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Palaeogeography and Voyage Modeling Indicates Early Human Colonization of Australia was Likely from Timor-Roti

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Abstract

Anatomically Modern Humans (AMHs) dispersed rapidly through island southeast Asia (Sunda and Wallacea) and into Sahul (Australia, New Guinea and the Aru Islands), before 50,000 years ago. Multiple routes have been proposed for this dispersal and all involve at least one multi-day maritime voyage approaching 100km. Here we use new regional-scale bathymetry data, palaeoenvironmental reconstruction, an assessment of vertical land movements and drift modeling to assess the potential for an initial entry into northwest Australia from southern Wallacea (Timor-Roti). From ∼70,000 until ∼10,000 years ago a chain of habitable, resource-rich islands were emergent off the coast of northwest Australia (now mostly submerged). These were visible from high points close to the coast on Timor-Roti and as close as 87km. Drift models suggest the probability of accidental arrival on these islands from Timor-Roti was low at any time. However, purposeful voyages in the summer monsoon season were very likely to be successful over 4–7 days. Genomic data suggests the colonizing population size was >72–100 individuals, thereby indicating deliberate colonization. This is arguably the most dramatic early demonstration of the advanced cognitive abilities and technological capabilities of AMHs, but one that could leave little material imprint in the archaeological record beyond the evidence that colonization occurred.

1. Introduction

By around 50,000 calendar years ago (50ka; Bulbeck, 2007; Allen and O'Connell, 2008; Hamm et al., 2016; Tobler et al., 2017) and potentially by as early as 65ka (Clarkson et al., 2017), Anatomically Modern Humans (AMHs) had rapidly dispersed through the continent of Sunda (modern island southeast Asia exposed as a single landmass due to lowered sea level) and crossed the isolated islands of Wallacea into the continent of Sahul – Australia and New Guinea, also joined during lowered sea level (Lambeck and Chappell, 2001; Williams et al., 2018). The genetic evidence suggests that Sahul was colonized from Wallacea in one 'event' loosely constrained by genetic clocks to a range consistent with the majority of the archaeological evidence for the timing of colonization (Hudjashov et al., 2007; Malaspinas et al., 2016; Tobler et al., 2017). Once established in Sahul, dispersing populations rapidly occupied the coasts and interior (O'Connell and Allen, 2015; Bird et al., 2016). The populations in northern Sahul (modern New Guinea) were isolated from those in southern Sahul (modern Australia) soon after arrival (by at least 35ka; Malaspinas et al., 2016; or much earlier, Tobler et al., 2017), and once colonization was complete gene flow between different settled regions across Sahul reduced rapidly and dramatically thereafter (Tobler et al., 2017).

The route by which AMHs traversed Wallacea and arrived in Sahul has been debated for decades. Birdsell (1977) provided the first assessment of possible routes, these being divided broadly into a 'southern route' through the Lesser Sunda island arc into northwest Australia and a 'northern route' via Sulawesi and numerous islands east into western New Guinea. Butlin (1993) recognized the role of changing sea level in controlling the distribution of land and hence island inter-visibility, target sizes and distances. An assessment of the regional bathymetry led him to conclude that the southern route, from Timor or Roti to reefs off the continental shelf of northwestern Australia that would be exposed as islands at lowered sea level (the modern 'Sahul Banks'), made the southern route the more likely. He also stressed the role of the carrying capacity of islands and the stress of demographic packing set against glacio-eustatic sea-level fluctuations as a colonizing prime mover. In order to arrive at a point from which the final water crossing to Sahul could be undertaken, a minimum of five water crossings (including across Wallace's Line) were required, even at times of lowest sea level. Crossing to Sahul by any route required at least one crossing approaching 100km, this generally being the final crossing onto Sahul itself. While knowledge of palaeoenvironments and chronologies of the occupation of Wallacea and Sahul have improved, there has been, as yet, no clear resolution of the debate (O'Connor, 2007; O'Connell and Allen, 2015; Kealy et al., 2016, 2017).

Importantly, either route requires a feat of maritime voyaging, and demonstrates that by 50ka, AMHs in Sahul shared sophisticated behavioural capacities to plan, coordinate and execute major marine voyages across open water. There is no direct evidence regarding the nature or capability of the watercraft that were used in the many marine crossings required to found a viable AMH population on Sahul. However, as the craft were most likely constructed from wood and fibre, it is not surprising that direct evidence has not survived. Indeed the fact that the crossings were made has been used as evidence that such craft must have existed (Balme, 2013). The migration demonstrates the earliest construction and use of watercraft anywhere in the world and is an important time-stamp for evidence of technological innovation, abstract thinking, planning ability, advanced cognition and complex language use (Davidson and Noble, 1992; Bulbeck, 2007; Allen and O'Connell, 2008; Balme et al., 2009; O'Connor et al., 2011).

Importantly for the likely routes from Sunda to Sahul, the earliest evidence for exploitation of marine resources by AMHs outside of Africa comes from limestone caves on both sides of the Lydekker Line from the continental Barrow Island on the Northwest Shelf of Australia (Veth et al., 2017) and the uplifted terraces of East Timor (Langley et al., 2016a). Equivalent-aged dietary molluscan remains have also been reported in other ancient limestone contexts from New Ireland (Leavesley and Chappell, 2004) and Niah Cave on Borneo (Barker, 2013). It should also be noted that the AMH population accumulated at the final crossing point also had to be large enough to then establish a genetically viable founder population in Sahul capable of survival and rapid dispersal (Moore, 2001; O'Connell et al., 2010).

While all routes into Sahul imply effective exploitation of coastal resources by AMHs (Bowdler, 1977), the terrestrial environments along the southern route were likely dominated by open savannah woodlands, and potentially joined to similar open terrestrial environments north of the equator and into mainland Southeast Asia via a 'savanna corridor' through what is now the Java Sea (Wurster and Bird, 2016). This would have allowed AMHs with a savannah-adapted skill set to expand south from mainland Asia into Sahul and exploit the savannas that covered most of the interior. Upon arrival in Sahul, colonists were able to penetrate deep into the Australian deserts as indicated by a range of sites from the northwestern deserts including Riwi, *Yurlu Kankala*, *Parnkupirti* and Serpent's Glen now dated to at least 50–45ka (Veth et al., 2009, 2017; Smith, 2013; Wood et al., 2016). In contrast, the environment along the northern route was largely forested and similar only to the extreme north of Sahul in New Guinea at that time (Russell et al., 2014). Forest cover was likely maintained into the Last Glacial Maximum at latitudes north of central Sulawesi (Martin Calvo and Prentice, 2015). Hence populations moving to Sahul via the northern route would have to move via coastlines, and/or require the capacity to traverse dense forest environments.

Defining the route and nature of the Sahul colonization process is important for inferring the cognitive, linguistic and technological capabilities of AMHs by ~50ka or earlier. For example, the rapid rate at which colonization of the interior of Sahul subsequently occurred implies considerable technological organization of organic and lithic extractive and maintenance implements.

There has been one early attempt to drift model arrival on Sahul from the eastern tip of Timor (Wild, 1986), a location from which Sahul has never been visible. The model used average currents thought to be broadly representative of January and July as understood in 1947, averaged over a coarse 5° x 5° grid, thus excluding many of key finer-scale processes that drive voyage pathways (e.g. ocean eddies). That study also assumed the characteristics of a modern vessel of Chinese design with a large sail (achieving 10% windage), and also that voyages were survivable over multiple weeks. Not surprisingly, the study found that, given enough time, some vessels departing in the Austral summer monsoon season would eventually arrive on the northern coast of Sahul, near Darwin, after travelling several weeks and generally more than 500km. Given our contemporary understandings of technologies available at the time, as well as the meteorology, palaeogeography and oceanography of the region, these simulations cannot now be considered at all realistic.

Here we use daily winds and currents from a data-assimilating model (Schiller, 2012) on a 0.1° x 0.1° grid, running over real historical years with the associated day-to-day variability. We also apply palaeogeographic information derived from new regional-scale bathymetry grid data (100m-resolution), an understanding of regional sea-level change and vertical land movements in the region, to revisit the issue of the plausibility of accidental or purposeful arrival on Sahul from Timor-Roti.

2. Methods

2.1. Digital elevation model

The new regional-scale bathymetry grid (100m-resolution) for the northern Australia region (latitude 8° to 18°S; longitude 121° to 133°E) utilized all available bathymetry datasets including multibeam, singlebeam, airborne lidar bathymetry surveys and electronic nautical chart spot depths provided by the Australian Hydrographic Office and Geoscience Australia. Source bathymetry data were edited for noise and adjusted to a consistent WGS84 horizontal datum and approximate mean sea level (MSL) vertical datum. The source bathymetry data were interpolated into a 100m-resolution Digital Elevation Model (Becker et al., 2009) and merged with 100m-resolution Shuttle Radar Topographic Model (Farr et al., 2007) land elevation data to produce the final grid (Figs. 1 and 2).

To determine inter-visibility the distance from each point to the horizon at sea level was calculated from:

$$d = 3.57 * \mathrm{sqrt}\,(h) \qquad (1)$$

where d equals the distance to the horizon at sea level in km and h equals the height of the point above sea level in metres. Where the radii of two points intersect the points are technically inter-visible, without accounting for the effects of refraction in the atmosphere which can extend the inter-visible range by ~7%.

2.2. Drift modelling

Modeling of voyages from three sites on Timor-Roti and two sites on the Sahul Banks were undertaken using ocean hydrodynamics and particle trajectory modeling based on a 4th-order Runge-Kutta ordinary differential equation solver that linearly interpolates in time and horizontal space to find the surface velocity at the required time (Schiller, 2012). Simulations used 15 years (1993–2007) of meteorological information and surface ocean currents (0.1° x 0.1° grid) to estimate the tracks of individual particles over time. In each of the 15 simulated years, one hundred vessels were released randomly over the 24h of the specified release date and within 10km of the specified starting location. Windage was assumed to be 4% of wind speed at 10m above the sea surface (appropriate for a raft or canoe), and for some runs purposeful voyaging was simulated by adding 0.5 knots ($0.25ms^{-1}$) in a specified direction (due south) to the wind and current vectors.

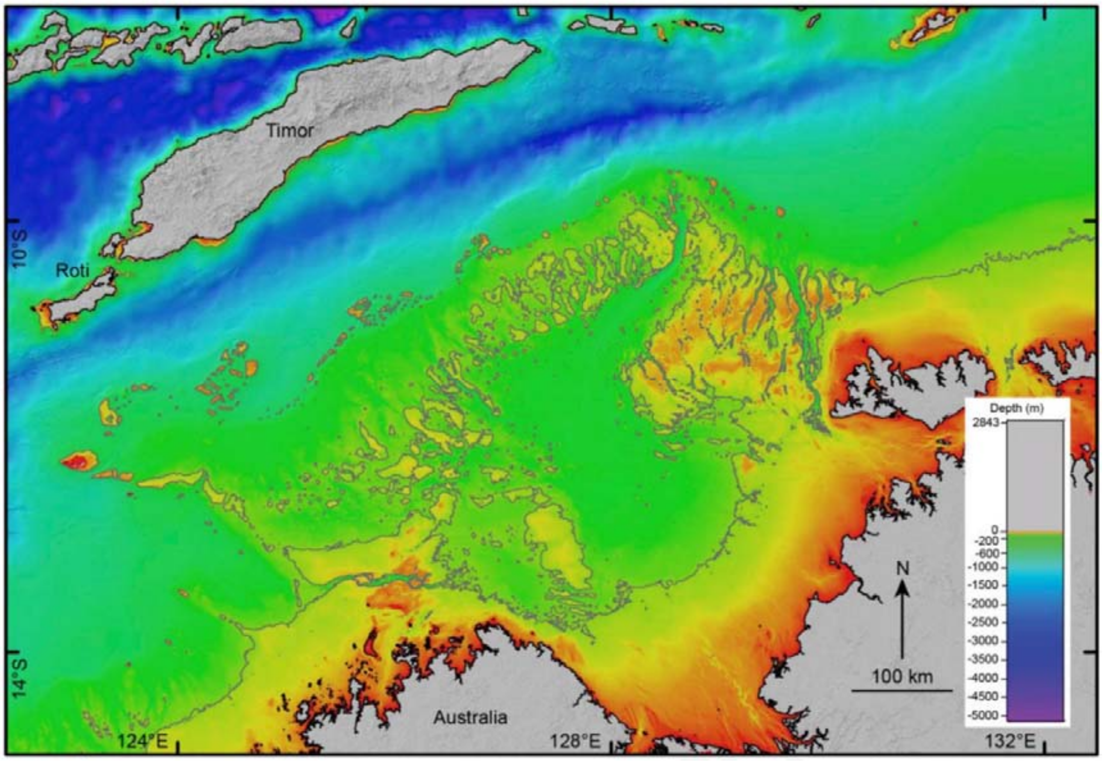

Fig. 1. Hillshade view of the bathymetry grid for the study region, northwestern Australia. Present coastline shown as a black line, 75m bathymetric contour as a grey line.

Results are presented as either the proportion of vessels within each 0.1° x 0.1° geographic cell at the end of the nominal voyage time (6 days) or as the proportion of vessels transiting each cell over the first 5 days of the voyage. In all cases these statistics are presented as 15-year averages, which are expected to be more relevant to palaeoenvironmental conditions than individual years.

3. Results and discussion

3.1. Palaeoenvironmental considerations

Determination of the viability of the southern route from Timor-Roti to northwest Australia first requires an assessment of the palaeogeography and palaeoenvironments in the region at the time of colonization. The time of colonization of Sahul is here taken to be between 65±5ka (Clarkson et al., 2017) and/or ∼49±2ka (O'Connell and Allen, 2015; Tobler et al., 2017), noting that there is currently no evidence anywhere in Wallacea for AMH occupation approaching these ages (Kealy et al., 2017).

The major determinant of the regional palaeogeography is sea level. A recent examination of high-resolution multibeam bathymetry datasets in the context of past sea-level variations on the Australian shelf identified several widespread palaeoshoreline features on the Sahul Shelf associated with past sea-level variations, and in particular a persistent modal position at 70–90m depth associated with a period of generally fluctuating sea level from 60 to 30ka (Brooke et al., 2017). This suggests that sea levels around Sahul were in this broad depth range during initial colonization and dispersal.

Post-glacial flooding of continental shelves can result in ongoing isostatic adjustment of continental shelf elevation (Lambeck and Chappell, 2001). In the case of the northwest Sahul Shelf, an extensive glacial lowstand escarpment runs along the shelf edge at 125m below sea level (James et al., 2004). This feature is consistent with there being little isostatic adjustment of shelf elevation landward of the shelf edge in response to water loading, as this elevation is consistent with the maximum eustatic drawdown of water during the Last Glacial Maximum of 125±4m (Ishiwa et al., 2016).

Sea level at the latest accepted time of AMH colonization is constrained locally by direct observation at −79±5mat 47±3ka in the Bonaparte Gulf (Lambeck et al., 2002). Prior to this time, while sea level was potentially higher than this for one or more ill-defined periods of a few millennia between 50 and 60ka, it was substantially lower prior to 60ka, around −85m (Lambeck and Chappell, 2001). Based on this analysis we adopt the 75m bathymetric contour as the most conservative measure of the minimum land area exposed at the time of colonization. We note that if colonization occurred at 65ka (Clarkson et al. (2017), then a sea level at least 10m lower would be more appropriate (Lambeck and Chappell, 2001), increasing inter-visibility and decreasing the distance to be travelled over water.

The new regional-scale bathymetry grid data used in this study is capable of clearly defining the maximum elevation of the small islands of the Sahul Banks (see Methods) enabling precise definition of the palaeogeography of the southern route, from Timor-Roti across the Timor Sea into northwestern Sahul (Fig. 1). The palaeoshoreline reconstruction for 75m below modern sea level (Fig. 2) reveals a string of reefs (the seaward edge of the 'Sahul Banks') as islands generally ~40m high that were directly visible from high points close to the coast on the islands of both Roti and Timor. The coastline of Timor-Roti remains broadly similar due to the steep offshore gradient, but a continuous chain of over 100 discrete islands becomes emergent close to the shelf edge of northwestern Sahul (the modern 'Sahul Banks'). The closest island is 87km from Roti to the west, and a minimum 135km distant from eastern Timor. These islands are classified as 'isolated carbonate build-ups' (Saqab and Bourget, 2015), typically 1–30km wide, flat-topped or with an interior depression, found as clusters of islands 2–85km from the edge of the 650km-wide Sahul continental shelf. The islands were steep-sided and rising from depths of generally >200m (Fig. 1), meaning that they were never connected to mainland Sahul even during maximum sea-level lowstands. The majority of the islands were within 5km of other islands, and gaps between island clusters were generally <30km.

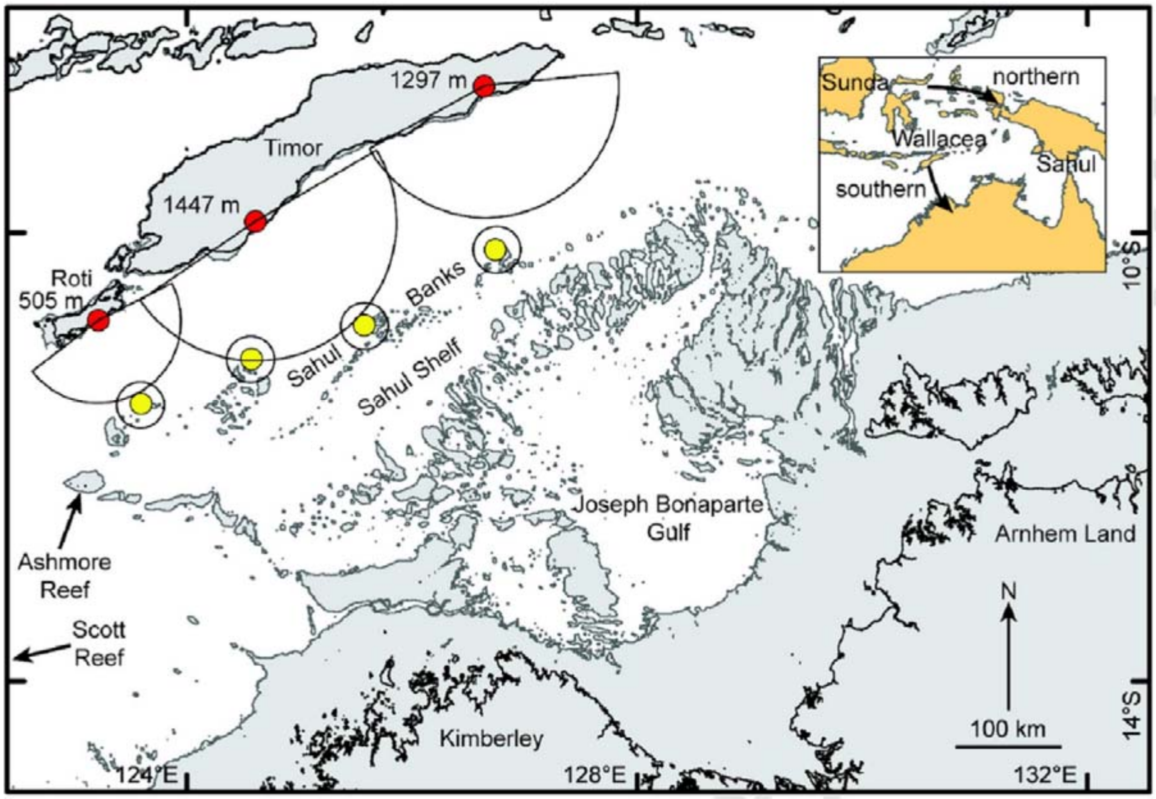

Fig. 2. Land exposed (grey) in the Timor Sea and northwest Australia shelf region at a sea level of 75m below modern sea level (see text). High points close to the coast of Timor (1447m: 9.90°S, 124.60°E, 7.5km from coast; 1297m: 8.70°S, 126.64°E, 9.5km from the coast; in red) and Roti (505m: 10.78°S, 123.21°E, 3.1km from the coast; in red) are shown with their altitude radius of visibility to the horizon, both calculated for a sea level equivalent to the 75m bathymetric contour. Points shown in yellow are radii of visibility of the Sahul Banks islands closest to Timor-Roti at 40m elevation. Overlapping radii indicate the sites that were inter-visible. Black line indicates present coastlines. Inset shows 'southern' and 'northern' routes to Sahul. Based on bathymetry shown in Fig. 1.

At the time of AMH colonization these islands had been exposed by prior sea-level fall for several millennia (Brooke et al., 2017). Modern environmental analogues for the islands include the Aldabra Atoll in the Indian Ocean (Stoddart et al., 1971), Ashmore Reef in the current study area (Lavers et al., 2014) and Niue Island in the Pacific (Terry and Nunn, 2003). These modern analogues suggest that the islands would have supported mature woody and/or open grassy vegetation, large populations of breeding seabirds and contained accessible water both as standing freshwater accumulations over impermeable strata and as coastal seeps of freshwater accumulated as a freshwater lens above saline water at sea level. The islands were therefore habitable with initially abundant high-ranked (marine and avian) resources, water, wood and fibre.

Inshore of the Sahul Banks islands facing the entire length of the Timor-Roti coast were a large number of islands exposed on the shallow continental shelf (Figs. 1 and 2), these being a mix of carbonate atolls and exposed shelf sediments. The latter areas are characterized by low-gradient coasts and by modern analogy, likely extensively colonized by mangroves across a broad inter-tidal zone, generated by a considerable tidal range (Condie and Andrewartha, 2008; Condie, 2011; Schiller, 2012; Ward et al., 2015).

The modern climate of the region is monsoonal, characterized by strong winds to the ESE in the Austral summer monsoon (January-February-March) reversing to WNW flows during the Austral winter monsoon (July, August, September), with relatively weak wind in the intervening months (Condie and Andrewartha, 2008; Schiller, 2012; Cappelli et al., 2016). Rain is concentrated in the summer monsoon period with a pronounced dry season in the winter monsoon period, and the region, including the Timor Sea away from land, is subject to a high frequency of lightning year round (Christian et al., 2003). The area is cyclone-prone, and based on the last 99 years, a cyclone passed within 200km of the southern Timor Sea (centred on 11°S, 124°E) once a decade, and within 100km once every five years (www.bom.gov.au).

The Timor Trough currently carries around half the total flux of water (~7.5 Sv) associated with the modern Indonesian Throughflow (ITF; Cappelli et al., 2016). Volume transport of water in the deep ocean is to the southwest year-round, but surface currents are variable in direction being strongly influenced by the strength and direction of the prevailing monsoonal winds, generally averaging around 0.5 knots ($0.25ms^{-1}$). Surface currents on the modern Sahul Shelf to landward of the Sahul Banks are broadly shore parallel and also undergo a seasonal monsoon-driven reversal in direction (Condie and Andrewartha, 2008; Schiller, 2012; Cappelli et al., 2016).

Modern conditions are likely broadly similar to those pertaining at colonization. Climate in the Wallacean region was approximately similar to today in terms of rainfall and vegetation (Westaway et al., 2009; Russell et al., 2014) with much of Timor-Roti covered by more or less open woodland-savanna vegetation. Monsoon intensity was generally similar to modern but with significant centennial scale variability in monsoon strength associated with Dansgaard-Oeschger cycles (Dürkop et al., 2008). Therefore, while the summer monsoon might, on average, have been stronger or weaker at the time of colonization, this simply means there would have been more or fewer windows where winds were favorably aligned for a successful transit of the Timor Sea. Cyclone incidence would be similar to now or reduced by the reduction in ocean area. The ITF was weaker over the period from 64 to 39ka with respect to modern ITF flows (Holbourn et al., 2011), possibly with a period of flow similar to modern prior to 47.5ka (Stumpf et al., 2015). Hence, the ITF was not more of an impediment to transiting the Timor Sea than is currently the case.

3.2. Inter-visibility

From this understanding of palaeogeography and palaeoenvironmental conditions it is possible to assess the likelihood that AMH populations in Timor were aware of the islands to their south. Figure 2 shows three highpoints on Timor-Roti, each within 10km of the Timor coast and four of the closest islands off the Sahul Shelf that each stood at least 40m above the conservative maximum sea level at the time approximated by the 75m bathymetric contour. Where the circumferences of horizon intersect on Figure 2, the locations were directly inter-visible. This calculation assumes that the elevation of the viewpoints has not changed, except as a result of changed sea level. This is unlikely to be the case for several reasons.

Both Roti and Timor are undergoing, on the one hand, tectonic uplift, and on the other, denudation as a result of uplift. For example, rates of uplift on Roti and western Timor have been measured at 0.3–1.5m/ka (Jouannic et al., 1988; Roosmawati and Harris, 2009), with higher rates calculated for central Timor. Conversely, modern denudation rates equivalent to 3.1m/ka can be calculated for the island of Timor (Milliman et al., 1999). This denudation rate is higher than long-term minimum denudation rates calculated for the island of Borneo of 0.33–0.96m/ka (Hall and Nichols, 2002), likely due to human disturbance in the recent past. However, even the long-term estimates from Borneo, which is less tectonically active than Timor-Roti suggest that uplift is more or less balanced by denudation. Therefore the elevation of the high points on Timor are likely to be within a very few tens of meters above or below their elevation at the time of colonization.

On the Sahul side, the Sahul Banks are *Halimeda*-dominated bioherms that have been accreting vertically during highstand periods since 0.6–0.8Ma (Heyward et al., 1997). Flooding of the reefs in the post-glacial likely occurred rapidly around 10ka (Collins et al., 2011; Williams et al., 2018). Accretion rates are unknown but given the rapid increase in depth of water, and loss of light for photosynthesis over the banks shortly after 10ka, accretion is likely to be at the low end of the ranges reported for *Halimeda* elsewhere, and unlikely to be more than 1m/ka (Marshall and Davies, 1988; Phipps and Roberts, 1988; Rees et al., 2007). However, the Sahul Banks lie dominantly beyond the shelf break and have been undergoing long-term subsidence. Scott Reef at the southern end of the region has undergone subsidence at a rate of 0.29–0.45m/ka (Collins et al., 2011) since the last interglacial, suggesting that the Sahul Banks islands, at their southwestern end at least, were 14.5–22.5m higher at the time of colonization. It is therefore a reasonable assumption that *Halimeda* accretion in the Holocene was more or less offset by subsidence, as is the case for uplift and denudation on Timor-Roti.

Taken together, changes in elevation by any mechanism since colonization do not materially impact the conclusion based on Figure 2, that the islands off Roti and western Timor were clearly inter-visible. Technical inter-visibility for the Roti site was not lost until the islands disappeared beneath the sea ~35m below current sea level. On any reasonably clear day, inter-visible land masses can be seen over distances of ~100km, with clarity of the atmosphere becoming increasing important at greater distance. On this basis, the islands off Roti were visible under average conditions at 92km between high points, the islands off the central Timor peak were only potentially visible under very clear conditions at 130km and the islands off the northeastern Timor peak were not visible.

The same conclusion – that the islands of the Sahul banks were visible from Timor-Roti – was reached by Norman et al. (2018). However, that study assumed that high points on Timor up to 2400m above sea level and at least 35km inland were accessed by AMHs. Here we find inter-visibility remains possible using the more limiting assumption that only high points within the typical daily foraging range of hunter-gatherers from the coast (<10km inland with return) were likely to be accessed by AMHs. The conclusion that the Sahul Banks islands were visible from Timor-Roti is at odds with the conclusion of Kealy et al. (2017) that the Sahul Banks were generally not visible. This is because Kealy et al. (2017) used coarse (~900m-resolution) global-scale bathymetry/topography that does not adequately represent the maximum elevation of small features, and while the study considered uplift it did not consider the impact of denudation accompanying uplift.

Direct inter-visibility was only one of the available cues indicating the existence of land to the south of Timor-Roti. The islands were vegetated and would have undergone regular dry season burning from lightning strikes (Christian et al., 2003) with the smoke clearly visible from Timor-Roti. In addition, many of the isolated islands would have supported large colonies of seabirds as is the case for similar islands on the Sahul Shelf today (Lavers et al., 2014). Currently, seabird colonies on the islands of the Sahul Shelf are sufficiently distant from Timor-Roti that several of the most abundant pelagic species are only occasionally seen in Indonesian waters (Trainor and Soares, 2004; Trainor, 2005a,b; Lavers et al., 2014). Populations of these same pelagic species on the exposed Sahul Banks islands would be close enough to regularly visit the waters off Timor-Roti, drawn in particular by seasonal upwelling off the south coast of Timor (Alongi et al., 2013). These birds would arrive from the south and disappear to the south. Many terrestrial bird species also overfly Timor annually on their annual migrations from Australia to the Northern Hemisphere. Indeed some, such as the Australian Pratincole, migrate only between the Australian mainland and southern Indonesia (Bamford et al., 2008). Based on all the available cues, it is highly likely that AMH populations knew of the existence of land to the south, although this does not of itself imply purposeful voyaging.

3.3. Voyage simulations

The discussion above suggests that the exposed islands of the Sahul Banks represented a resource-rich, continuously inter-visible habitable island chain almost 700km in length, lying 87–∼150km south of Timor-Roti. These islands constituted a very large target for either accidental or purposeful arrival, with favourable monsoon winds greatly assisting passage for around three months of the year during the Austral summer monsoon. Having established inter-visibilty, we use coupled ocean-atmosphere drift modelling (Schiller, 2012) (see Methods) to assess the likelihood of accidental drifting and/or purposeful voyaging resulting in successful arrival in Sahul. Voyage trajectories were computed using modelled surface ocean currents with an additional 4% windage, appropriate for a small raft or canoe. Simulated voyages began from three points on the Timor-Roti coast close to the sites with inter-visibility (Figs. 3 and 4). To cover a broad range of wind and current conditions, 100 model vessels were launched on February 1st every year for 15 years. The date was chosen to correspond to the main summer monsoon period when winds are generally blowing to the ESE, thereby maximizing the chance of successful crossings.

The results clearly indicate that accidental arrival by drifting for six days (Fig. 3a and Fig. 4a) is very unlikely from eastern Timor, but possible in a small percentage of cases from western Timor and Roti. However, the addition of even modest paddling towards the Sahul Bank islands results in a high proportion of successful arrivals from central Timor and Roti, and some from eastern Timor (Figs. 3c and 4c). These 'purposeful voyaging' models assumed a minimal paddling ability over a period of six days by adding a southward velocity of 0.5 knots (0.25ms^{-1}) to the local current and wind components. This is one half to one sixth of the paddling speed assumed for Polynesian voyagers in the Holocene for journeys sustained over several months (Montenegro et al., 2016).

It is also necessary to consider opportunity and agency when interpreting the simulations. While fishing craft (O'Connor et al., 2011) may have occasionally accidentally ended up adrift in the Timor Sea, only those in the summer monsoon/cyclone season would have any chance of making a southern landfall, with the long distances involved reducing survivability for unplanned travel. Given that Timor and Roti would both remain visible well into the Timor Sea, it is also likely that individuals on a drifting craft would attempt to return to their point of origin, retarding their passage south and further reducing the likelihood of successful arrival on Sahul (Figs. 3c and 4b). Conversely, a purposeful voyage would be strategically initiated when conditions were most favourable, maximizing the likelihood of a successful crossing (Figs. 3c and 4c).

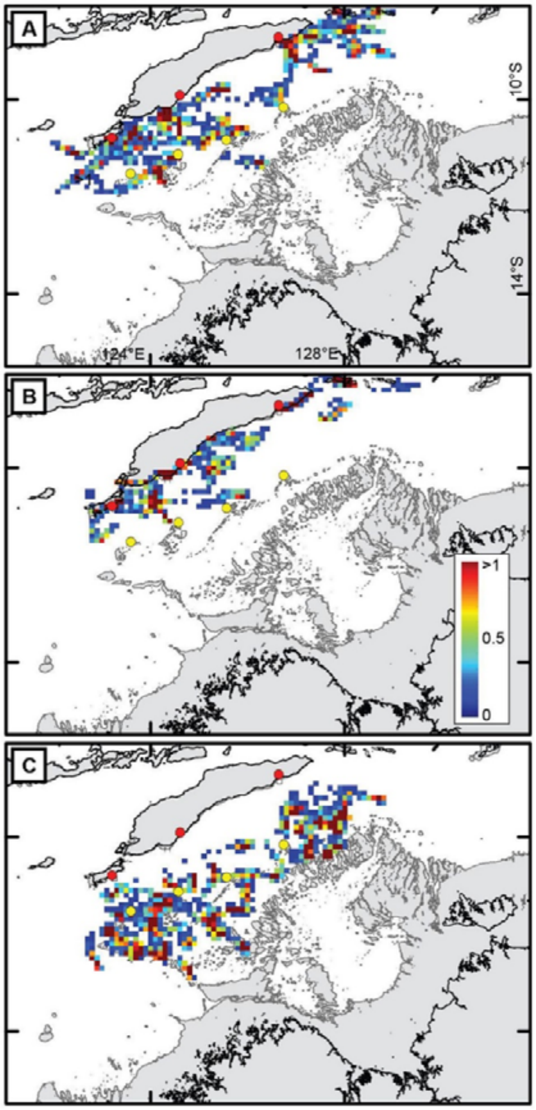

Fig. 3. Model results for drifting in February from three points of departure: eastern Timor (8.78°S, 126.65°E), western Timor (10.25°S, 124.35°E) and Roti (10.83°S, 123.23°E). Colours represent the percentage of boats occupying each 0.1° x 0.1° grid cell on day 6 of each simulation. (A) 'accidental' drift voyaging where only wind and currents affect movement, (B) drifting for two days, followed by the addition directed headway of 0.25ms^{-1} to the north, to simulate an attempt to return to land visible to the north and (C) 'purposeful' voyaging simulated by addition of directed headway of 0.25ms^{-1} to the south. The disposition of vessels through days 1–5 are provided in Fig. 4.

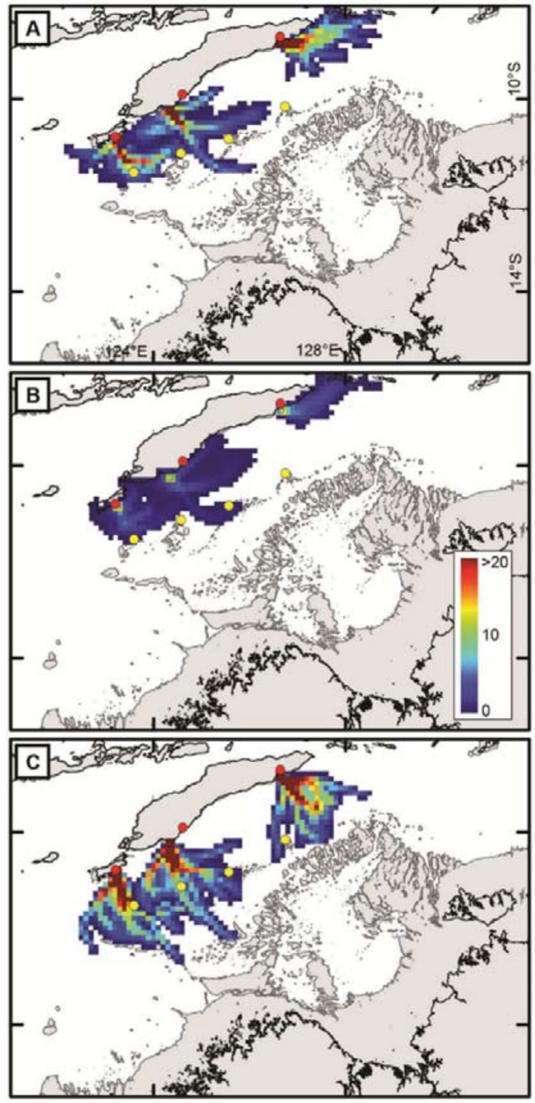

Fig. 4. Model results for departures in February from three points of departure: eastern Timor (8.78°S, 126.65°E), western Timor (10.25°S, 124.35°E) and Roti (10.83°S, 123.23°E). Colours represent the percentage of all boats transiting each 0.1° x 0.1° grid cell from days 1–5 of each simulation. (A) 'accidental' drift voyaging where only wind and currents affect movement, (B) drifting for two days, followed by the addition directed headway of 0.25ms^{-1} to the north, to simulate an attempt to return to land visible to the north and (C) 'purposeful' voyaging simulated by addition of directed headway of 0.25ms^{-1} to the south. The disposition of vessels on day 6 is provided in Fig. 3.

Simulations suggest that the journey would take 4–7 days, similar to the five days taken by a ‘Middle Palaeolithic’ craft under sail in 1998 to cross from Roti to the area above the now submerged Sahul Banks (Bednarik, 2000). Subsequent movement from the Sahul Banks islands to the Sahul mainland generally involved distances of <10km and never more than 30km, aided by seasonally reversing coastal currents and diurnally reversing tidal currents (Schiller, 2012; Ward et al., 2015). Two main island-hopping routes were available to the Sahul mainland (Figs. 1 and 2), both with inter-visibilty along the route (Norman et al., 2018). A route to the east would see final landfall northwest of Arnhem Land while the southern route would make landfall in the Kimberley, both areas known to contain some of the oldest archaeological sites in Sahul (Wood et al., 2016; Clarkson et al., 2017). Movement through the islands would have been possible using similar wood and fibre resources to those available in Wallacea, including for example, sea hibiscus, colloquially known as ‘the supermarket tree’ (*Hibiscus tiliaceus*; Elevitch and Thomson, 2006).

3.4. Genetic evidence

The diversity of founding mitochondrial lineages observed in indigenous Sahul populations to date (Tobler et al., 2017; Nagle et al., 2017) permits minimum size estimates of the colonising population. Conservatively, the ancestors of mitochondrial haplogroups S/O, P5/P11, M42, and P8, M14, M16, N13, N14, R12, and Q2b appear to have been present in the founding population, representing at least 9-10 separate mitochondrial lineages. It is likely that further basal sequences will be detected as more surveys are performed. Assuming every mitochondrial lineage was represented by 4–5 founder females (e.g. family group of mother/sister, 2 daughters) the currently known 9–10 lineages would equate to ~36–50 females. This is a conservative estimate as founding populations of <10 females per lineage have a low chance of long-term survival (Moore, 2001). In addition, many founding mitochondrial lineages are likely to have died out within the first few generations as a result of a lack of female off-spring due to fluctuations in the sex ratio of children. If an overall, again conservative, female to male ratio of 1:1 is assumed for the colonising party, the inferred founding population would be >72–100 individuals. However, it was likely much larger (e.g. 200–300) due to the strong potential for related family groups to share similar mitochondrial lineages, which would be underestimated as a single founding lineage. Clearly, a population of even the minimum estimated size is unlikely to have arrived ‘accidentally’ on Sahul.

4. Conclusions

The combined information from palaeoenvironmental reconstruction, modeling, and genetics presented above suggest that colonization of Sahul by AMHs by 50ka was achieved by purposeful and coordinated marine voyaging, undertaken in the knowledge that land existed to the south of Timor-Roti. Compared to the multiple previous shorter crossings required to establish a viable population of AMHs in Wallacea, the crossing to Sahul was two to three times longer, requiring watercraft construction, sailing and navigation technology, planning ability, information sharing and provisions to sustain an open ocean voyage over 4–7 days. Purposeful voyaging on this scale clearly required advanced cognitive, linguistic, symbolic and technological capabilities (Davidson, 2010). This is consistent with archaeological evidence for hand stencils and figurative art (Aubert et al., 2014), ornamentation (Langley et al., 2016a), fibre technologies (Bulbeck, 2007), deep-sea fishing (O’Connor et al., 2011) in Wallacea, as well as bone implements (Langley et al., 2016b) and stone handaxes in Sahul (Groube et al., 1986; Hiscock et al., 2016), all by 35ka and most by 40ka or earlier.

Furthermore, some of the earliest evidence of economic and utilitarian use of marine resources by AMHs outside of Africa occurs precisely along the Timor-Roti to northwestern Australia nexus we infer here (Langley et al., 2016a; Veth et al., 2017). Several studies favour a model whereby depletion of high-ranked coastal resources drives rapid further dispersal of expanding AMH populations (O'Connell et al., 2010; Allen and O'Connell, 2012). In this context, the most likely point of departure identified in this study is Roti, not only because it was the closest point to the Sahul Banks islands but because it is a small island amd therefore potentially subject to rapid resource depletion that would then stimulate continued dispersal to Sahul, given that Timor was already colonized.

It should be noted that demonstrating the southern route as a viable option for the colonization of Sahul does not preclude the possibility of other arrivals via the northern route. However, apart from requiring (slightly) longer voyages, the monsoonal wind flows, which are key to successful voyages in the region, are not well-aligned with crossings along the northern route. Nevertheless, it is possible that the deep genetic divergence between modern indigenous populations of northernmost Sahul (New Guinea) and the rest of Sahul (Nagle et al., 2016; 2017) might reflect a second successful and roughly contemporaneous colonization of mountainous, perhumid, forested New Guinea – presumably from similar forested Wallacean island environments immediately to the west. This would further underscore the behavioural modernity and plasticity of AMHs by ~50ka to not only undertake multi-day, open ocean voyaging to successfully colonize new continents, but to disperse very rapidly through widely divergent tropical forest and savanna environments.

Conflicts of interest

The authors declare that they have no conflict of interest.

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