2 from Betesca I, all in Chile, and 1 from Piedra Museo, Argentina), which increases the probability that the true extinction date will be within 700 years of the last-appearance date now recorded (see Section 3.3).

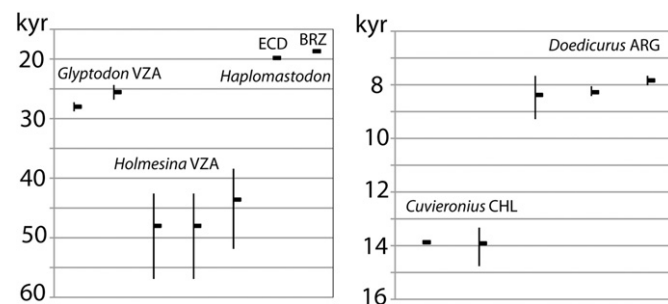
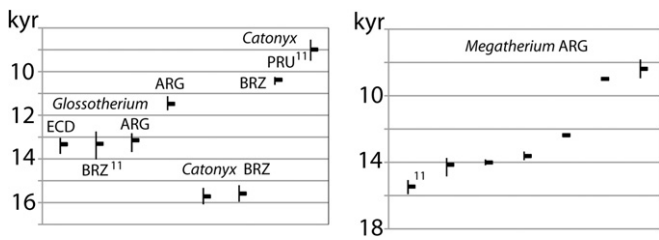
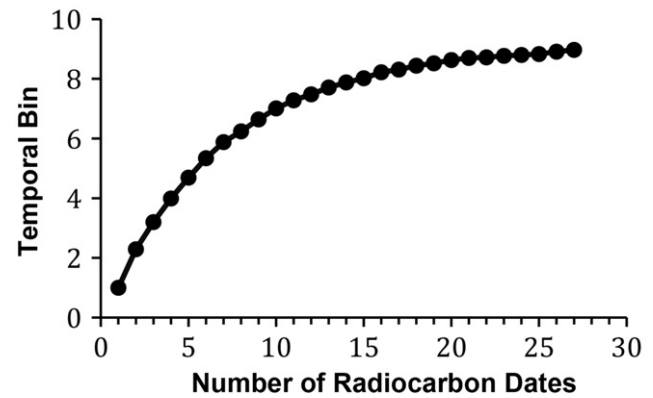
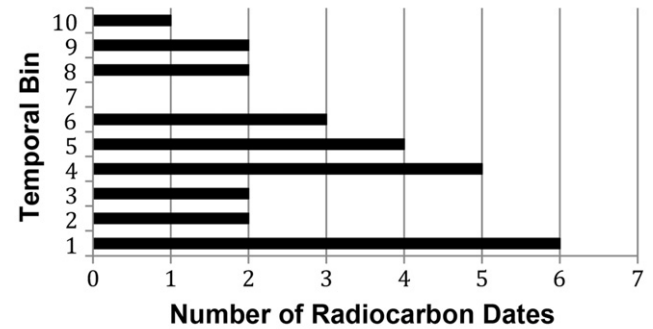
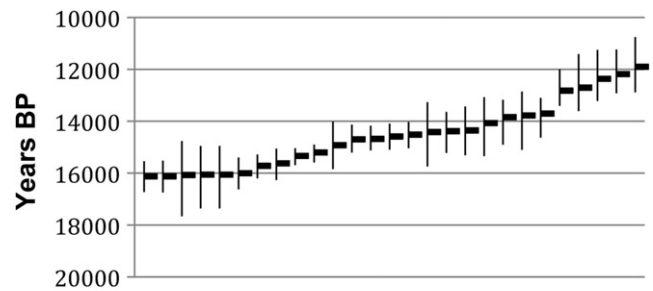


Fig. 3. Range of dates for *Glyptodon*, *Holmesina*, *Doedicurus*, and proboscideans. Horizontal bars show median calibrated radiocarbon date, vertical bars show 95.4% confidence interval for the date. All dates are rank-12. Abbreviations: ARG, Argentina; BRZ, Brazil; CHL, Chile; ECD, Ecuador; VZA, Venezuela.



**Fig. 4.** Range of dates for *Glossotherium*, *Catonyx*, and *Megatherium*. Horizontal bars show median calibrated radiocarbon date, vertical bars show 95.4% confidence interval for the date. All dates are rank-12 except for one rank-11 (indicated by <sup>11</sup>) for *Glossotherium* from Brazil, one for *Catonyx* from Peru, and one for *Megatherium* from Argentina. Abbreviations: ARG, Argentina; BRZ, Brazil; ECD, Ecuador; PRU, Peru.

The youngest rank-12 last-appearance dates are for *Smilodon*, *Catonyx*, *Megatherium*, and *Doedicurus*, known from 1, 3, 6, and 3 rank-12 dates, respectively (Figs. 2–4). The single *Smilodon* date is from Lapa da Escrivânia 5, Lagoa Santa, Brazil; the calibrated range of 9.792–10.712 ka is entirely within the Holocene. The 3 age determinations for *Doedicurus* date just a single specimen (from La Moderna, Argentina), different pieces of which were analyzed and which produced dates with median ages of 7.838, 8.275, and 8.379 ka (ranges of 7.663–8.014, 8.054–8.414, and 7.665–9.280 ka, respectively) (Appendix 1, Fig. 3). As with the dates for other taxa, given that only one individual each of *Smilodon* and *Doedicurus* are dated, it is very unlikely that these dates represent the actual last-appearance of the species. However, for that same reason they remain strong evidence that these species lasted well into the Holocene, if the age determinations are in fact reliable (see Section 3.4). The youngest *Megatherium* rank-12 dates are from Campo La Borde, Argentina. *Catonyx* has 3 rank-12 dates, 2 from Lapa dos Tatus and 1 from Gruta Cuvieri, Lagoa Santa, Brazil, with the latter being the youngest at a median age of 11.375 ka (range 11.252–11.606 ka). A

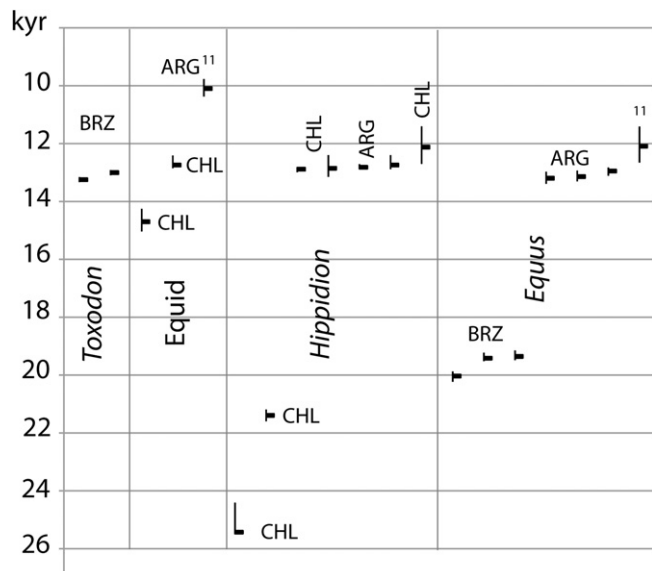


**Fig. 6.** Dates for *Mylodon* from Cueva del Milodón: (Top) calibrated radiocarbon dates, median and 95.4% confidence interval. (Middle) Frequency distribution of dates, turned vertically, and binned in 500-year intervals, with bin 1 = 16,500–16,000 ybp and bin 10 = 12,500–12,000 ybp. (Bottom) Bootstrapping curve showing that sampling 20 of the total 27 dates usually will yield dates from all the bins, which means the least frequent (youngest) date will be sampled at that point, and that most bins will be sampled with 10 dates. The y-axis represents the temporal bins; the accumulation curve essentially shows how many more age bins would be expected to be added with each random draw.

substantially younger rank-11 date is known from *Catonyx* from Peru (see below).

### 3.2. The effect of accepting rank-11 dates for megafauna

Five genera have rank-11 dates as well as rank-12 dates: *Glossotherium*, *Myiodon*, *Catonyx*, *Megatherium*, and *Equus* (Figs. 3–5). Considering rank-11 dates as ‘robust enough’ does not change the last appearance of *Glossotherium*, *Myiodon*, *Megatherium*, but extends the median for the last-appearance date of *Catonyx* upward from 11.375 to 9.988 ka, and *Equus* upward from 12.950 to 12.088 ka. Many of the numerous age determinations obtained on sloth dung from *Myiodon* Cave in Chile over the past three decades are rank-11 (Fig. 6); allowing those 27 dates extends the last appearance of *Myiodon* from about 13.329 ka to 11.902 ka. Rank-11 dates also place unidentified sloth dung (GrN-5722) and equid dung (LP-925, possibly *Hippidion*) from Gruta del Indio, Argentina,



**Fig. 5.** Range of dates for *Toxodon* and equids. All dates are rank-12 except for two rank-11 (indicated by <sup>11</sup>) dates from Argentina: one on *Equus*, and one on equid dung, possibly from *Hippidion* (García, 2003; García et al., 2008). Given the problem of identifying which species of animal a sample of dung is produced by, the assignment to *Hippidion* is regarded as probable but not certain. The middle date in the equid column (OxA-9247 from Chile, 12.744 ka) was attributed to *Hippidion saldiasi* in a recent publication (Borrero, 2008). Abbreviations: ARG, Argentina; BRZ, Brazil; CHL, Chile.

at 10.913 and 10.009, respectively (García, 2003; Steadman et al., 2005; Hubbe et al., 2007; García et al., 2008).

All of these rank-11 dates are conventional rather than AMS dates. Thus the key issue in whether or not they should be accepted lies in whether conventional dates on bone yield systematically younger ages than AMS dates. A comparison of AMS and conventional dates on mammoth bones from permafrost areas found no systematic differences, and the two techniques provided overlapping ages for the same specimens (Vasil'chuk et al., 2000). Likewise, the analysis identified no systematic differences in age between conventional rank-11 dates and AMS rank-12 dates. For *Glossotherium*, a single rank-11 date from Brazil broadly overlapped rank-12 AMS dates from Brazil and Ecuador (Fig. 4). For *Mylodon*, there are five rank-11 dates for which the 95% confidence interval encompasses the median of the single rank-12 AMS date (median 13.329, 95.4% confidence interval from 13.467–13.199 ka, from Baño Nuevo Cave, Chile (Mena et al., 2003), and more of the rank-11 dates are older than, rather than younger than, the rank-12 date (Fig. 6a). For *Equus*, the gap between the calibrated ranges for rank-11 date and the youngest rank-12 date is only 173 years (Fig. 5, Appendix 1). For *Catonyx*, the gap between the calibrated ranges of the rank-11 date and the youngest rank-12 date is 755 years (Fig. 4, Appendix 1). That wide separation may well simply reflect paucity of dates: four dates total are available for *Catonyx*, and the three rank-12 AMS dates are from the same site in Brazil, whereas the rank-11 date is from Peru. Finally, for this data, there is little correlation between the youngest age known by a rank-12 date and how much the addition of a rank-11 date can be expected to decrease the youngest-occurrence datum ( $R^2 = 0.14$ ,  $y = 0.1378x + 1003.3$ ). These observations suggest that, in terms of assessing youngest records, there is little difference between rank-11 and rank-12 dates, so the rank-11 dates are accepted as robust.

The most significant upward range extension provided by a rank-11 date potentially is for equids. If the dung that provided analysis LP-925 does belong to *Hippidion* (rather than to a different equid), it would extend the youngest record of *Hippidion* from a median age of 12.123 to 10.099 ka, with a separation of 1033 years between the calibrated ranges of rank-11 and rank-12 dates. It would also extend the youngest record for any equid upward considerably. The gap between the calibrated ranges for the date on dung and the youngest *Equus* date on bone (also rank-11) is 1038 years. The authors reserve judgment on the meaning of the late survival suggested by LP-925 until more information is known about its taxonomic attribution.

### 3.3. Relationship between numbers of dates and timing of extinction

Given that taxa typically are represented by very few radiocarbon dates, the question arises: what do those few dates actually say about extinction timing? The answer largely depends on the underlying temporal distribution of datable specimens, which ultimately should be largely governed by abundance of animals that lived on the landscape: the more animals, the more deaths, the more bones, and the more fossils, assuming all other preservation biases are approximately equal through time for a given taxon. Furthermore, abundance of individuals within a species fluctuates through time, generally beginning with few individuals as a species first appears in an area, maximum abundance during the times most favorable for that species, and then dwindling numbers of individuals as conditions become less favorable, ultimately falling off to zero as extinction occurs (Vrba and DeGusta, 2004). Under that scenario, the theoretical underlying distribution of fossils through time for a taxon very likely approximates a bell-shaped curve, with very few fossils available from the initial colonization of

an area, most fossils representing times of maximum abundance, and very few fossils from near the time of extinction or extirpation. It follows that most radiocarbon dates will represent the time a taxon was most abundant on the landscape—that is, the middle portion of the bell-shaped curve—rather than its earliest or last appearance.

The 27 published dates for *Mylodon* from southern Patagonia provide empirical justification for this logic (Fig. 6). In general, the frequency distribution for these dates resembles a normal curve with its older (or bottom, when turned vertically) half truncated either because preservation in the cave did not begin early enough to capture the earliest *Mylodon* in the area, or excavations have not gone deep enough (Fig. 6). All but five of the dates cluster within the interval of 16 to 14 ka. Bootstrap sampling of the dates from this distribution indicates that the least common dates—that is, the youngest ages—would usually require at least 20 dates, although the chances of sampling from the least frequent (youngest) bins

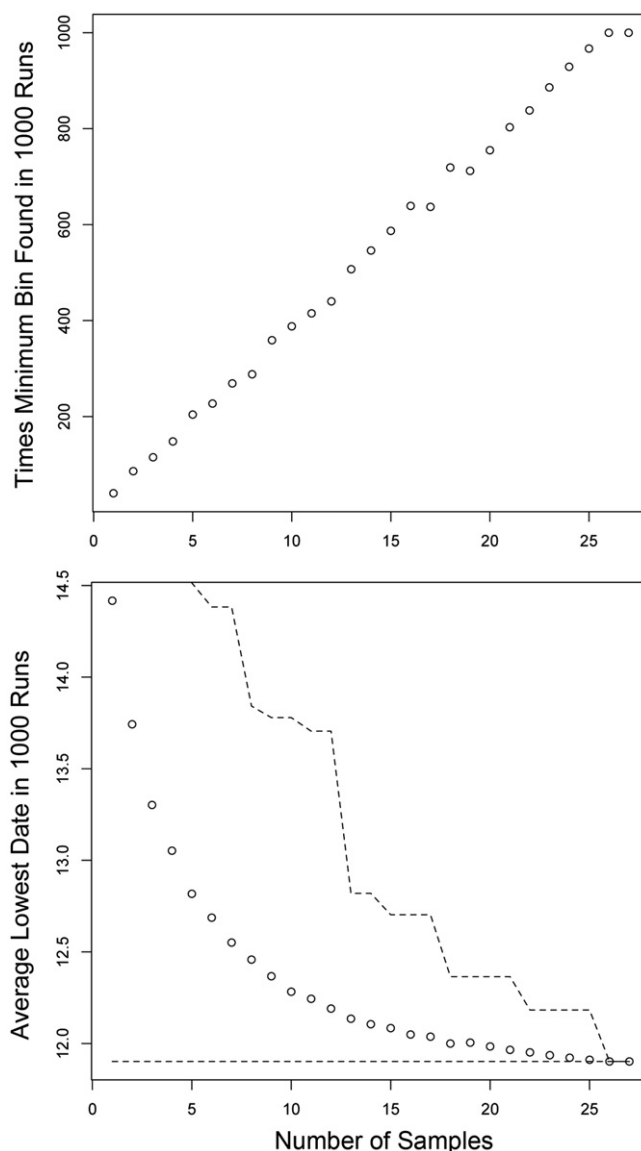


Fig. 7. For the *Mylodon* date distribution shown in Fig. 6: (Top) probability of drawing samples from the youngest bin by sampling 1 date, 2 dates, and so on, up to all 27 dates; (Bottom) dots are the average youngest date found by increasing the number dates sampled, dashed lines are the 95% confidence interval.

become much better after about 10 dates (Fig. 6). Simulations that repetitively sampled the underlying *Myiodon* distribution of dates 1000 times indicated that if 22 dates are obtained randomly, there is an 82% probability of obtaining a date from the youngest bin (Fig. 7). Obtaining 15 dates yields a 60% probability of sampling from the youngest bin (Fig. 7), and on average yields a date that is within 200 years of the minimum date in the distribution, with 95% confidence of being within the upper 20% of the entire range of ages represented by the distribution (Fig. 7). At 7 dates, there is only a 25% probability of sampling the youngest bin, the average youngest date sampled is 700 years older than the youngest date in the sample, and has 95% confidence of falling within the upper 60% of overall age distribution. For 5 dates, the probability of sampling the youngest bin falls to 20%, the average date sampled is 900 years older than the youngest possible date, with 95% confidence of falling in the upper 62% of the possible age distribution (Fig. 7).

Using these well-constrained *Myiodon* dates as a guideline, it seems clear that the <7 dates available for other taxa indicate not their last occurrence *per se*, but instead the last time they appeared abundant on the landscape. In that context, *Myiodon* in southern Patagonia is probably the only taxon and region for which adequate numbers of dates are available to assume that the youngest dates begin to approach (but probably are still older than) the actual time of extinction. For all other taxa in this study, it seems likely that actual extinction was at least a few hundreds of years (in cases where only one date exists, up to thousands of years) later than the youngest dated specimen.

Despite the fact that for any given taxon, adding more dates generally should cause the last-appearance datum to get younger, cross-taxon comparisons show very little correlation between sheer numbers of dates for a taxon (whether they are rank-11 or rank-12) and age of the taxon's last-appearance datum in the megafauna sample. For the range of 1–7 dates, there is a very weak inverse correlation ( $R^2 = 0.11$ ,  $y = -0.0001x + 5.7142$ ), and when taxa that have 30 dates (*Myiodon*) are added, the correlation disappears entirely ( $R^2 = 0.012$ ,  $y = 0.0002x + 9.115$ ). This suggests that the underlying temporal abundance distribution (and thus the temporal distribution of dates) is probably somewhat different for each taxon and/or each region, which in turn would argue against tightly synchronized extinction for all affected taxa.

#### 3.4. Reliability of Holocene dates for South American megafauna

At least four taxa have last-appearance dates that apparently fall in the Holocene (younger than 11.5 ka): *Smilodon*, *Catonyx*, *Megatherium*, and *Doediccoerus* (Fig. 2). In addition, unidentified sloth bones and dung (GrN-5772, A-1282) and equid dung (LP-925) have been dated to the Holocene (Appendix 1).

The *Megatherium* dates come from a single site, Campo La Borde, Argentina. Earlier reported Holocene dates on this taxon from Arroyo Seco 2 (also Argentina) proved to be late Pleistocene with new analyses (Politis and Messineo, 2008). Politis and Messineo (2008) reported five dates on *Megatherium* bones from Campo La Borde, with calibrated ages that ranged from a low of 7.157 to a high of 11.503 ka. They discounted most of these (samples AA-55119, AA-71665, AA-71666, and AA71667) because of low collagen and carbon percentages, indicating preservation problems that could affect dates. Samples they considered most reliable, AA-55117 and AA-55118, exhibited 9% and 5.5% collagen, and 1.4 and 1.9% carbon, respectively. Two to 20% collagen is considered normal (Cione et al., 2001; Hedges and Klinken, 1992; Politis and Messineo, 2008; Stafford et al., 1987), but even so Politis and Messineo (2008) urged caution in ascribing confidence to these dates because of possible problems with

collagen preservation. Other dating evidence from the site, including radiocarbon dates on a variety of organic material from nearby strata considered correlative, and oxidizable carbon ratio (OCR) dates of the stratigraphic column from which the bones came, suggested the *Megatherium* bones came from Holocene strata ranging between about 7.8 and 10.6 ka. Therefore, it seems likely that *Megatherium* can be regarded as extending into the Holocene, although exactly how far still is unknown.

The Holocene age for *Doedicurus* comes from 4 age determinations on what is suspected to be a single individual from La Moderna, Argentina. The youngest of these (BETA-7824) yielded a median calibrated age of 7.452 ka. This is a standard date (rank-11) and is up to about 1000 years younger than three AMS dates (rank-12) that were run later and yielded ages of 7.838, 8.379, and 8.275 ka (Appendix 1). Other dates on organic materials from strata that contained these bones had median calibrated ages of 9.368 and 8.260 ka (Borrero et al., 1998; Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis et al., 1995). In view of the consistency of the three rank-12 AMS dates and non-bone dates from the same strata, there is no objective reason to discount an early Holocene occurrence of *Doedicurus*.

A single rank-12 date on a bone from Lapa da Escrivânia 5, Lagoa Santa, Brazil provides the last-appearance date for *Smilodon populator*. The measured radiocarbon age was  $9130 \pm 150$  radiocarbon years, equating to a median calibrated age of 10.320 ka (Neves and Piló, 2003; Auler et al., 2006). Hubbe et al. (2007) reported the same date as a conventional radiocarbon age of  $9260 \pm 150$  radiocarbon years, median 10.468 ka. Multiple dates on *Equus neogeus* from the same site are substantially older, ranging from median ages of 19.355 to 20.034 ka (Appendix 1). The stratigraphic relationship of the *Equus* and *Smilodon* bones has not been reported, but it is clear that the depositional situation at the site is complex (Neves and Piló, 2003; Auler et al., 2006). Thus at present there is no objective reason to discount the young *Smilodon* date, but clearly more analyses are needed at this important site to resolve how much time the deposits span.

*Catonyx* has one rank-12 and one rank-11 date that place it in the Holocene (Appendix 1; Fig. 4). The rank-12 date, from Gruta Cuvieri, Lagoa Santa, Brazil, places it just barely on the Holocene side of the Pleistocene–Holocene boundary. The rank-11 date from Pampa de Fosiles in Peru places it some 1000 years younger. Steadman et al. (2005) rejected the validity of this date on the grounds that a replicate date on the same individual produced a date of  $16,000 \pm 2000$  radiocarbon years. The very high margin of error on the replicate date suggests that it is unreliable; however, the date listed in Appendix 1 (GIF-4116) has no obvious problems. Clearly additional AMS dating from this site is needed, but at present the only reason for discounting GIF-4116 would be that it is younger than expected if all species were extinct by the beginning of the Holocene, clearly circular logic.

In addition to these identified taxa, dung (LP-925) from an unidentified species of equid (likely *Hippidion*), dung of an unidentified sloth (A-1282), and dermal ossicles (GrN-5772) questionably identified as *Myiodon* from Gruta del Indio, Argentina, produced rank-11 Holocene dates. These are younger dates than any other on dung or bones from the site, which range from median calibrated ages of 11.915 to 24.825 ka. Because they were younger than other dates, Steadman et al. (2005) rejected them, but the authors find no objective reason to do so.

Holocene dates reported for *Glyptodon* are not from direct dates on bone, rather, the bones were in cultural association with artifacts and charcoal, with the latter being the dated material at Pay Paso 1, Uruguay (Suárez, 2003). This is not regarded as firm evidence that *Glyptodon* survived into the Holocene, given the



potential for stratigraphic mixing and time averaging, but the occurrence is noted as opening the possibility of the taxon's late survival.

### 3.5. Interpreting South American megafauna extinction on the continental scale

*Hippidion*, *Equus*, *Mylodon*, and *Megatherium* (\* on Fig. 2) all have at least five dates of rank-11 or rank-12; *Catonyx* and *Glossotherium* have four. As discussed in Section 3.3, that number of dates probably estimates when the taxa were abundant on the landscape, not when they went extinct. Assuming the relationships illustrated in Fig. 7 at least generally apply, the youngest dates for each taxon likely pre-date their actual extinction by as much as several hundred years, but because each taxon is represented by similar numbers of dates, the lag between the dates that indicate maximum population abundance and those that would indicate actual extinction should be roughly similar. Thus the relative ordering of extinction is likely reflected in the dates. Because there is no objective reason to reject the rank-11 and rank-12 dates for *Smilodon*, *Doedicurus*, and *Catonyx*, these are accepted as indicating persistence at least into the Holocene, while recognizing that additional dates would be expected to make their last appearance even younger than presently known (+ on Fig. 2).

Using only these minimum last-appearances the pattern that emerges is a pulse of taxa dropping out of the record between 12.4 and 11.9 ka (*Hippidion*, *Glossotherium*, *Equus*, *Mylodon*), then a more gradual dwindling of taxa spread over the interval of about 11.9–7.8 ka (*Smilodon*, *Catonyx*, *Megatherium*, *Doedicurus*) (Fig. 2). The single available dates for each of *Eremotherium* and *Toxodon* would place their youngest records just prior to the beginning of the initial disappearance pulse. However, as for other taxa known by only one or two age determinations (*Holmesina*, *Haplomastodon*, *Cuvieronius*, *Nothrotherium*), it can be expected that last-appearance will move upward as additional dates become known.

### 3.6. Interpreting megafauna extinction on the regional scale

Only a few taxa are known from localities widely distributed across South America, and those are represented by few dates at each locality, complicating assessment of geographic patterns of extinction. Nevertheless, some points are worth mentioning.

First, the last appearances of certain taxa differ among the six broad regions that have enough data to compare (Fig. 8). *Hippidion* and *Mylodon* both have considerably earlier last-appearances in central Chile (Fig. 8E) than they do in Patagonia (Fig. 8B), though they are known by only two and one dates, respectively, in central Chile. *Glossotherium* has its youngest dates 1500 years earlier in Brazil (Fig. 8D) and northern South America, compared to the Argentina-Uruguay area (Fig. 8F). *Equus* has a last-appearance in Brazil that is earlier than further south in Argentina and Patagonia. At face value, these differences could imply a continental trend of earlier extinction for these taxa in the north than in the south. However, it is not possible to reach any firm conclusions given the paucity of dates.

Second, the temporal range of last occurrences decreases from north to south. In northern South America and Brazil the last known occurrences are evenly distributed through some 40,000 and 10,000 years, respectively. In mid-latitude Argentina and Uruguay, the last-occurrence window is narrower, with last appearances spread evenly across about 5000 years. In Patagonia, all the last-appearances cluster tightly within 2000 years. Data are inadequate to assess range of last appearances in central Chile and

Peru. The decrease in the time spanned by last-appearance dates per region is not correlated with numbers of dated taxa if all regions are considered ( $R^2 = 0.04$ ,  $y = -1423.7x + 20475$ ), but there is a strong correlation if northern South America is dropped from the equation ( $R^2 = 0.96159$ ,  $y = 1368.4x - 2421.1$ ). This may indicate that in northern South America extinction was less abrupt than further south, but this should be regarded only as an idea to be tested given the paucity of dates.

Third, there are no Holocene occurrences known south of 40°S; this is not for lack of Quaternary sites, as many are known in Patagonia and places like Cueva del Milodón and Monte Verde in Chile have produced exceptionally well documented series of radiocarbon dates for megafauna (Appendix 1). This brings up the interesting possibility that extinctions were earlier in Patagonia than in central Chile, and Argentina, but more dates are needed to test that idea.

### 3.7. Earliest human records in South America in respect to megafauna last-appearance

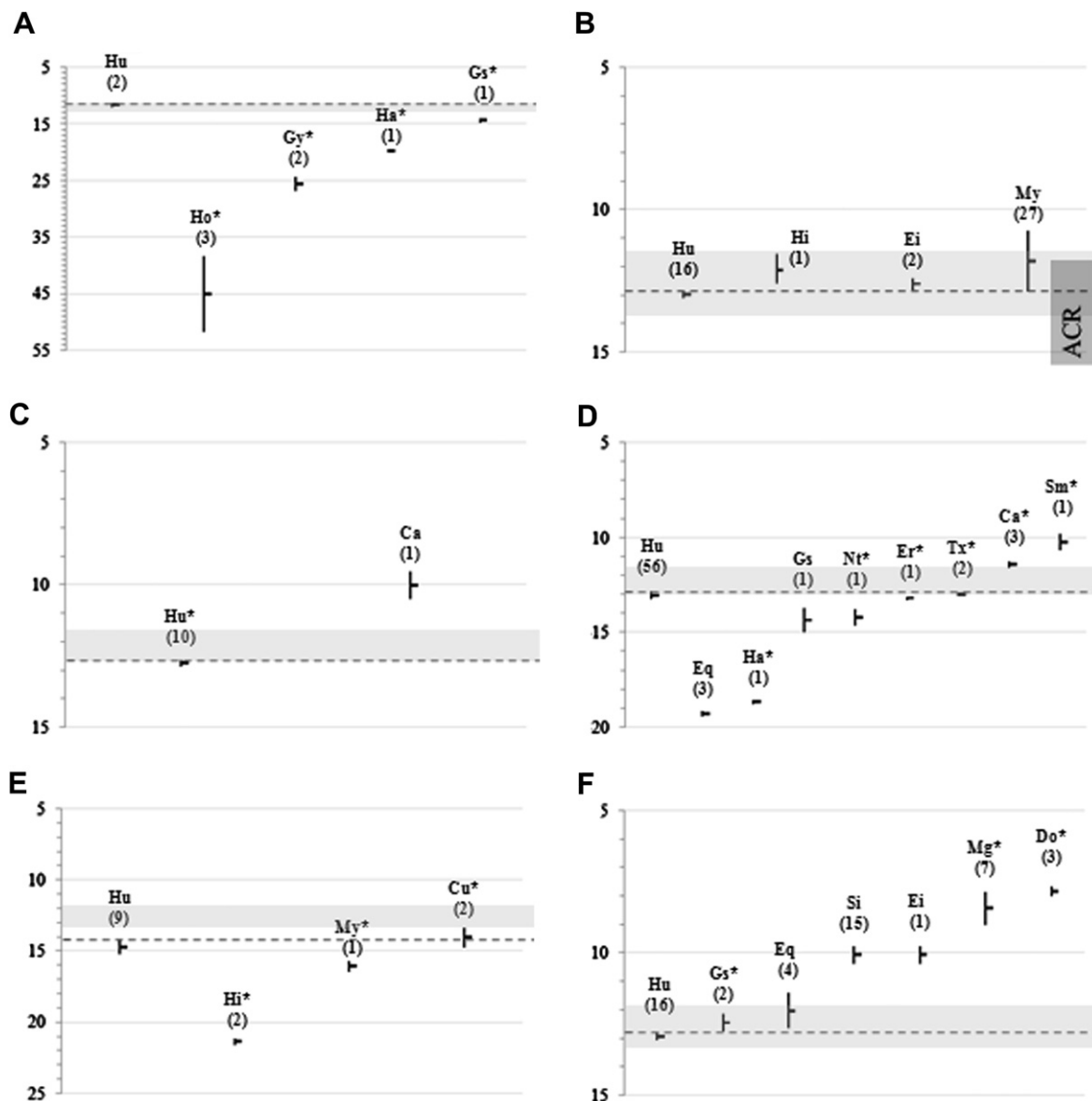
Appendix 2 and Fig. 8 imply that the earliest firm records for humans differ slightly for different parts of the South American continent. Following the logic explained in Section 3.3, earliest dates for human presence probably signal the time humans first became abundant on the landscape, rather than their first arrival *per se*. However, assuming a similar lag time between first arrival and becoming abundant enough on the landscape to leave an archaeological trace in each region, the earliest dates probably reflect the relative order of occupation.

First arrival appears to have been near Monte Verde, Chile by 14.8 ka (Fig. 8E). Occupation of north-central Brazil seems to have taken place by 13.0 ka at Pedra Pintada (Fig. 8D). Also by 13.0 ka, occupation is evident from mid-latitude Chile (Quebrada Santa Julia) and Argentina (Agua de la Cueva) south into Patagonia (Cueva del Medio, Tres Arroyos), along both sides of the Andes (Fig. 8B). At around 12.7 ka the earliest known sites show up in the Argentine Pampas at Cerro el Sombrero (Fig. 8F) and in Peru at Quebrada Tacahuay (Fig. 8C). By 11.6 ka, the earliest dates are evident in Colombia at San Isidro (Fig. 8A).

At the continental scale, 12 of the 15 dated taxa have last appearances within the time frame humans were probably present (Fig. 2). Of those, only *Nothrotherium* and *Cuvieronius* have last appearances that fall within the 95% confidence interval of earliest human appearance. However, those two taxa, like *Eremotherium* and *Toxodon*, are known by less than 3 dates so it is likely their last appearances will eventually be found to be younger than shown on Fig. 2. Using only taxa that have at least four dates, the oldest last appearance seems to be some 1500 years after humans first arrive, and the youngest last appearances as much as 6500 years later. These represent the minimum separation in time between the first human versus last megafauna appearances, because it is highly probable that the earliest dates on human occupation post-date actual occupation, and the youngest dates on megafauna pre-date actual extinction. Thus there is no evidence for blitzkrieg (Mosimann and Martin, 1975) in South America.

At the regional scale (Fig. 8), there is no evidence for correlation between earliest archaeological dates and latest megafauna dates in northern South America or Peru; in the former (Fig. 8A), all last-appearance dates are before the earliest archaeological dates, and in the latter (Fig. 8C), the only dated taxon has a last-appearance date that is some 2800 years younger than the earliest sign of human arrival.

In Brazil (Fig. 8D), there is possibly correspondence between first evidence for humans and last appearances of *Glossotherium*,



**Fig. 8.** OxCal 95.4% confidence intervals for robust first-appearance dates of humans (Hu), and robust last-appearance dates of Pleistocene megafauna: *Catonyx* (Ca), *Cuvieronius* (Cu), *Doedicurus* (Do), *Equus* (Eq), *Eremotherium* (Er), *Glossotherium* (Gs), *Glyptodon* (Gy), *Haplomastodon* (Ha), *Hippidion* (Hi), *Holmesina* (Ho), *Megatherium* (Mg), *Mytilodon* (My), *Nothrotherium* (Nt), *Smilodon* (Sm), *Toxodon* (Tx), indeterminate Equid (Ei), and indeterminate Sloth (Si). y-axis shows calibrated years before present  $\times$  1000. Dashed horizontal line designates likely presence of humans (95.4% CI). Gray bands denote timing of Younger Dryas cooling in (A) northern South America (Mahaney et al., 2008); (B) Patagonia (Coronato et al., 1999); (C) Peru (Bush et al., 2005); (D) Brazil (Ledru, 1993; Maslin and Burns, 2000); (E) central Chile (Hajdas et al., 2003; Moreno, 2000); (F) mid-latitude Argentina (Hajdas et al., 2003; Kröhling and Iriondo, 1999). In (B), the darker gray box at right indicates the timing of the Antarctic Cold Reversal (ACC) in southern Patagonia. The \* indicates that the illustrated date is a rank-12 for megafauna, or rank-15 to rank-17 for humans. Parenthetical numbers denote total number of robust dates (rank-11 or -12 for megafauna, rank-13 or above for humans) that exist for a given taxon in a given region.

*Nothrotherium*, *Eremotherium*, and *Toxodon*, taking into account that each of these last records is based on just one or two dates, so the real last records are almost certainly younger. However, *Catonyx* and *Smilodon* remain for about 1500 and 2900 years longer, respectively, after first human evidence. *Equus* and *Haplomastodon* have last records much earlier than first human dates, although *Haplomastodon* is known by only one date.

In central Chile (Fig. 8E), the youngest (and only) dates known for *Cuvieronius* indicate its bones were being utilized at Monte Verde about 900 years after first human occupation, but no younger records are known. Farther north in Chile, at Los Vilos, the only *Mytilodon* record is at 16.05 ka, long before humans arrived, and farther north still, at Betecsa I, the last appearance of

*Hippidion* is 21.392 ka (the younger of two *Hippidion* dates from the site).

To the south, in Patagonia (Fig. 8B), *Mytilodon* disappears from Cueva del Milodón at 11.9 ka, after humans are evident in the area beginning 13.0 ka, and after its apparently continuous presence there for the previous 4400 years (Fig. 6). At 12.123 ka, *Hippidion* disappears from Cueva Lago Sofia 1. About 1000 km northeast across the Andes on the coast of Argentine Patagonia, *Hippidion* from Piedra Museo is last known at 12.9 ka, and farther south at Tres Arroyos an equid bone, identified as *Hippidion saldiasi* (Borrero, 2008), was dated to 12.744 ka. Therefore in Patagonia, extinction of *Mytilodon* and *Hippidion* may have been roughly contemporaneous and lagged human arrival by about 1000 years.

In the mid-latitudes of Argentina and Uruguay, all megafauna last-appearances occur after humans arrive, but only two, *Glossotherium* and *Equus*, show reasonably close temporal correspondence with earliest archaeological evidence. The rest—various unidentified sloths, equids, *Megatherium*, and *Doedicurus*—apparently survived for approximately 5000 years after humans arrived.

To summarize this regional comparison, 10 out of the 25 known last-appearance dates for taxa follow within 1000 years the first-appearance dates for humans, the rest do not. The ones that do correspond are: both taxa dated in Patagonia (*Mylodon*, *Hippidion*); possibly half of those known from Brazil (*Toxodon*, *Glossotherium*, *Nothorotherium*, *Eremotherium*, assuming more dates from the latter three raise the last-appearance date by a few hundred years); two of six taxa dated from mid-latitude Argentina (*Glossotherium* and *Equus*); and one of three taxa dated in mid-latitude Chile (*Cuvieronius*). All of the taxa which at face value disappear long before human arrival (eight of the total 25 dated last occurrences in Fig. 8) in an area are known by very few dates, thus it is likely that additional dating of these taxa will produce younger last-appearance dates. The seven last-appearance occurrences that are substantially younger than first-appearance dates for humans would be expected to get younger yet if more dates were obtained.

### 3.8. Late Quaternary climate changes in South America

As in North America, the late Pleistocene to Holocene transition in South America is characterized first by a rapid, pronounced cooling, then rapid warming as the Holocene interglacial begins in earnest. In North America and the northern Hemisphere in general, the cooling event is known as the Younger Dryas and dates to approximately 12.9–11.55 ka. Most likely triggered by glacial-melt diluting the North Atlantic with fresh water and causing a temporary shut-down of thermohaline circulation, Younger Dryas cooling was abrupt and severe, by as much as 5 °C or more in middle northern latitudes over as little as a few decades. Recent controversial evidence suggests that a comet explosion may have caused or exacerbated the onset of the Younger Dryas (see Firestone et al., 2007; Buchanan et al., 2008; Haynes, 2008; Kennett and West, 2008; Kerr, 2008; Marlon et al., 2009).

In South America, palynological and glaciological data from some sites indicate a cool phase that overlapped the Younger Dryas, but conflicting studies suggest the exact timing and intensity of the cool phase may vary from region to region. In mid-latitude Chile and Argentina near the Andes, the cool phase is well-supported in certain lake records but seems to begin about 400 years earlier (e.g., about 13.3 ka) than the northern hemisphere Younger Dryas, and is known as the Huelmo/Mascardi Cold Reversal (Moreno, 2000; Hajdas et al., 2003). The southern Atacama Desert exhibited a roughly contemporaneous decrease in winter precipitation that started about 14 ka (Maldonado et al., 2005; Latorre et al., 2006). Further south in Patagonia, some pollen records and glacial chronologies support a cooling that began even earlier, around 13.9 ka (Coronato et al., 1999). Other studies place the cold spell roughly contemporaneous with the classical Younger Dryas, whereas still other pollen records and studies of fossil beetles do not document a cold phase (Glasser et al., 2008). In farthest south Patagonia, a cooling known as the Antarctic Cold Reversal seems to dominate, with glacier advance beginning between 15.507 and 14.348 ka and ending between 12.587 and 11.773, earlier than and out of phase with the Younger Dryas event (McCulloch et al., 2005; Sugden et al., 2005). In the Argentine Pampas, the cold phase may also have begun even earlier than the

classical Younger Dryas, around 14 ka, but this date is not well constrained (Kröhling and Iriondo, 1999). In Peru, the cold phase is evident in some paleoclimate proxy records but not in others; where it is evident, it seems to commence around 12.5 ka (Bush et al., 2005). In the Venezuelan Andes (Mahaney et al., 2008), a glacial advance apparently took place roughly contemporaneous with the Northern Hemisphere Younger Dryas. In Brazil, a cool phase also begins at about the same time (Ledru, 1993; Maslin and Burns, 2000).

North of southernmost Patagonia and where it is well dated (Peru, Chilean Lake District), the South American cold phase seemed to have ended at about the same time as the Younger Dryas ended in North America. As noted above, in southern Patagonia, the Antarctic Cold Reversal ended about in the middle of the Younger Dryas. In all areas, by 11.5 ka rapid warming was underway, which by around 10 ka had raised average global temperature some 5 °C, with some regions in the northern hemisphere seeing temperatures rise 10 °C or more (references cited above).

The sum of the evidence suggests that in mid-latitude South America, the end-Pleistocene saw climate shift to substantially cooler conditions, (e.g. the 'Cold Reversal'; Moreno, 2000; Hajdas et al., 2003) between approximately 13.3 and 11.5 ka just prior to the dramatic warming that heralded the Holocene. There the overall pattern of climate change seems to mimic the Younger Dryas–Holocene transition of the northern Hemisphere, although exact timing, details, and causes are not yet well understood. In southern Patagonia, the Younger Dryas may have been less dominant, with the Antarctic Cold Reversal occurring earlier. However, in all areas, Holocene warming had begun in earnest by around 11.5 ka.

On a continental scale, more last-appearance records for South American megafauna cluster within the Cold Reversal than in any other 2000-year period: at least *Toxodon*, *Glossotherium*, *Eremotherium*, *Mylodon*, *Hippidion*, and *Equus* (Fig. 2). Even assuming that the true extinction time for these taxa is a few hundred years younger than the last-appearance dates, their true last appearances would still fall in the time of rapid climatic transition from the Pleistocene to the Holocene.

At the regional scale, all of the last appearances that occur shortly after human arrival are also within the interval of rapid climate change, consistent with the idea of a fatal synergy between both impacts for *Cuvieronius*, *Glossotherium*, *Equus*, *Hippidion*, *Mylodon*, and possibly *Eremotherium* and *Toxodon*. It is particularly striking that in Patagonia, the last appearances of *Mylodon* and *Hippidion* are essentially contemporaneous in the temporal window that includes both first human arrival and rapid climate change (Fig. 8B). This is consistent with the idea that climate change at higher latitudes was particularly fatal for these taxa when combined with the new presence of humans.

Matching paleoenvironmental, paleoclimatic, and last-appearance data at an even more resolved geographic scale further links last-appearances with climate change. Near Monte Verde, Chile, pollen and charcoal records indicate local cooling beginning 13.8 ka, resulting in a vegetation change that featured expansion of cold-resistant rainforest trees until 12.5 ka (Moreno, 2000; Hajdas et al., 2003). The onset of this cold period corresponds with the last dated occurrence of *Cuvieronius* in the region, and in the middle of it *Hippidion* disappears from further south in Patagonia. At 12.5–11 ka, climatic variability increased (Moreno, 2000; Hajdas et al., 2003), and that interval also holds the youngest dates for *Mylodon* and *Hippidion* in Patagonia. These correlations in time are consistent with environmental changes contributing to megafaunal extinctions, and highlight the need

for detailed studies that compare timing of extinction with independent evidence of ecological change on a region-by-region basis.

#### 4. Conclusions

Much work remains to be done on dating megafaunal extinctions in South America. Bootstrapping and probability analyses indicate that with less than five dates per taxon, there is a very high probability that additional dates will be younger, and that presently available last-appearance dates likely illustrate the last time taxa were abundant on the landscape, rather than their last appearance *sensu stricto*. Nevertheless, even given the paucity of dates that are presently available, at least 15 of the 52 genera that went extinct have been radiocarbon dated to the extent that interesting patterns are beginning to emerge.

First, taken at face value, the dates analyzed suggest extinction intensity and timing may have varied across the South American continent, starting in the north long before humans ever arrived, and becoming most intense and rapid in the southern, higher latitudes as human arrival and climate change had more dramatic effects there. Clearly, however, many more radiocarbon dates are needed to test this speculation.

Second, the extinction event in South America seems to have taken considerably longer than it did in North America. In South America, the pace of the extinction event seems to have accelerated sometime just younger than 13.5 ka, roughly 1000 years after humans arrived on the continent but coincident with the rapid terminal Pleistocene climatic fluctuations. Most of the dated taxa have last known disappearances by 11.5 ka, corresponding with the end of the Younger Dryas-type event (or in the case of southern Patagonia, the Antarctic Cold Reversal) and rapid warming that heralded the onset of the Holocene, but at least two taxa lasted until as recently as 8.5 ka, and as many as three others seem to have lasted into the earliest Holocene. Therefore at minimum the extinctions seem to have been spread out over 5000 years. In contrast, in North America all 15 of the well-dated genera seem to have disappeared between 13.0 and 11.5 ka, indicating a maximum of around 1500 years for the extinction event (Grayson and Meltzer, 2003; Fiedel and Haynes, 2004; Grayson, 2006).

South America also seems to differ from North America in how closely in time the onset of extinction correlates with first arrival of humans on the continental scale. Given that all the reasonably well-dated taxa disappear after human arrival, it seems that humans likely played a role in the extinctions. However, taking the radiocarbon dates at face value and assuming that the lag between the last dated appearance and true last-appearance is similar across taxa and across continents, the extinction pulse began in South America some 1000 years after humans first arrived there. In North America, the onset of the major extinction pulse and Clovis first appearance are virtually indistinguishable in time (Waters and Stafford, 2007), although non-Clovis humans were likely in North America earlier (Gilbert et al., 2008). At a more regionally resolved scale, both dated taxa from Patagonia illustrate close correspondence in time between extinctions and human arrival, whereas less than half of the taxa dated from other regions disappear within 1000 years of the time humans arrived.

The extinction timing on the two continents is similar in an important respect, however; at the continental scale, the main pulse in both places took place only after humans first arrived, and at the same time as end-Pleistocene climates oscillated from a rapid, intense cool spell followed by dramatic Holocene warming. That coincidence, along with the fact that earlier climatic

transitions resulted in little if any extinctions, suggests that combining ecological pressures from humans entering the respective ecosystems with dramatic climate change was fatal for many kinds of megafauna. In that respect, the two continents seem to be replicate natural experiments indicating that synergy between human impacts and unusually fast climate change, such as is occurring today, inevitably accelerates the pace of extinction. In a more generalized sense, the megafaunal extinctions on the two continents are consistent with the 'press-pulse' theory for mass extinctions, which claims that major extinction events are most likely when two or more unusual ecological perturbations coincide (Arens and West, 2008).

Interestingly, *Smilodon*, *Catonyx*, *Megatherium*, and *Doedicurus* all seem to have survived the initial extinction pulse, lasting through first human presence and the period of rapid climate change (Fig. 2). That they persisted up to 2000 years into the Holocene suggests that rapid climate change did not affect them much, nor did the initial appearance of humans. Contrasting the life history strategy and habitats of these taxa against those of taxa that succumbed early on may hold valuable clues about what kinds of animals and places are resistant to extinction pressures, and which ones may be in particular danger.

Assuming that additional dating efforts uphold the last-appearance chronologies that seem to be emerging, the indication of a much wider extinction window in South America in comparison to North America is intriguing. It may indicate that the relative pressures of human influence and environmental change differed somewhat on the two continents, either because of cultural differences between the first human immigrants in each place, or because South America, with a greater diversity of habitats ranging from the high Andes to the tropical Amazon, held a wider variety of refuges in the face of climatic change and human pressures. Alternatively, the differences in extinction timing may relate to intrinsic features of the largely evolutionarily distinct megafauna of the two continents; or it may relate to the fact that there were more megafauna genera in South America to start with (63, as opposed to 47 in North America), so given the same rate of extinction it would take longer for the continent with more genera to lose them all. Distinguishing between these and other possibilities to explain the patterns reported here will require additional dating efforts for the taxa discussed and for the 37 genera that have not yet been dated. Also critical to understanding the causes of extinction will be detailed study of the paleobiology of each extinct taxon, and the integration of independent paleoecologic and paleoclimatic data with the extinction chronology on a region-by-region basis.

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#### Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.quaint.2009.11.017.

## Appendix 1

Table A.1. presents radiocarbon dates of rank-12 and rank-11 on megafauna considered robust and discussed in the text. See Supplementary Online Material for the complete list of dates and associated references that were evaluated.

Site name	Genus	OxCal old	OxCal young	OxCal median	Lab number	Material dated	Rank	Reference
Lapa da Escrivânia 5, Lagoa Santa	<i>Smilodon</i> (BRZ)	10712	9792	10320	BETA-174722	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Ponta de Flecha, Ribeira do Iguaçu	<i>Toxodon</i> (BRZ)	13330	13158	13248	BETA 215330	Bone	12	Neves et al., 2007
Ponta de Flecha, Ribeira do Iguaçu	<i>Toxodon</i> (BRZ)	13093	12916	13004	BETA 218193	Bone	12	Neves et al., 2007
Tres Arroyos 1 Level Va	<i>Equid</i> (CHL)	12851	12410	12744	OXA-9247	Bone	12	Borrero, 2003; Borrero, 2008
Tres Arroyos 1 Level VI	<i>Equid</i> (CHL)	15033	14257	14701	Beta-123152	Bone	12	Borrero, 2003
Gruta del Indio	<i>Equid</i> (ARG)	10373	9770	10099	LP-925	Dung	11	García, 2003
Cueva del Medio Última Esperanza Fell 1	<i>Hippidion</i> (CHL)	12887	12398	12743	NUTA-1811	Bone	12	Borrero et al., 1998; Nami and Nakamura, 1995
Cueva del Medio, Última Esperanza Fell 1a	<i>Hippidion</i> (CHL)	13149	12399	12853	NUTA-2331	Bone	12	Borrero, 2008; Borrero et al., 1998; Nami and Nakamura, 1995
Cuevo Lago Sofia 1, Última Esperanza	<i>Hippidion</i> (CHL)	12881	12711	12818	OXA 9319	Bone	12	Borrero, 2008
Cuevo Lago Sofia 1, Última Esperanza	<i>Hippidion</i> (CHL)	12698	11406	12123	OXA 9504	Bone	12	Borrero, 2008
Betecsa 1	<i>Hippidion</i> (CHL)	...	24920	25429	GrA-29389	Bone	12	Alberdi et al., 2007
Betecsa 1	<i>Hippidion</i> (CHL)	21596	21190	21392	GrA-29388	Bone	12	Alberdi et al., 2007
Piedra Museo AEP1-I6	<i>Hippidion</i> (ARG)	12991	12813	12886	OXA 8528	Bone	12	Alberdi et al., 2001; Borrero, 2008
Lapa da Escrivânia 5, Lagoa Santa	<i>Equus</i> (BRZ)	19519	19226	19417	BETA 174712	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Lapa da Escrivânia 5, Lagoa Santa	<i>Equus</i> (BRZ)	19483	19152	19355	BETA 174713	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Lapa da Escrivânia 5, Lagoa Santa	<i>Equus</i> (BRZ)	20231	19877	20034	BETA 174711	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Zanjón Seco, Río Quequén Grande	<i>Equus</i> (ARG)	12656	11411	12088	LP-1235	Bone	11	Tonni et al., 2003
Arroyo Seco 2 Lower component	<i>Equus</i> (ARG)	13110	12829	12950	OXA-4590	Bone	12	Gutiérrez and Martínez, 2008; Politis and Madrid, 2001; Politis et al., 2004
Arroyo Seco 2	<i>Equus</i> (ARG)	13305	12937	13140	AA-7964	Bone	12	Borrero et al., 1998; Politis et al., 1995
Arroyo Seco 2	<i>Equus</i> (ARG)	13390	12976	13198	AA-39365	Bone	12	Politis and Messineo, 2008
Monte Verde MV-II, area D column 5 unit 4	<i>Cuvieronius</i> (CHL)	14574	13389	13874	TX-3760	Bone	12	Dillehay, 1997
Monte Verde MV-II, area B column 9 unit 5	<i>Cuvieronius</i> (CHL)	14765	13330	13914	OXA-105	Bone	12	Dillehay, 1997
Itaituba Quarry alluvial site on the lower	<i>Haplomastodon</i> (BRZ)	18809	18561	18685	BETA sample 1	Bone	12	Rossetti et al., 2004; Steadman et al., 2005
Río Tapajós, Pará State								
Quebrada Cuesaca	<i>Haplomastodon</i> (ECD)	20012	19550	19816	EQ96003	Bone	12	Coltorti et al., 1998
La Moderna	<i>Doedicurus</i> (ARG)*	8014	7663	7838	TO-1507-1	Bone	12	Borrero et al., 1998; Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis et al., 1995
La Moderna	<i>Doedicurus</i> (ARG)*	9280	7665	8379	TO-1507-2	Bone	12	Borrero et al., 1998; Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis et al., 1995
La Moderna	<i>Doedicurus</i> (ARG)*	8414	8054	8275	TO-2610	Bone	12	Borrero et al., 1998; Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis et al., 1995
Inciarte	<i>Glyptodon</i> (VZA)	26805	24378	25546	AA33646A	Collagen	12	Julli et al., 2004; Rincón et al., 2006; Rincón et al., 2008
Inciarte	<i>Glyptodon</i> (VZA)	28757	27272	27997	AA33646B	Collagen	12	Julli et al., 2004; Rincón et al., 2006; Rincón et al., 2008
Inciarte	<i>Holmesina</i> (VZA)	51857	38413	43587	AA33647C	Collagen	12	Julli et al., 2004
Inciarte	<i>Holmesina</i> (VZA)	56901	42581	47987	AA33647B	Collagen	12	Julli et al., 2004
Inciarte	<i>Holmesina</i> (VZA)	56901	42581	47987	AA33647A	Collagen	12	Julli et al., 2004; Rincón et al., 2006; Rincón et al., 2008
Itaituba Quarry alluvial site on the lower	<i>Eremotherium</i> (BRZ)	13302	13116	13217	BETA sample 2	Bone	12	Rossetti et al., 2004; Steadman et al., 2005
Río Tapajós, Pará State								
Arroyo Seco 2	<i>Megatherium</i> (ARG)*	14842	13742	14143	CAMS-58182	Bone	12	Hubbe et al., 2007; Politis et al., 2004
Arroyo Seco 2	<i>Megatherium</i> (ARG)*	14172	13830	14010	OXA-10387	Bone	12	Politis and Messineo, 2008
Arroyo Seco 2	<i>Megatherium</i> (ARG)*	13864	13352	13619	AA-62513	Bone	12	Politis and Messineo, 2008
Paso Otero 5	<i>Megatherium</i> (ARG)	12732	12036	12370	AA-39363	Bone	12	Gutiérrez and Martínez, 2008; Martínez, 2001
Campo Laborde	<i>Megatherium</i> (ARG)	9480	8522	8988	AA-55118	Bone	12	Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis and Messineo, 2008; Politis et al., 2004
Campo Laborde	<i>Megatherium</i> (ARG)	9010	7871	8381	AA-55117	Bone	12	Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis and Messineo, 2008; Politis et al., 2004
Campo de Arce Río Quequén Chico	<i>Megatherium</i> (ARG)	15908	15067	15458	LP-174	Bone	11	Tonni et al., 2003
Arroyo Seco 2 Lower component	<i>Glossotherium</i> (ARG)	14683	13827	14145	OXA-4591	Bone	12	Gutiérrez and Martínez, 2008; Politis and Madrid, 2001; Politis et al., 2004

(continued on next page)

Appendix 1 (continued)

Site name	Genus	OxCal old	OxCal young	OxCal median	Lab number	Material dated	Rank	Reference
Arroyo Seco 2 Lower component	<i>Glossotherium</i> (ARG)	12769	12132	12478	AA-9049	Bone	12	Borrero et al., 1998; Gutiérrez and Martínez, 2008; Hubbe et al., 2007; Politis et al., 1995
Quebrada Pistud	<i>Glossotherium</i> (ECD)	14765	14041	14331	EQ 96010	Bone	12	Coltorti et al., 1998
Touro Passos/Lageado dos Fosseis	<i>Glossotherium</i> (BRZ)	15014	13744	14305	unknown	Bone	11	Prous and Fogaça, 1999
Gruta Cuvieri, Lagoa Santa	<i>Catonyx</i> (BRZ)	11606	11252	11375	BETA 165398	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Lapa dos Tatus, Lagoa Santa	<i>Catonyx</i> (BRZ)	17077	16329	16721	BETA 174688	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Lapa dos Tatus, Lagoa Santa	<i>Catonyx</i> (BRZ)	16957	16208	16587	BETA 174689	Bone	12	Auler et al., 2006; Neves and Piló, 2003
Pampa de Fosiles	<i>Catonyx</i> (PRU)	10497	9535	9988	GIF-4116	Bone	11	Hubbe et al., 2007; Marshall, 1984
Los Vilos	<i>Myiodon</i> (CHL)	16469	15675	16050	NSRL-11081	Bone	12	Jackson, 2003
Cueva del Milodón	<i>Myiodon</i> (CHL)	17362	14951	16059	R-4299	Hair and skin	11	Long and Martin, 1974
Cueva del Milodón	<i>Myiodon</i> (CHL)	16747	15522	16123	A-1390	Dung	11	Long and Martin, 1974
Baño Nuevo Layer 5 Below cultural	<i>Myiodon</i> (CHL)	13467	13199	13329	CAMS-32685	Bone	12	Mena et al., 2003
Cueva del Milodón	<i>Myiodon</i> (CHL)	12885	10754	11902	SA-49	Dung	11	Long and Martin, 1974; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	12919	11237	12183	A-1391	Hide	11	Long and Martin, 1974; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	13216	11254	12365	GX-6248	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	13609	11411	12703	C-484	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	13406	11998	12820	GX-6243	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	15099	12859	13779	GX-6246	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	14634	13102	13705	BM-1210	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	14901	13174	13842	GX-6247	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	15343	13074	14071	GX-6244	Dung	11	Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	15310	13435	14354	A-2445	Dung	11	Long et al., 1998; Markgraf, 1985; Steadman et al., 2005
Cueva del Milodón	<i>Myiodon</i> (CHL)	15744	13266	14418	GX-6245	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15220	13645	14383	BM-12108	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15096	14093	14588	BM-1209	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15122	14174	14681	BM-1375	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15039	14032	14514	A-2447	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15692	15041	15335	BM-728	Collagen	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	16266	15055	15623	BM-1208	Collagen	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	16200	15281	15721	LU-794	Collagen	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	17662	14765	16072	NZ-1680	Hide	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	17362	14951	16059	R-4299	Hide	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15585	14900	15204	A-2448	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	16626	15401	16003	A-2446	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	16728	15544	16124	A-1390	Dung	11	Borrero, 1999
Cueva del Milodón	<i>Myiodon</i> (CHL)	15207	14131	14697	LP-257	Dung	11	Borrero, 1999
Cueva Lago Sofia 1, Ultima Esperanza	<i>Myiodon</i> (CHL)	16741	13945	15347	PITT-0939	Bone	11	Borrero, 2008
Ultima Esperanza	<i>Myiodon</i> (CHL)	15844	14013	14923	NUFA	Bone	11	Borrero et al., 1998; Nami and Nakamura, 1995
Gruta de Brejões	<i>Nothrotherium</i> (BRZ)	14640	13786	14091	NZA-6984	Dung	12	Czaplewski and Cartelle, 1998; Steadman et al., 2005
Cuchillo Cura	<i>Sloth</i> (ARG)	18486	17065	17735	Ua-13871	Dung	12	Steadman et al., 2005
Salto de Piedra Arroyo Tapalqué	<i>Sloth</i> (ARG)	13995	13640	13805	LP-1193	Bone	11	Tonni et al., 2003
Gruta del Indio	<i>Sloth</i> (ARG)	11180	10605	10913	GrN-5772	Bone	11	García, 2003; Hubbe et al., 2007; Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	13250	9142	11186	A-1282	Dung	11	Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	12823	11133	11915	A-1636	Dung	11	Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	2761	11312	12054	A-9494	Dung	11	Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	12961	11826	12518	A-1351	Dung	11	Long and Martin, 1974; Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	13225	12398	12885	A-9493	Dung	11	Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	13020	12829	12898	GrN-5558	Dung	11	Long and Martin, 1974; Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	13194	12827	12988	A-9570	Dung	11	Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	14043	13303	13672	A-1371	Dung	11	Long and Martin, 1974; Long et al., 1998; Steadman et al., 2005
Gruta del Indio	<i>Sloth</i> (ARG)	14912	14021	14412	A-9571	Dung	11	Long et al., 1998; Steadman et al., 2005

## Appendix 2

Table A.2. presents radiocarbon dates of rank-13 to rank-17 for first evidence of humans considered robust and discussed in the text. See Supplementary Online Material for the complete list of dates and associated references that were evaluated.

Country	Site name	OxCal old	OxCal young	OxCal median	Lab number	Material dated	Stratigraphic association	Archeological association	Rank	References
Argentina	Fell-1	12349	11210	11682	I-5146	Ash/charcoal from hearth	Same layer	Hearth, lithics	13	Bird, 1988; Borrero, 1996; Borrero, 1999; Miotti and Salemm, 2003; Faught, 2008
Argentina	Fell-1	10664	9773	10273	I-5144	Ash/charcoal from hearth	Same layer	2 hearths	13	Bird, 1988; Borrero, 1996; Borrero, 1999; Miotti and Salemm, 2003; Faught, 2008
Argentina	Fell-1	10746	9539	10154	I-5145	Ash/charcoal from hearth	Same layer	Several hearths	13	Bird, 1988; Borrero, 1996; Borrero, 1999; Miotti and Salemm, 2003; Faught, 2008
Argentina	Fell-1	9887	9092	9469	I-5143	Ash/charcoal from hearth	Same layer	1 spear thrower contact point and 1 projectile point	13	Bird, 1988; Borrero, 1996; Borrero, 1999; Miotti and Salemm, 2003; Faught, 2008
Argentina	Fell-1	9473	8725	9143	I-5142	Ash/charcoal from hearth	Same layer	Several hearths	13	Bird, 1988; Borrero, 1996; Borrero, 1999; Miotti and Salemm, 2003; Faught, 2008
Argentina	Piedra Museo AEP-1	12651	12035	12298	AA-8428	Camelid vertebra	"primary association" (should equal same stratum)	Fishtail point	13	Miotti, 1992; Miotti et al., 2003; Borrero, 1999
Argentina	Agua de la Cueva	10557	10239	10380	Beta 64539	Charcoal	Same stratum	Hearths, bone remains, lithic artefacts	14	Garcia et al., 1999; Paez et al., 2003
Argentina	Agua de la Cueva	12346	11713	11983	Beta 61408	Charcoal	Same stratum	Hearths, bone remains, lithic artefacts	14	Garcia et al., 1999; Paez et al., 2003
Argentina	Agua de la Cueva	12796	11404	12168	Beta 26250	Charcoal	Same stratum	Hearths, bone remains, lithic artefacts	14	Garcia et al., 1999; Paez et al., 2003
Argentina	Agua de la Cueva	11695	10886	11272	Beta 26781	Charcoal	Same stratum	Hearths, bone remains, lithic artefacts	14	Garcia et al., 1999; Paez et al., 2003
Argentina	Agua de la Cueva	13072	12817	12910	Beta 61409	Charcoal	Same stratum	Hearths, bone remains, lithic artefacts	14	Garcia et al., 1999; Paez et al., 2003
Argentina	Agua de la Cueva	11752	10676	11157	Beta 61410	Charcoal	Same stratum	Hearths, bone remains, lithic artefacts	14	Garcia et al., 1999; Paez et al., 2003
Argentina	Cerro el Sombrero	12890	12405	12764	AA-4765	Charcoal	Same stratum	Lithic artefacts	15	Flagenheimer and Zarate, 1997; Flagenheimer, 2003
Argentina	Cerro el Sombrero	12554	11642	12045	AA-4766	Charcoal	Same stratum	Lithic assemblage, tools, ochre	15	Flagenheimer and Zarate, 1997; Flagenheimer, 2003
Argentina	Cerro el Sombrero	12877	12385	12702	AA-4767	Charcoal	Same stratum	Lithic assemblage, tools, ochre	15	Flagenheimer and Zarate, 1997; Flagenheimer, 2003
Argentina	Cerro el Sombrero	12699	12130	12466	AA-5220	Charcoal	Same stratum	Lithic assemblage, tools, ochre	15	Flagenheimer and Zarate, 1997; Flagenheimer, 2003
Argentina	Cerro La China – Sitio 3	12912	12031	12544	AA-1328	Charcoal	Same stratum	Lithic assemblage, mineral pigment	15	Flagenheimer, 1986/87; Flagenheimer and Zarate, 1997; Paez et al., 2003; Faught, 2008
Argentina	Cueva Tixi	11973	11260	11585	AA-12131	Vegetal charcoal from hearth	Same stratum	Hearth, lithics, pigment, bone artefacts, "butchering"	15	Mazzanti and Quintana, 2001; Mazzanti, 2003
Argentina	Cueva Tixi	12650	11842	12262	AA-12130	Vegetal charcoal from hearth	Same stratum	Hearth, lithics, pigment, 2 bone artefacts, "butchering"	15	Mazzanti and Quintana, 2001; Mazzanti, 2003
Brazil	Pedra Pintada	13415	12053	12852	GX17407	Carb seeds	Same strata	Occupation (hearths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996
Brazil	Pedra Pintada	13711	12391	13055	GX17406	Carb seeds	Same strata	Occupation (hearths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996
Brazil	Pedra Pintada	13397	12002	12816	GX17414	Carb seeds	Same strata	Occupation (hearths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996
Brazil	Pedra Pintada	13264	12865	13056	GX17413	Carb seeds	Same strata	Occupation (hearths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996

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Appendix 2 (continued)

Country	Site name	OxCal old	OxCal young	OxCal median	Lab number	Material dated	Stratigraphic association	Archeological association	Rank	References
Brazil	Pedra	12789	11252	12030	GX17421	Carb seeds	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996
Brazil	Pintada	13177	11643	12521	GX17420	Carb seeds	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996
Brazil	Pedra	12799	11270	12075	GX17422	Carb seeds	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	13	Roosevelt et al., 1996
Brazil	Pintada	12781	12389	12594	B76953CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12639	12003	12285	GX17400CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12233	11650	11961	B75001CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12354	11762	12021	B75002CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12569	11825	12154	B75006CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12630	12036	12279	B75003CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12654	12122	12397	B75005CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12565	11837	12174	B75009CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12602	12041	12261	GX19524CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12640	12074	12328	GX19529CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12594	12004	12243	GX19531CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	11984	11400	11722	GX19532CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12388	11769	12086	GX19527CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12388	11769	12086	GX19528CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12370	11715	12001	GX19537CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12621	12073	12305	GX19538CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12144	11641	11917	B76955CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12570	12034	12224	B76954CAMS	Carb wood	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pintada	12654	12122	12397	GX19523CAMS	Carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	14	Roosevelt et al., 1996
Brazil	Pedra	12586	11828	12178	GX19525CAMS	Humate from wood char	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pintada	12751	12185	12511	GX19524CAMS	Humate from carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra	12805	12380	12604	GX19526CAMS	Humate from wood char	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pintada	12144	11641	11917	GX19530CAMS	Humate from wood char	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra	12370	11715	12001	GX19529CAMS	Humate from carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pintada	12090	11508	11872	GX19531CAMS	Humate from carb seed	Same strata	Occupation (hearthths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996



Brazil	Pedra Pintada	12102	11617	11886	GX19532CAMS	Humate from carb seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12078	11648	11891	GX19534CAMS	Humate from seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12586	11828	12178	GX19527CAMS	Humate from carb seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12028	11400	11741	GX19528CAMS	Humate from carb seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12338	11506	11915	GX19535CAMS	Humate from wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12160	11644	11937	GX19533CAMS	Humate from wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12687	12121	12450	GX19537CAMS	Humate from carb seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12599	11843	12216	GX19536CAMS	Humate from carb seeds	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12630	12036	12279	GX19538CAMS	Humate from carb seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	11751	11263	11486	GX19523CAMS	Humate from carb seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12233	11650	11961	GX19540CAMS	Humate from wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	11751	11263	11486	GX19539CAMS	Humate from wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12737	12127	12472	GX19541CAMS	Humate from seed	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12654	12122	12397	B76952CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996; Haynes et al., 1997; Faught, 2008
Brazil	Pedra Pintada	12563	11755	12089	B75007CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12385	11825	12104	B75004CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12381	11768	12064	B75008CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12605	11989	12248	GX19525CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12699	12130	12466	GX19526CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12377	11753	12022	GX19530CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12561	11818	12131	GX19535CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12581	11992	12228	GX19533CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12605	12050	12275	GX19540CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Brazil	Pedra Pintada	12687	12121	12450	GX19539CAMS	Wood char	Same strata	Occupation (hearths, lithics, charred flora and fauna)	15	Roosevelt et al., 1996
Chile	Cueva del Medio	13149	12399	12853	NUTA-2331	<i>Hippidion saldiasi</i> tibia	Same stratum (in fireplace)	Fireplace, lithics	13	Nami and Nakamura, 1995
Chile	Cueva del Medio	13455	12397	12999	NUTA-2197	<i>Lama</i> cf. <i>Owenii</i> diaphysis fragment	Same stratum (in fireplace)	Fireplace, lithics	13	Nami and Nakamura, 1995
Chile	Cueva del Medio	12706	12001	12352	NUTA-1734	<i>Lama</i> cf. <i>Owenii</i> metapodial	Same stratum (in fireplace)	Fireplace, lithics	13	Nami and Nakamura, 1995
Chile	Lago Sofia-1	13585	13279	13404	PITT-0684	Charcoal	From hearth	Hearth	13	Prieto et al., 1991; Borrero, 1996; Borrero, 1999; Miotti and Salenme, 2003; Massone, 2003; Faught, 2008

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Appendix 2 (continued)

Country	Site name	OxCal old	OxCal young	OxCal median	Lab number	Material dated	Stratigraphic association	Archeological association	Rank	References
Chile	Monte Verde	14781	13791	14162	BETA-6755	Wood artifact	Same	"digging stick"	13	Dillehay, 1989; Dillehay, 1997
Chile	Monte Verde	15265	14240	14856	TX-4437	Wood artifact	Same object	Grooved/burned/planned wood	13	Dillehay, 1989; Dillehay, 1997
Chile	Monte Verde II - Chinchihuapi Site	14980	14045	14483	BETA-65842	Burned wood	Same object	Burned/modified wood w/ cut/chopping marks	13	Dillehay, 1989; Dillehay, 1997
Chile	Tres Arroyos	12825	12397	12693	OxA-9246	Vicuña mandible	Same stratum (but mixing?)	Hearths, lithics, pigment, bone artefacts, bones	13	Borrero, 2003; Massone, 2003; Miotti and Salemme, 2003; Nami, 1987; Faight, 2008
Chile	Tres Arroyos	12851	12410	12744	OxA-9247	Equid bone	Same stratum (but mixing?)	Hearths, lithics, pigment, bone artefacts, bones	13	Borrero, 2003; Massone, 2003; Miotti and Salemme, 2003; Nami, 1987; Faight, 2008
Chile	Tres Arroyos	13125	12885	13004	OxA-9248	Panther metatarsal	Same stratum (but mixing?)	Hearths, lithics, pigment, bone artefacts, bones	13	Borrero, 2003; Massone, 2003; Miotti and Salemme, 2003; Nami, 1987; Faight, 2008
Chile	Monte Verde	15049	14042	14527	OXA-381	Wood artifact	Same object	Cut, burned and planned timber	14	Dillehay, 1989; Dillehay, 1997
Chile	Monte Verde	16248	13792	14970	TX-5575	Wood artifact	Same object	Cut, fire-hardened stake	14	Dillehay, 1989; Dillehay, 1997
Chile	Monte Verde	15772	14168	15035	BETA-59082	Burned wood from lance	Same object	Wooden lance	14	Dillehay, 1989; Dillehay, 1997
Chile	Tres Arroyos	12834	12242	12632	Beta-101023	Charcoal	Same stratum (but mixing?)	Hearths, lithics, pigment, bone artefacts, bones	14	Borrero, 2003; Massone, 2003; Miotti and Salemme, 2003; Nami, 1987; Faight, 2008
Chile	Tres Arroyos	12612	11202	11791	OxA-9666	Charcoal	Same stratum	Hearths, lithics, pigment, bone artefacts, bones	14	Borrero, 2003; Massone, 2003; Miotti and Salemme, 2003; Nami, 1987; Faight, 2008
Chile	Quebrada Santa Julia	13149	12879	13008	Beta 215089	Hearth charcoal	Same stratum	Hearth, lithics, "processed" bone, tools	15	Jackson et al., 2007; Faight, 2008
Chile	Quebrada Santa Julia	13037	12808	12887	Beta 194725	Hearth charcoal	Same stratum	Hearth, lithics, "processed" bone, tools	15	Jackson et al., 2007; Faight, 2008
Chile	Tres Arroyos	12788	12397	12639	Beta-113171	Charcoal	Same stratum	Hearths, lithics, pigment, bone artefacts, bones	15	Borrero, 2003; Massone, 2003; Miotti and Salemme, 2003; Nami, 1987; Faight, 2008
Chile	Quebrada Santa Julia	13121	12866	12989	Beta 215090	Wood instrument	Same	Hearth, lithics, "processed" bone, tools	16	Jackson et al., 2007; Faight, 2008
Chile	Bano Nuevo-1	10169	9710	9960	CAMS-36663	Bone	Same	Human remains	17	Mena et al., 2003; Miotti and Salemme, 2003
Colombia	San Isidro	11170	10583	10872	B-65877	Charcoal	Same stratum	Lithic assemblage	14	Gnecco, 2003
Colombia	San Isidro	11977	11261	11597	B-65878	Charcoal	Same stratum	Lithic assemblage	14	Gnecco, 2003
Peru	Quebrada de los Burros	13211	9523	11361	Gif-10628	Charcoal	"Associated" with burials	Human remains	13	Levallee, 2003
Peru	Quebrada de los Burros	10119	9540	9722	Gif-10632	Charcoal	From occupational strata (undifferentiated?)	Faunal remains, lithics, bone and shell tools, hearths, postholes	13	Levallee, 2003
Peru	Quebrada Tacahuay	10559	9914	10266	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	14	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	12127	11241	11680	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	14	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	12741	11974	12334	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	14	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	12824	12062	12481	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	14	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	13069	12380	12767	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	14	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	12713	11342	12071	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	15	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	12730	12239	12517	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	15	deFrance et al., 2001; Faight, 2008
Peru	Quebrada Tacahuay	12893	12638	12791	BETA	Charcoal	Same stratum (within midden)	Butchering site (middens, hearths, lithics)	15	deFrance et al., 2001; Faight, 2008
Uruguay	Pay Paso 1	11172	9937	10514	Uru-248	Charcoal	Same stratum (within midden)	Lithics, hearth, other	14	Suarez, 2003
Uruguay	Pay Paso 1	10404	10207	10264	Beta 156973	Charcoal	Same strata	Lithics, hearth, other	14	Suarez, 2003
Uruguay	Pay Paso 1	10154	9259	9596	Uru-246	Charcoal	Same strata	Lithics, hearth, other	14	Suarez, 2003

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