



Updating Martin's global extinction model

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ABSTRACT

Australia has been cited as a weak link in anthropogenic models of megafauna extinction, but recent work suggests instead that the evidence for rapid extinction shortly after human arrival is robust. The global model is revisited, based on the contention that late Pleistocene megafauna extinctions took place rapidly on islands, and some islands (such as Australia and the Americas) are much larger than others. Modern dating methods are increasingly able to refine chronologies, and careful scrutiny suggests that hundreds of dates should be deleted from archives. An updated summary of results from New Zealand, North America and Australia is presented, with a brief discussion on why temperate refugia offering protection from climate change ultimately did not work, strongly supporting the global extinction hypothesis pioneered by Paul Martin.

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1. Introduction

A frank exchange of views between Paul Martin and Louis Leakey four decades ago in the pages of *Nature* foreshadowed the flavour and texture of late Quaternary megafauna extinction debates still in progress. Martin (1966, 1967) proposed the anthropogenic overkill hypothesis, while Leakey (1966, 1967) supported a climate change hypothesis for the African extinctions. Nestled among their disagreements was a contested radiocarbon date from Kalambo Falls (Clark, 1965). The charred wood sample in question had undergone acid and base decontamination chemistry, and was originally reported as >52,000 years (GrN-1396), but the laboratory had redated the sample using isotope enrichment with a result of $57,600 \pm 750$ years (GrN-2644), which was accepted as valid for Late Acheulean tools at the site. While also accepting the date, Martin noted that it was at the limits of available ^{14}C technology, and correlated the archaeology with Olduvai Bed IV. Leakey argued that the faunal assemblage in the Olduvai sequence was indicative of a much greater antiquity, and suggested drought was the most likely cause of the African extinctions. He was also an early adopter of the incredulity stance — how could primitive hominins possibly cause elephant extinctions?

Elephants are conspicuously absent from the Australian geological record, but the 'two tonne wombat' *Diprotodon opatum* features in a similar radiocarbon problem. Teeth from one such extinct marsupial, excavated at Lake Callabonna in South Australia (Stirling, 1894), yielded a 'dentine' age of 6700 ± 250 years but 'gut contents' found within the same skeleton gave >40,000 years

(NZ-205, 206; Fergusson and Rafter, 1959). Redating of plant fragments from the gut contents using a cellulose preparation recorded an age of >53,400 BP (ANUA-32711; Gillespie et al., 2008), but no protein was found in the skeletal remains.

Recent estimates for the Final Acheulean are ~300 ka (Ambrose, 2001) and for the Australian megafauna extinctions are 40–50 ka (Roberts et al., 2001; Miller et al., 2005; Gillespie et al., 2006), but with ^{14}C conundrums like these it has been easy to draw radically different conclusions about the past from the same dataset. In the context of modern human origins, Millard (2008) notes that "some dates on fossils are widely accepted ... while others are disputed or uncertain so that different authors choose different chronologies to suit their evolutionary schemes". It is similarly easy, by choosing your dates and statistical methods carefully, to support any number of mutually incompatible models of human migration and megafauna extinction.

The aim here, following a brief diversion on geography, is to document some recent improvements in the chronology of megafauna extinctions in New Zealand, North America and Australia, and to examine whether the global overkill model (Martin, 1984, 2005) stands up to scrutiny today in the face of repeated criticism from supporters of climate change models.

2. Islands, continents and climate

The validity of projecting onto 'continents' the pattern of extinction observed on islands such as New Zealand has often been challenged (e.g. Grayson and Meltzer, 2002; Wroe et al., 2004). There are, however, several ways of counting continents, which depend more on political persuasion than physical geography: a quick trip to Wikipedia lists six ways of naming 4, 5, 6 or 7 continents. Throughout most of the 2.6 million-year Quaternary,

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there has been one supercontinent comprising Africa, Eurasia, North America and South America (the ‘mainland’), while Australia and Antarctica may be considered either as large islands or small continents. This makes a total of just 3 continents, but for ~10% of the time this number increases to 4, because during interglacials such as the Holocene, the conjoint Americas become a very large island continent accessible only by boat from the Afro-Eurasian mainland, Australia or Antarctica. From this perspective, it is perhaps no surprise that the biogeography of the permanently contiguous Afro-Eurasian mainland appears different to that of islands, small and large.

As a backdrop for some of the discussion below, Fig. 1A shows deuterium variations over the past 60 ka from the Dome C Antarctic ice core (EPICA, 2004). This southern hemisphere climate proxy is similarly distributed in time to $\delta^{18}\text{O}$ variations in the same core and to benthic $\delta^{18}\text{O}$ variations in deep sea cores, all of which depict global-scale climate change. Fig. 1B shows sea level change derived from Huon Peninsula coral terraces on the north coast of Papua New Guinea (Lambeck and Chappell, 2001) and Heinrich events 3, 3.5, 4 and 5 recorded in the same corals (Yokoyama et al., 2001). Fig. 1C shows emergence and submergence of the Bassian landbridge between Tasmania and Australia as reconstructed by

Lambeck and Chappell (2001), who suggest that sustainable pedestrian crossing would have been possible only after ~43 ka, and note that the oldest archaeology reported for Tasmania is ~40 ka.

That landbridge ceased to be viable ~14 ka when rapidly rising sea level once again made Tasmania an island; Bass Strait is challenging even for modern sailors, and indigenous Tasmanian culture declined during the long isolation (Jones, 1978). Similarly, the Beringian landbridge went submarine about 11–12 ka (Keigwin et al., 2006) as the Americas became a large island again. Bering Strait and environs, straddling the Arctic circle, was likely most unpleasant for sailing then.

3. Methods and results

A comprehensive attempt has been made to apply ‘chronometric hygiene’ (Spriggs, 1989) to the available archaeology and extinct megafauna databases for New Zealand, North America and Australia. Radiocarbon dates for North America and Australia were converted to 95% confidence calendar age ranges using CalPal07_{Hulu} (Weninger et al., 2007), while New Zealand results were converted to cal AD/BC ages with OxCal 4.0 and the Southern Hemisphere calibration curve (McCormac et al., 2004).

3.1. New Zealand

By the time humans reached New Zealand, Polynesian sailors had already colonised most of the smaller habitable Pacific islands and caused many extinctions, particularly of birds (Steadman, 1995; Anderson, 2001). Datasets examined here include Higham (1994), Higham et al. (1999) and Wilmshurst et al. (2008), which suggest that the oldest ^{14}C dated archaeological evidence for the human occupation of New Zealand is 1280–1382 cal AD, but controversy over earlier dates on bones of the introduced Pacific rat (*Rattus exulans*) has clouded debate (e.g. Anderson, 1996; Beavan and Sparks, 1998; Higham and Petchev, 2000). This argument has been neatly resolved by Wilmshurst et al. (2008), who dated *Rattus exulans* bones using the Oxford ultrafiltration method and confirmed their results by also dating holocellulose prepared from seeds with toothmarks matching those of the rat. They may have dated some of the first rats to jump ship, but no rats (or rat-gnawed seeds) were older than the archaeology, refuting the ‘long chronology’ based on previous acceptance of Pacific rats in New Zealand ~2000 BP (Holdaway et al., 2002; Sutton et al., 2008). Acceptable ^{14}C dates shown in Fig. 3A are on ultrafiltered bone gelatin from the commensal *Rattus exulans* or rat-gnawed seed holocellulose, as proxies for human occupation, and on extinct Moa eggshell carbonate; eggshell dates older than 13th century AD are from natural deposits, the remainder from archaeological sites.

3.2. North America

The ancestors of those who first colonised North America were acclimatised to life in the cold, fluctuating environments of northeastern Eurasia during MIS 3 and 2. As continental ice sheets and glaciers advanced and retreated, some of those modern humans built complex shelters from mammoth bones in treeless landscapes (e.g. Soffer, 1993). It is therefore unsurprising that those people eventually crossed Beringia to penetrate the New World, as postglacial warming created a viable habitat for both humans and mammoths in a corridor between the Cordilleran and Laurentide ice sheets, and perhaps on newly-emerged coastal plains. North American datasets include Ho et al. (1969), Guthrie (2006), Waters and Stafford (2007) and Friscia et al. (2008).

The first Alaskans may well have become stranded by rising sea level, and there has been much debate on whether the new

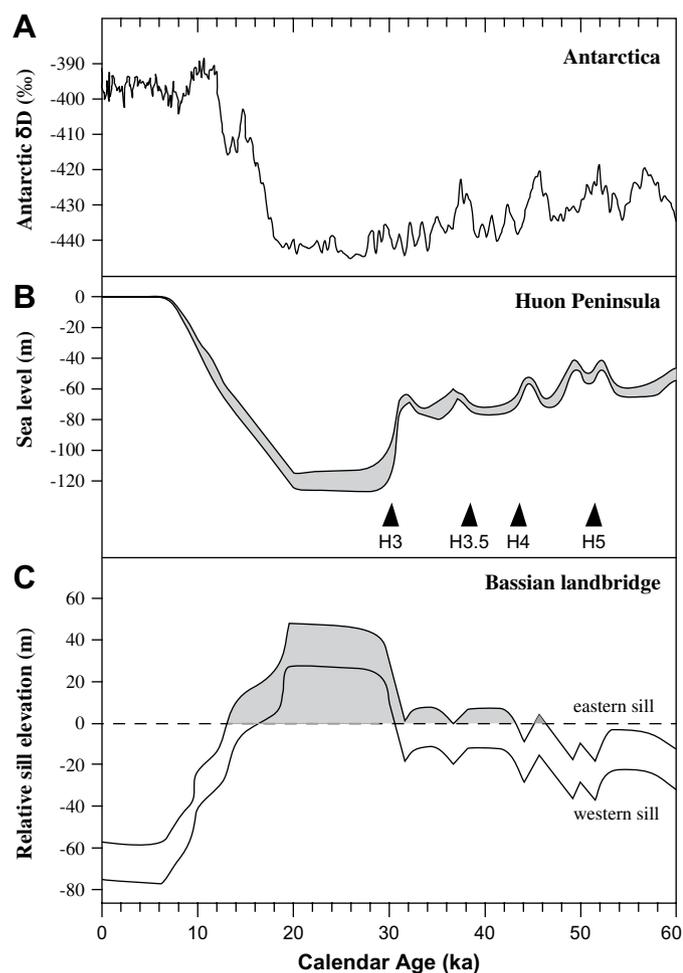


Fig. 1. (A) Antarctica: ice core deuterium variations as proxy for southern hemisphere climate 0–60 ka (EPICA Community Members, 2004); (B) Huon Peninsula: ice-volume equivalent sea level (Lambeck and Chappell, 2001) and Heinrich Events 3, 3.5, 4 and 5 (Yokoyama et al., 2001) recorded in Papua New Guinea coral terraces. (C) Bassian landbridge: elevation relative to coeval sea level of eastern and western sills of the landbridge between Tasmania and Australia, shaded area represents emergent land with sustained pedestrian crossing possible on the eastern side 43–14 ka (Lambeck and Chappell, 2001).

colonists were responsible for megafauna extinctions there or not (e.g. Guthrie, 2006). The ^{14}C dates appear to show that both horses and mammoths vanished from the Alaska–Yukon region after humans arrived but before the start of the Younger Dryas (Solow et al., 2006; Buck and Bard, 2007). However, these Alaska–Yukon events were merely local extirpations, skirmishes before the main game: Clovis-age extinction of the Rancholabrean megafauna. Haynes (2008) closely examined the stratigraphy of 97 North American sites spanning the Pleistocene–Holocene transition, finding in two-thirds of those a 'black mat' coeval with the Younger Dryas, which invariably overly Clovis-age horizons containing extinct megafauna, and "only bison survived to the Younger Dryas, probably because they vastly outnumbered other species." I am as skeptical as Vance Haynes that extraterrestrial events (Firestone et al., 2007) were responsible for the Younger Dryas, black mats, decimation of the Clovis culture, and megafauna extinction in North America. The demographics of Beringian bison suggest that populations of megafauna declined during the LGM (Shapiro et al., 2004), but were likely rebounding when humans arrived, causing a bottleneck in bison recovery ~ 11 ka (Drummond et al., 2005), which if confirmed is post-Clovis and after the extinction of most other large-bodied genera that consigned Folsom-age cultures to bison barbecue only.

Although it is possible to suggest, as Goebel et al. (2008) have, that a few sites with possible elephant kills at 14–15 ka cal BP fit with a Coastal Migration hypothesis, the coast of British Columbia is no tropical paradise today and would have been much less hospitable then. Even if there was a coastal foray 15,000 years ago, and people did go boating all the way to Monte Verde, they may (like early modern humans in the Levant) have failed to establish a viable population. There are no directly-dated human skeletal remains in the Americas older than the Clovis First hypothesis proposes, and certainly no pre-Clovis site remains uncontested (e.g. Fiedel, 2002). North American archaeological results shown in Fig. 3B are ^{14}C dates on charcoal, purified bone gelatin or single amino acids (Waters and Stafford, 2007), from which I have rejected results following those authors but not penalised dates with large error bars as their only sin. Extinct megafauna results are ^{14}C dates on bone collagen or gelatin fractions from the herbivore *Mammuthus* from Guthrie's extensive Alaska–Yukon list, and the carnivores *Smilodon fatalis* and *Canis dirus* from Rancho La Brea in sunny California; I have eliminated only a few dates because of inadequate chemistry.

3.3. Australia

According to mtDNA and Y chromosome markers, the first Australians can trace their origins to an African exodus about 70–60,000 years ago (Hudjashov et al., 2007). Those who first prospered in Australia were acclimatised to the tropical coasts and estuaries along the 'southern dispersal' route, via India and Indonesia (e.g. Forster, 2004; Bulbeck, 2007; Pope and Terrell, 2008). It is unlikely that remains of the very first boat, or the first boat people, to make landfall will ever be found, because unless the landing site has been tectonically uplifted, as the Huon Peninsula coral terraces of northern Papua New Guinea have, it is probably now under water. Vigorous argument about when the first Australians arrived continues, some scholars supporting long chronologies — Webb (2007), for example, speculates that *Homo erectus* arrived ~ 150 ka — while others favour a shorter one (e.g. Allen and O'Connell, 2003). Many scientists now accept an age range for first occupation near 50 ka (Brook et al., 2007), and there was a sharp rise in sea level ~ 52 ka recorded in the Huon corals (Heinrich Event 5; Yokoyama et al., 2001) to encourage boating from the small and rapidly shrinking islands of Wallacea (Chappell, 2000).

The Australian dataset is based on that analysed by Gillespie et al. (2006), with two significant new additions discussed below. Roberts et al. (2001) used OSL dating on fossil horizons at 28 Australian sites, 7 of which were used to calculate the widely-quoted megafauna extinction time ~ 46.4 ka (95% confidence interval 40–51 ka), and Miller et al. (2005) used Useries, OSL and AAR dating to estimate a *Genyornis* extinction time of 45–50 ka. Barry Brook's simulation and analytical modelling in Gillespie et al. (2006) suggests that humans were well-established across the Australian mainland by 46.5 ka and the megafauna were extinct by 40 ka, with a human–extinct megafauna overlap of less than 5000 years centred ~ 44 ka. These results, calculated from a larger dataset and with no articulation criterion, strongly support the conclusions of Roberts et al. (2001) and Miller et al. (2005).

As an illustration of the culling procedure employed, Fig. 2 shows ^{14}C dates on freshwater shell (*Velesunio ambiguus*) and fish otolith (*Macquaria ambigua*) carbonate (thin black lines) from archaeological middens in the Murray–Darling basin, and two sets of results for the extinct giant bird *Genyornis newtoni*: eggshell carbonate ^{14}C dates (dark gray lines), and Useries dates on eggshell or OSL dates on quartz from layers containing eggshells (light gray lines). The fish and shellfish carbonate ^{14}C dates have given stratigraphically consistent results, notably in the Willandra Lakes (Bowler 1998), and have usually been considered reliable. In contrast, the *Genyornis* eggshell carbonate ^{14}C dates are significantly younger than Useries, OSL and AAR results from the same stratigraphic contexts (Miller et al., 1999), suggesting that carbonate contamination is limiting near the radiocarbon 'event horizon' (Chappell, 1991). Because it is possible that the oldest shells and otoliths (also soil carbonates and flowstones) suffer carbonate contamination, as the *Genyornis* eggshells have, all carbonate ^{14}C dates were rejected. Sedimentary 'organics' of dubious origin and inadequate pretreatment were rejected, as were well-decontaminated charcoal results, following Mead and Meltzer (1984), if the association between sample measured and extinct animals was poor to non-existent. Australian archaeological dates were similarly culled, and only ages >30 ka calBP were considered, rejecting ^{14}C dates on carbonates, 'organics' and human skeletal remains.

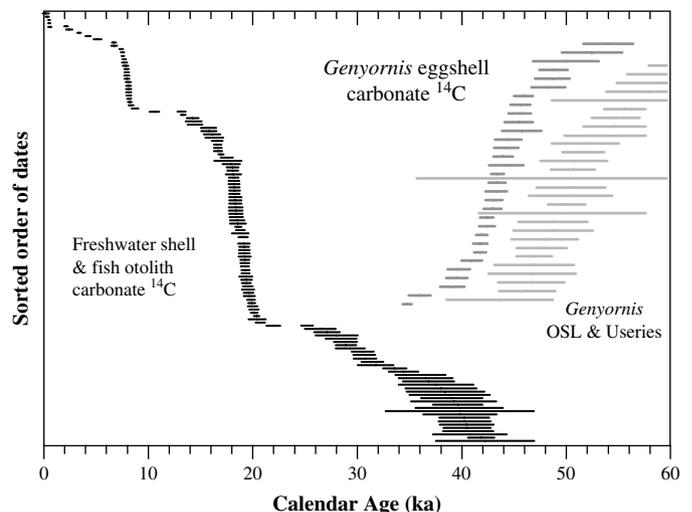


Fig. 2. Radiocarbon dates on freshwater shell and fish otolith carbonate from Australian archaeological sites (black lines), with ^{14}C dates on extinct *Genyornis* eggshell carbonate and Useries or OSL dates (gray lines); data from Bowler (1998), Gillespie (2002), Miller et al. (2005). Oldest shellfish and fish dates ~ 42 ka cal BP agree with charcoal ^{14}C and OSL results, but the *Genyornis* ^{14}C dates are significantly younger than OSL and Useries results from the same stratigraphic contexts.

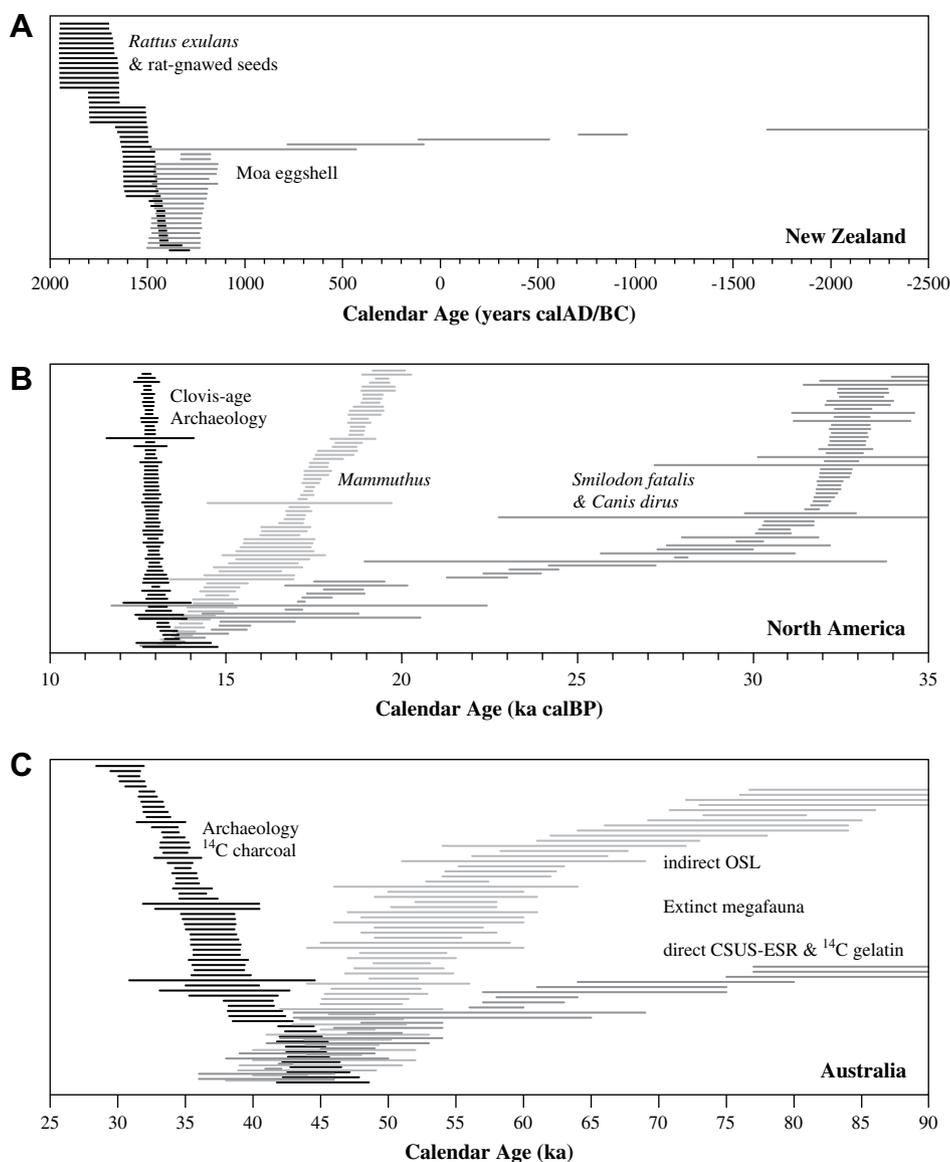


Fig. 3. (A) New Zealand: proxy archaeological ^{14}C dates on ultrafiltered gelatin from commensal *Rattus exulans* bone or rat-gnawed seed holocellulose (black lines), and ^{14}C dates on extinct Moa eggshell carbonate (gray lines). Data from Higham (1994), Higham et al. (1999) and Wilmshurst et al. (2008), the latter suggesting that older rat bone dates used in support of a longer archaeological presence are incorrect, with megafauna extinction AD \sim 1400. (B) North America: archaeological charcoal ^{14}C dates or human bone collagen fractions (black lines), and ^{14}C dates on extinct megafauna bone collagen fractions (light gray lines *Mammuthus* from Alaska-Yukon, dark gray lines *Smilodon fatalis* and *Canis dirus* from Rancho La Brea, California). Data from Ho et al. (1969), Guthrie (2006), Waters and Stafford (2007) and Friscia et al. (2008), suggesting megafauna extinction \sim 13 ka. (C) Australia: archaeological charcoal ^{14}C dates (black lines), indirect OSL dates on quartz from strata containing extinct megafauna (light gray lines), and direct CSUS-ESR dates on extinct marsupial teeth or ^{14}C dates on ultrafiltered gelatin from extinct marsupial bone (dark gray lines). Data from Roberts et al. (2001), Miller et al. (2005), Cupper and Duncan (2006), Gillespie et al. (2006), Grün et al. (2008) and Turney et al. (2008), suggesting megafauna extinction \sim 45 ka.

4. Discussion

The standard definition of megafauna minimum body mass is 44 kg (Martin, 1984), which approximates the 98 lb weakling getting sand kicked in his face that some may remember from advertisements for the “Charles Atlas Chest Expander” on the back of 1950s comics. Megafauna therefore have a body mass similar to, or bigger than, an adolescent modern *Homo sapiens*. On this human scale, most Australopithecines would struggle to make the cut and they were probably not much of a threat to the elephants. Likewise the diminutive *Homo floresiensis*, but *Homo erectus* and *neanderthalensis* definitely qualify as extinct megafauna (Stewart, 2004).

The timing of *erectus* extinction is unresolved (e.g. Swisher et al., 1996; Storm, 2001; Webb, 2007), but it is probably beyond ^{14}C range (Westaway et al., 2007) and not considered here. There is no

consensus on when, how, or even if the Neanderthals became extinct, and the debate attracts supporters from all flavours of extinction hypotheses (e.g. Zilhão and d’Errico, 1999; Stewart, 2007; Finlayson et al., 2006; Jiménez-Espejo et al., 2007). My attempts to select reliable ages for Neanderthal extinction from the Cambridge Stage 3 Project databases, mined by many others, were thwarted by incomplete access to the original literature, but it is easy to reject quite a few ^{14}C dates from annotations in the database or by reference to sample identity, laboratory and year of measurement. Even such a simple cull makes a significant difference to the apparent overlap between Neanderthals and modern humans, and continuing work on calibrating MIS3 dates for the middle-upper Palaeolithic transition in Europe (e.g. Jöris and Weninger, 1996; Mellars, 2006; Tzedakis et al., 2007), offer prospects for direct comparison with ice core and other proxy climate records. My money is on extinction \sim 10 ka later than the demise of

the endemic Australian megafauna, most likely caused by newly arriving modern humans, but I leave that for others to resolve.

Most small oceanic islands, as well as the island-continent, Australia and the Americas, have the impoverished distinction of colonisation by the single remaining species of our genus, *Homo sapiens*. If you were heading east from Africa, following the rising sun and the coast, the mainland ended at Bali and from there you needed a boat for island-hopping to Australia.

Many perennial favourites among purported late-surviving Australian megafauna sites, including Lancefield Swamp (Gillespie et al., 1978), Nombe Rockshelter (Gillieson and Mountain, 1983) and Cuddie Springs (Dodson et al., 1993), have been eliminated because of dating and/or association problems noted above. This has not, of course, precluded repeated attacks on Roberts et al. (2001) and Gillespie et al. (2006) in particular, and the Martin (1984) global extinction hypothesis in general (e.g. Wroe et al., 2004; Field et al., 2008). There are, however, many reasons to discount discussion of the Australian data by Field, Wroe and colleagues, as three non-trivial examples from the latest offering illustrate:

- "... the ABOX-SC dates obtained for the Cuddie Springs site were excluded by Gillespie et al. because they argue that these samples have not been demonstrated to be charcoal." This is the opposite of what Gillespie et al. (2006) actually said: "One exception to this trend of ^{14}C ages being too young because of contamination is Cuddie Springs, where the ages on excavated charcoal are technically good with ABA and ABOX chemistry yielding indistinguishable results."
- "Limestone dilution has not been demonstrated" at Nombe Rockshelter. This is an oxymoron; it is a limestone cave and flowstone ^{14}C dates are shown with corrected ages attempting to account for limestone dilution.
- Field et al. claim that their Table 5 shows dating results from the 7 sites used by Roberts et al. (2001) for calculation of the 40–51 ka extinction window. Three of these sites are incorrect; Roberts et al. explicitly excluded the 67–171 ka ages from Lake Menindee, Victoria Fossil Cave and Moondyne Cave because they used only "articulated remains with optical ages of ≤ 55 ka".

Promotions of Cuddie Springs and Nombe Rockshelter by Field, Wroe and coworkers omit key references, contain factual errors and misleading assertions, many already noted by Brook et al. (2007), and are reminiscent of misdemeanours in commentaries by Grayson, Meltzer and colleagues on Monte Verde, Meadowcroft and other purportedly pre-Clovis sites in the Americas rebutted by, e.g. Fiedel and Haynes (2004). Incredulity in the Leakey tradition lives on, not to mention "misrepresentations and doubletalk" (Haynes, 2007). Meanwhile, two recent additions to the megafauna database significantly strengthen arguments that the Australian extinctions were human-mediated.

Grün et al. (2006), Wells et al. (2006) and Grün et al. (2008) illuminate many of the pitfalls along the road to reliable direct dating of fossil marsupial teeth, including those of extinct Australian megafauna. Six sites were studied on a north–south transect across a rainfall gradient with different environments (swamps, alluvial fans, aeolian dunes) in South Australia; some have stone artefacts as well as megafauna, and indirect evidence from ^{14}C dates on soil organics at Black Creek Swamp on Kangaroo Island suggested that the fossil layer could be as young as 20 ka (Forbes et al., 2004). Using high-resolution laser ablation ICP-MS in combination with Useries and ESR dating (CSUS-ESR), Grün and colleagues found no extinct megafauna significantly younger than the Roberts et al. (2001) extinction window. This was not what some of the investigators expected, and I have no doubt that repeated claims for 30 ka megafauna at Cuddie

Springs will also be refuted by forthcoming direct dates from Grün's team.

There are striking parallels in this work to the history of bone ^{14}C dating, where careful attention to details of chemistry and context resulted in better, usually meaning older, dates on specific compounds such as single amino acids (Gillespie et al., 1984; Stafford et al., 1991). Mainland Australian sites lack collagen (Gillespie and Brook, 2006), but further south in Tasmania could offer better prospects. Some commentators have noted the absence of megafauna remains in southwest Tasmanian archaeological sites, which are rich in extant fauna, arguing that the megafauna must have been extinct before humans arrived there (e.g. Cosgrove, 2007; Field et al., 2008). However, no directly-dated megafaunal remains are known from any archaeological site on mainland Australia either, and new evidence convincingly refutes that argument.

Turney et al. (2008) report ^{14}C dates of 40.9–42.9 ka cal BP on *Protemnodon anak* bones from a cave site at Mt Cripps in north-western Tasmania, the first direct ^{14}C dates on extinct Australian marsupial bones that can be defended on technical grounds. The Oxford ultrafiltration pretreatment (Higham et al., 2006) yielded $\sim 10\%$ collagen with C:N ratios of 3.2, and the $\delta^{13}\text{C}$ values around -23‰ are typical for herbivores subsisting mainly on C3 vegetation. Treating the same bones using a modified Longin technique with stepped-combustion was unsatisfactory, giving lower collagen yields, lower C:N ratios, and significantly younger ages. This study, if confirmed by further results on other sites and other taxa, suggests that humans crossed the Bassian landbridge to Tasmania very soon after it became possible ~ 43 ka (Lambeck and Chappell, 2001), and that the megafauna became extinct by 40 ka, just as they had on mainland Australia.

All the Australian archaeological ^{14}C results in Fig. 3C are on decontaminated macroscopic hearth charcoal, many strongly supported by matching OSL dates (e.g. David et al., 1997; Turney et al., 2001; Bowler et al., 2003), which have a better-than-even chance of correctly dating human occupation. Australian megafauna results are indirect OSL dates on fossil strata (Roberts et al., 2001; Miller et al., 2005; Cupper and Duncan, 2006), and direct CSUS-ESR dates on extinct marsupial teeth (Grün et al., 2008) or ^{14}C dates on ultrafiltered gelatin from extinct marsupial bones (Turney et al., 2008).

Fig. 3 shows that the youngest ^{14}C dates on extinct Moa eggshell and bone overlap with those from the oldest New Zealand archaeology, the well-established relationship of Clovis-age archaeological ^{14}C dates overlapping with the youngest extinct herbivore and carnivore ^{14}C dates in North America, and the overlap of Australian archaeological charcoal ^{14}C dates with extinct megafauna OSL, CSUS-ESR and ^{14}C dates. These diagrams show megafauna extinctions at ~ 0.6 ka, ~ 13 ka and ~ 45 ka respectively, and as many others have noted it is not easy to suggest climate changes that could account for them all. Conversely, the pattern clearly follows first human arrivals in those locations, and Fig. 3 also shows how uncertainty in the dates contributes to the apparent tempo of extinctions. In the New Zealand case, extinction can probably be narrowed down to decades, in North America it could be centuries and in Australia the error bars are multiple millennia. I do not think this means only the New Zealand megafauna were taken out in a blitzkrieg — from the megafauna's point of view, these are all blink-of-an-eye catastrophes.

Modelling studies demonstrate that modern humans entering new lands will inevitably lead to rapid megafauna extinctions (e.g. Mosimann and Martin, 1975; Alroy 2001; Brook and Bowman, 2005). Because human hunting pressure is sustained on an annual timescale, large mammals with a generational replacement timescale are particularly at risk, leading Brook and Bowman (2005) to suggest that 'blitzkrieg' should be replaced by 'chronic overkill' in

extinction debates. Even when only the occasional juvenile *Diprotodon* is taken and the species decline would have been imperceptible to the new top predator, extinction probably happened within a few hundred years (Brook and Johnson, 2006), which may help explain the dearth of juvenile mammoth footprints found in trackways at Wally's Beach in Canada (McNeil et al., 2005). An intriguing new dimension for the debate suggests that the Quaternary megafauna extinctions caused a radical change in the distribution of biomass between humans and other megafauna (Barnosky, 2008). As modern human populations increased rapidly after their first arrival in Australia, the Americas and numerous smaller oceanic islands, populations of the endemic megafauna declined catastrophically. These rapid extinctions were followed by very slow recovery of the survivors, despite subsequent favourable climates, and human biomass increased beyond pre-extinction total megafauna biomass only within the last millennium.

It seems likely that the Australian megafauna became extinct near Heinrich 4 (~43 ka), the Neanderthals near Heinrich 3 (~30 ka), and the North American megafauna near Heinrich 0, the Younger Dryas (12.9–11.6 ka). These abrupt climate events had local significance on latitudinal and coastal proximity gradients, but they were minor changes compared with complete glacial–interglacial cycles, and ‘wiggles’ in climate proxies from ice cores, similar to the Dansgaard-Oeschger and Heinrich events of MIS3–2, are visible back to at least 400 ka. But similar extinctions have not been found in previous glacial cycles, so it is not profitable to say extinction ‘near’ any given minor climatic event was caused by that event; in North America, for example, it was all over bar the bison before the YD took hold.

Many megafauna species regularly sought refugia because where they had previously made a living became too hot, cold, wet, dry or buried under kilometres of ice. Retreat to temperate refugia allowed species to survive no matter what the climate was doing, and megafauna survival through the last 400–500 ka of Quaternary time reflects the value of such relocation. But adding a new element — hungry humans — to the mix changed everything. In the case of elephants, Surovell et al. (2005) find a global pattern of extinctions that closely matches human presence, not climate change, and Haynes (2001, 2006) suggests that Clovis-age hunters may have targeted mammoth refugia for an easy feed. And if the supposedly cold-adapted Neanderthals anomalously sought refuge in southern Iberia (Stewart, 2007), they were probably there to avoid confrontation with modern humans rather than for the weather. At many Australian fossil localities, including those studied by Grün et al. (2008), protracted drought conditions found the large herbivores and carnivores at waterholes to which they became tethered; archaeological artefacts are intrusive.

5. Conclusions

Martin (1984) summarised the when, where and what of late Pleistocene extinctions from geological and archaeological records then available, based almost exclusively on ^{14}C dates before AMS was widely deployed. Both accuracy and precision for results relevant to the extinction debates have significantly improved, and calibrated ^{14}C ages are increasingly being complemented and extended in range with similarly improved OSL and combination Useries–ESR dating methods. It is also true that many published results should never be mentioned again.

Fiedel and Haynes (2004), Brook et al. (2007) and others argue that supporters of climate change as the major extinction mechanism should put forward their testable hypotheses for scientific assessment. So far they have not, nor have they offered any compelling evidence to explain the time-transgressive global extinction pattern. As alluded to above, the extinction of *Homo erectus*, *Homo neanderthalensis* and many other large mammals on

the Afro-Eurasian mainland may well be different to extinctions on islands small and large. Modern humans are physically and mentally capable of surviving anywhere on the planet, can cope with whatever climate dictates wherever they choose to live, whereas populations of megafauna may have been forced into temporary refugia as far from the modern human advance as possible. The evidence suggests that although temperate refugia on the Afro-Eurasian mainland slowed the extinction of some large mammals, they ultimately did not work — otherwise the megafauna would not have become extinct.

There is no evidence that climate changes such as the LGM or Younger Dryas impacted sufficiently on megafauna populations to cause their extinction, and as Martin (1984) reminds us, the appearance in new lands of sustainable modern human populations is a harbinger of doom for animals as big as (or bigger than) themselves. While the updated chronologies for New Zealand, North America and Australia do not ‘prove’ that modern humans were responsible for megafauna extinctions, they do constrain the time dimension of the debate and rule out many non-anthropogenic mechanisms. None of the discussion here is good news for supporters of climate change hypotheses, and it is time to stop “shopping for the facts we prefer and ignoring the facts we do not want to think about” (Haynes, 2007). Once a stumbling block for the overkill hypothesis, Australia now fits the extinction pattern observed for other islands, a pattern that follows modern human migrations, not climate change, as Paul Martin has for decades been staunchly advocating.

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