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Human refugia in Australia during the Last Glacial Maximum and Terminal Pleistocene: A geospatial analysis of the 25-12ka Australian archaeological record.

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Abstract

A number of models, developed primarily in the 1980s, propose that Aboriginal Australian populations contracted to refugia – well-watered ranges and major riverine systems – in response to climatic instability, most notably around the Last Glacial Maximum (LGM) (~23-18ka). We evaluate these models using a comprehensive continent-wide dataset of archaeological radiocarbon ages and geospatial techniques. Calibrated median radiocarbon ages are allocated to over-lapping time slices, and then K-means cluster analysis and cluster centroid and point dispersal pattern analysis are used to define Minimum Bounding Rectangles (MBR) representing human demographic patterns. Exploring data between 25-12ka, we find a refugia-type hunter-gatherer response during the LGM (~23-18ka) and again during the Antarctic Cold Reversal (ACR) (~14.5-12.5ka), with expansion in the intervening period. Several refugia persist between 25-12ka, including (by Interim Biogeographic Regionalisation for Australia areas) Gulf Plains/Einasleigh Uplands, Brigalow Belt South, Murray Darling Depression, and Tasmanian Central Highlands. Others appear sporadically through the same period. These include South Eastern Highlands, NSW South Western Slopes, Sydney Basin, Warren, Murchison, Gascoyne, Central and Northern Kimberley, Ord Victoria Plain, Arnhem Plateau, MacDonnell Ranges and Central Ranges. The Pilbara may also have been a refugium during the LGM, but geospatial results are problematic for this region. Areas devoid of human activity ('barriers') include the main desert regions, especially in the south and west of the continent, although some of these may be the result of an absence of archaeological fieldwork. Point dispersal pattern analysis indicates a reduction in occupied territory of nearly 80% during the LGM. A reduction of close to 50% was also evident during the ACR. A large number of the refugia were in close proximity to glaciated areas during the LGM, and probably benefitted from increased summer snowmelt along the major river systems. The remaining refugia are likely the result of a range of local environmental and resource factors. We identify areas for future research, including a focus on regional studies to determine possible cryptic or idiosyncratic refugia emerging in phlyogeographic studies.

Keywords: Last Glacial Maximum, Antarctic Cold Reversal, Terminal Pleistocene, radiocarbon data, prehistoric movement, geospatial analysis, refugia, minimum bounding rectangles

1. Introduction

This paper evaluates archaeological models of human responses to climate change during the Late Pleistocene in Australia, with particular emphasis on the Last Glacial Maximum (LGM) and the Terminal Pleistocene. The LGM is the most significant climatic event to face modern humans since their arrival in Australia some 40,000-50,000 years ago. Recent studies have demonstrated that the LGM in Australia was a period of significant cooling and increased aridity beginning ~30ka and peaking between ~23-18ka (e.g. Williams et al., 2009; Petherick et al., 2011; Fitzsimmons et al., 2012). This period saw a decline in annual temperatures by as much as 10ºC compared with the present day (Miller et al., 1997), glaciation of uplands in the Snowy Mountains and Tasmania (Barrows et al., 2001, 2002, 2004), a reduction in rainfall by 60% or more, especially in the interior through a weakening of the summer monsoon and poleward displacement of winter westerlies (Wyrwoll et al., 2000; Wyrwoll and Miller, 2001; Griffiths et al., 2009), and, linked to the latter, markedly lower lake-levels (Magee et al., 2004). The LGM also resulted in changes in vegetation structure to generally more steppe-like and grassland-dominated environments (Johnson et al., 1999; Petherick et al., 2011), increased dune activity and dust transport (Fitzsimmons, 2007), and an expansion of the arid zone into semi-arid and mesic environments (Smith, 2013).

The subsequent Terminal Pleistocene also saw rapid environmental change. Increasing temperatures initially outpaced precipitation and probably led to drier conditions than the LGM (Markgraf et al., 1992; Kershaw and Nanson, 1993). Sea-levels rose by 120m by 12ka and inundated ~1.6 million km^2 of the continental shelf (Hanebuth et al., 2009; Lambeck and Chappell, 2001; Lambeck et al., 2002). Recent studies show this period to be one of increasing complexity, with the southern parts of the continent having a brief humid phase between ~17-15ka before increasing aridity at ~14-10ka, while in the north the lapsed monsoon saw dry conditions until after 14ka (Fitzsimmons et al., 2012). Between ~14.5-12.5ka, a return to cooler (Antarctic Cold Reversal [ACR]) conditions is widely documented in ice core records (e.g. Jouzel et al., 1995), although evidence for the event in Australia is equivocal (e.g Barrows et al., 2002; Fitzsimmons et al., 2012: Figure 9).

Human response to climate change during the Late Pleistocene has formed a persistent theme in Australian archaeological research and interpretations for over 30 years. First explored in the late 1980s in a number of studies, it was hypothesized that during the LGM humans experienced a major reduction in population size, resulting in settlement contraction and abandonment across much of Australia (Veth, 1989a, 1989b, 1993; O'Connor et al., 1993; Smith, 2013). These studies argued for the importance of refugia – well-watered ranges and major riverine systems – and the abandonment of large tracts of desert and marginal country (Lampert and Hughes, 1987; Smith, 1988; Hiscock, 1988; Veth, 1989a). Using biogeographic approaches, Veth (1989b, 1993) summarized these ideas into a conceptual model that identifies refugia, corridors and barriers for people through the LGM (Figure 2). This 'Islands in the Interior' model emphasizes the importance of persistent water sources in piedmont/montane uplands and riverine/gorge systems as refugia in periods of climatic extremes, the three major sand-ridge deserts as continuous barriers, and the rest of the continent as temporary barriers to occupation during the height of the LGM. Recently, Simmons (2007) extended the Islands in the Interior model into the Holocene. Focusing on the Diamantina channel country in southwestern Queensland, Simmons found that territorial expansion outside core areas and aggregation of populations only occurred when ephemeral lakes or waters were available, and concluded that the Islands in the Interior model explained the pulse-like use of marginal areas during favourable climatic conditions.

The idea that periods of climatic deterioration during the Late Pleistocene resulted in decreases in the human population of Australia is reasonably well supported. It appears to be the case that during the LGM many archaeological sites were abandoned and not re-occupied until the early Holocene (e.g. Cloggs Cave, Serpent's Glen rockshelter, Mandu Mandu rockshelter) (Flood, 1980; Morse, 1988; O'Connor et al., 1998; Smith, 2013; Ulm, 2013). Those sites that do contain archaeological deposits dating to the Terminal Pleistocene typically reveal discrete hearths and/or low numbers of artefacts, suggesting only ephemeral use of the landscape (e.g. Drual rockshelter, New Guinea II cave, ORS 7, Roof Fall cave) (Ossa et al., 1995; Cosgrove 1996; Bird & Frankel, 1998; Eales et al., 1999). Demography-oriented time-series analyses of radiocarbon dates carried out by Smith et al. (2008) and Williams (2013) reinforce this picture. These authors found that despite fairly stable population growth rates of 0.01% over the last 50,000 years, the LGM and ACR saw significant declines in population of up to 60%, and recovery was not observed until the early Holocene (Figure 1).

In contrast, the notion that there were refugia separated by barriers during the LGM and periods of climatic deterioration during the Terminal Pleistocene is debated. Some studies support it. For example, in a regional study of the Riversleigh and Lawn Hill regions in northwest Queensland, Slack (2007) demonstrated that the Gregory River region was a likely refugium during the LGM. An abandonment of some river systems, reduction in the use of exotic raw materials and a broadening of diet breadth to focus on lower-ranked resources were inferred to indicate a contraction into the gorge regions of Riversleigh during the LGM, before re-expansion of populations after 16ka. However, other studies have contested this part of the Islands in the Interior model. Hiscock and Wallis (2005), for instance, argued that deserts were unlikely to have been barriers, because occupation of the interior and the margins of these features had occurred by ~40-35ka. Rather, they proposed that margins of desert regions with nearby co-ordinated drainage would have formed a focus of occupation prior to the LGM, and only abandoned briefly during the driest parts of the LGM (see also Smith, 1993). Smith (2013) has also argued for a more complicated response to glacial conditions than envisaged by the Islands in the Interior model. Smith used phylogeographic studies of endemic plant and animal species to suggest a model of cryptic or idiosyncratic refugia in which human populations survive across the continent as scattered occurrences and at low densities, effectively in pockets of microhabitat (see also Byrne, 2008; Neaves et al., 2012). He conceded that some regions may have been abandoned, but suggested that this was likely of only marginal areas within local territories, and that direct evidence for abandonment of large parts of the interior is unfounded.

Here we report a study that was designed to shed light on the uncertainty about the claim that during periods of climatic deterioration in the Late Pleistocene humans populations contracted into refugia separated by barriers. In the study, we used the most comprehensive radiocarbon dataset for archaeological sites across Australia and exploratory geospatial analytical techniques to examine human activity and occupation through the LGM and Terminal Pleistocene. While preliminary, the results of the study suggest that there were major changes in the relative density of human populations in the different biogeographic regions of Australia during the Late Pleistocene, as predicted by the Islands in the Interior model.

2. Key Assumptions and Limitations

Several assumptions underpin this analysis. Despite the authors (AW and SU) compiling all published and extensive unpublished archaeological radiocarbon data for the Australian continent, few data fall before 25ka, and this constrains the starting date of our analysis to the peak of the LGM, rather than earlier parts of the Pleistocene. Four-hundred-and-seventy-seven dates fall between 25-12ka. While a relatively low number, this broadly conforms with sample size requirements for time-series analysis techniques based on methods in Williams (2012). The results produced here will, however, not be as robust as for later periods into the Holocene where more data are available. The analysis should therefore be considered a pilot study to be supplemented as more data become available.

Time-series radiocarbon data are now frequently used as a proxy for human activity or prehistoric population size (e.g. Buchanan et al., 2008, 2011; Collard et al., 2010a, 2010b; Peros et al. 2010; Smith et al. 2008; Williams et al. 2008, 2010; Williams, 2012, 2013). Analysis and interpretation of this form of data is complex and has several limitations (Williams, 2012). In Australia the two main criticisms of the technique include: 1) how detrital charcoal in archaeological sites (i.e. samples not recovered from features directly attributable to humans such as hearths, burials, etc) relates to the archaeological record; and 2) whether the radiocarbon data reflect demographic change, or changing behaviour in hunter-gatherer societies (i.e. more dates equals greater mobility, rather than more people). Recent work by Williams (2012, 2013) has sought to address these issues, and demonstrated that detrital charcoal data correlate well with other radiocarbon data directly attributable to human activity within archaeological sites and can be reliably used. Williams' work also shows that the radiocarbon data correlate well with other archaeological indices (such as artefact discard rates), and provides greater certainty that the data reflects demographic change. Here, we similarly assume the data can be broadly attributed to demographic change. However, it is worth noting that the form of geospatial analysis adopted in this paper does allow alternate interpretations to be made.

A further limitation of the analysis of time-series radiocarbon data is taphonomic bias – the over-representation of younger sites due to the loss of older sites from environmental and climatic factors. In standard time-series approaches, statistical techniques have been developed to allow correction of the data to accommodate for taphonomic loss (e.g. Surovell et al., 2009; Williams 2012). However, we currently have no way to apply such correction to the geospatial analysis undertaken here, and we acknowledge this as potential a limitation of the study.

Lastly, while we acknowledge recent advances in phylogeography suggesting cryptic or idiosyncratic refugia across Australia – the use of microhabitats by a reduced population across all parts of the continent – time-series data alone are not detailed enough to identify these regions. We therefore focus our study on the identification of macro-scale refugia, barriers and corridors, within which to explore these more complex settlement patterns as data become available.

3. The Dataset

This paper uses the most comprehensive radiocarbon dataset for the Australian continent assembled to date. The dataset contains over 5000 published and unpublished dates and covers the whole of mainland Australia as well as Tasmania. The dataset has been published sequentially (AustArch 1, AustArch 2, Austarch 3, Index of Dated Archaeological Sites in Queensland) (Ulm and Reid, 2000; Williams et al., 2008; Williams and Smith, 2012, 2013), and includes the unpublished Pleistocene Sahul Archaeological Site Dataset (Langley, 2009). Despite the dataset encompassing all published and extensive unpublished data, only 477 dates from 136 sites can be assigned to 25-12ka (Figure 3) and therefore can be used in the analysis.

Chronometric and data hygiene review was undertaken of the entire dataset and only those dates with suitable information (including spatial location, sample material type, context, etc) and not considered erroneous by the researcher were included in the analysis. For the purpose of this analysis, the data include terrestrial (n=469) and marine (n=8) dates, and are divided into major bioregions (after Thackway and Cresswell, 1995) (Figure 4). For spatial analysis, each date is represented by a point with latitude and longitude coordinates projected into Lambert Conformal Conic projection (GDA 1994 Geoscience Australia).

The strengths of the dataset include a wide geographical range covering over 7 million km^2, encompassing major bioregions, including arid, semi-arid, semi-tropical, tropical, and temperate zones; and a wide variety of archaeological site types and contexts (including rockshelters, burials, shell middens, earth mounds, hearths, rock engravings, fish traps, stone arrangements and open sites). However, the dataset has poor coverage in areas where field research has been limited (see Langley, 2009 and Langley et al., 2011 for discussion) and is dominated by data derived from Holocene sites.

4. Methods

All radiocarbon data were calibrated using Oxcal (version 4.1) (Bronk Ramsey, 2009). Terrestrial dates were calibrated using INTCAL09 and marine dates using MARINE09 (Reimer et al., 2009) with ΔR values after Ulm (2002, 2006). Oxcal was used to obtain a median value for each radiocarbon date (95.4% confidence). We acknowledge that when calibrating a radiocarbon date, the age may occur anywhere within the minimum and maximum values provided by the calibration program (rather than the median value). However, on average, calibrated ages in the dataset had less than a 400 year range, and would have remained within the same time slice (52-75% of the time) regardless of which part of the calibrated age range was selected.

Spatial analysis of these median calibrated values was undertaken in ArcGIS, R and Geospatial Modelling Environment (GME) software using a three-step process after the method outlined by Chilès and Delfiner (2012). These steps are 1) allocating points to over-lapping time slices, 2) K-means cluster analysis, and 3) cluster centroid and point dispersal pattern analysis.

The purpose of using over-lapping time slices was to divide the dataset into discrete time slices for use in K-means analysis, by removing points associated with radiocarbon ages that were considered statistically distinct. An alternative technique was to use firm thousand year time slices, but if this approach was adopted then calibrated dates of, for example, 19,005 and 19,995 would have been considered ‘the same’ and resolution would have been reduced, whereas in over-lapping time slices they are not (i.e. de-clustering). Given the low number of data available for the analysis, it was considered that the loss of data through the use of firm slices was unacceptable and over-lapping ones were instead adopted. In addition, trials indicated that using firm time slices would have increased the number of dates with calibration age ranges outside their respective slice, and increased uncertainty in the results.

Over-lapping time slices were created by using Moran’s Local I test (Anselin, 1995) to remove any spatial outliers within a 2,000 year time slice, commencing with all calibrated radiocarbon dates between 25ka to 23ka BP. Subsequently, the mean and standard deviation of calibrated dates at the same location was calculated and any points with values greater than mean ± 1 SD were removed and re-evaluated within the next chronologically younger time slice. Following this assignment of data to individual time slices, all points were converted into a $10km^2$ grid and then back into points in order to ‘average’ calibrated data values within local neighbourhoods, and to de-cluster the dataset removing bias from the subsequent K-means analysis. This stage was used to ensure that areas where archaeological research has been extensive, multiple LGM dates have been obtained from the same site (e.g. Narwala Gabarnmang rockshelter) (David et al., 2011), and/or Pleistocene landscapes are readily apparent (e.g. Murray Darling Depression) did not overwhelm the analysis and mask any real trends. $10km^2$ was considered the optimum size, with a range of larger grid sizes continuing to retain bias in subsequent stages of the analysis. No point was used more than once in the entire analysis.

After data were allocated to the time slices, a partitioning clustering technique, K-means, was implemented (Hartigan, 1975, 1977). K-means clustering is a statistical method for grouping data. It aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean (in our case the latitude and longitude position of the point). The output of the analysis is a centroid representing the centre point (mean latitude and longitude) of the observations included in the cluster, along with a rectangle that represents the minimum bounding extent of all observations included in that cluster. K-means is an iterative process in which points are assigned to a predetermined number of clusters (k) beginning with an initial ‘seeding point’ selected by automated stochastic process (Connolly and Lake, 2006). Points are subsequently allocated to the cluster they are nearest to and as new points are added, the centre of the cluster is re-defined and the point-cluster relationship re-evaluated to a maximum number of iterations (n=100). The results are evaluated by studying the squared Euclidean distances between each point and their respective cluster centroid (Figure 5). In our study, we used the 'elbow' method to determine the optimum number of clusters to explain the data. In statistical terms the elbow represents the point where percentage variance against the number of clusters reaches a threshold where adding another cluster does not reduce overall variance, and therefore ceases to give a much better model of the data (see Chiang and Mirkin 2007 for an evaluation of techniques). Relative to other clustering techniques, K-means strength is faster and produces more discrete clusters. However, it is a stochastic process, so it may not yield the same results on each model run (the stochasticity arises as the initial seeding point is generated randomly in dimensionless space). This is addressed by re-running the model with the same parameters and performing diagnostic checks on any systematic inconsistencies. Ultimately the analyst must exercise judgement in relation to the number of clusters, which can be challenging where there is convergence to a local minimum (as seen in the Western Australia, where obvious clusters in include unrelated points in central Australia – see discussion below).

Using the K-means results, the final stage of the analysis was to evaluate changes to the cluster centroid and point dispersal pattern. The point dispersal pattern is visualised by creating minimum bounding rectangles (MBR); the rectangle demonstrates which points are assigned to which cluster centroid. From an archaeological perspective, these rectangles theoretically represent the range of human groups associated with each cluster centroid. Additional exploration of convex hull approaches were also undertaken. This approach explores the relationship of a point with the cluster centroid through direct measurement of each point back to the centre producing irregular polygons or bounding boxes. The analysis indicated that the convex hull approaches produced very similar trends to the MBRs, but were generally 38% on average smaller. Given, we are interested in the broad trends in this paper, rather than quatitative values, we have opted to use the MBR results below.

5. Results

The K-means analysis yields a relatively consistent number of cluster centroids for each time slice of between six and nine throughout the Late Pleistocene (Figure 6). Temporally, there appears to be little trend in the number of clusters, although there is a slight increase from 19ka onwards (Table 1).

Spatially, there are several peristent clusters throughout 25-12ka, including (by Interim Biogeographic Regionalisation for Australia [IBRA] areas) the Murray Darling Depression, Tasmanian Central Highlands, Gulf Plains/Einasleigh Uplands, Warren, Brigalow Belt South, and Gascoyne/Murchison (Figure 6). The Gulf Plains/Einasleigh Uplands show some of the most stable results and dispersion patterns throughout the LGM and Terminal Pleistocene, with possible expansion only between 16-14ka. Based on the MBR distribution (see below), it is likely that the Gascoyne/Murchison is an artefact of the analysis – southwestern sites being incorporated into the Pilbara sites, and dragging the cluster centroid south. These clusters should probably reflect occupation of the Pilbara region, and highlight one of the limitations with this type of analysis.

Other cluster centroids are evident through parts of the LGM, but not into the Terminal Pleistocene, including the Nullarbor, Great Sandy Desert, Southeastern Highlands, Ord Victoria Plain/Central and Northern Kimberley, and NSW South Western Slopes (Figure 7). While a number of these IBRA areas are considered arid or semi-arid, the archaeological sites and cluster centroids are generally located on their periphery and may reflect the use of the margins rather than occupation within the bioregion (e.g. JSN site, Puritjarra rockshelter, Koonalda Cave, Allens Cave).

Several cluster centroids begin to appear in the Terminal Pleistocene, including Central Ranges, MacDonnell Ranges, Avon Wheatbelt/Coolgardie, Arnhem Plateau/Pine Creek, Mulga Lands/Channel Country, Sydney Basin (and surrounds), and Mulga Lands/Channel Country (Figure 6), and suggest increasing occupation or expansion across Australia during this period. In west and northwest Australia, cluster centroids are all in similar locations through the LGM, before increasing spatial dispersion in the Terminal Pleistocene. There may have been general abandonment of much of this region with few cluster centroids evident between 17-12ka (Figure 6).

The ACR (~14.5-12.5ka) saw a slight contraction of centroids from the preceding periods, with most clusters focussed in the eastern portion of the continent (Figure 6). In addition to the centroids outlined above, several new areas are highlighted, Tanami, Channel Country, Stony Plains, and Nandewar. With the exception of Nandewar (on the east coast of Australia), several of these may be an artefact of the analysis, which has few data points during this period – the analysis combining central Australian sites with those on the periphery of the continent, and thereby dragging the centroids into marginal parts of the arid interior.

The MBRs are presented in Figure 6. They suggest that there are a number of patterns in the data, although the broad scale nature of the analysis makes interpretation complex. This is especially the case in western and southwestern Australia, where the few data values available have combined regions (such as the Pilbara and Warren) that were probably never linked archaeologically. However, taking these limitations into account, the MBRs suggest a relatively small dispersal area during the early part and peak of the LGM (25-19ka), especially in the Gulf of Carpentaria and southeastern Australia, before expansion between 19-15ka. The period between ~14.5-12.5ka (ACR), again, saw range contraction, albeit on a lesser scale than the LGM. Plotting the size of MBRs through time for the eastern portions of Australia (where our data are strongest) clearly shows this pattern with initial values of ~2.4 million km^2 at 24ka; dropping to ~0.56 million km^2 at 21ka; increasing to ~2.2 million km^2 at 15ka; and finally falling to values of ~1.3 million km^2 at 13ka (Figure 7). This suggests a decrease of some 77% of MBR area through the onset and peak of the LGM.

Through the LGM, there were several areas that were not encompassed within MBRs, and suggest an absence of human activity during this period, including the Gibson Desert; Great Victoria Desert; Central Arnhem; Arnhem Coast; Simpson Strzelecki Desert; Stony Plains; Gawler; and parts of the Nullarbor, Central Ranges, Gulf Fall and Uplands, Burt Plains, Mitchell Grass Downs and Channel Country. Cumulatively, these regions would have formed a 500km (or more) barrier across the entire length of the continent. There is also some suggestion of a barrier between the west coast and central Australia. Several of these regions remain devoid of MBRs throughout 25-12ka, and indicate movement through these regions was low, and occupation unlikely. We stress, however, that in many cases these apparent barriers more likely reflect an absence of archaeological fieldwork rather than a true barrier to human mobility.

6. Discussion

For the first time, we use statistical techniques to assess the Late Pleistocene conceptual hunter-gatherer refugia models that have been developed for Australia. Using the most comprehensive continental archaeological radiocarbon dataset available, we suggest several areas that were likely refugia for Aboriginal populations through the LGM and ACR. The analysis further indicates an expansion and relocation of populations in the intervening period, ~19-15ka. We must acknowledge, however, that the data are still temporally and spatially patchy and the results presented here should be considered a first attempt into the use of these type of techniques to address spatial archaeological questions in Australia.

Only one time slice in our analysis is available during the initial onset of the LGM, 25-23ka. This interval shows a low number of cluster centroids and very large MBRs. This may be a reflection of the limited data available, but does correlate with our current knowledge of the period, specifically that pre-LGM archaeological records all indicate low numbers of highly mobile prehistoric people (Beaton, 1983; Smith, 2013; cf. Birdsell, 1957). Williams (2013) has recently proposed continental population estimates in the order of 20,000 people prior to the LGM, and applying this to the MBR areas would equate to 1 person per ~120-170km^2, values that correlate well with ethnographic observations of hunter-gatherers in the poorer resourced (more arid) zones of Australia (e.g. Gould, 1969; Long, 1971; Berndt, 1972; Cane, 1990; Keen, 2004).

As the LGM intensifies between 22-19ka (time slices 24-22ka, 23-21ka, 22-20ka, 21-19ka), cluster centroids converge into a small number of bioregions and the size of the MBRs reduce by some 77% in eastern Australia. We interpret this process as populations contracting into well-resourced refugia environments as one response to climatic deterioration through this period. Assuming the MBRs provide an indication of territory used, this reduction suggests a shift in foraging and social strategies from highly mobile practices to increased use of local resources and abandonment of more marginal areas (Gould, 1982, 1991; Veth, 1989b). This form of response was probably also dictated by significant population collapse during this time (Williams, 2013), that may have hindered other survival mechanisms such as trade and exchange systems. This reduction in foraging and social strategies is also reflected in the distribution of material culture whose primary role centers around the mediation of social relationships (i.e. body ornamentation, rock art and potentionally notational pieces), with these items all decreasing in the archaeological record at this time (Langley, 2009; Langley et al., 2011).

The persistence of occupation during the peak of the LGM in the Murray Darling Depression, South Eastern Highlands/NSW South Western Slopes and the Tasmanian Central Ranges can all be readily explained as climatic refugia, with glaciation of the Australian Alps, Snowy Mountains, Victorian Alps, Ben Lomond Plateau and West Coast Ranges (Barrows et al., 2001, 2002, 2004) leading to increased summer snowmelt along the surrounding river systems through this period. High lake-levels in the Willandra Lakes system, in the heart of the Murray Darling Depression, are considered a result of snowmelt feeding the Murrumbidgee and Lachlan Rivers (Bowler et al., 2012), and similar mechanisms probably occurred for the major river systems in central and western Tasmania. Several of the Tasmanian rockshelters that show peak occupation around the LGM are in close proximity to (probable) glacially-fed rivers, including Parmerpar Meethaner (Forth River), Pallawa Trounta (Acheron River) and Wareen (Upper Maxwell River) (Cosgrove, 1995; Stern and Allen, 1996; Allen, 1996). Similarly, the highest occupation evident in the Willandra Lakes system occurs through the LGM (e.g. Balme and Hope, 1990; Webb et al., 2006; Smith et al., 2008). The headwaters of Maribyrnong River in central Victoria, where several sites around Keilor date to the LGM period (e.g. Godfrey et al., 1996), also starts in the Victorian Alps. In the Sydney Basin, Williams et al. (2012) have shown intense occupation on the banks of the Hawkesbury River through the LGM and Terminal Pleistocene, and hypothesised that increased snowmelt in the Blue Mountains may have sustained populations during this period. Dense occupation deposits at Mannalargenna Cave on Seal Island in Bass Strait during the LGM (Brown, 1993), suggest marine resources may also be a factor in the Tasmanian refugium.

The reduction in rainforest to more open productive plains allowing pursuit of the red necked wallaby and other game was also likely to be a key factor in Tasmanian settlement during the LGM (Colhoun and Shimeld, 2012; Cogrove, 1995; Stern and Allen, 1996). A similar explanation may also account for ongoing human occupation of southwest Australia. Dortch and Wright (2010) demonstrated the hunting and exploitation of large macropods (and other game) throughout the LGM, but became increasingly difficult as the vegetation canopy closes in the Holocene, with complex hunting practises and greater numbers of people being required.

With the exception of the snowmelt-fed refugia above, only the Brigalow Belt South and the Gulf Plains/Einasleigh Uplands show consistent use throughout the late Pleistocene. Fieldwork projects along the Norman River, Gregory River, and Lawn Hill (Hiscock, 1988; Cosgrove et al., 2007; Slack et al., 2004; Slack, 2007; Wallis et al., 2009) have all demonstrated the refugia qualities of the Gulf Plains/Einasleigh Uplands previously, a finding now supported statistically here. It is interesting to note that the *Pama-Nyungan* language is argued to have expanded from this region in the early Holocene shortly after this long period of stability (McConvell, 1996; Smith, 2005). The importance of the Brigalow Belt South most likely stems from its location on the headwaters of parts of the Murray Darling river system and its encompassment of the Fitzroy River catchment. Croke et al. (2011) have recently demonstrated that the Fitzroy River remained active during the LGM, in contrast to most other parts of sub-tropical and tropical Queensland. Godwin (2012) has recently also proposed a close link between Artesian Basin mound springs (*a priori* groundwater availability) and archaeological sites (including the Brigalow Belt South) during the LGM.

The rationale for the ongoing use of the remaining refugia (Kimberley region, Pilbara, Murchison, Gascoyne, Sydney Basin, Warren and Nullabor) is unclear. All of these bioregions appear to be situated within the main monsoon or westerly belts (Sturman and Tapper, 1996), although both systems were severely reduced (or completely absent) during the LGM and Terminal Pleistocene. There is some evidence for ongoing albeit episodic and sporadic rainfall across various parts of Australia through the LGM and Terminal Pleistocene (e.g. Rittenour et al., 2000; Petherick et al., 2011), but it is likely that a range of local environmental and resource factors may prove a more suitable explanation for the continuous use of these regions.

The refugia in the western portion of Australia are problematic owing to the analysis combining the low numbers of data in the southwest, with those of the Pilbara. Based on the archaeological evidence, there is little evidence for human activity in the LGM/Terminal Pleistocene in Murchison or Gascoyne area, with the possible exception of Serpent’s Glen rockshelter just prior to the LGM (O’Connor et al., 1998). Most of the archaeological sites exhibiting LGM occupation occur on the gorges along the Hamersley Ranges, including Milly’s Cave, Yirra, Juukan 2, Malea (Marwick, 2002; Edwards and Murphy, 2003; Veitch et al., 2005; Slack et al., 2009), and we therefore believe the Pilbara bioregion should be considered the main refugia in this part of Australia (Figure 8). Smith (2013), however, notes that several sites in the Pilbara were abandoned during the peak of the LGM (Manganese Gorge 2, Juukan-1, Newman P2055, GRE8, Mandu Mandu, Riwi and Jansz) and suggests that the human response in this region may provide an example of a cryptic refugia, with people moving away from the edges of the plateau into more reliable water on the plateau itself with a re-organisation of land-use, involving fewer sites in marginal areas on the plateau and contraction toward use of focal waters associated with major gorge systems.

Following the LGM, cluster centroids start to become spatially divergent and the MBRs increase, suggesting a re-organisation of populations as climate ameliorates. Increasing activity is evident in the southeastern corner of Australia, and across much of Western Australia, and may be in response to increasing humid conditions in the southern part of the continent during this time (Fitzsimmons et al., 2012). Here again the distribution of material culture supports the notion of a re-organisation of populations and their social systems at this time. In particular, those artefacts which had previously decreased in the archaeological record as the LGM intensified (ornamentation, rock art, pigment use etc), now begin to increase in the archaeological record with populations increasing, and conditions improving environmentally and climatically (Langley, 2009; Langley et al., 2011).

There is little palaeo-climatic evidence of the ACR in Australia, although here again we see a reduction in MBRs of up to 47%, and a possible return of populations into broad refugia areas. Previous time-series analyses have also shown a decline in the number of radiocarbon dates during this climatic event, which was inferred as falling populations in response to increasing climatic variability (Williams, 2012, 2013). However, in contrast to the LGM were critical population and/or climatic thresholds may have been crossed, social interaction appears uninterrupted by the ACR, with the deposition of symbolic material culture into the archaeological record continent wide increasing exponentially. Evidence for many time-invested cultural behaviours including, the production of rock art, ritual burials, and the manufacture and transport of ornamentation become more and more frequent. Furthermore, forms of cultural expression never before identified in the archaeological record appear, such as the intentional deformation of crania as seen at Cohuna, Kow Swamp, Coobool Creek and Nacurrie (Antón and Weinstein 1999; Brown 1981; Langley et al. 2011; Pardoe 1993).

In relation to barriers to prehistoric movement and occupation, several bioregions remain empty throughout the time period under consideration. Unsurprisingly, these are primarily the main desert regions of Australia, including the Gibson Desert, Great Victorian Desert, Simpson-Strzelecki Desert and Little Sandy Desert. Several studies across these and other surrounding regions demonstrate Holocene deposits (Figure 3) showing that they have been investigated, but fail to identify Pleistocene use. This strongly suggests that they are true barriers to human movement. However a number of regions contain no archaeological data and it is therefore unclear whether these were barriers, or have simply yet to be adequately characterised archaeologically.

Using our analysis, we have developed a new model of refugia across Australia (Figure 8). This model presents only those areas that can be reasonably confidently identified as refugia. Due to the uncertainty of the barriers outlined above, which may relate to an absence of archaeological data, we have not considered them in the model. Similarly, those areas that cannot be characterised have been left undetermined at this stage, and warrant further consideration as data become available. Generally, our model is quite similar to Veth's (1989b, 1993) (Figure 2). In most cases, the general regions of refugia are the same, although the adoption of bioregions provides a more accurate delineation of the edges of such zones. We have identified larger areas along the Gulf of Carpentaria and in the Murray Darling Depression, and smaller areas in the Kimberley and southwest Australia. The Brigalow Belt South is identified in both models, but the focus of our refugium is further west, closer to Roma than Rockhampton as proposed by Veth. In central Australia, Veth identifies both the MacDonnell Ranges and Central Ranges, whereas our map only identifies the latter. Archaeologically, both ranges were probably used during the LGM and Terminal Pleistocene, but our analysis combined data between the Nullarbor and central Australia, and moved the centroids south. In the west, Veth proposes the Pilbara and much of southwest Australia as refugia, as outlined above our analysis had data issues in these areas. Based on recent archaeological evidence, we agree with Veth's identification of the Pilbara, but believe that the southwest Australian refugium is overly large, and should probably only include the coastal fringe (Warren).

In terms of barriers, our data are too patchy to provide a definitive comparison with Veth's original model. There is some evidence that the major desert systems were not occupied or utilised during the LGM and Terminal Pleistocene, but this may be reflection of patterns and intensity of archaeological research, rather than actual barriers to human occupation (Langley et al., 2011). Our model does show evidence of activity in the Channel Country, Nullarbor, and Mulga Lands, all of which were previously identified as barriers, and this suggest a reduction in the areas proposed by Veth may be warranted.

7. Conclusion

In this pilot study, we explore the conceptual refugia-corridor-barrier models proposed by archaeologists over the last three decades to explain human response to climatic instability through the LGM and Terminal Pleistocene. Using a comprehensive dataset of radiocarbon dates from archaeological sites across Australia, and geospatial analysis, we conclude that some bioregions were preferred by people through this period, and can be considered refugia. We also identify several areas that were abandoned and/or never used, and can be considered barriers in accordance with these models. We highlight that several of these refugia persisted throughout the Terminal Pleistocene, and suggest that hunter-gatherers may have struggled to adapt to the climatic instability evident through this period. We stress, however, that the archaeological data for this period are still spatially and temporally patchy, and that consequently these results should be considered preliminary.

Adopting cluster analysis, we identify between 6 and 9 refugia in 2,000 year time slices between 25-12ka. Of these, several areas are consistently highlighted as of importance to people, including (by IBRA bioregion) Gulf Plains/Einasleigh Uplands, Murray Darling Depression, and Tasmanian Central Highlands. Other areas were used less consistently, but still contain several periods of activity and include the South Eastern Highlands, NSW South Western Slopes, Sydney Basin, Central and Northern Kimberley, Arnhem Plateau, MacDonnell Ranges, Central Ranges, Murchison, Gascoyne and Warren. Archaeological evidence also suggests that the Pilbara formed a refugium during the LGM, but our analysis of Western Australia proved problematic owing to the low number of data points in some areas.

We postulate that these refugia can be explained through a range of local environmental and climatic conditions making them favourable to hunter-gatherers during periods of resource stress, most notably the exploitation of snowmelt from increased glaciation in the uplands, feeding river systems across southeastern Australia and Tasmania. In Tasmania and southwest Australia, changing vegetation pattern to more open conditions and leading to modifications of hunting strategies may also have played a role. Elsewhere, local environmental and resource factors may provide a better explanation for their use.

Using point dispersal patterning, we demonstrate that the size of each cluster's 'catchment', a proxy for population territory, was significantly reduced during the peak of the LGM (by some 77% in eastern Australia from previous or subsequent time intervals), and suggest a change in foraging and social strategies through this period. Increased effective territory occupation only increases between 19-15ka to pre-LGM levels, before again decreasing with the onset of the ACR.

Our analysis correlates well with the Islands in the Interior model proposed by Veth (1989b, 1993). By adopting the use of bioregions, our map provides a more accurate delineation of possible refugia, and in so doing changes their size and location as considered by Veth, but in general both highlight similar areas. Our map, however, only includes regions that have archaeological information, and for this reason several areas, remained undetermined as to their relevance to people through this period.

The analysis undertaken here provides greater reliability in the largely conceptual models proposed by researchers in the 1980s and 1990s. We highlight a number of regions that were probably refugia during periods of climatic instability. These areas should now form a focus of more detailed research to both confirm/refute their assignment as refugia. Further, given recent phylogeographic results, detailed regional studies need to be undertaken in these bioregions to identify more complex cryptic or idiosyncratic refugia responses that may be evident in the archaeological record.

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Table 1. Optimum number of cluster centroids based on Figure 3.

Figure 1. The impact of climate variability on Aboriginal populations in the Late-Terminal Pleistocene (after Williams, 2013). Using a radiocarbon dataset of several thousand dates from archaeological sites across Australia (C) (all data were calibrated and data-binned into 250 year intervals; uncorrected data is presented as a stacked bar chart with white bars = rockshelters and black bars = open sites; taphonomically corrected data after Williams (2012) are presented as grey bars with a 600-year moving average trendline), Williams developed a method of producing annual population growth rates (GR_{Ann}) for the last 50,000 years (A). (B) presents the same data as (A), but using the taphonomically corrected data from (C). While overall the GR_{Ann} in both (A) and (B) shows an increase in population of 0.01% over the last 50,000 years, as presented here the Terminal Pleistocene, especially the LGM and ACR (highlighted), caused significant impacts to Aboriginal populations, with declines of up to 60% observed through this period. See Williams (2013) for further explanation of methods and discussion.

Figure 2. Map of refugia, barriers and corridors for human occupation through the Last Glacial Maximum (after Veth, 1989b, 1993).

Figure 3. Map of all archaeological radiocarbon data for the Australian continent. The dataset consists of a number of sequentially published regional datasets, which cumulatively cover the entire continent within the limits of archaeological research. The map shows archaeological sites containing radiocarbon dates used in this analysis (squares). All other radiocarbon data (>25ka - <12ka) compiled by the authors is also presented (dots) to demonstrate where archaeological research has occurred across Australia, but failed to identify human activity during the LGM or ACR; using these data, we infer where barriers to human activity may have been during the late Pleistocene.

Figure 4. Map showing the Interim Biogeographic Regionalisation for Australia (IBRA) regions (after Thackaway and Cresswell, 1995) discussed in text. IBRA codes are also listed and can be found in the original publication.

Figure 5. Graph showing the optimum number of cluster centroids (*k*) based on the elbow method. Optimum values varied between time intervals, but was generally between 6 and 9 cluster centroids (refer to Table 1).

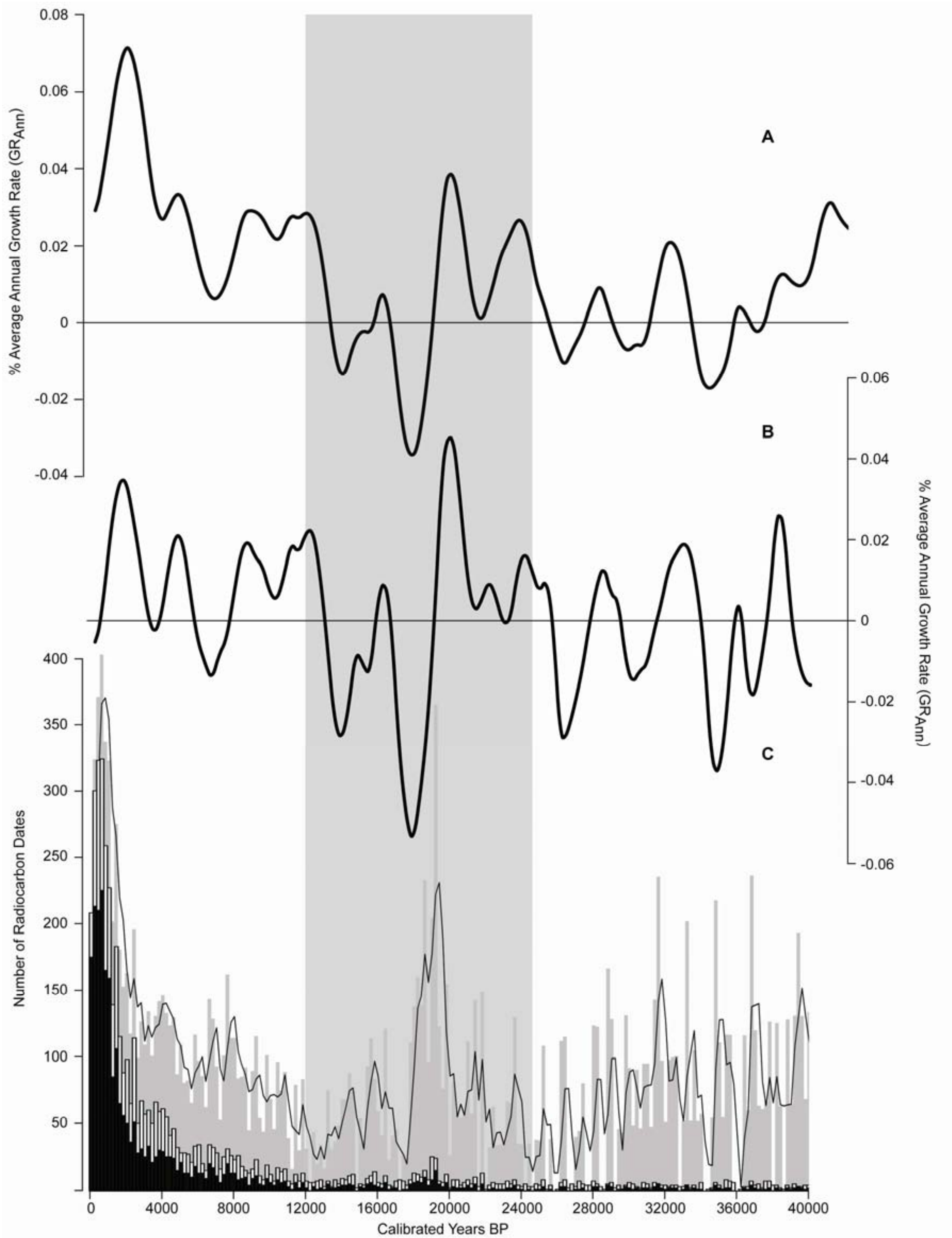
Figure 6. Map showing the location of cluster centroids and MBRs by over-lapping time slice and bioregion after Thackway and Cresswell (1995).

Figure 7. Graph of MBR values (km^2) for the eastern portion of Australia between 25-12ka.

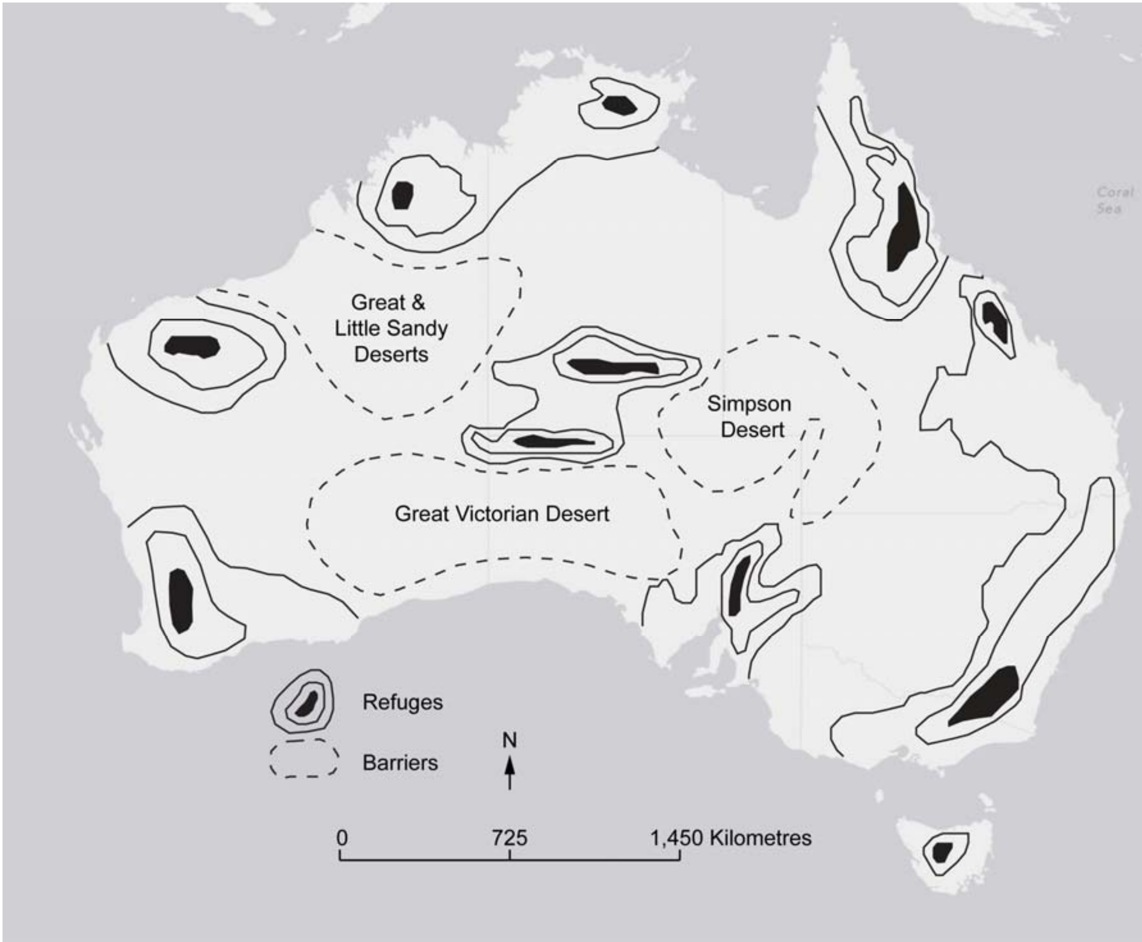
Figure 8. Map showing likely refugia (green) based on bioregions after Thackaway and Cresswell (1995) and the analysis undertaken here. Only bioregions with two or more clusters have been highlighted as refugia. The Pilbara has been identified in blue, and is considered a refugium based on information outlined in the text. The edge of the Nullarbor should also be considered a refugium, but highlighting the entire bioregion here would have provided an unrealistically large area given all archaeological sites are <20km from the coast. Areas without colour do not have enough information to determine their relevance to human activity between 25-12ka.

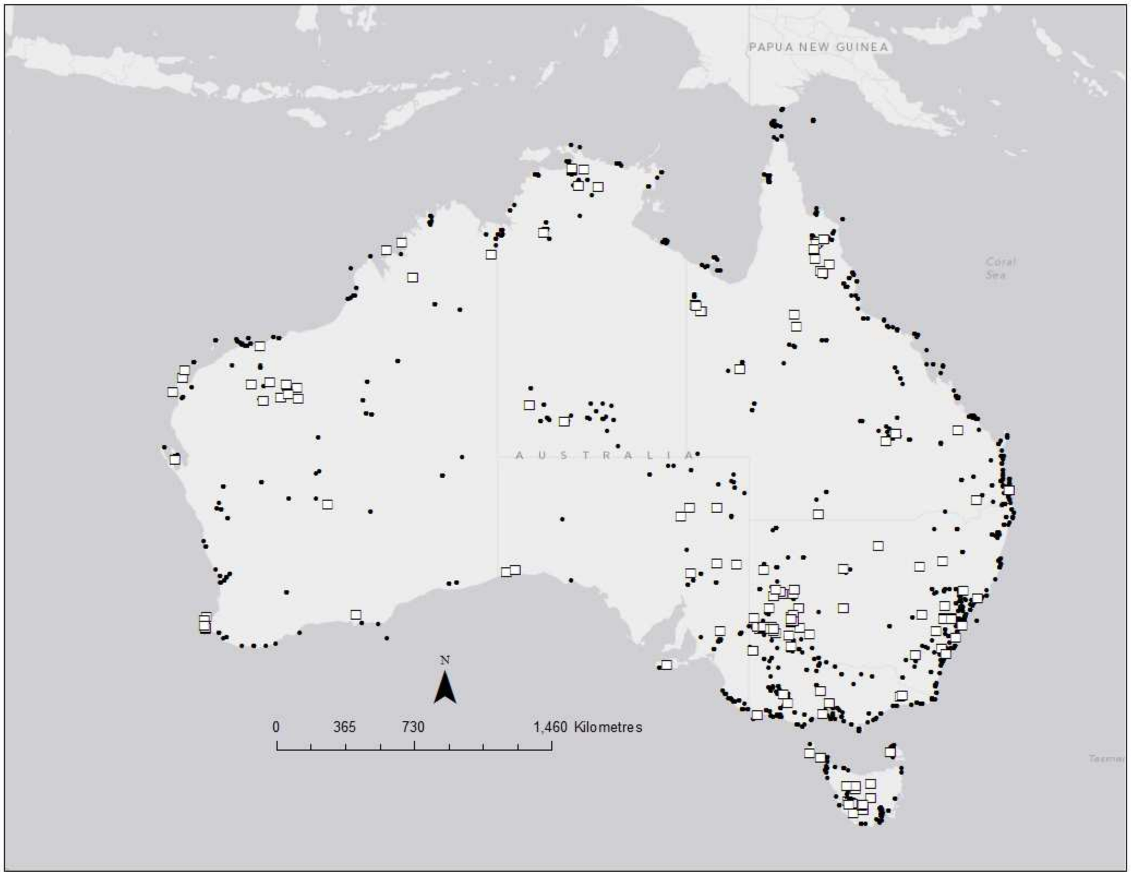
Research Highlights

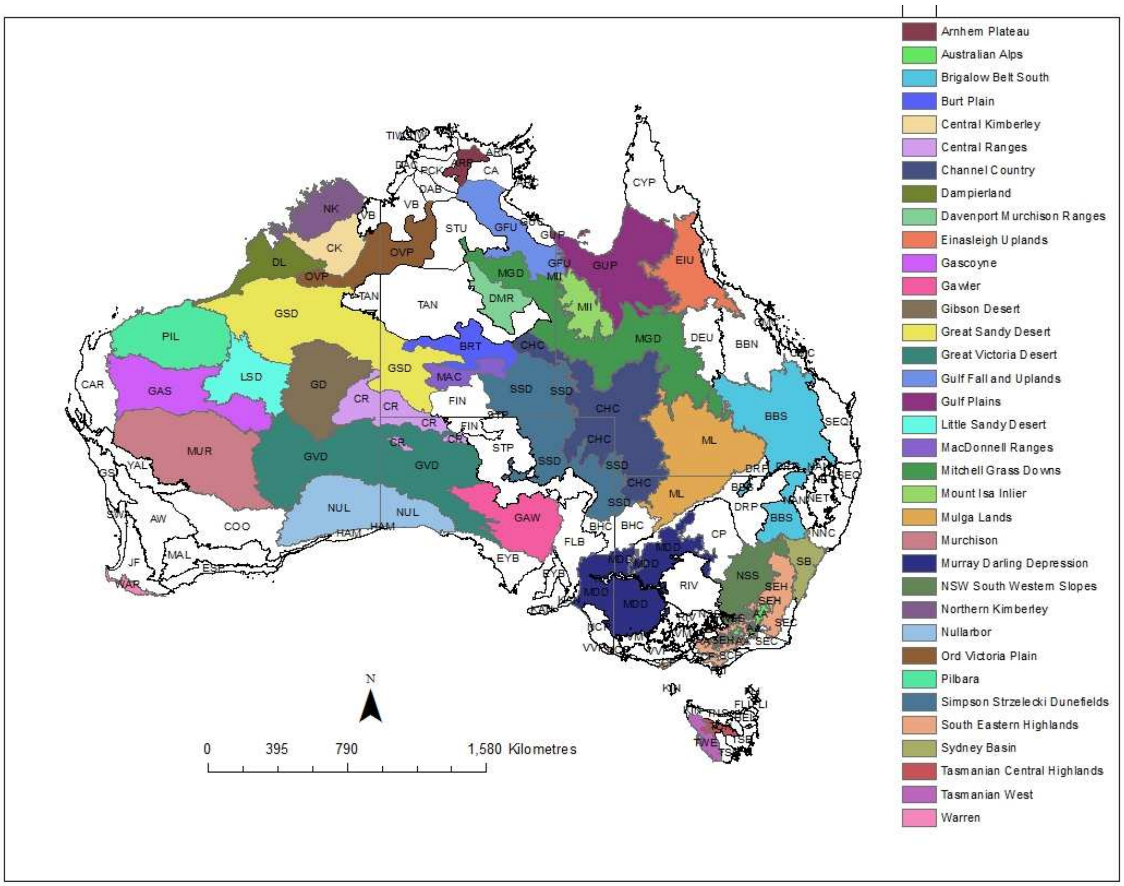
- This paper uses a continental wide dataset of archaeological radiocarbon dates to explore human behaviour between 25-12ka.
- Geospatial analysis shows hunter gatherers retreated into refugia as one response during the Last Glacial Maximum and Antarctic Climate Reversal, with expansion in the intervening period.
- The analysis suggests a number of bioregions that would have acted as refugia across Australia – most receiving increased melt-water from glaciated regions.
- The analysis corroborates and empirically supports LGM refugia models proposed in the 1980s.
- We identify areas for future research, including a focus on regional studies to determine possible cryptic or idiosyncratic refugia emerging in phlyogeographic studies.

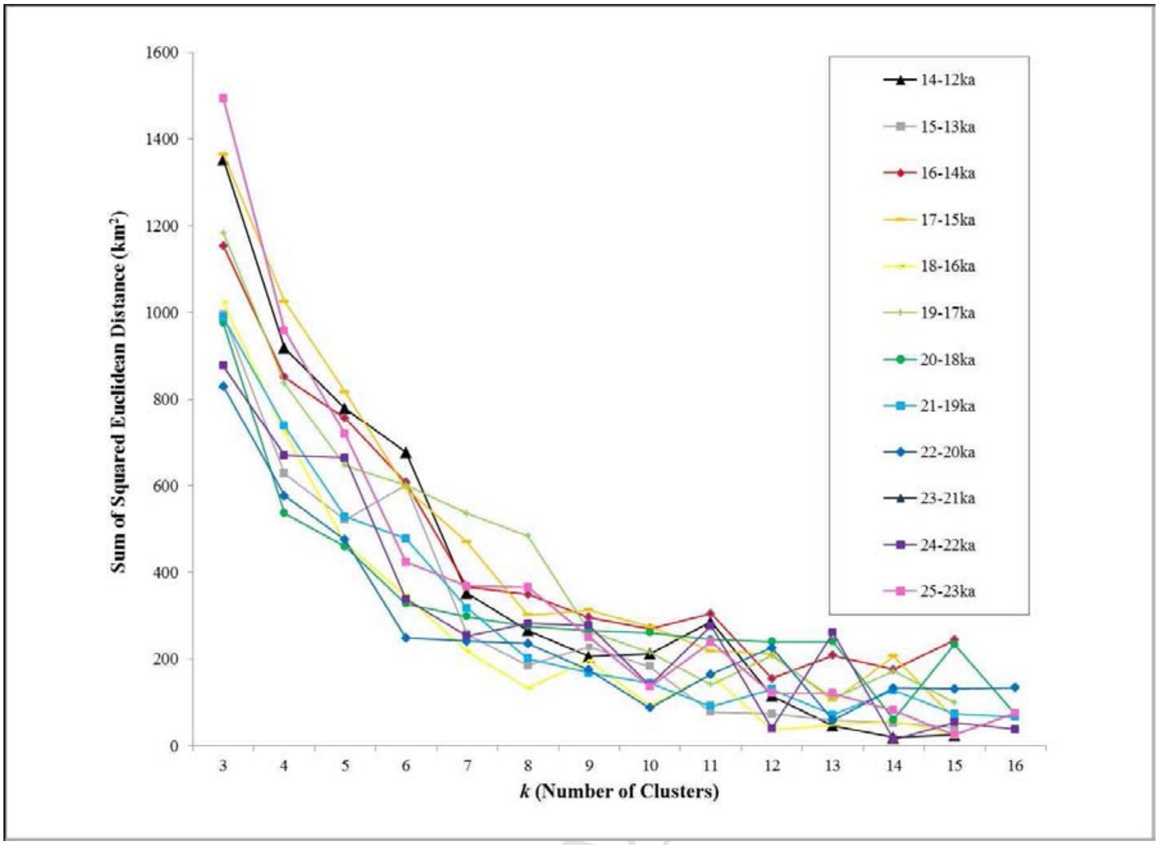


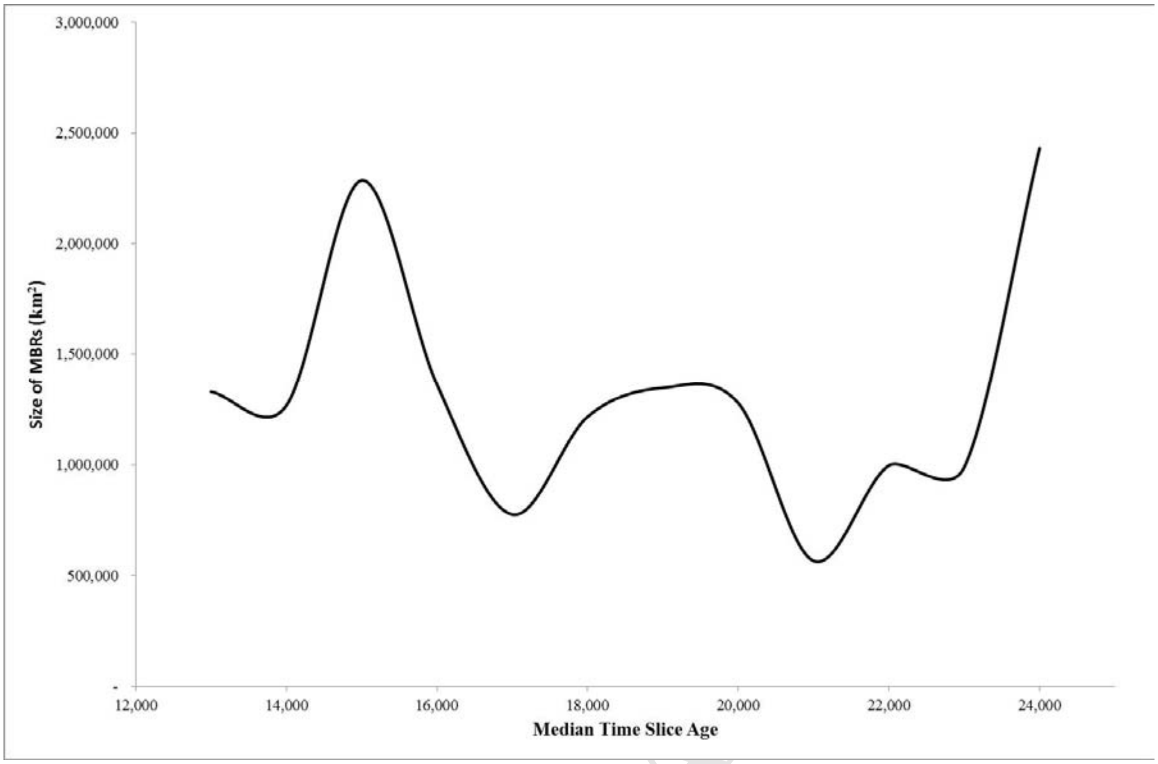
0.08
0.06
0.04
0.02
0
-0.02
-0.04
% Average Annual Growth Rate (GR$_{Ann}$)
A
B
C
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
% Average Annual Growth Rate (GR$_{Ann}$)
400
350
300
250
200
150
100
50
Number of Radiocarbon Dates
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
40000
Calibrated Years BP

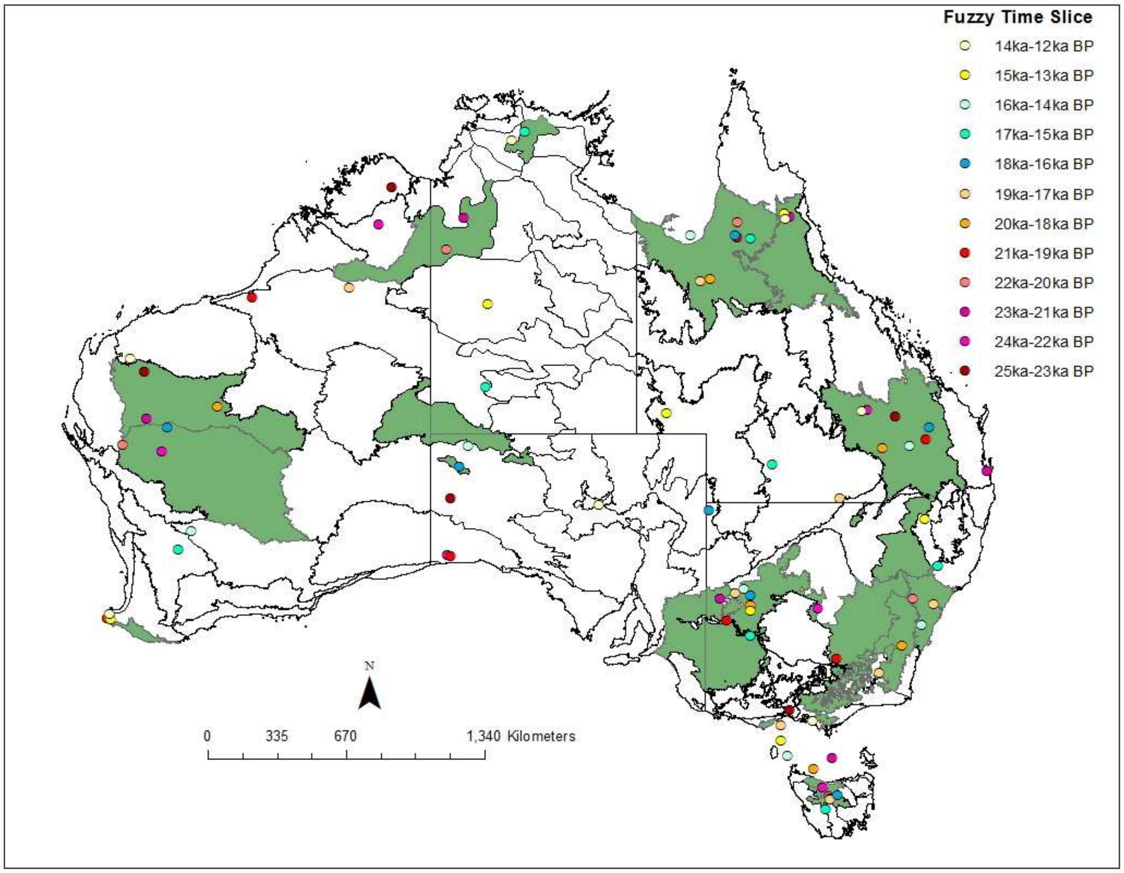

Coral Sea
Great & Little Sandy Deserts
Simpson Desert
Great Victorian Desert
Refuges
Barriers
N
0
725
1,450 Kilometres

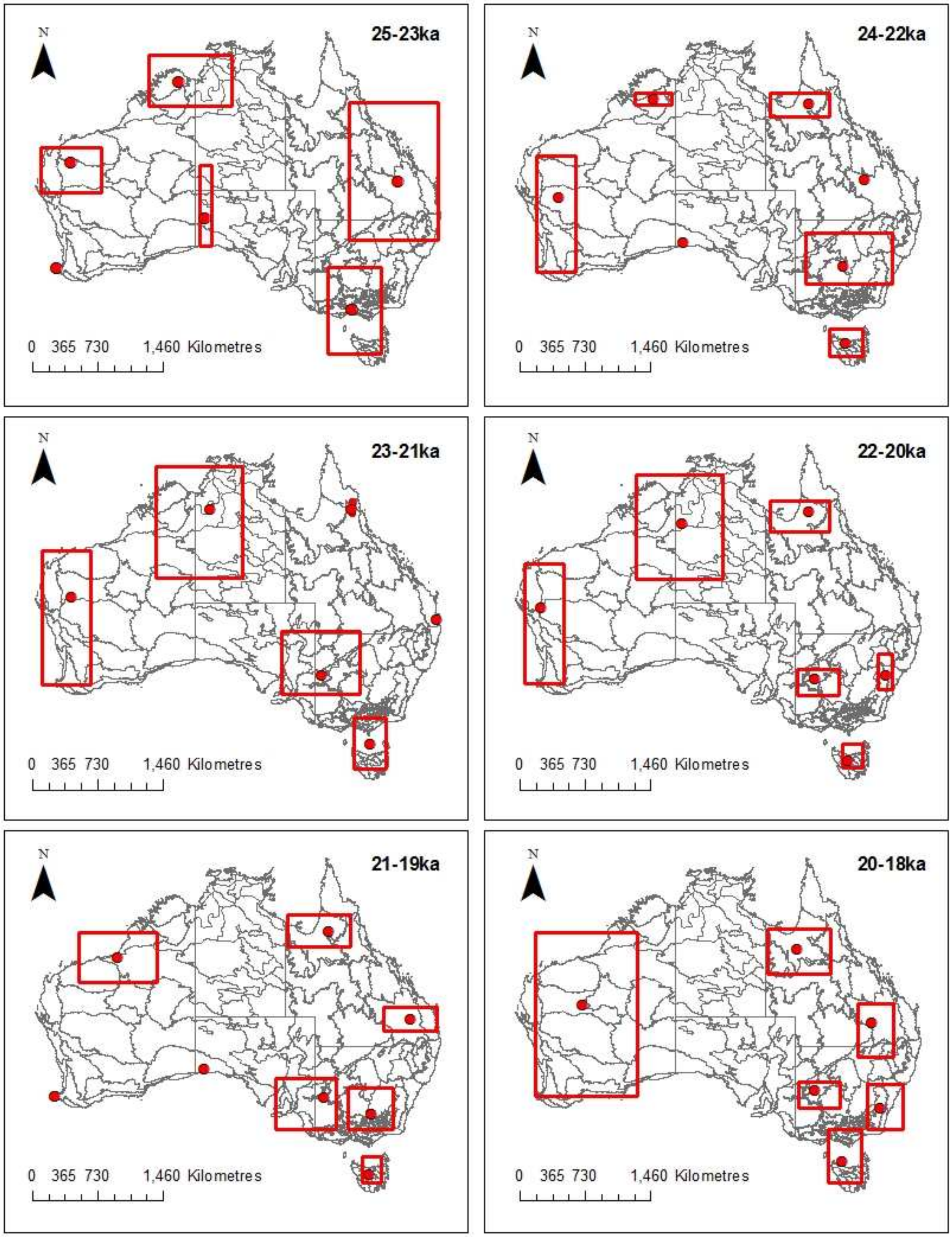

PAPUA NEW GUINEA
Coral Sea
AUSTRALIA
N
0 365 730 1,460 Kilometres


Arnhem Plateau
Australian Alps
Brigalow Belt South
Burt Plain
Central Kimberley
Central Ranges
Channel Country
Dampierland
Davenport Murchison Ranges
Einasleigh Uplands
Gascoyne
Gawler
Gibson Desert
Great Sandy Desert
Great Victoria Desert
Gulf Fall and Uplands
Gulf Plains
Little Sandy Desert
MacDonnell Ranges
Mitchell Grass Downs
Mount Isa Inlier
Mulga Lands
Murchison
Murray Darling Depression
NSW South Western Slopes
Northern Kimberley
Nullarbor
Ord Victoria Plain
Pilbara
Simpson Strzelecki Dunefields
South Eastern Highlands
Sydney Basin
Tasmanian Central Highlands
Tasmanian West
Warren
N
0 395 790 1,580 Kilometres


1600
1400
1200
1000
800
600
400
200
0
Sum of Squared Euclidean Distance (km²)
3
4
5
6
7
8
9
10
11
12
13
14
15
16
k (Number of Clusters)
14-12ka
15-13ka
16-14ka
17-15ka
18-16ka
19-17ka
20-18ka
21-19ka
22-20ka
23-21ka
24-22ka
25-23ka


3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
-
Size of MBRs (km²)
12,000
14,000
16,000
18,000
20,000
22,000
24,000
Median Time Slice Age


Fuzzy Time Slice
14ka-12ka BP
15ka-13ka BP
16ka-14ka BP
17ka-15ka BP
18ka-16ka BP
19ka-17ka BP
20ka-18ka BP
21ka-19ka BP
22ka-20ka BP
23ka-21ka BP
24ka-22ka BP
25ka-23ka BP
N
0
335
670
1,340 Kilometers


N
25-23ka
0 365 730 1,460 Kilometres
N
24-22ka
0 365 730 1,460 Kilometres
N
23-21ka
0 365 730 1,460 Kilometres
N
22-20ka
0 365 730 1,460 Kilometres
N
21-19ka
0 365 730 1,460 Kilometres
N
20-18ka
0 365 730 1,460 Kilometres

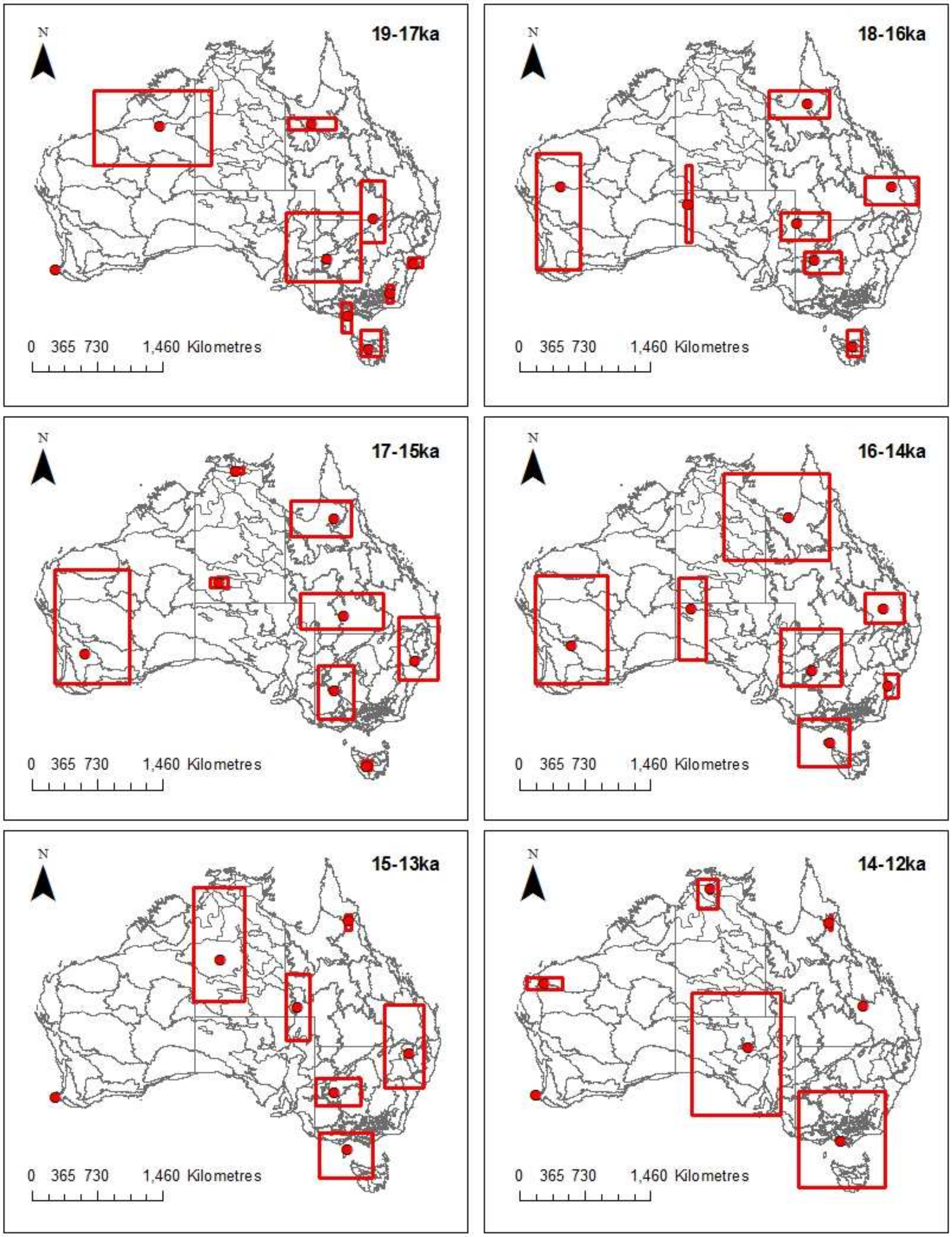

19-17ka
18-16ka
17-15ka
16-14ka
15-13ka
14-12ka
N
0 365 730 1,460 Kilometres

Table 1.

Fuzzy Time Slice	Median Age	Number of Cluster Centroids (*k*)
25-23ka	24ka	6
24-22ka	23ka	7
23-21ka	22ka	6
22-20ka	21ka	6
21-19ka	20ka	8
20-18ka	19ka	6
19-17ka	18ka	9
18-16ka	17ka	7
17-15ka	16ka	8
16-14ka	15ka	7
15-13ka	14ka	7
14-12ka	13ka	7