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Smallest Late Pleistocene inhabited island in Australasia reveals the impact of post-glacial sea-level rise on human behaviour from 17,000 years ago

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ABSTRACT

Late Pleistocene records of island settlement can shed light on how modern humans (*Homo sapiens*) adapted their behaviour to live on ecologically marginal landscapes. When people reached Sahul (Pleistocene New Guinea-Australia), between 65 and 50 ka, the only islands they would have encountered were in the tropical north. This unique geographic situation therefore offers the only possibility of modelling human adaptive behaviour to islands in Australasia during the Late Pleistocene. Cave excavation on the uplifted limestone island of Panaeati in the Massim region of Southeastern New Guinea revealed a cultural sequence commencing from 17,300–16,800 cal. BP, suggesting habitation of higher coastlines occurred as low-lying shorelines destabilised during the initial stages of deglacial sea-level rise. No cave use was evident between 12,400 and 4780 cal. BP when the continental shelf was fully inundated, and Panaeati reduced in size by 90%. It is likely that diminished coastlines and the reduced resources of low-lying islands could no longer support pre-agricultural populations during this time. Cultural groups that were better adapted to living on small islands returned to Panaeati by 4780–4490 cal. BP when sea levels had stabilised, lagoons formed, and coastal ecosystems had diversified. Investigations demonstrate the role of larger islands as refugia during deglacial sea-level rise and the effects on human dispersals and cultural diversity.

1. Introduction

The dispersal of modern humans (*Homo sapiens*) from Eurasia to Sahul (the joint Pleistocene New Guinea-Australia landmass) between 65 and 50 ka was the first time our species migrated away from a continental landscape (Bird et al., 2019; Bradshaw et al., 2019; Clarkson et al., 2017; Summerhayes et al., 2010a; Veth et al., 2017; Will et al., 2019). Archaic human species had occupied the Wallacean islands separating these ecologically distinct continents for at least one million years (Brumm et al., 2010; van den Bergh et al., 2016). However, on current evidence, Wallacea formed an ecological and technological barrier preventing earlier dispersals to Sahul (Hawkins et al., 2017; Kealy et al., 2016; O'Connor et al., 2017) (Fig. 1a). Once in Sahul, people would have only encountered islands in the tropical north where deep submarine trenches separate volcanic arcs from New Guinea (northern Sahul). These islands were separated from Sahul even during the Last Glacial Maximum (LGM, ~23–19 ka) when sea levels were 135–125 m lower (Hanebuth et al., 2009; Ishiwa et al., 2016; Lambeck et al., 2014). No islands were present around Australian (central-southern Sahul) or southern New Guinea shores until the

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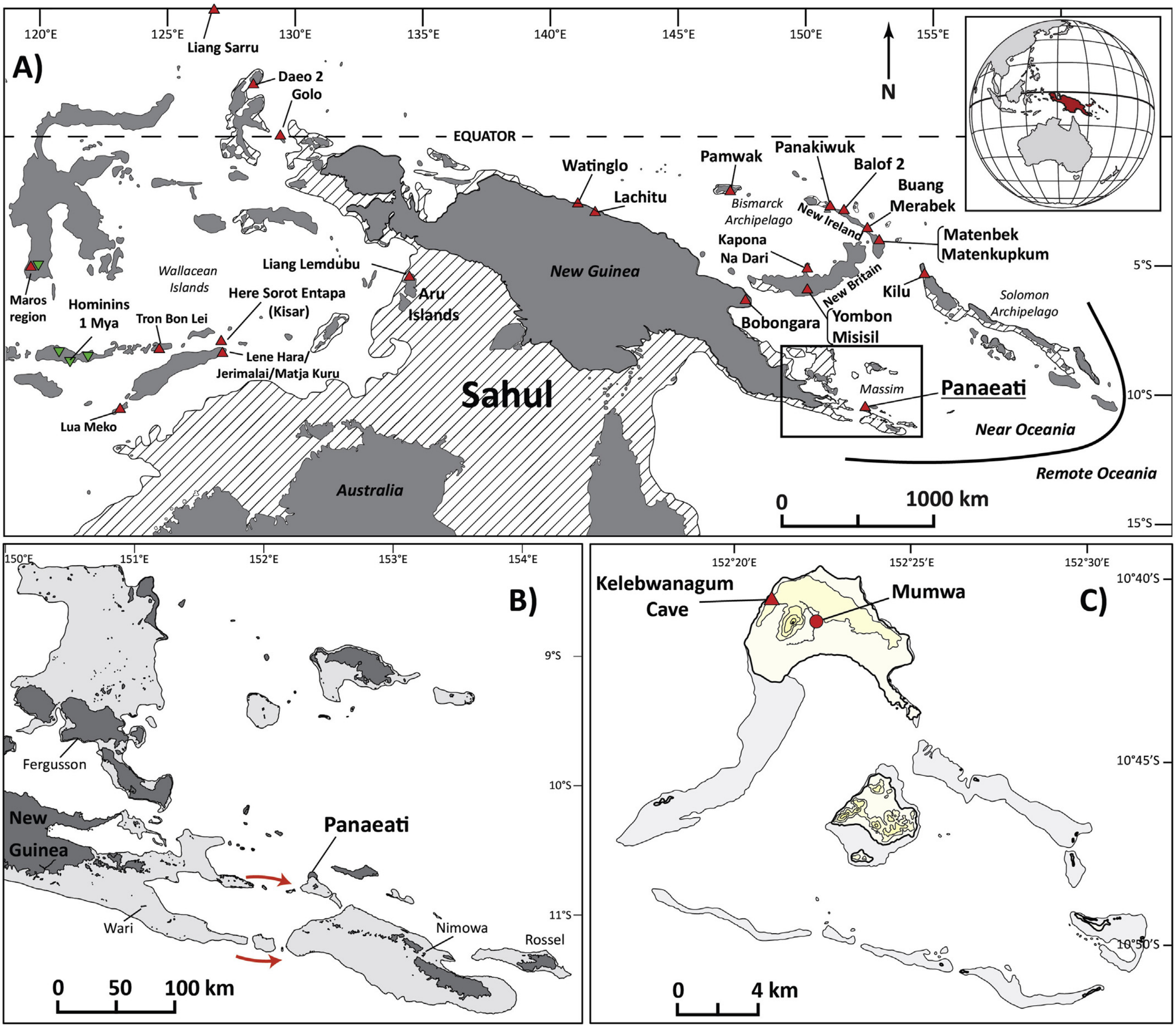

Fig. 1. Location of Panaeati Island within (A) Northern Sahul showing other island and coastal archaeological sites with Late Pleistocene human occupation, and (B) Massim island region. (C) location of Kelebwanagum cave and the excavated mid-Holocene Mumwa site on Panaeati Island. Red triangles: Modern human site. Green inverted triangle: Hominin site. Inland Late Pleistocene sites are not indicated. Hashed outline in (A) shows the maximum extent of coastline during the LGM, and the rectangle indicates the geographic extent of the Massim Island Region. Light shaded reef outline in (B) and (C) marks the area of the Late Pleistocene coastline. Red arrows in (B) indicate the two pathways to the Pleistocene islands in the southern Massim. Sites mentioned in the text are labelled. Inset: Global position of New Guinea. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Holocene (≤11.7 ka) when post-glacial sea-level rise drowned the shallow continental shelf and the Late Pleistocene coastline (Beaton, 1995; McNiven et al., 2014; O'Connor et al., 2006; Rowland et al., 2015; Sim and Wallis, 2008; Ulm, 2011; Veth et al., 2017). New Guinea, therefore, presents the only opportunity to model Late Pleistocene (≥11.7 ka) human behavioural adaptations to Near Oceanic island ecosystems immediately adjacent to Sahul (See Green, 1991 for Near/Remote Oceanic definition) (Fig. 1a).

The Bismarck and Solomon Archipelagoes were settled by 43.8–42.4 cal ka (Buang Merabak) and 33.1–31.4 cal ka (Kilu cave), respectively, marking the furthest extent of modern human dispersals into the Pacific region during the Late Pleistocene (Allen et al., 1988; Green, 1991; Leavesley and Allen, 1998; Wickler and Spriggs, 1988). Late Pleistocene populations lacked the technological and navigational capability needed to make the longer open sea voyages (≥350 km) to Remote Oceanic archipelagoes further east (Irwin, 1992). These remote islands were only colonised around 3000 years ago by agriculturalist seafarers defined as the Lapita culture (Bedford et al., 2019; Sheppard et al., 2015; Summerhayes, 2007).

Ten cave and rockshelter sites with evidence for Late Pleistocene human habitation are known on the islands of New Britain (37,050 km^2), New Ireland (7620 km^2), Manus (1740 km^2), and Buka (638 km^2) in the Bismarck and Solomon archipelagoes. A further three sites dating from at least 42.5–36.5 cal ka (Latchitu Cave) are also known on the north coast of New Guinea, the only part of Sahul where because of its steep bathymetry changes in sea level had not significantly altered the position of the coastline (Fig. 1a). Near coastal sites have been identified on the Aru Islands, to the southwest of New Guinea, dating from 27.3 to 26.7 cal ka (Liang Lemdubu) which at this time formed part of the now submerged Sahul landbridge (O'Connor et al., 2006). An extensive suite of Late Pleistocene sites are otherwise known in the interior lowlands, mountains and deserts of New Guinea and Australia (Hiscock, 2008; Smith, 2013; Summerhayes et al., 2017). Meta-analytic modelling of these records indicate that widespread human dispersals had occurred across Sahul prior to the Extended Glacial Period from 30 ka (Bird et al., 2016; O'Connell and Allen, 2007; Williams et al., 2015).

A significant decrease in land size and endemic biota in the Bismarck and Solomon Archipelagoes relative to the vast mosaic landscapes of continental Sahul required innovative behavioural adaptations in resource use, settlement and long-distance seafaring (Fredericksen et al., 1993; Leavesley, 2006; Summerhayes et al., 2017). For the first 20 ka following colonisation relatively small and mobile groups of people exploited marine foods predominantly from fringing reefs and vertebrate fauna from the surrounding rainforest (Gosden and Robertson, 1991; Leavesley, 2004). Low-density settlement continued during significant sea-level drawdown from 30 ka, with reduced cave use or complete abandonment apparent at most sites during the LGM (Leavesley, 2006). Behavioural adaptations during the LGM reinforced foodways and social networks, which included the introduction of cuscus (*Phalanger orientalis*) as a protein resource in a depauperate terrestrial ecosystem, and the commencement of inter-island obsidian trade across distances over 200 km (Allen and Gosden, 1996; Summerhayes and Allen, 1993). Landscape use increased over subsequent millennia and intensified throughout the Holocene (Fig. 2, Fig. S1).

Islands in the Massim region of southeastern Papua New Guinea, unlike the Bismarck Archipelago, the north coast of New Guinea, and Wallacea, reduced significantly in size and changed configuration following the LGM. These changes greatly affected ecosystem biodiversity and proximity to the Sahul supercontinent (Fig. 1b). The extensive reef systems encompassing many of the southern Massim islands mark the former position of the Pleistocene coastline which lie on a shallow continental plate 30–90 m below current sea levels (Lambeck et al., 2014; Shaw, 2016b). Robust waisted blades, a technological tool innovation known across Sahul from at least 50 ka, have been found in undated surface contexts on the easternmost Massim island of Rossel (Allen and O'Connell, 2014; Bulmer, 1977; Clarkson et al., 2017; Groube et al., 1986; Lampert, 1981, 1983; Shaw, 2017). Rossel is inhabited by a linguistically unique population, possibly with distant connections to the Solomon Islands, suggesting long-term isolation since the Late Pleistocene (Dunn et al., 2008; Shaw, 2015). Genetic evidence further suggests increased diversification of mitochondrial lineages in Massim and other Near Oceanic island populations during and immediately after the LGM (Pedro et al., 2020). The waisted blades, linguistic and genetic evidence have, until now, provided the only indication for human settlement of this antiquity in the region.

Here we present evidence for human behavioural adaptations to a small island ecosystem which underwent a ~90% reduction in size (280–30 km^2) following the LGM. Systematic excavations were undertaken at the newly discovered archaeological site of Kelebwanagum cave [Pronounced: Kell-ee-bwwa-nah-gum] on the uplifted Miocene-aged limestone island of Panaeati (Louisiade

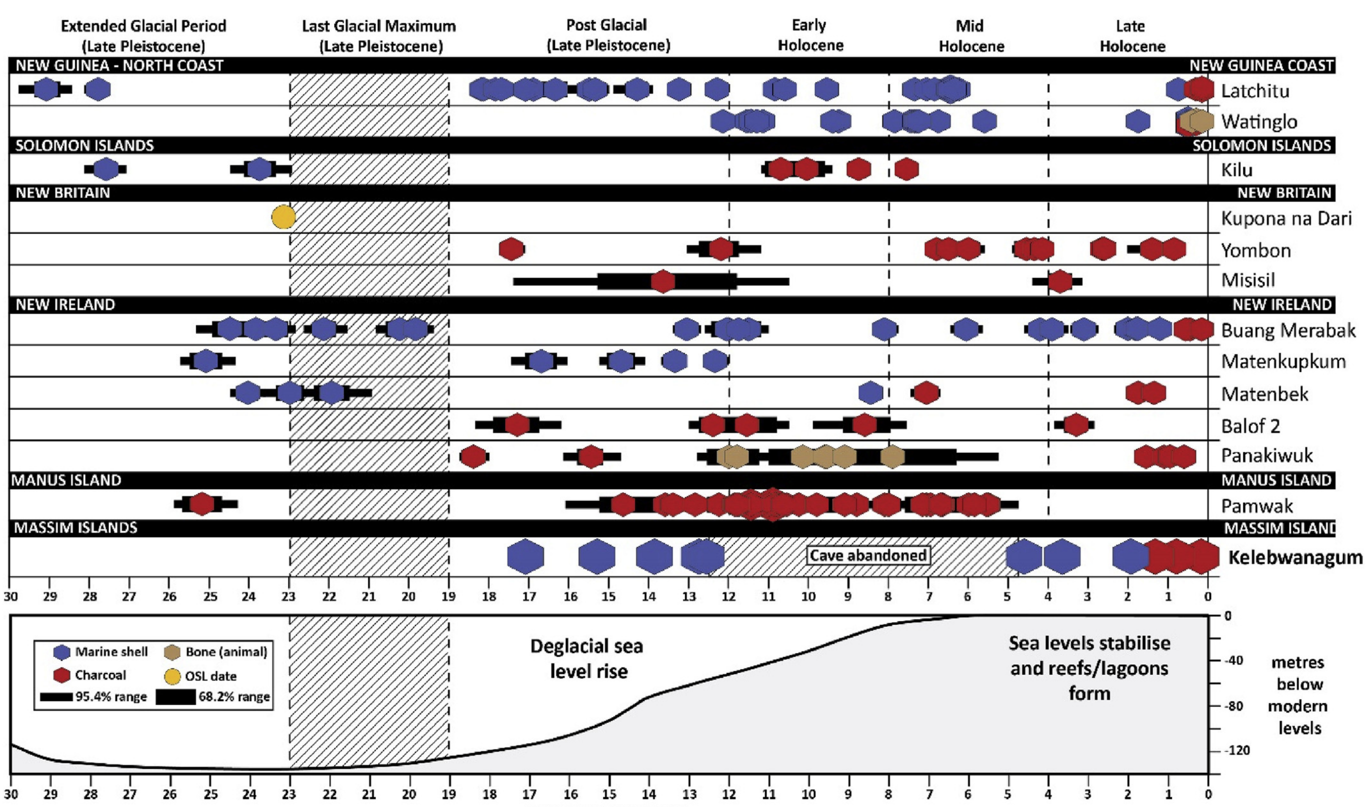

Fig. 2. Calibrated radiocarbon dates from excavated Late Pleistocene sites in northern coastal Sahul (New Guinea), and the Bismarck, Solomon and Massim islands over the last 30 ka relative to sea level. Calibrated Kelebwanagum dates shown. See Table S1 for dates used, and Figure S1 for the extended figure to 45ka. Sea levels based on Lambeck and Chappell (2001).

Archipelago, Milne Bay Province; Fig. 1c) (Smith and Pieters, 1973). A cultural sequence from 17.3 to 16.8 cal ka defines Panaeati as the smallest island in Australasia known to have been occupied during the Late Pleistocene and extends records for human occupation in the Massim region by over 14 ka. Post-glacial human adaptations to a small island ecosystem in Near Oceania can therefore be modelled, for the first time, against cultural records of a similar age on considerably larger and more stable island environments, as well as from across Sahul. We report the first Late Pleistocene paleoenvironmental record for a Near Oceanic island and define the regional antiquity for inter-island obsidian transfer, shell technology and the arrival of pottery-using cultural groups. The evidence from Kelebwanagum fills a critical gap in understanding the effects of post-glacial sea-level rise on population dispersals in island Near Oceania, which also affected global dispersals (See ArchaeGLOBE-Project, 2019).

2. Site location and setting

Panaeati Island (30 km^2, 206 m asl) is located 170 km east of the New Guinea mainland and comprises a central meta-volcanic hill surrounded by an uplifted coral limestone platform (Smith and Pieters, 1973). Kelebwanagum cave (S10°40′28.2″ E152°21′01.9″, WSW aspect) is situated 160 m inland at the base of a low-lying limestone rise on the northwest coast where coastal cliffs rise vertically ~10 m above sea level (Fig. 3). Archaeological investigations were initiated on Panaeati as it is one of the few islands in the Massim region where uplift had likely preserved Late Pleistocene coastal habitation sites against post-glacial sea-level rise. The island is also positioned along one of two major routes into the archipelago at this time (See Fig. 1b).

The densely forested limestone plateau along the northern half of Panaeati was the focus of surveys (Cobb et al., 2004; Paijmans, 1976). The north plateau was the only part of the island where long-term sediment accumulation had occurred and where more extensive uplift had formed overhangs and caves potentially suitable as shelters (Fig. 3a). The limestone on Panaeati likely formed in the Early Miocene (23-16 Ma) (Smith and Pieters, 1969). Coral from lower-lying limestone platforms (5 m asl) on nearby Misima Island (212 km^2) has been dated to 27.5–26.6 cal ka (See Kaplin, 1994: MGU-593: 23,200 ± 180 BP), providing a possible proxy and minimum age for equivalent uplift on the southern side of Panaeati. There is, however, no established uplift history for the higher northern Panaeati platform where Kelebwanagum cave is located.

A barrier reef and shallow lagoon encloses the southern side of Panaeati and encompasses two smaller islands that prior to and during the LGM formed a single 280 km^2 landmass situated only ~40 km from the coast of Sahul (Fig. S2) (Smith and Pieters, 1973). The vertebrate fauna (bats, birds, snakes, rats and cuscus) on Panaeati are relatively depauperate compared to New Guinea due to its complete isolation (Flannery, 1995; Wikramanayake et al., 2002). Panaeati also receives half the annual rainfall of Misima island (3000–4000 mm), only 14 km to the east. The central mountain range of Misima is 800 m higher and frequently traps clouds, generating orographic rainfall. It is one of only a few islands in the region with permanent flowing rivers which can support populations during periods of prolonged drought (Jones and Ellis, 1995).

3. Results and interpretation

3.1. Cave excavation, stratigraphy, and chronology

In July 2018, a 100 × 50 cm (0.5 m^2) trench was systematically excavated near the mouth of Kelebwanagum cave, immediately adjacent to a 60 × 60 cm (0.36 m^2) spade test pit dug the previous year (Table S2). The cave floor comprised a 15 m^2 exposed sedimentary deposit with accumulated solution limestone (7 m^2) at the rear of the cave. Excavation removed ~6% of the exposed sediment, and alkaline soils throughout the deposit (pH: 9) provided excellent conditions for the preservation of faunal remains (Fig. S3 & Table S4). Eleven AMS radiocarbon dates on unidentified wood charcoal and identified marine shell recovered *in situ* provide a well-constrained chronology. Dates are presented as calibrated 95.4% ranges rounded to the nearest 50 years and 10 years for Pleistocene and Holocene determinations, respectively (Table S3).

Five layers were identified based on colour and particle size, with three major cultural horizons defined using radiocarbon dating and the distribution of material culture (Fig. 4 & S4). The lower cultural horizon (Layer 5a-c) reflects cave use during the Late Pleistocene. Habitation at this time is associated with relatively dense shell refuse, an obsidian core and a perforated *Turbo argyrostomus* tool or ornament. Two dates from a thin basal deposit (Layer 5b) of calcium carbonate hardened sediment indicate initial use from 17,300–15,100 cal. BP (Beta-479384, Beta-502620), and three dates from Layer 5a/c define subsequent use from 14,050–12,400 cal. BP (OZX907, Beta-502621, OZX908). Together the dates reflect intermittent and low-density habitation over a 4900-4150 year period. The absence of culturally sterile sediments at the base of the cave suggests human use in the Late Pleistocene may have been the primary mechanism for the onset of sediment accumulation. The date from Layer 5c (OZX908) was the youngest of the Pleistocene series of determinations. The sampled shell had been collected from relatively unconsolidated sediment associated with substantive roof fall accumulation deposited at the cave entrance before the deposition of Layer 4b (Fig. S4). Limestone around the entrance likely collapsed following deposition of Layer 5b, further opening up the cave chamber and creating a larger sediment trap.

The middle cultural horizon (Layer 4a-b) developed following an 8160-7620 year hiatus in human activity and sediment accumulation, reflecting more intensive cave use during the Mid-Late Holocene, with two dates spanning 4780-3480 cal. BP (OZX905, Beta-502622). A third date of 2030–1840 cal. BP (OZX906) was out of sequence and likely derived from anthropogenic disturbance of overlying layers during more intensive use of the cave (Fig. S5). The majority of obsidian and modified shell objects were deposited in the middle horizon, as well as a single pottery sherd. A low volcanic stone wall and clay-based hearth was also identified, perhaps suggesting more regular and sustained cave use (Fig. S4c). Fluctuation in sediment particle size at the Layer 4–5 interface indicates a break in sediment deposition concordant with the chronological hiatus, as opposed to erosion for which there is no indication. Roof fall debris, aeolian particulate, and faunal activity may have contributed to sediment mixing on the exposed surface during a hiatus in sediment accumulation (Fig. 4 & S3). The upper cultural horizon (Layers 1–3) spans 1350-1290 cal. BP to 310-0 cal. BP based on three dates (OZX904 to 902). The deposit here contained several shallow fireplaces as well as reduced quantities of shell and obsidian artefacts.

3.2. Limestone uplift and open site settlement on Panaeati

To ascertain the timing of uplift for the higher northern and central portion of the limestone plateau on which Kelebwanagum cave is situated buried branch coral from a former lagoon in the interior of the island (Mumwa) was radiocarbon-dated (Fig. 1c). The coral's age extended beyond the limits of radiocarbon indicating uplift had already occurred by at least 46.2 cal ka (Beta-502624). Substantive uplift therefore occurred before the known settlement

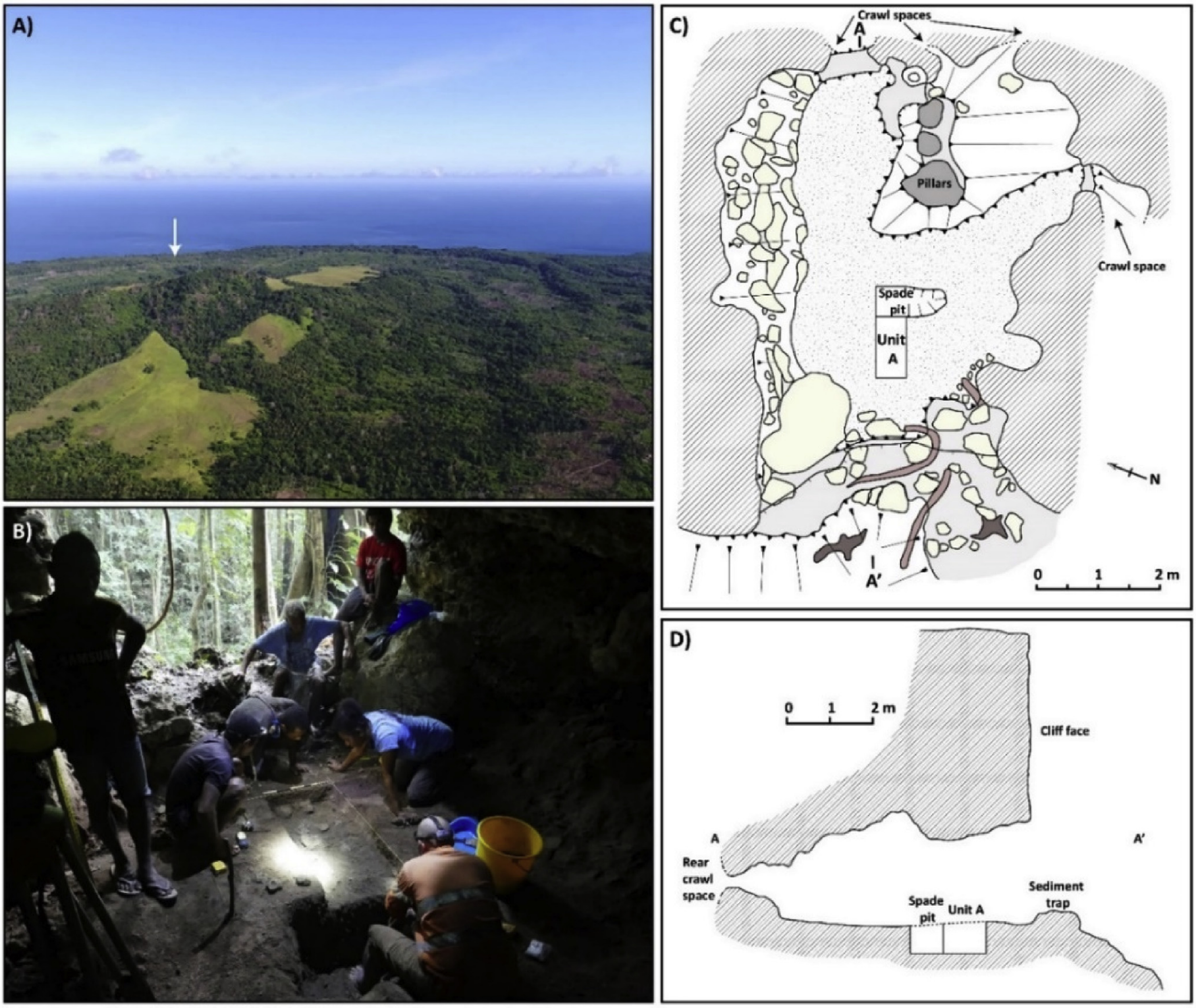

Fig. 3. Location and setting of Kelebwanagum Cave. A) View north across Panaeati Island showing the uplifted and folded limestone, with the location of the cave indicated by the arrow. B) Location of excavation unit within the cave. C-D) Plan and profile of the cave.

of island Near Oceania, demonstrating that changing sea levels will not have affected access to the cave.

Preliminary open site excavations at the Mumwa site further establishes a broader cultural context for the Kelebwanagum cave sequence. Both human visitation and sediment accumulation at Mumwa commenced by 4430–4240 cal. BP (Beta-482842), with habitation becoming increasingly intensive within the past 790-680 cal years (Beta-502623). Numerous limestone niches in the vicinity of Kelebwanagum cave had also been used for secondary human burial from at least 800 years ago, based on relative dating of associated pottery (See Irwin et al., 2019; Shaw, 2019). A human metacarpal on the surface of Kelebwanagum cave indicates it had also been a secondary burial repository in the past.

3.3. Forest composition since the Late Pleistocene

The first pollen-based vegetation record for a Near Oceanic island has been developed from sediment samples (3–6, 26–29 and 62–65 cm) at Kelebwanagum cave, representing the upper, middle, and lower cultural horizons respectively (See column sample location in Fig. 4a). A total of 607 pollen grains were identified, with higher concentrations in the upper ($454,10^3$ x grains/cm^3) and lower (50.5 10^3 x grains/cm^3) horizons relative to the middle horizon (4.9 10^3 x grains/cm^3). A more detailed analysis of the pollen spectra is forthcoming. The results indicate Kelebwanagum cave had been surrounded by forest canopy since it was first utilised. Cave abandonment from 12,400–4780 cal. BP was therefore not related to an absence in forest resources (Table S5).

Lower montane forest taxa were present on the island from 17,300 cal. BP (Layer 5a-b, lower cultural horizon) reflecting a response to lower global temperatures at this time. Taxa were composed mostly of *Syzygium* sp. (Myrtaceae) and to a lesser extent, Euphorbiaceae. *Dodonaea* shrub species were also prevalent, which indicate an open canopy forest during the Late Pleistocene and may signify early human vegetation clearance around the cave. Forest cover between 4780 and 1840 cal. BP (Layer 4a, middle cultural horizon) was dominated by Myrtaceae and Euphorbiaceae taxa reflecting primary forest composition before sustained anthropogenic disturbance in the area. Within the past 1350 cal. BP (Layer 2–3, upper cultural horizon) forest composition

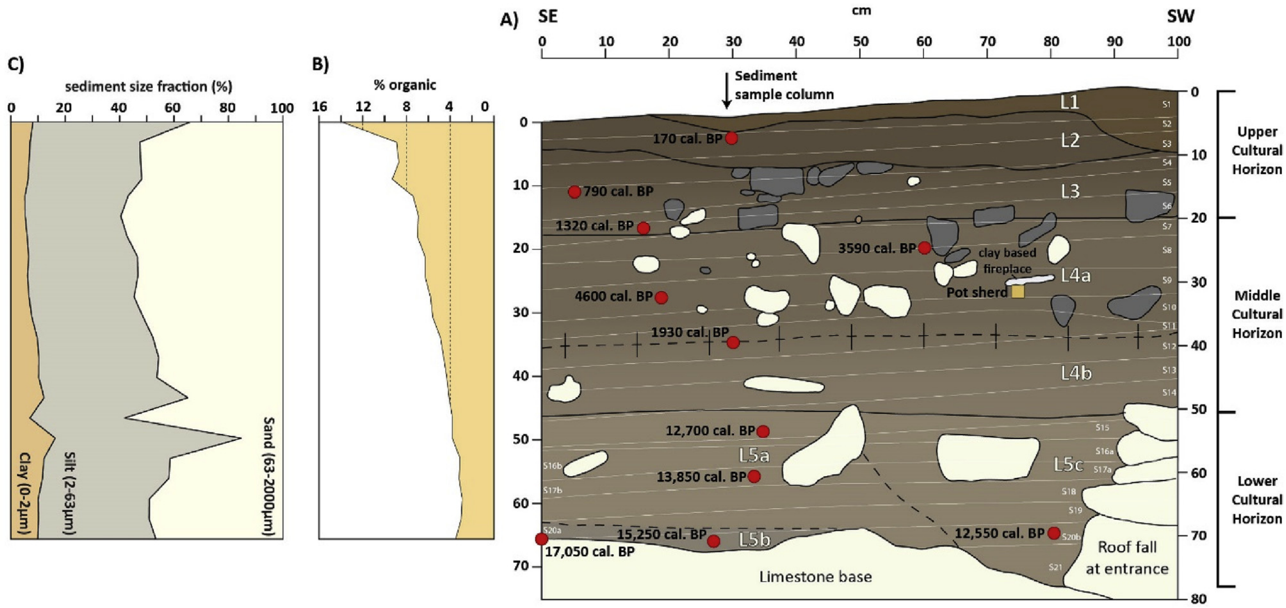

Fig. 4. Excavated section and sediment characteristics in Kelebwanagum Cave. A) Southern section with median AMS determinations provided and the position of dated samples indicated by red circles. Light coloured fill is limestone, dark coloured fill is volcanic rock. Location of the pottery sherd is indicated by the yellow square. Cave entrance is to the right. The three cultural horizons are shown. B) % Organic based on Loss-On-Ignition (LOI) analysis of sediment sampled at 3 cm intervals from the excavated section, indicated by sample column. C) Particle size fractions from the same sediment samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was similar to the modern-day and comprised lowland forest taxa (Melastomataceae/Combretaceae). Secondary regrowth of disturbance/successional indicator *Dodonaea* shrub and *Trema* tree species are consistent with increased landscape use over this time as indicated by the secondary burial niches and occupation of Mumwa.

3.4. Faunal exploitation reflects changing island ecosystem

A substantive shellfish assemblage (3350g) demonstrates the exploitation of a more diverse range of genera in the middle and upper horizons (<4780-4490 cal. BP) compared to the lower horizon (17,300–12,400 cal. BP). Burnt shell (665g) throughout the deposit confirms an association with human use (Table S6; Fig. S6). Chiton (*Acanthopleura* sp.) and crab (Decapoda) were the most common taxa in the lower cultural horizon (17,300–12,400 cal. BP), which could have been harvested from the limestone shoreline and plateau near the cave. Cave proximity to the sea would not have changed as sea levels fluctuated because of the vertical cliffs, and therefore distance to marine resources would also not have substantively changed. Snails (*Nerita* sp., *Tectarius* sp., Camaenidae) were also abundant in the lower horizon, although some land snail may have been deposited naturally. The range of taxa identified from Late Pleistocene contexts at Kelebwanagum was also exploited in similarly aged layers at Buang Merabak and Matenkupkum on New Ireland in the Bismarck Archipelago (See Fig. 2 for site chronologies). Harvesting of these taxa likely reflects low-level opportunistic foraging of shellfish beds on exposed but relatively depauperate limestone shorelines (Gosden and Robertson, 1991; Rosenfeld, 1997).

A marked increase in the density of reef and sandy shore taxa (*Turbo* sp., *Tridacna* sp., *Trochus* sp., *Cypraea* sp., *Conus* sp., Cerithiidae and bivalves) in the middle cultural horizon (Layer 4a-b) demonstrates a substantive shift in the availability of exploitable habitats, with beaches and reef systems established around the island by the mid-Holocene. A coincident middle horizon peak in hardshore taxa also suggests cave use had generally increased at this time, with a subsequent reduction in the quantity of harvested shellfish in the upper cultural horizon. A decrease in shellfish exploitation over the last millennium may relate to increased habitation intensity of open sites elsewhere on the island, as has been identified at the interior Mumwa site.

The faunal bone (NISP = 99; 10 g) assemblage indicates only marine resources (turtle and fish) were exploited in the lower cultural horizon, whereas both marine and terrestrial fauna were harvested in the middle and upper horizons (Table S7). Most marine bone was calcined from fire confirming human predation, and bird bone had fracture patterns consistent with hunting and processing. However, digestion pitting on lizard, frog, snake and tetrapod bone likely occurred from bird predation and is therefore considered in this context as non-anthropogenic. A Phalangeridae (Cuscus) tooth and Murid maxilla from the middle cultural horizon (4780-1840 cal. BP) provides a minimum antiquity for the translocation of these animals to the Massim islands (see Taylor et al., 1982). A Requiem shark bone (Carcharhinidae) in the upper cultural horizon suggests hunting strategies included larger marine taxa within the past 1350-1290 years.

3.5. Low-density obsidian transfer since Late Pleistocene

Eleven obsidian pieces were recovered from excavation, including a bipolar core (2.03 g) from the lower cultural horizon demonstrating a Late Pleistocene antiquity for inter-island obsidian transfer in the Massim (Figs. 5a & 6a). Late Pleistocene obsidian transfer to Kelebwanagum cave was relatively limited compared to in the Bismarck Archipelago where larger quantities were being transported to cave localities (Matenkupkum, Matenbek and Buang Merabak) from New Britain sources by 24 to 22 cal. ka. Obsidian in the middle (n = 6, 1.09 g) and upper (n = 4, 0.77 g) cultural horizons included complete flakes, flake fragments and a bipolar core fragment. A lack of debitage and their small size (X = 11 mm) suggests technology was not formalised, and reduction did not occur inside

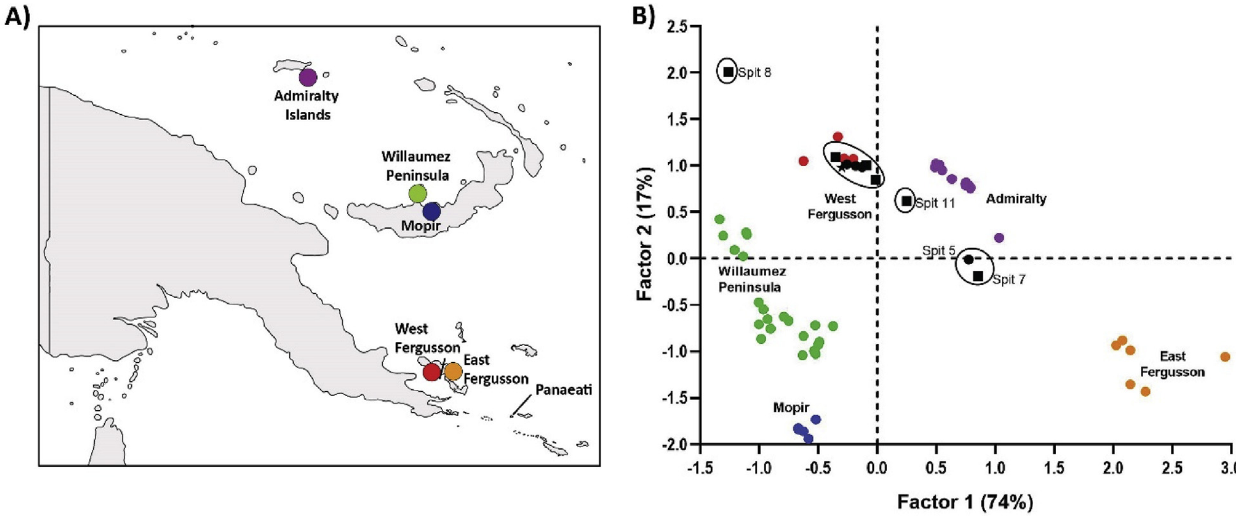

Fig. 5. Obsidian exploitation at Kelebwanagum cave since the Late Pleistocene. A) Location of known obsidian sources in New Guinea relative to Panaeati Island. B) Factor Analysis of the Log10 transformed pXRF Kelebwanagum obsidian data (black icons) compared against source reference samples. At least four West Fergusson sub-sources are represented. Star = Lower cultural horizon, square = Middle cultural horizon, circle = upper cultural horizon.

the cave (Table S11). No other modified lithic types were recovered from the excavated deposit.

The obsidian was chemically characterised using portable X-Ray Fluorescence spectrometry (pXRF) to determine source origin. All eleven pieces were attributed to the West Fergusson Island source region, located ~200 km west of Panaeati. Four groupings were identified which reflect chemical variation between obsidian flows across West Fergusson, and do not correlate to the size of the obsidian pieces. All four sub-sources were exploited in the middle cultural horizon, and two in the upper horizon (Figs. 5b & 6a, Tables S8-11). The wider range of sub-sources utilised in the middle horizon tentatively suggests an expanded interaction network from 4780 to 4490 cal. BP associated with increased movement of people into and between islands. Increased inter-island mobility from this time is consistent with models of expanding social interaction networks across highland-lowland New Guinea, the Bismarck Archipelago and the Massim throughout the mid-Holocene based on the distribution and dating of formally manufactured pestles, mortars and stemmed obsidian tools (Shaw et al., 2020b; Swadling, 2016; Torrence and Swadling, 2008).

3.6. Late Pleistocene antiquity and Holocene proliferation of shell technology

A perforated *Turbo argyrostomus* shell net sinker or ornament from the lower cultural horizon also extends the known antiquity of shell technology in the Massim islands to the Late Pleistocene (Fig. 6p). Use wear around the circumference of a well-defined perforation on the outer whorl of the shell suggests it was hung from a fibrous string, with flaking around the aperture margin indicating deliberate manufacture distinct from food processing breakage (Table S12). The *T. argyrostomus* object is functionally similar to *Turbo* sp. shell technology identified at the New Ireland sites of Matenbek and Matenkupkum dating from at least 24-22 cal. ka. Shell reduction at these sites has been argued to reflect fishing technology, and perhaps the production of hooks (Gosden and Robertson, 1991; Smith and Allen, 1999).

The evidence from Kelebwanagum cave and the Bismarck Archipelago together suggests *Turbo* sp. shells were deliberately selected for tool manufacture because of their shape and robust matrix (Smith and Allen, 1999).

A proliferation of shell technology in the Mid-Late Holocene was evident and is correlated with the emergence of a more diverse range of shellfish habitats, including lagoonal reefs and beaches. Functional and ornamental shell artefacts from the middle (n = 8) and upper (n = 3) cultural horizons included scrapers, beads and utilised flakes manufactured from at least six shellfish taxa (*Cypraea* sp., *Turbo* sp., *Conus* sp., *Tectarius* sp., *Asaphis* sp. and *Tridacna* sp.) (Fig. 6e,i-o). A possible bead made from a bird bone diaphysis was also identified in the middle horizon (Fig. 6f).

3.7. Pottery introduction, origins, and Late Holocene cultural influences

A single slipped plain body pottery sherd from the middle cultural horizon (4780-1840 cal. BP: Fig. 6c) was technologically consistent with the earliest pottery traditions in the Pacific region associated with the Lapita Cultural Complex, dating from 3250 to 3150 cal. BP (Specht and Gosden, 2019; Summerhayes et al., 2010b). Distinctively decorated Lapita pottery (dentate stamped) is recognisable in the Bismarck Archipelago and elsewhere in New Guinea through to 2500-2350 cal. BP, after which time regional traditions and interaction patterns emerge (David et al., 2012; Summerhayes, 2007). The sherd was recovered from beneath an intact clay-based hearth and is considered to be from a secure context.

Scanning electron microscopy with energy dispersive spectroscopy determined the composition of the sherd as containing shell, coral, quartz, and ilmenite. The inclusions are consistent with a volcanic beach sand temper (Fig. S7). Calcareous tempered pottery with volcanic sands has previously been recovered from a Lapita site on Wari Island in the Massim dating from 2800 to 2600 cal. BP (See Fig. 1b for site locations). By contrast, calcareous Lapita pottery on Nimowa Island dating from 2500 to 2300 cal. BP did not contain volcanic minerals as islands in the southeast Massim are not of volcanic origin (Chynoweth et al., 2020; Negishi and Ono, 2009; Shaw et al., 2020a). An age range of 3250–3150 to 2800-2600 cal. BP is therefore attributed to the Kelebwanagum sherd, falling within the established middle horizon cave chronology.

Ilmenite is not present in the bedrock of islands in the Louisiade Archipelago. However, it is present in metamorphic core complexes on Fergusson Island within the same vicinity as the exploited obsidian outcrops. Therefore, Fergusson Island is the likely origin

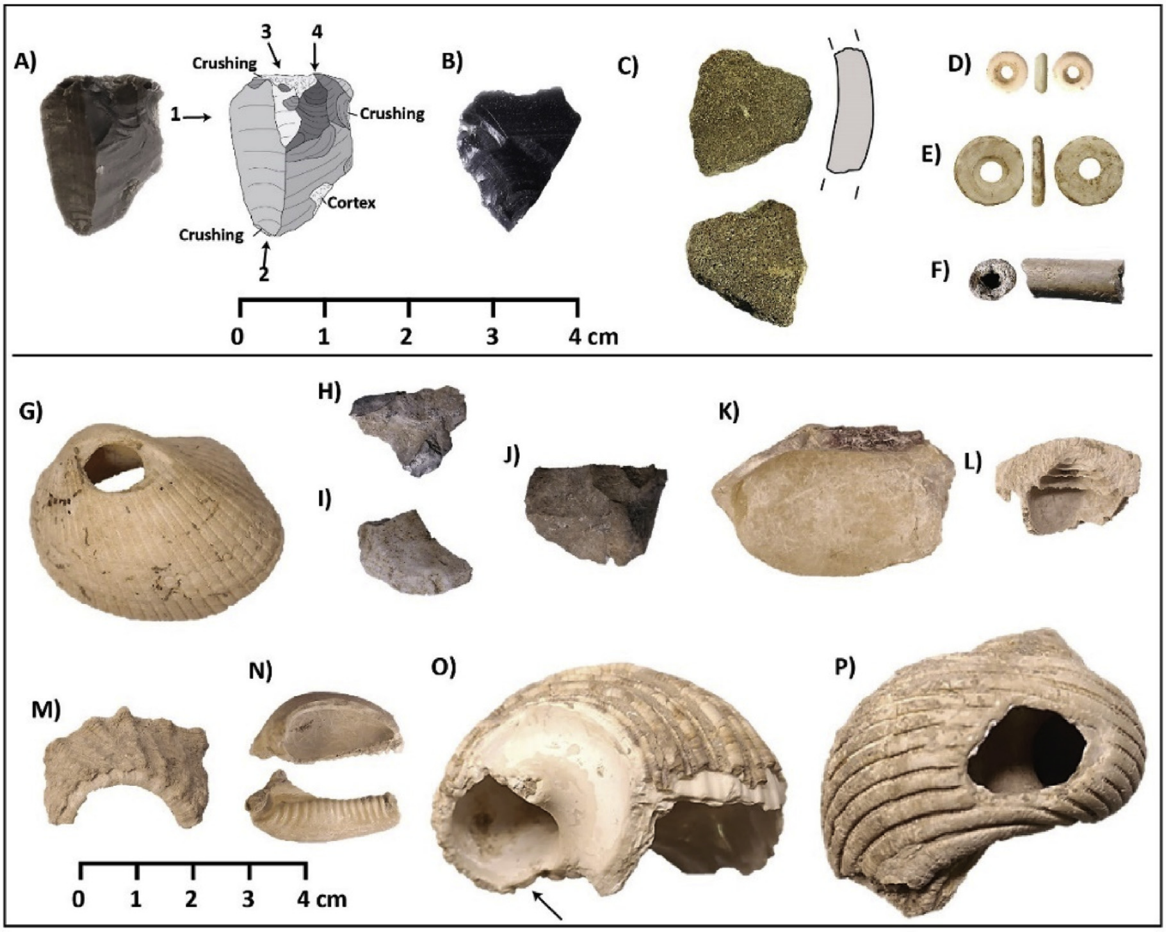

Fig. 6. Excavated material culture from Unit A, Kelebwanagum cave. A) Bipolar obsidian core with an annotated drawing showing flake scars, crushing and direction of flaking, Spit 19. B) Retouched distal flake fragment with usewear, Spit 9. C) Calcerous tempered pottery body sherd, Spit 9. D) *Conus* sp. shell bead, Spit 3. E) *Conus* Sp. shell bead, Spit 7. F) Bird bone tubular bead with worked ends, Spit 10. G) Perforated *Anadara antiquita* net weight. Spit 4. H) flaked and burnt *Tridacna* sp. fragment, Spit 5. I) Retouched shell, Spit 7. J) Flaked and burnt *Tridacna* sp. fragment, Spit 7. K) *Asaphis violascans* with use wear, scraper, Spit 11. L) Split *Conus* sp. spire with a worked edge, Spit 11. M) *Tectarius pagodus* with use wear, scraper, Spit 11. N) *Cypraea* sp. base fragment with use wear on end, Spit 14. O) *Turbo argyrostomus* with reduced edge and use wear, Spit 13. P) Perforated *Turbo argyrostomus* shell with use wear, possibly a net weight, Spit 16.

for the potsherd (Davies and Ives, 1965; de Keyser, 1961; Monteleone et al., 2007; Shaw, 2016a; Smith and Pieters, 1969). While only a single sherd, it provides a strong indicator of the timeframe and direction for the arrival of Lapita cultural groups into the Massim which profoundly influenced genetic and cultural diversity (Shaw, 2019; van Oven et al., 2014). A high degree of language replacement also occurred in the millennia following Lapita arrival (Ross, 1988).

4. Discussion

Climatic changes leading up to and during the LGM have long been considered global drivers for the dispersal of modern human populations (Will et al., 2019). It is now becoming clear that the subsequent millennia were also critical in shaping human diversity in coastal and island post-glacial landscapes as sea levels inundated vast shallow stretches of the continental shelf (O'Connell and Allen, 2007; O'Connor et al., 2019). Although people migrated across Sahul and into the interior relatively quickly following colonisation, coastlines remained attractive areas of habitation with marine resources forming an important component of subsistence regimes (Hiscock, 2008; Smith, 2013; Veth et al., 2017). However, most coastal Late Pleistocene landscapes are now underwater, and few islands existed around Sahul prior to the Holocene. The unique position of islands in the Massim region - on a shallow continental shelf and close to the New Guinea coast - has allowed investigations to provide novel insights on modern human adaptive behaviours to small island ecosystems and in response to post-LGM deglacial sea-level rise.

4.1. Cave use and abandonment as adaptive behaviour

Kelebwanagum cave provides the only Late Pleistocene record of human occupation in the Massim Island Region. Initial cave use by 17,300–16,800 cal ka occurred when sea levels had risen 20–25 m from their lowest levels during the early stages of global deglaciation. Both the timing and location of the cave suggests people had begun utilising the higher limestone platform on Panaeati (~10 m asl) as lower-lying coastlines became increasingly unstable. The timing of initial use may also reflect expansion or perhaps re-expansion of people into the Massim islands which were less attractive for settlement during the LGM, as has been modelled archaeologically in the Bismarck Archipelago and Wallacea (Leavesley, 2006; O'Connor et al., 2019). Genetic evidence supports this model with the diversification of mitochondrial genomes in the Massim and the Bismarck Archipelago during and after the LGM, from 26–18 ka (Pedro et al., 2020).

There is currently a lack of evidence for pre-LGM island habitation in the Massim. However, the presence of lower montane economic tree taxa in the lower cultural horizon of Kelebwanagum cave does indicate forest resources had adapted to colder climatic conditions during the LGM. Forest resources could therefore have supported a substantive vegetation base for pre-agricultural populations to exploit. If people were present in the Massim before 17.3–16.8 ka, populations would likely have been centred near lower-lying and gently sloping coastlines where marine craft landings, sheltered moorings and fringing reef food resources could be more readily accessed.

An apparent lack of cave use at Kelebwanagum during the extended glacial period (30–18 ka, see Reeves et al., 2013), when sea levels were lowest and islands largest, indicates extreme sea-level drawdown did not influence population movements to the higher coastline of northern Panaeati. However, as sea levels rose, it would have been necessary to follow the coast inland or to move away from low-lying areas. The vertical limestone cliffs near Kelebwanagum cave would have provided a stable shoreline resistant to rising seas and tsunamis. Breaks in the cliff structure would have also allowed ongoing access to hardshore shellfish beds. The low density of material culture suggests only small groups of people had intermittently utilised the cave during the Late Pleistocene and were likely relatively mobile across these island landscapes. Such a pattern is consistent with Pleistocene records from the Bismarck Archipelago (Allen and Gosden, 1996; Gosden and Robertson, 1991; Leavesley, 2006; Summerhayes et al., 2017).

Apparent abandonment of Kelebwanagum cave after 12,650–12,400 cal. BP coincided with substantive flooding of the continental shelf around Sahul and globally. Over the time the cave was used during the Late Pleistocene sea levels had risen a further 60 m at a relatively rapid rate of 1 m per 82 years. Such a rise would have drowned established coral reefs and gradually but significantly increased the distance between Panaeati and Sahul by as much as 130 km (Fig. 2) (Chappell and Polach, 1991; Webster et al., 2018). Over this time and in the millennia after 12,400 cal. BP the island reduced in area by 90%, with up to 250 km^2 of the vegetated landscape and freshwater catchments no longer available as a subsistence base to support pre-agricultural populations. Such a marked reduction was likely a tipping point that innovations in technology or social organisation were not able to overcome. It is likely populations at this time re-located to Sahul or to larger and steeper islands where sea-level rise had a less pronounced effect on land area reduction.

Reuse of Kelebwanagum cave in the middle cultural horizon from 4780–4490 cal. BP occurred under vastly different ecological conditions. The shellfish assemblage indicates a lagoonal-reef system had formed around parts of Panaeati and sea levels had stabilised 1–3 m above current levels (Dickinson, 2003) (See Fig. 1c). Western Pacific coral records indicate reef growth commenced or increased substantively on many islands during the mid-Holocene (8.2–4.2 ka), with beach ridges also beginning to form in emerging lagoon environments (Dickinson, 2014; Woodroffe et al., 2000). Sheltered waters within lagoons and the increased number of sand bars/atolls between Panaeati and New Guinea from the end of the mid-Holocene would have enabled more regular interaction between islands. Settlement and sediment accumulation at the Mumwa open site in the interior of Panaeati commenced from 4430 to 4240 cal. BP, which is equivalent in age to the middle cultural horizon. The coincident timing suggests the island was probably abandoned during the prolonged hiatus in cave use, with people returning to the island by the end of the Mid-Holocene.

4.2. Landscape use across Sahul and island Near Oceania during post-LGM deglaciation

The Kelebwanagum cave sequence, when integrated with Late Pleistocene records from elsewhere in Island Near Oceania and Wallacea, indicates increased levels of population movement in these regions coincided with the lower cultural horizon at Kelebwanagum cave (17,300–12,400 cal. BP). In the Bismarck Archipelago, only two cave sites (Buang Merabak and Matenbek) have evidence for LGM habitation (Fig. 2), during which time other sites were either abandoned or ephemerally utilised (Allen et al., 1988; Leavesley, 2004). These two Bismarck cave sequences may reflect deliberate retraction of populations to densely forested refugia ecosystems in southern New Ireland during the LGM. Whatever the case, initial habitation of two rockshelters (Panakiwuk, Balof 2) and reuse of other previously inhabited locales (Matenkupkum, Yombon, Latchitu, Pamwak) within a relatively defined period of 18.4 to 14.7 cal ka indicates an expansion of populations back into a broader range of island ecosystems soon after the LGM (Allen and Gosden, 1996; Allen et al., 1988; Gosden and Robertson, 1991; O'Connor et al., 2011; Pavlides, 2004) (Fig. 2). A similar pattern of landscape use is also evident on Kisar, Timor and Alor Islands in Wallacea (Hawkins et al., 2017; O'Connor et al., 2019; Samper Carro et al., 2016).

Across Sahul as well, settlement patterns changed in the millennia following the LGM as people responded to significant changes in temperature, aridity and sea level (Maloney et al., 2018; O'Connor and Veth, 2006; Slack et al., 2009; Smith, 2013; Veth, 1993). From 20 to 19 Ky deglaciation had commenced and sea levels had begun to rise which eventually flooded up to one-third of Australia's continental landmass. A meta-analysis combining 477 radiocarbon dates from 136 sites across south-central Sahul (Australia) spanning the period 25–12 ka demonstrates that population density increased within well-resourced 'refugia' regions between 19 and 15 ka (Williams et al., 2013). Patterns of population expansions therefore spanned island, coastal and interior landscapes of Sahul and Near Oceania, reflecting adaptive settlement strategies in response to changes in ecosystem habitability.

4.3. Island refugia and cultural diversity

Large islands (>100 km^2) with steep bathymetry in the Massim region were likely to have been refugia as low-lying islands flooded and significantly reduced in area. Rossel Island, although having reduced in size by as much as 70% during deglacial sea-level rise, maintained a relatively large land area (290 km^2). The presence of waisted stone tools on Rossel suggests habitation and vegetation clearance occurred sometime during the Late Pleistocene (Groube, 1989; Shaw, 2017). Except for Rossel, all Massim island populations speak Austronesian languages which are linked with the expansion of Lapita cultural groups into the region some 3000-2500 years ago (McNiven et al., 2011; Negishi and Ono, 2009; Ross, 1988). Although Panaeati was inhabited during the Late Pleistocene the language/s once spoken on the island must have been entirely replaced following the arrival of Lapita cultural groups in the Late Holocene. By contrast, the unique language and genetic patterning of Rossel Islanders strongly suggests greater structural preservation of this population since the Late Pleistocene. Yet, until now, archaeological evidence to support settlement of this antiquity in the Massim had been lacking, which precluded the region's inclusion in global models of Late Pleistocene modern human dispersals (Dunn et al., 2008; Levinson, 2008; Liep, 2009; van Oven et al., 2014).

5. Conclusion

Kelebwanagum cave has provided evidence for human settlement on the smallest island in Australasia during the Late Pleistocene, and the first evidence for settlement of this antiquity in the Massim region. The available evidence indicates that the uplifted limestone island of Panaeati was an ecological refugia from 17.3 to 16.8 cal ka as lower-lying islands and coastlines became unstable as a result of post-LGM deglacial sea-level rise. Kelebwanagum cave, and perhaps also the island, was abandoned by 12.4 cal. ka. When the timing for Late Pleistocene cave use and abandonment is modelled against cultural records dating to before, during and after the LGM across island Near Oceania and Sahul, an inter-regional pattern for population re-location and adaptation is apparent. We argue these adaptations in landscape use and social behaviour occurred in response to post-glacial climatic conditions affecting habitability and had a profound effect on emerging cultural diversity.

5.1. Materials and methods

5.1.1. Excavation procedure

Systematic excavation was undertaken by trowel within apparent stratigraphic layers. Excavation proceeded in 3–4 cm spits except where it was necessary to increase spit depth due to notable changes in sediment characteristics. All sediment was wet and dry sieved through 3 mm mesh. Excavation proceeded until bedrock was reached. A datum was established before digging commenced, and all measurements were taken using a dumpy level, stadia rod and hand tape. *In situ* finds, including charcoal fragments, were bagged individually with context numbers and their location recorded in three dimensions. Hearths were excavated and labelled individually as features. Feature depth was determined by measuring the horizontal and vertical position in the square where it was first identified and at its deepest point. The sieve residues were bagged, weighed and sorted. Sediment samples were collected during excavation, and the unit backfilled when excavation was completed. The site elevation profile was surveyed with a dumpy level.

5.1.2. Radiocarbon dating

Radiocarbon determinations were obtaining using Accelerator Mass Spectrometry (AMS) at BETA Analytic (Miami, Florida, US) and the Centre for Accelerator Science at ANSTO (Sydney, NSW, Australia). All charcoal and marine shell samples were physically cleaned of sediment adhering to the surface. The samples were pretreated using the acid-base-acid method, by washing the samples with hot HCl acid to eliminate carbonates, then washed with NaOH to remove secondary organic acids, followed by a final HCl rinse to neutralise the solution before drying. Pretreated samples were combusted to CO_2 gas by oxidation then reduced to graphite for AMS analysis (Fink et al., 2004; Hua et al., 2001). All ^{14}C determinations were calibrated using the IntCal13 or Marine13 calibration curves (Reimer et al., 2013) and the OxCal 4.3 program (Ramsey, 2009). No island-specific ΔR value is available for Panaeati Island, although regional datasets for the Massim suggest minimal old carbon effects in Late Holocene marine shell samples (Petchey and Ulm, 2012). Nonetheless, the western Massim value of 38 ± 14 was used to counter potential hard water effects of dissolved limestone uptake in locally harvested shellfish since the Late Pleistocene (Petchey et al., 2008).

5.1.3. pH and munsell soil analyses

pH was determined on a sediment sample fraction using a Searles soil pH test kit. Several drops of indicator liquid were added to the sediment to make a paste, and the indicator powder added. The colour of the powder was recorded after waiting 30 s. Sediment colour was determined by matching dry samples with a Munsell (2000) soil chart.

5.1.4. Particle size analysis

Approximately 1–3 g of sediment was sieved through 2000 μm mesh, and pretreated with 30% NaOH heated to 80–90 °C to dissolve the organic component. Reverse osmosis (RO) water and several drops of 5.5 g/L sodium hexametaphosphate [$(NaPO_3)_6$] were added to the sample as a particle deflocculant 24hrs before analysis (Beierle et al., 2002; Sperazza et al., 2004). A Malvern mastersizer 2000 laser-diffraction particle size analyser with a Hydro2000G dispersal unit was used. Three consecutive runs (15s; 15,000 measurements) were made for each sample, with the average reported. Obscuration was kept within the accepted range of 10–20%. Particle size parameters were calculated using GRADISTAT software using the following grain size dimensions: Clay <2 μm, silt: 2–63 μm, sand: 63–2000 μm (Blott and Pye, 2001).

5.1.5. Loss on ignition analysis

Sediment samples of approximately 1 cm^3 were placed in a labelled and weighed crucible and weighed again. The samples were oven-dried at 105 °C for 24 h and reweighed to give the dry mass. The samples were then fired in a muffle furnace at 550 °C for 4 h, with the remaining ash weight representing the minerogenic fraction (Chambers et al., 2011). The percentage of mass lost between oven-dry weight and ash weight represents the organic component (%) of the sediment. All samples were placed in a desiccating jar to cool before being weighed on a 0.001 g balance.

5.1.6. Obsidian artefact analysis

All lithic material was assessed to identify raw material and reduction characteristics. The following technological categories were used: tool, core, complete flake, flake fragment (medial, distal, longitudinal), and angular fragment. Retouch and usewear were also recorded, defined by deliberate flaking on the margins to create a useable edge, and smaller chipping along a side of the stone respectively. A tool was any artefact that has been modified through shaping for use, and often includes use wear and retouch. A flake is a stone artefact with a defined ventral and dorsal surface, as well as at least one of the following: a platform, bulb of percussion, ripple marks, distal termination. A flake fragment has some of the identified flake characteristics. A core is a parent piece of raw lithic material with negative flake scarring. An angular fragment is any piece of stone produced during the flaking process but does not contain the attributes of a flake (Holdaway and Stern, 2004).

5.1.7. pXRF analysis of obsidian

The Kelebwanagum obsidian ($N = 11$) and 53 obsidian geological samples from all known sources in Papua New Guinea were analysed using an Olympus Delta Premium Portable XRF Spectrometer at the University of New South Wales Mark Wainwright Analytical Centre. Obsidian samples were analysed three times each using the in-built *Geo-chem* mode with elemental composition recorded in parts per million (ppm). Final values were an average of the three runs. Two X-Ray beams, operating at 40 keV and 10 keV, were emitted from a Rhodium tube anode. Each beam was run for 90 s, with a total analysis time of 180 s per sample. The spectrometer was calibrated against the factory standard *Alloy 316 Stainless Steel* at the beginning of each testing period to ensure the X-Ray beams and detectors were functioning correctly (Sheppard et al., 2010; Torrence et al., 2013).

Obsidian specific spectrometer calibration was developed using 29 pelletised geological standards with elemental concentrations and ranges spanning the known range of obsidian sources (JA-3, VS-N, DT-N104, W-2, SDC-1 2010, RGM-1, MRG-1, DNC-1, BIR-1, SCO-1, MA-N, BE-N, AN-G, SY-3, SY-2, JB-10a, JB-1, MAG-1, JR-2, GXR-6, GXR5 (2), GXR-2, JLK-1, JG-1, JB-2, JB-3, JG-2, NBS69b (2), NIM-G). Element specific calibration factors were determined using linear regression offsets between pXRF data and published values (Potts et al., 1992). Two obsidian geological standards (NIST278 and RGM-2) were analysed at the beginning and end of each run and between every four samples. Principal component analysis (PCA) was undertaken using *SPSS Statistics Package Version 23.0* with Mn, Fe, Zn, Rb, Sr, Y, Zr, Nb elemental concentrations. Values were transformed using a base-10 logarithm before statistical analysis (Glascock and Neff, 2003).

5.2. Faunal analysis

Faunal remains were identified by comparison with the ANU Archaeology and Natural History Osteology Laboratory reference collection. Skeletal elements were identified to the lowest taxonomic level possible. The assemblage was quantified using Number of Identified Specimens (NISP) as NISP typically tracks Minimum Number of Individuals (MNI) closely to relative abundance and avoids issues of aggregation, interdependence, and sample size (Lyman, 2008). The taphonomy of the vertebrate assemblage was assessed by observing bone surface modifications under light magnification (x10). Bone modifications examined included signs of butchery via cut marks and fracture patterns, as well as burning.

5.3. Shellfish analysis

Shellfish remains were analysed at UNSW. Gastropod and bivalve shells were separated into taxa, quantified by weight (g), with the aid of Hinton (1975) and Cernohorsky (1972). Further analysis is underway to quantify MNI for each shell taxon. Four major environmental zones were used to characterise the known preferred shellfish habitats – sand inter-tidal, rock inter-tidal, reef inter-tidal and mangrove, following Wells and Kinch (2003), and Bedford (2006).

5.4. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS)

The potsherd was resin mounted and its surface ground and polished using a sequence of SiC and diamond polishing pads to a 1 μm finish. The polished sample was evaporatively coated with ~25 nm carbon to provide a conductive surface. SEM imaging was conducted using a Hitachi S–3400N SEM; EDS analysis was done using a Bruker XFlash SDD-EDS detector fitted to the SEM. A beam energy of 20 kV was used for both imaging and analysis.

5.5. Sediment pollen analysis

Bulk sediment samples of 2 cm^3 volume were homogenised and prepared using standard HCl, KOH and acetolysis pollen processing methods described in Fagri and Iversen (1989). *Lycopodium* marker grains were added to permit calculation of pollen concentrations (Stockmarr, 1971). Lithium polytungstate was used at a specific gravity of 2.0 to further concentrate pollen in the samples (Caffrey and Horn, 2013). Pollen grains were identified to the lowest taxonomic level possible using a Zeiss Axiophot microscope at 400x and 1000x magnification. Terrestrial pollen counts exceeded 100 grains per sample and identifications were based on the Australasian Pollen and Spore Atlas (apsa.anu.edu.au; APSA-Members, 2007), the pollen reference collection at the Australian National University.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106522.

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Data and materials availability

All data are available in the main text and in the supplementary materials.

Author contribution

B.S. formulated and obtained funding for the project. B.S., S.C. and J.H. developed the excavation strategy and conducted the excavations. E.H. conducted the pXRF analysis of the obsidian. E.H., S.C. and B.S. analysed the obsidian artefacts. B.S. conducted the particle size and loss on ignition analyses of the sediments, the pottery, lithic, and shell artefact analyses, and the shellfish subsistence analysis. S.H. and F.H. undertook the sediment pollen analysis. K.P. and B.S. completed the SEM/EDS analysis of the pottery. S.H. analysed the faunal bone assemblage. G.J. facilitated the radiocarbon dating. B.S. drafted the manuscript, with all co-authors contributing to the final version.

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