

FORUM

THE RESTAURANT AT THE END OF THE UNIVERSE:

Modelling the colonisation of Sahul

James F. O'Connell¹ and Jim Allen²

Abstract

Elsewhere we have developed a speculative model of the early human colonisation of Sahul (Pleistocene Australia-New Guinea). Here we elaborate it, using theory from behavioural ecology, and data from palaeoclimatology and modern hunter-gatherer ethnography. We argue that colonisers focused mainly on coastal ecotones while crossing Wallacea, but spread more widely across favourable habitats after landing on Sahul. Movement was archaeologically instantaneous, driven primarily by serial depletion of high-ranked prey. Human populations subsequently remained far smaller than sometimes imagined, probably because of difficult climatic and environmental conditions. Archaeological data are generally consistent with these expectations. These findings challenge the frequent assertion that human colonisation alone led to significant changes in Sahul ecology, and may help explain the simplicity of its Pleistocene lithic technology.

Introduction

The history of every galactic civilization tends to pass through three distinct and recognizable phases: those of survival, inquiry, and sophistication; otherwise known as the how, why, and where phases. For instance, the first phase is characterized by the question, 'How can we eat?' The second by the question, 'Why do we eat?' And the third by the question, 'Where shall we have lunch?' The menu goes on to suggest that Milliways, the Restaurant at the End of the Universe, would be a very agreeable and sophisticated answer to that third question. What it doesn't go on to say is that while it will usually take a large civilization many thousands of years to pass through the how, why and where phases, small social groupings under stressful conditions can pass through them with extreme rapidity. (Douglas Adams, *The Restaurant at the End of the Universe* 1980:115-116.)

In earlier work (Allen and O'Connell 2008; O'Connell *et al.* 2010), we have argued that Sahul was colonised deliberately, that sizeable numbers of people were involved, and that the exercise entailed the use of watercraft larger and technically more sophisticated than those known from most of Australia at the time of European contact. Several considerations support these propositions:

- The earliest uncontested dates for *Homo sapiens* east of Sunda fall mainly in a relatively narrow time range (44-46 ky BP), suggesting rapid movement through Wallacea, across large parts of Sahul and into the Bismarcks (Table 1). This distribution is unlikely to have been achieved so quickly by accident. If it were, then pre-modern humans, known to have reached Flores by 800 ky BP (Morwood *et al.* 1998), should also have landed on Sahul. No evidence suggests this.
- Analyses of mitochondrial, non-recombinant Y-chromosome and nuclear DNA from living Sahul indigenes and others suggest that New Guinea and Australia were colonised in a single or several closely spaced waves that created deep, geographically unique genetic connections between these two regions (Reich *et al.* 2011; van Holst Pellekaan 2011).
- At least three, possibly four mitochondrial haplogroups (*M**, *N**, *R** and possibly *M42*) were represented in the founding population(s) (Hudjashov *et al.* 2007; Kumar *et al.* 2009; cf. van Holst Pellekaan 2011). Simulation studies suggest that the establishment of each haplogroup on Sahul required the nearly simultaneous arrival of several separate landing parties, each including at least 5-10 women of reproductive age, and located close enough to at least one other to exchange mates (Moore 2001). In short, a minimum effective population for each haplogroup of 10-20 and a minimum census population for each numbering in the scores was required (O'Connell *et al.* 2010). If representatives of all four haplogroups arrived at roughly the same time, as mutation sequences can be read to suggest, a colonising wave numbering *at minimum* in the hundreds of individuals is implied.
- Inferences about the size of the colonising wave, the speed with which it passed across the region, and the requirement that local groups remain in contact with one another in order to exchange mates all indicate access to relatively sophisticated watercraft, particularly in Wallacea and the Bismarcks.
- The arrival date for *H. sapiens* in the islands of Japan (40-42 ky BP cal.; Pope and Terrell 2008) provides further evidence of the presence of watercraft on the western Pacific Rim at this time.

We reject inferences that characterise the colonisation process in minimalist terms, those that focus on timing defined by lowest sea-levels and shortest inter-landfall distances, that rely on assumptions about marine technology constrained by the Australian ethnographic record, and that offer unrealistic suggestions about the size of founding populations. These ideas deny the characteristics that define modern humans – the capacity for abstract thought and communication, technological

¹ Department of Anthropology, University of Utah, Salt Lake City UT 84112, USA james.oconnell@anthro.utah.edu

² Archaeology Program, La Trobe University, Bundoora VIC 3086, Australia jjallen8@bigpond.net.au

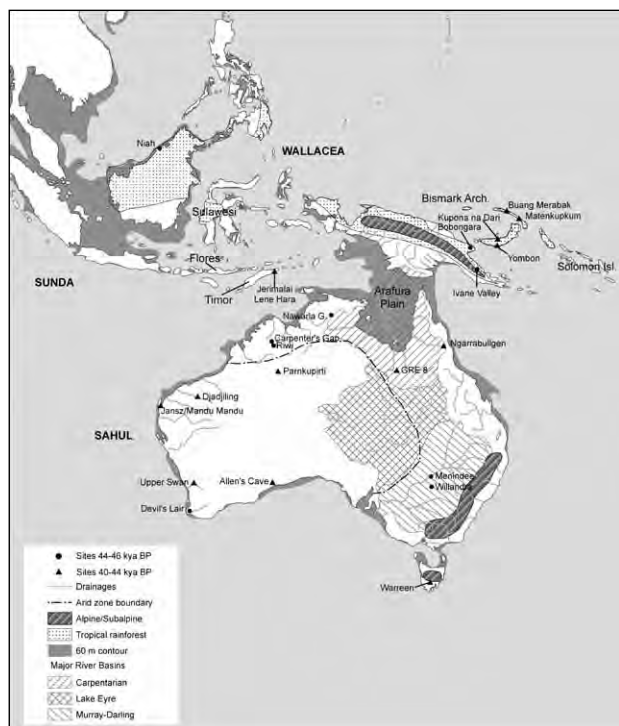


Figure 1 Map of Sunda, Sahul, Wallacea and Bismarck Archipelago showing distribution of sites dated ≥ 40 ky BP across selected patch types. Sea-level -60 m relative to modern; selected high elevation areas >1000 m above modern sea-level also indicated. Approximate limits of major drainage basins defined after Warner (1986); approximate limits of arid zone and selected patch types after Hope *et al.* (2004:Figure 1).

innovation and behavioural flexibility – elements that were fundamental to the successful settlement of Sahul. Here we attempt to provide testable arguments that account for this complexity.

The Model

Contemporary hunter-gatherer settlement patterns are determined in part by factors related to subsistence. We assume this was also true for early Sahul colonisers. This warrants an appeal to optimal foraging theory, a family of formal models used to investigate aspects of food acquisition (Kelly 1995; Stephens *et al.* 2007). One of these models ('prey choice') predicts the subset of foods a consumer should select from an available array; three others ('patch choice', 'marginal value' and 'ideal free distribution') predict how consumers should be distributed in space, under what circumstances they should move, and where. Their implications can be reduced to four rules of thumb:

- Foods can be ranked by the net calorific gain earned from collecting and processing them for consumption. High ranked items (e.g. many kinds of fruit) generally have low collecting and processing costs; low ranked items (e.g. hard-surfaced seeds and nuts, tough or toxic roots) have high ones.
- Foragers will always collect the highest ranked prey on encounter. Lower ranked items will be added to the diet in descending order as the abundance of higher ranked prey declines, but dropped in reverse order if the latter are found more frequently.
- In any complex environment, foragers will always favour the habitat (i.e. patch) where return rates relative to *all* foraging costs – search *plus* collecting *plus* processing – are highest.

We refer to the best of these locations as 'sweet spots' (cf. Elston 1992). If return rates in these locations fall, foragers should either add lower ranked prey to their diets or move to a patch offering higher returns, depending on the cost of relocation.

- Diet breadth and patch choice may be complicated by conflicts of interest among foraging group members, especially between men and women (Hawkes and Bliege Bird 2002). Women's reproductive success depends on the procurement of a steady, day-to-day nutrient stream for themselves and their children. In middle and low latitude situations, this leads them to favour localities and resources offering high mean returns, low risk of procurement failure and low variance in daily return rates. Men's fitness depends on access to women. In those same situations, they commonly defer to women's choice of residential site location (e.g. Zeanah 2004). We assume this was so in Pleistocene Sahul as well.

Colonisation East of Sunda: A Simple Scenario

We envisage passage across Wallacea and into Sahul in terms of two patch types, 'coastal' and 'interior'. We assume that foraging options in both situations were similar to those reported historically; also that they were acted upon in similar ways. In coastal situations, men's options included terrestrial hunting and near-shore and pelagic fishing; women's were small game and plant collecting, littoral and estuarine shellfish gathering, and near-shore fishing. Given present day species distributions, littoral and marine resources were probably similar all along the Sunda-Bismarcks arc, so that foraging strategies once developed provided a familiar constant in assessing the costs of relocation. The same probably was true with respect to plant foods (Golson 1971).

As indicated above, we assume that declines in women's foraging return rates were the primary catalyst for relocation. Reduced encounter rates for large marine bivalves may have been an especially critical factor for movement within Wallacea. Some taxa, notably tridacnids, offer very high post-encounter returns (some $>10^4$ kcal/hr), making them especially attractive targets (Bird and Bliege Bird 1997). They are also highly susceptible to over-predation due to their slow growth rates, low densities, intertidal and shallow sub-tidal distribution, large sizes and tendency to aggregate (Lucas 1994). If high ranked but highly vulnerable resources like these were important for humans moving across Wallacea and along Sahulian coastlines, then even relatively small, predation-driven reductions in encounter rates should often have prompted relocation to previously unexploited patches.

Inter-site movement may have been fairly rapid. If women operated as central place foragers over distances of up to 10 km from their residential bases (a commonly reported ethnographic pattern), and if it required no more than a decade to reduce the encounter rates from high ranked prey within each site 'catchment' to the point that shifting to an unexploited locality made good economic sense, then the entire Sunda-Bismarcks could have been crossed in 2000 years. If foragers targeted only those catchments yielding above-average return rates, bypassing 'less-sweet' spots in the process, or if key resources were depleted more quickly than just suggested, the crossing would have been faster. Access to marine watercraft would have been crucial to this process, reducing the cost of inter-patch movements and increasing their frequency and scale. The depauperate nature of island faunas, particularly in eastern Wallacea and on smaller

islands in general, would have limited terrestrial foraging options in these situations, and so accelerated the inter-island relocation process even further. The model does not assume constant eastward movement: the next best available patch might have been in any direction, or in the interior on larger islands. Such 'digressions' notwithstanding, passage along the entire 4500 km-long northern arc could probably have been accomplished well within a millennium.

In Sahul the archaeological data suggest continued use of the coasts, along the north into the Bismarck Archipelago and south along the Western Australian littoral. Use of the east coast is less certain (see below) and in all cases much evidence must now be submerged. Movement to the interior of Sahul evidently began shortly after initial landfall, again driven mainly by foraging-related trade-offs. Perennial rivers and streams offered particularly attractive avenues of advance, providing reliable sources of water and access to broad resource arrays along the ecotones they created, and facilitating the maintenance of social networks crucial to demographic success. We imagine potential inland movement up major rivers on both the north and south sides of the New Guinea Highlands and southeast into the Carpentaria, Lake Eyre and Murray-Darling Basins (Figure 1). Foraging options in these interior situations were broadly similar to those along the coast minus the littoral and marine components: for men, mainly hunting and fishing; for women, small game, plant collecting and fishing. Specific opportunities changed as groups relocated, but we assume that new high ranked resources were identified as such and added to diets as they were encountered.

Rates of movement may have been determined to a significant degree by the impact of fire on resource availability. Natural fires have been important across much of Sahul for millions of years – in the time since European arrival affecting 5-15% of Australia annually (Lynch *et al.* 2007). Patches burned in the preceding 1-4 years are often very attractive to hunter-gatherers. High ranked fruit- and geophyte-producing species frequently cover many parts of these areas at high densities; large animals drawn by emergent grasses and forbs typically congregate there as well (e.g. Latz 1995; Russell-Smith *et al.* 1997). But as revegetation proceeds, these patches become less appealing; travel and search within them are progressively more difficult and high ranked plant resources are gradually crowded out by less useful taxa. Where inter-patch variance in return rates was high and high ranked prey in the highest ranked patches were depleted rapidly, frequent relocation to more productive patches would have been a common pattern.

Foragers also set fires themselves and the resulting subsistence benefits have long been recognised (see Bliege Bird *et al.* 2008 for a recent example). However, once fired and harvested, burned areas are of limited utility to foragers until rain prompts revegetation, a process that might not begin for several months, sometimes longer. In the early stages of continental colonisation, foragers relying on their own fires are likely to have moved as soon as the immediate benefits of burning had been achieved, often within days, at most within weeks.

Impact of Climate Change

Ethnographically known hunter-gatherer populations have grown at annual rates as high as 1-3% (Pennington 2001). Hypothetically

speaking, colonising groups moving into unoccupied Sahul might also have grown this quickly, thus doubling in size every 25-75 years. At these rates, their numbers would have equalled those estimated for proto-historic Australia alone (0.3-1.0 million) within 300-1000 years after landing, and overshot the maximum estimate for Australia-New Guinea combined (3-4 million) within 400-1200 years. As this process unfolded, the best habitats would have filled and a broader range of progressively poorer ones would have been occupied. Opportunities to move in reaction to high ranked resource depletion would have been reduced; diet breadth continent-wide would have increased in tandem with a steady decline in nutrient return rates – all in little more than a millennium, if that. As we will see, this did not happen.

Instead, this hypothetical progression was almost certainly disrupted by the frequent, high amplitude climate changes characteristic of Marine Isotope Stage 3 (MIS-3, 28-59 ky BP) (Figure 2). Details remain uncertain but it seems likely that the first 15-20,000 years of continental occupation were marked by sharp, intra-decadal through millennial-scale fluctuations in temperature and precipitation, superimposed on a longer-term trend toward cooler, drier conditions (Burns *et al.* 2003; Ditlevsen *et al.* 1996; Dürkop *et al.* 2008; Hesse *et al.* 2004; Hope *et al.* 2004; Mooney *et al.* 2011; Prentice *et al.* 2005; Wang *et al.* 2001; Williams *et al.* 2009). Mean intra-Sahul temperatures, lower than those of today, varied across a 1-2°C range near sea level in the north and at values $\geq 5^\circ\text{C}$ at higher latitudes and elevations. Warmer conditions across all time scales provoked relatively widespread northern monsoons; cooler times saw that pattern reversed. Precipitation further south varied with the strength and location of mid-latitude westerlies. El Niño events, marked today by 0.2-1.5°C increases in surface air temperatures and significant reductions in rainfall across New Guinea and much of Australia, generally at intervals of 3-5 years (Chiang 2009), created additional complexity. Atmospheric CO₂ levels (lower than at present throughout MIS-3) were relatively higher in warm periods and lower in cool ones, with parallel implications for biotic productivity (Ahn and Brook 2008). As a function of the temperature changes, sea levels repeatedly rose and fell by 20 m or more, alternately flooding and exposing large parts of the continental shelf, again at relatively frequent intervals (Siddall *et al.* 2003).

Across most of Sahul, human reactions to these changes should have varied on a continuum determined primarily by shifts in precipitation. Changes in temperature were important at higher latitudes and elevations and in the continental core. Cool/dry spells, which generally reduced resource availability, prompted increases in diet breadth and retreats to well-watered locations. Lower human population growth rates were associated with these intervals; regional population declines were common, local extinctions not unusual. Warm/wet conditions, which typically provoked widespread resource 'flushes,' had the opposite effects: immediate reductions in diet breadth and relocation to exploit the flushes. Depending on the length of time over which 'good' conditions prevailed, human populations may have grown and spread to progressively lower ranked patches, then retreated and fell as conditions deteriorated.

Patch Choice Implications

We assume that terrestrial patch rank was determined primarily by the availability of freshwater, as measured by the volume and

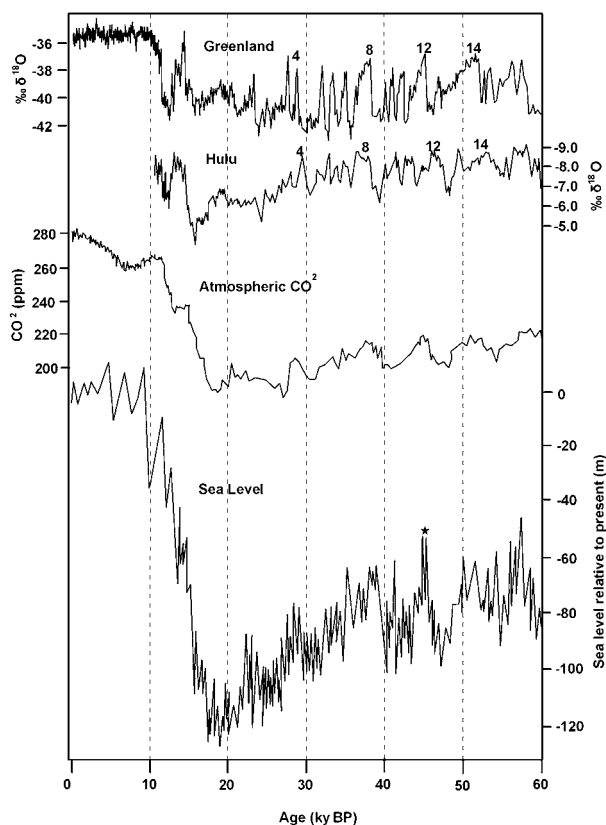


Figure 2 Palaeoenvironmental data, Marine Isotope Stages 1-3. Greenland (GISP2) and Hulu (South China) oxygen isotope curves after Weninger and Joris (2008:Figure 1), atmospheric CO₂ curve after Ahn and Brook (2008:Figure 1), sea-level curve after Siddall *et al.* (2003:Figure 4) – all simplified relative to original sources. Numbered points 4, 8, 12, 14 refer to Dansgaard-Oeschger Events; starred peak on sea-level curve indicates D-O Event 12. Marine Isotope Stage boundaries: 1 = present-11 ky BP, 2 = 11-28 ky BP and 3 = 28-59 ky BP.

reliability of precipitation and/or local stream flow, and by local temperature through its effect on resource productivity. Both have been shown to be broadly accurate predictors of potential foraging returns and related hunter-gatherer population densities (Binford 2001; Birdsell 1953). These considerations lead us to expect that river basins contained the highest ranked terrestrial patches, particularly along their lower reaches, where stream flow was generally heaviest and most reliable. Those at lower latitudes were further favoured by higher temperatures. Most of the arid zone was low ranked as a function of sparse, infrequent, unpredictable rainfall and the absence of perennial rivers. Rainforest may also have been low ranked (but see below). All other terrestrial patches were ranked intermediately, scaled positively by the availability of water, negatively by latitude and elevation. We expect that absolute returns available to foragers in any given patch varied with local human population size and diachronic variation in climate – especially rainfall, and did so at several time scales, notably intra-decadal through centennial. We also expect that relative patch rank was broadly persistent – the lower ends of larger river basins always highest ranked, most of the arid zone always lowest.

Coastal patch rank varied with shoreline morphology and the speed and direction of sea level change (Beaton 1995). Prey types associated with steeply sloping shorelines and rocky substrates redistributed themselves quickly in response to changes in sea-level, but the narrowness of the intertidal zone meant that high

ranked items in these situations were relatively few in number and subject to rapid depletion by consumers. Prey types typical of broad, shallow coastal flats and estuaries, though locally abundant and relatively resistant to predation pressure, were devastated over wide areas by even minor rises but especially falls in sea-level, depending on the speed with which those changes occurred (Chappell 1993). Holocene data suggest that favourable sedimentary substrates and the abundant prey populations they support generally recover only on multi-century timescales, even after sea-level has stabilised (Beaton 1985). We expect that littoral patches along precipitous coastlines were high ranked despite frequent changes in sea-level, but that associated human occupation was highly ephemeral due to predation-related resource depression. Shallow tidal flats and estuaries of the sort that supported large human populations in late Holocene times were high ranked when present, but rare and short-lived throughout most of MIS-3 due to the frequency and amplitude of sea-level change and the time required for productive habitats to be re-established.

Archaeological Assessment

Space limitations preclude a detailed review of the relevant archaeological record, but we offer some general observations on aspects critical to our argument.

Crossing Wallacea

Movement east of Sunda probably began 46-47 ky BP, coincident with a 30-40 m rise in sea-level (Dansgaard-Oeschger Event 12, Figure 2), that may have stabilised at its peak long enough to create diverse and attractive coastal habitats all across Wallacea (Lambeck and Chappell 2001). The impulse for movement may have come from the build-up of human populations on the Asian mainland reflected in mitochondrial DNA (Atkinson *et al.* 2008), tentatively dated at ca 52 ky BP. Recent reassessment of the basis for that date suggests the build-up may have occurred later in time, closer to but still in advance of initial movement across Wallacea (Endicott *et al.* 2009). Whenever it began, this pattern of population growth should have been associated with a decline in the availability of high ranked resources. That decline may be reflected in the remains of toxic aroids (*Alocasia longiloba*) and nuts (*Pangium edule*) in deposits at Niah Cave (Borneo) dated 40-48 ky BP (Barton and Paz 2007). These items require extensive processing before they are edible and are thus low ranked prey. Their use at Niah may imply that overall foraging return rates there and elsewhere in Sunda were low at this time. If so, then movement into unoccupied areas to the east, where higher ranked prey were more abundant, should have been favoured.

We prefer Birdsell's (1977) northern route – Sulawesi to the Bird's Head – as the primary axis of migration, mainly on grounds of island intervisibility from Sunda to the Bismarck Archipelago (Irwin 1992). The earliest southwest Pacific evidence of crossings where the target was initially well beyond sight dates more than 10,000 yrs later (New Britain-Buka, total crossing length 140 km, dated ca 34 ky BP; Wickler and Spriggs 1988). The last crossing on Birdsell's southern route – Timor to Australia – may have been as much as 200 km wide in the period of interest here, meaning that travellers would have been beyond sight of land in either direction for much of the voyage. We suspect that intervisibility was a significant determinant of relocation early in

the migration process, and that the Timor route was rarely (if at all) used at that time.

Genetic data indicate that, after human populations were established on Sahul, contact to the west, across Wallacea, was suspended until as recently as the mid-Holocene (e.g. Friedlaender *et al.* 2007; Hudjashov *et al.* 2007; Rasmussen *et al.* 2011). This may have been related to the steep fall in sea-levels (-60 m to -120 m) that began ca 37 ky BP and the subsequent, nearly continuous rise from the Last Glacial Maximum (LGM) lows to modern levels after 10 ky BP (Figure 2). Both

processes would have impeded the development of productive sedimentary substrates in coastal settings throughout the region (Beaton 1995). If these habitats were as important as suggested by theoretical considerations, late Holocene archaeological data and ethnographic records, their absence should have contributed to declines in human population sizes and reductions in the frequency and scale of inter-island contact all across Wallacea. cursory examination of island Southeast Asian archaeological sequences is consistent with this proposition (e.g. Bellwood 1998; O'Connor 2007).

Table 1 Sites in Wallacea, Sahul and the Bismarck Archipelago dated ≥ 40 k solar years and containing remains of *Homo sapiens* or archaeological materials produced by *H. sapiens*. Settings: A=arid zone, C=coastal, HE=high elevation, HL=high latitude, R=riverine, RL=riverine or lacustrine and RF=rainforest. Dates listed are the oldest reliable ages assigned to these materials (Allen and O'Connell 2003; O'Connell and Allen 2004). Radiocarbon dates are reported in both C^{14} and solar years, the latter estimated by reference to the IntCal09 calibration program (Reimer *et al.* 2009). Dates derived by other methods (mainly luminescence) are the equivalent of solar years. Sites are grouped by latitudinal zone: Far North=Wallacea, Bismarck Archipelago and New Guinea; Mid-North, Mid-South=northern and southern halves of mainland Australia, respectively; Far South=Tasmania. Locations marked (*) include more than one site dated ≥ 40 ky BP.

Region/Site	Location	Setting	Earliest archaeological dates ($\times 10^3$ yr BP)			References
			C^{14} 1 σ range	C^{14} calibrated 2 σ range (median)	Other	
Wallacea						
Jerimalai	Timor	C	38.3 \pm 0.6	41.9-43.7 (42.7)		O'Connor 2007; O'Connor <i>et al.</i> 2010
Lene Hara	Timor	C	38.2 \pm 0.6	41.8-43.6 (42.7)		O'Connor <i>et al.</i> 2002, 2010
Sahul Far North						
Bobongara	NE New Guinea	C			$\geq 44.5 \pm 0.7$	Chappell <i>et al.</i> 1996
Buang Merabak	New Ireland	C	39.6 \pm 0.6	42.8-44.6 (43.7)		Leavesley 2004
* Ivane Valley (Kosipe)	SE New Guinea	HE/RF	42.0 \pm 1.6	43.0-48.5 (45.5)		Summerhayes <i>et al.</i> 2010
Kupona na Dari	New Britain	C			35.0-45.0	Torrence <i>et al.</i> 2004
Matenkupkum	New Ireland	C	35.4 \pm 0.4	39.4-41.4 (40.6)		Allen and Gosden 1991
Yambon	New Britain	RF	35.6 \pm 0.5	39.4-41.7 (40.7)		Pavlidis and Gosden 1994
Sahul Mid-North						
Carpenters Gap	Kimberley	R	40.6 \pm 0.8	43.1-45.6 (44.4)		Fifield <i>et al.</i> 2001
Djadjiling	Pilbara	R	35.4 \pm 0.5	39.4-41.7 (40.7)		Law <i>et al.</i> 2010
GRE 8	Carpentaria	R	37.1 \pm 3.0	35.3-46.1 (41.4)		Slack 2008
Jansz	Cape Range	C	35.2 \pm 0.5	39.0-41.3 (40.3)		Przywolnik 2005
Mandu Mandu	Cape Range	C	34.2 \pm 1.0	36.8-41.2 (39.1)		Morse 1993
Nawarla Gabarnmang	Arnhem Land	R	41.4 \pm 1.5	43.4-47.0 (45.2)		David <i>et al.</i> 2011
Ngarrabullgen	Atherton	R	35.2 \pm 0.7	38.8-41.6 (40.2)		David <i>et al.</i> 2007
Riwi	Kimberley	R	41.3 \pm 1.0	43.3-46.3 (44.9)		Balme 2000
Parnkupirti	Great Sandy Desert	A/RL			45.0-50.0	Veth <i>et al.</i> 2009
Sahul Mid-South						
Allens Cave	Nullarbor Plain	A			39.8 \pm 3.1	Roberts <i>et al.</i> 1996; Turney <i>et al.</i> 2001a
Devils Lair	SW Australia	C	41.4 \pm 1.3	42.8-47.2 (45.0)	44.4 \pm 2.1	Turney <i>et al.</i> 2001b
* Menindee	Darling Basin	RL	41.5 \pm 1.3	42.9-47.3 (45.0)	43.1 \pm 1.5	Cupper and Duncan 2006
Upper Swan	SW Australia	R	38.5 \pm 2.0	40.2-46.9 (43.6)		Pearce and Barbetti 1981
* Willandra	Murray Basin	RL				
	Earliest human remains				40.9 \pm 4.5	Olley <i>et al.</i> 2006
	Earliest stone artefacts		38.1 \pm 1.1	41.1-44.3 (42.6)	45.4 \pm 2.5	Bowler <i>et al.</i> 2003
Sahul Far South						
Warreen	SW Tasmania	HL	34.8 \pm 0.5	38.8-41.0 (39.9)		Allen 1996

Site Distribution and Patch Choice

Table 1 lists the 23 Sahul, east Wallacean and Bismarcks archaeological sites and site complexes reliably dated 40–46 ky BP; Figure 1 shows their geographic distribution relative to rainforest, the arid zone, certain upland areas and larger river basins, and the -60 m continental shoreline. The earliest locations, dated 44–46 ky BP (Carpenters Gap, Nawarla Gabarnmang and Riwi in the northwest, Bobongara and Ivane Valley in the northeast, Devils Lair in the southwest, and Menindee and Willandra in the southeast), are either at the extremities of the continent or deep in relatively well-watered parts of the interior, consistent with expectations about rapid, long-distance movement during initial colonisation.

Most sites listed in Table 1 are in or near what we suspect were high ranked patches. Eight were within 10 km of the coast at the times they were first occupied, with Devils Lair ca 20 km inland. Offshore profiles near all are steep, suggesting the presence of rocky shoreline habitats and resources. Three are in the lower reaches of large river basins: Menindee and Willandra in the Murray-Darling and the Swan River site. The first two of these were well-watered 40–45 ky BP; both have substantial archaeological records dating from this period. Six sites are located in the upper reaches of medium/large river drainages: Carpenters Gap and Riwi in the Fitzroy-Meda, Djadjiling in the Fortescue, GRE 8 and Ngarrabullgen in the Carpentarian, and Nawarla Gabarnmang in the Katherine.

Three are in what would have been cold and/or perennially wet settings. The Ivane Valley sites (four dated ≥ 40 ky BP) were located on the grassland/subalpine forest ecotone at 2000 m asl. Archaeological data point to an intermittent human presence through the latter part of MIS-3; pollen and charcoal suggest fire-related manipulation of the surrounding habitat during the early period of occupation (Hope 2009; Summerhayes *et al.* 2010). Yombon, in the heavily forested interior of New Britain, roughly a day's walk from the coast, was visited about 40 ky BP, primarily in connection with the use of a high-quality tool stone source (Pavlidis and Gosden 1994). Habitat manipulation by fire may have been practised there as well (Lentfer *et al.* 2010). High-latitude southwest Tasmania was also occupied at about 40 ky BP, shortly after the Bassian land bridge opened, with small hunting parties targeting medium-sized *Macropus rufogriseus* ecologically tethered to nearby edaphic grasslands (Cosgrove and Allen 2001). This pattern persisted in the region through the LGM, then disappeared as temperate rainforest reclaimed the area.

Parnkupirti, adjacent to Lake Gregory on the edge of the Great Sandy Desert, was occupied during a lake full period before 37 ky BP and probably before 40 ky BP (Veth *et al.* 2009). Allens Cave, an early site in the arid zone away from the coast and major rivers, also dates to about 40 ky BP (Roberts *et al.* 1996), when it was tens of kilometres or more inland. The earliest date for the arid core of the continent comes from Puritjarra, west of the MacDonnell Ranges, pegged on both calibrated C^{14} and OSL at about 35 ky BP (Smith 2006). Widespread occupation of the arid zone dates no earlier than the mid-Holocene (Smith *et al.* 2008).

The Ivane Valley dates are unexpected from the perspective of our model. Movement into the mountainous interior of New Guinea probably depended on the availability of edible plants and animals in both lowland rainforest and the subalpine forests

above. Rainforest may have been low ranked due to a paucity of high yield, easily processed foods (Cosgrove *et al.* 2007; Sillitoe 2002), but a strong contrary view has recently been argued (Denham 2007; Denham *et al.* 2009; Roscoe 2005). Whatever the ranking of the closed forests, modern New Guinean hunting parties routinely target the shrub-rich and alpine grasslands above the tree line. Those grasslands were far more extensive in the past than today, at times covering an altitudinal zone up to 1400 m wide (Hope and Hope 1976). Late Pleistocene faunas included now extinct diprotodontids and macropods, and a range of other mammals, such as giant rats, bandicoots, anteaters, wallabies, cuscus, possums and tree kangaroos (Hope and Hope 1976; Hope *et al.* 1993).

Much reliance has been placed on the importance of pandanus along the tree line ecotone, but Denham (2007) suggested that its potential has been overstated, begging questions about the availability of carbohydrates in this habitat. Recent experimentation shows that a tree fern tentatively identified as *Cyathea muelleri*, common in subalpine grasslands, is edible. It is 'fairly easy' to process and yields 5–10 kg of starch per plant (Matt Prebble and Geoff Hope pers. comm. 2011). Such a staple could have elevated these grasslands to a highly ranked habitat. Ethnographic trade routes frequently run both across and along the grasslands, suggesting that an easily negotiated route along the mountainous central cordillera of New Guinea was available to first colonists. In short, the Ivane dates may be less surprising than initially thought.

Other distributional data that challenge our model include the low numbers of early sites so far reported from the Carpentarian-Eyre Basin-Murray/Darling corridor and their almost complete absence along the well-watered eastern slopes of the Great Dividing Range and adjacent lowlands (compare the Pleistocene site map in Langley *et al.* 2011 with the Holocene map in Ulm 2011). This might mean that post-depositional processes in the drainages have covered or eroded the evidence, or that research has been insufficient to identify it. The latter explanation is unlikely east of the Great Dividing Range, given the development large parts of that landscape have witnessed over the last century.

Subsistence and Diet Breadth

Prehistoric diet breadth can be assessed by comparing evidence of resource exploitation recovered archaeologically with post-encounter return rates established by ethnographic observation or controlled experiment. Tools used in collecting and processing offer additional information, in that more complex forms generally imply broader diets (Hawkes and O'Connell 1992). Ethnographic data from arid and coastal Australia show that resources targeted by women yield returns in the 10^2 – 10^4 kcal/hr range (Bird and Bliege Bird 1997; Bird *et al.* 2009). Rates in this range were probably typical for women continent-wide at the time of European contact. Items yielding <1000 kcal/hr were low ranked; those yielding >1000 kcal/hr were intermediate or high ranked.

Pleistocene-age archaeofaunal assemblages generally include a narrow range of taxa, most of intermediate or high rank. The Willandra complex offers the largest inland example of these patterns (Johnston 1993). Pre-40 ky BP sites are concentrated along the shorelines of two now-dry lake basins. Most date from

the period 40-42 ky BP, a time of transition from persistently lake full to seasonally drier conditions. All are marked by the presence of small, shallow middens. Associated food remains are mainly those of fish and shellfish but terrestrial animals are also represented. Deposits made up entirely of one prey taxon – either mussels (*Velesunio ambiguus*) or perch (*Macquaria ambigua*) – are not uncommon. *Velesunio* today occurs in densely populated beds (up to 100 individuals/m²) in still or slow-moving waters. Intertidal taxa of about the same size and found at similar densities are harvested by hand today at rates <3000 kcal/hr (e.g. Bird and Bliege Bird 1997; Thomas 2007). The size distributions and numbers of *Macquaria* (mean 20-30 cm in length, estimated weights up to 15 kg; up to 500 individuals/midden) probably indicate selective spearing or harvesting by hand, where fish were concentrated in seasonally drying, highly saline pools, though netting is also a possible capture technique (Balme 1983; cf. Bowler 1998). Return rates reported for mass capture of fish by traditional foragers elsewhere are in the 10³-10⁵ kcal/hr range (Ugan 2005). Marsupials found at these sites include hare-wallaby, rat-kangaroo, bandicoot and native cat (Walshe 1998), all commonly taken by fire ethnographically. Estimated return rates for rabbits and hares taken in communal drives by Native Americans in the arid western US are in the range 600-4300 kcal/hr/driving party member (Ugan 2005).

Similar patterns are reported elsewhere. As indicated above, in southwest Tasmania wallabies were taken with what investigators reckon were relatively high short-term returns (Cosgrove and Allen 2001). In New Ireland bats dominate the early assemblages at Buang Merabak and, to the degree they were susceptible to capture *en masse*, may also have yielded high short-term returns (Leavesley 2004). In both cases, once the immediate benefits were gained, foragers' best moves may have been to shift another high ranked patch.

Since plant residues are either not preserved or remain unidentified in the absence of trace fossil analysis they are rarely reported archaeologically. Target plant taxa should have included easily handled fruit and geophytes, some of which yield low-variance returns >3000 kcal/hr and respond positively to habitat disturbance by fire (e.g. Bird *et al.* 2009). The presence of macroscopic stems of the geophyte *Cyperus* (post-encounter returns >4000 kcal/hr; O'Connell and Hawkes 1981) in deposits dated ~44 ky BP at Carpenters Gap (McConnell and O'Connor 1997) is consistent with this expectation. Charred remains of *Pandanus* nuts have been recovered from the early Ivane Valley sites; starch grains found on stone tools reflect the processing of yams (*Dioscorea* sp.) (Summerhayes *et al.* 2010). Return rates for the particular species represented have not yet been established. Importantly, the distinctive grinding and pounding tools required to process hard seeds and tough roots are absent from Sahul sites dated ≥40 ky BP, and uncommon anywhere in the region until <5 ky BP, suggesting that such resources were rarely exploited until then, probably because returns from doing so are typically <1000 kcal/hr.

Dietary data from Buang Merabak and Matenkupkum on New Ireland, and Jeremalai and Lene Hara on Timor present a more complex picture. Fish (mainly inshore species) are represented at all four locations (Gosden and Robertson 1991; Leavesley 2004; O'Connor *et al.* 2011); pelagic forms, notably tuna, are found at Buang Merabak and Jeremalai. Pre-LGM

use of shell for artefacts is well attested (Smith and Allen 1999; Szabó *et al.* 2007), including the possible manufacture of shell fish hooks essential to deep-sea angling in Matenkupkum, adjacent to Matenkupkum. Substantial investment in the manufacture and maintenance of related tackle is implied. With the tentative indication of net use in the Willandra/Darling region, they are the only evidence of complex technology known from Sahul in this time period.

Shellfish remains from these sites offer what might appear to be the best basis for challenging the model of small, highly mobile, narrow diet-oriented human populations supported by the balance of the early record. Taxa most often reported include gastropods, notably *Turbo* and *Nerita*. Large bivalves (tridacnids), predicted to have been a favoured resource, are so far reported only at Buang Merabak as refuse from the manufacture of simple cutting tools (Leavesley and Allen 1998). *Turbo* at some sites are said to be relatively large (Gosden and Robertson 1991), a possible index of infrequent predation, but the limited distribution of tridacnids and the common presence of low ranked nerites (100-1600 kcal/hr; Bird and Bliege Bird 1997) could suggest otherwise. If overall human collecting pressure was light and intermittent, as proposed by the model, then tridacnids should have been encountered and taken frequently and nerites generally ignored. The opposite pattern in midden contents might imply larger and/or less mobile human populations, higher collecting pressure and broader diets than other aspects of the early Sahul record seem to suggest.

However, prey representation at forager base camps is determined not only by acquisition patterns but also by the economics of resource processing and transport. Broadly speaking, the probability of carrying a prey item intact to a central place varies directly with processing costs and inversely with the increase in load utility gained by discarding heavy, low value parts at the point of acquisition (Metcalf and Barlow 1992). Coastal processing (and sometimes consuming) stations of Pleistocene age – the equivalent of Meehan's (1982) 'dinnertime camps' – are likely to be both ephemeral and currently mostly submerged. Ethnographic research among southwest Pacific shellfish collectors provides excellent examples of the trade-offs involved in differential discard and their archaeological consequences (Bird and Bliege Bird 2000; Bird *et al.* 2004; Thomas 2007). As in these recent cases, the high proportions of nerites and relatively limited representation of tridacnids in early coastal sites may be more a reflection of processing and transport considerations than they are an accurate, comprehensive measure of local forager diets.

Overall, indications of pelagic fishing on oceanic islands apart, we see no compelling evidence of broad diets in the Sahul archaeological record before the Holocene.

Site Structure and Mobility

The sizes of most Pleistocene sites, the rates of refuse deposition within them and the nature of prey represented are all consistent with infrequent, short-term occupation by small, highly mobile human groups. Well-known examples are reported from the Willandra/Darling region and southwest Tasmania. Open-air middens in the former are all small, seldom covering more than 10 m² or measuring more than a few centimetres in thickness. Their sizes and the limited nature of food items they contain

suggest that most were deposited within a few days by small numbers of individuals (Allen 1998). Late Pleistocene southwest Tasmanian sites display a similar pattern: small sizes and very slow rates of refuse deposition (Cosgrove and Allen 2001) indicating brief, infrequent occupation by small groups.

Discussion

Archaeological data, briefly reviewed, are consistent with the proposition that Wallacea and Sahul were deliberately colonised by highly mobile, Southeast Asian-derived human populations practising economies based on the exploitation of intermediate and high ranked plant and animal foods. Migration was provoked by demographic pressure on Sunda and facilitated by the relatively favourable climatic and environmental conditions associated with the onset of Dansgaard-Oeschger Event 12, conditions analogous to those that propelled 'anatomically modern' human populations into western Eurasia at about the same time (Müller *et al.* 2010). Despite their inherent capacity for growth, Sahul populations subsequently remained surprisingly small and spatially concentrated in persistent 'sweet' spots, enjoying occasional growth spurts and expanding geographically, but always retreating to the same or similar refuges, mainly along steeply sloping coastlines, in better-watered parts of the continental interior and on the islands of the Bismarck Archipelago. Genetic data indicate that, after Sahul populations were established, contact across Wallacea was limited (if not terminated entirely) for as long as 30,000 years. They also indicate that northern and southern Sahul populations separated soon after arrival and had little subsequent contact (Friedlaender *et al.* 2007; Hudjashov *et al.* 2007; van Holst Pellekaan 2011). The same may prove to have been true of west coast versus east-central Australian populations. Patterns in archaeological site structure and assemblage composition point to high mobility in each of the regions occupied. With limited exceptions, diets and technologies remained narrow and relatively simple for many millennia. Historically known patterns in economy, technology and demography emerged only in the Holocene.

We argue that the Pleistocene pattern is primarily the product of short-term climatic instability (see also Davidson 1990; Richerson *et al.* 2001). Analysts have long remarked on the effect of the LGM on continental demography and economy. We recognise its significance but it cannot account for the long period of low human population size that preceded it, or for the slow recovery that followed. Part of the explanation surely involves the relatively low temperature, precipitation and CO₂ levels characteristic of MIS-3, but intra-decadal through centennial-scale climatic fluctuations must also have been implicated, given the speeds with which forager populations can grow. Though evident in climatic proxies elsewhere (e.g. Burns *et al.* 2003; Ditlevsen *et al.* 1996), such fluctuations have not yet been identified unambiguously in Sahul other than as a function of ENSO (e.g. Turney *et al.* 2004). Nevertheless, the strength and pervasiveness of global climatic teleconnections point to their likely importance there as well (e.g. Durkop *et al.* 2008; see also Kanner *et al.* 2012). Their collective effect on potential food and water sources critical to Indigenous foragers should have been enormous: high levels of variation in availability at decadal through centennial time scales, and significant shifts in the spatial distribution of potential prey and in the composition

of biotic communities of which they were a part. The lack of topographic relief over much of the continent meant that these impacts were similar in form and magnitude over very wide areas and thus difficult to avoid, even through relatively long-distance relocation.

Developing and testing our model will require more information on climate change at several temporal scales, its effects on resource availability at those same scales, the costs and benefits of exploiting various resources, and the archaeological consequences of doing so. The prospects for fully marshalling that information may be limited, but even partial data should allow critical tests. In any case, the inference that Pleistocene human populations were small and patchily distributed across Sahul is undeniable. Whatever the explanation, this observation has at least two important implications.

The Effect of Human Arrival on Regional Biota

Pollen and charcoal data show that past changes in Sahul vegetation were often associated with sharp increases in fire frequency (Mooney *et al.* 2010). Noting that fire was widely used by Sahul indigenes for resource management and extraction at the time of European contact, many have argued that these practices began with initial colonisation and immediately led to one or another of the changes indicated by the pollen and charcoal records (e.g. Kershaw 1986; Singh *et al.* 1981; Wang *et al.* 1999). Other environmental proxies are seen to support a similar inference (Miller *et al.* 2005). A parallel argument attributes the late Pleistocene disappearance of many species of large-bodied animals (megafauna) to the arrival of humans, either through their fire-related effect on vegetation or by direct predation (Miller *et al.* 2005; Roberts *et al.* 2001).

The idea that early human colonists were responsible for major changes in Sahul fire and vegetation regimes should be rejected. Analyses reported over the last decade increasingly point to climate change as the main catalyst (e.g. Bowman 2002; Haberle and Ledru 2001; Mooney *et al.* 2010; Murphy *et al.* 2012). Archaeological evidence of early human population size and distribution is consistent with this assessment. The impact of human colonisers using fire on Sahul biota is likely to have been both small-scale and short-term, similar to, but much less extensive than that documented historically, and usually below the threshold of visibility in pollen records.

The seemingly eternal megafaunal extinctions debate currently centres on the six large-bodied marsupials and a giant flightless bird that were present when humans arrived but that disappeared sometime thereafter (Field *et al.* 2008; Roberts *et al.* 2001). Eliminating human-induced habitat modification leaves climate-related environmental change and human predation as the principal competing explanations. Commentators favouring predation reject any role for climate, despite clear indications of environmental instability throughout MIS-3. Although there is no direct archaeological evidence that humans hunted members of these genera, 'rapid overkill' is, for many, the preferred model. Essential to this argument are the assumptions that human populations grew at sustained rates >1% annually and that they were widely distributed across the continent. A well-known simulation model showing that rapid, predation-driven extinction was inevitable (Brook and Bowman 2004) stipulated annual human population growth rates of 1-2.5%. At these rates, a founding

population of 500 individuals grows to more than one million in 300-800 years. The archaeological record falsifies this scenario and the inferences about overkill it is seen to support. Megafauna were probably hunted or scavenged whenever possible, but climate-related habitat change, range reduction and demographic isolation contributed more significantly to the extinction process (Field *et al.* 2008; see also Koch and Barnosky 2006).

Simple Tools

Explanations for the simplicity of Pleistocene Sahul tool-kits have long cited a supposed relationship between human cognitive capacity and technological complexity, the implication being that, Sahul indigenes lacked the intelligence to develop more complex technologies (cf. White 1977). Proponents of 'cultural transmission' models have recently modified this theme, arguing that while such abilities were clearly present in ancestral African and South Asian populations, critical ideas were lost on route to Sahul due to a series of demographic 'bottlenecks' that ultimately reduced the technological repertoire of early colonisers (Mellars 2006). The maintenance of complex seafaring and pelagic fishing technologies in the Bismarcks at least through the end of MIS-3 (O'Connell *et al.* 2010) in the context of very low population densities (Summerhayes 2007) belies both propositions. It also raises an obvious question: why is Pleistocene Sahul technology simple in some settings but complex in others?

A possible answer lies in the correlation between diet breadth and technological complexity (Barlow 2002; Bettinger *et al.* 2006; Hawkes and O'Connell 1992; Ugan *et al.* 2003). By definition, foragers pursuing relatively high ranked prey spend most of their time on search and relatively little on collecting and processing. Limited handling times imply simple technologies and few potential gains to be made from improving their respective efficiencies relative to what might be derived from increasing encounter rates for high ranked prey (i.e. improving search efficiency). But as diets broaden the payoff matrix changes: more time spent handling increases the incentive for improving handling efficiency. To the degree that exploiting a broader, more diverse array of resources increases the complexity of achieving such efficiencies, technological diversity – specifically that related to handling – should increase accordingly.

If human populations remained low, and diet breadth in terrestrial settings narrow due to severe climatic and environmental constraints, then technology should also have remained relatively simple, as seems to have generally been the case throughout mainland Sahul, at least as far as lithics are concerned. On the other hand, recurrent trends toward cooler, drier conditions should not only have forced population declines and retreats to persistent sweet spots but also favoured greater diet breadth in those same locations. Evidence of intermittent, low intensity, high cost tree and grass seed use in various parts of the continent during MIS-2 and 3 (Gorecki *et al.* 1997) may be consistent with this expectation. The occasional early Holocene appearance of backed microliths in advance of their widespread late Holocene distributions (Hiscock and Attenbrow 1998; Slack *et al.* 2004) might also be reflecting temporary and localised expansions of diet.

Seafaring and pelagic fishing seem likely to have been high cost, high risk, but not always high return, enterprises. Complex technologies were essential to their successful pursuit and may

have been mandated in the Bismarcks by the relative lack of terrestrial foraging opportunities there (Allen 2000). That said, the logic of the patch choice model leads us to wonder why, under these circumstances, some members of these island populations did not relocate instead of maintaining these technologies, say to the mainland, if marginal returns associated with simpler tool kits were better there. It may be that pelagic fishing gear was less expensive to make and maintain than we imagine relative to the returns available from deploying it, or that fishing was favoured mainly at times when terrestrial foraging returns were climatically depressed. It may also be that pelagic fishing was practised for reasons unrelated to the goal of maximising short-term nutrient return rates, as is the case in parts of the southwest Pacific today (e.g. Bliege Bird *et al.* 2001). In any case, we suspect that both the overall simplicity of Sahul technology, and the relatively limited variation it displays through time and space, were more a function of ecological context and foragers' intellectual solutions to the problems of making a living than in any way related to the strength of cultural transmission mechanisms. Clearly this is an issue that merits further treatment elsewhere.

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ON A FAST-TRACK: HUMAN DISCOVERY, EXPLORATION AND SETTLEMENT OF SAHUL

Jon M. Erlandson

Department of Anthropology and Museum of Natural and Cultural History, University of Oregon, Eugene OR 97403, USA
jerland@uoregon.edu

Recent decades have seen the emergence of new scientific paradigms for the origins of anatomically modern humans (AMH), a series of relatively rapid migrations that took these people from Africa to the far corners of the world, and the role of coastlines, boats and fishing in facilitating such dispersals. These paradigm shifts all meet in Sunda, Sahul and western Melanesia, where archaeology and anthropological genetics are illuminating some of the earliest evidence for seafaring and maritime migrations by AMH. The exact timing, routes and adaptive diversity involved in such migrations remain to be fully documented.

O'Connell and Allen argue that the peopling of Sahul was an 'archaeologically instantaneous' process occurring between ca 46,000 and 44,000 ya. They offer a 'speculative model' that deals parsimoniously with numerous complex issues. I have no qualms about rapid coastal migrations, as coastlines offer linear migration routes, entirely at sea-level and with few geographic barriers, often with very similar marine resources over vast areas. For the Pacific Rim, Erlandson *et al.* (2007) argued that maritime skills and similarities in the ecology of kelp forest and other coastal habitats may have facilitated a rapid coastal migration and colonisation from Asia to the Americas shortly after the end of the LGM. A similar model could apply to the margins of the Indian Ocean, where mangroves, coral reefs and other nearshore ecosystems support a diverse array of similar shellfish, fish, birds and marine mammal taxa from Africa to Asia and Australia.

I find nothing in O'Connell and Allen's 'fast track' migration that is not eminently reasonable. I agree that such a colonisation process almost certainly involved relatively sophisticated watercraft and seafaring capabilities. I also agree that maritime immigrants would have spread rapidly into resource-rich interior areas. Coastal habitats are partly terrestrial, after all, and coastal peoples worldwide are well-attuned to subsistence opportunities in the adjacent interior. As O'Connell and Allen note, moreover, not all coastlines are equally productive, so those offering fewer aquatic or terrestrial resources might have been skipped over to focus on coastal sweet spots described by Bulbeck (2007) and others. O'Connell and Allen's model may overestimate the vulnerability of estuarine ecosystems to sea-level fluctuations, as intertidal organisms and communities tend by nature to be highly resilient. During a critical period (ca 50,000-35,000 BP) for their model, moreover, Pope and Terrell (2008:8) suggested that estuarine habitats were relatively extensive in South and East Asia.

O'Connell and Allen may be correct that the colonisation of Sahul occurred very rapidly, but understanding a late Pleistocene human colonisation of Sahul – as well as other Pleistocene coastal migrations – is clouded by significant problems (Erlandson 2001, 2010). First, the colonisation process took place at, near, or just beyond the effective range of ^{14}C dating,