A REVIEW OF ARCHAEOLOGICAL DATING EFFORTS AT CAVE AND ROCKSHELTER SITES IN THE INDONESIAN ARCHIPELAGO

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ABSTRACT

In the last 35 years Indonesia has seen a substantial increase in the number of dated, cave and rockshelter sites, from 10 to 99. Here we review the published records of cave and rockshelter sites across the country to compile a complete list of dates for initial occupation at each site. All radiocarbon dates are calibrated here for standardization, many of them for the first time in publication. Our results indicate a clear disparity in the distribution of dated archaeological sites across Indonesia, which seem to be mostly influenced by ease of access, international collaboration focus, and the history of prior research success in a region. In addition, our review of the literature revealed a clear lack of standardization in the presentation of radiocarbon dates and their usage in publications. Despite the impressive increase in dating across Indonesia, our review of the literature suggests numerous excavated prehistoric sites in Indonesia remain undated at this time. Studies such as this, and possible others focused on Indonesia's other archaeological sites, are useful for providing researchers with a dataset for investigations of some of the bigger questions in archaeology in the region.

ABSTRAK

Sejak 35 tahun terakhir, Indonesia mengalami peningkatan dalam usaha pertanggalan situs gua dan ceruk dari 10 ke 99. Di sini, kami meninjau ulang data gua dan ceruk yang telah dipublikasikan untuk menghimpun daftar yang lengkap terkait jejak hunian tertua di setiap situs. Kami melakukan kalibrasi terhadap setiap pertanggalan radiocarbon sebagai bentuk standardisasi. Beberapa di antaranya belum pernah dilakukan kalibrasi sebelumnya. Temuan kami mengindikasikan disparitas yang jelas pada distribusi situs yang telah dipertanggali di seluruh Indonesia, yang sebagian besar kemungkinan dipengaruhi oleh kemudahan akses, fokus kolaborasi internasional, dan kesuksesan penelitian sebelumnya di area yang bersangkutan. Sebagai tambahan, tinjauan pustaka kami menemukan kurangnya standardisasi dalam mempresentasikan dan cara menggunakan data pertanggalan dalam publikasi. Meski terdapat peningkatan yang sangat mengesankan dalam jumlah pertanggalan di Indonesia, masih banyak situs yang sudah diekskavasi namun belum dipertanggali hingga saat ini. Studi seperti ini, dan beberapa yang lebih berfokus pada situs-situs arkeologi di Indonesia lainnya, sangat bermanfaat untuk menyediakan data yang lengkap demi menjawab pertanyaan yang lebih besar.

INTRODUCTION

Archaeology has benefited enormously from the development of scientific dating methods. Most modern societies see time as a scale unit to measure events and determine their order, duration, and/or interval. In archaeology however, time is most often used as a tool to conceptualize the development of human communities, cultures, and technologies, based on their artifacts, unearthed remains, ruins, and other archaeological data (Simonetti 2013). Archaeological interpretation is very dependent on the context of the material data. Having the answer for 'what' and 'where' is not enough to continue to 'how' and 'why' questions without having the answer of 'when' already understood. With knowledge of the temporal context related to select archaeological data, we are able to measure their lifespan and form inferences on the story behind it. For instance, an artifact has its own lifespan beginning from when it is being made, then transported, marketed, used, and finally discarded (Adams 2003).

Two different dating methods are used by archaeologists, both of which have been developed to serve the same purpose; providing the best temporal explanation about the archaeological materials in question. The earliest method available to archaeologists was 'relative' dating, whereby the age of an object is inferred based on its association with other materials in a sequence from oldest to youngest; hence it is dated as older or younger *relative* to the other material. Absolute dating on the other hand refers to the direct, *actual* age of the object in question in a quantitative rather than qualitative manner (Michels 1972; Walker 2005). Modern relative dating techniques rely heavily on data obtained with absolute dating methods.

Absolute dating techniques have been applied in archaeological research all over the world in various degrees. Dating records in prehistoric sites have a practical application to establish the period of occupation, changes in occupation intensity or site abandonment, changes to subsistence strategies (technological and dietary), and to mark the deposition of important discoveries such as a burial layer or unique artifact. Furthermore, partial dating records from each site can potentially be accumulated to help answer larger, more generalized archaeological questions such as migration, trade, cultural distribution, and regional occupation trends. For instance, dating records in relation with paleoenvironmental or paleogeographical data allow us to estimate the type of landscapes which *Homo sapiens* encountered as they migrated from mainland East Asia into Sunda (continental Southeast Asia; Bird *et al*. 2005), or from Sunda to Sahul (Australia-New Guinea; Kealy *et al*. 2016). In terms of artifactual analysis, dating records allow us to see cultural and technological distribution among sites during the same period, and the possibility of trading activities (Reepmeyer *et al*. 2019; Shipton *et al*. 2020a).

An effort to make a list of absolute dating records (i.e., radiocarbon) in Indonesia was made by Bronson and Glover in 1984. Thirty-five years after the method was developed, they successfully gathered 65 radiocarbon records from sites all over Indonesia. Even then this number of dated sites was considered very few compared to other countries. As they stated: "… [the] single site of Ban Chiang in north-east Thailand has more radiocarbon dates than the whole of Indonesia." (Bronson and Glover 1984:37). More than three decades after that paper was published, the numbers of archaeological sites, and sites for which there are corresponding dates, have increased substantially across Indonesia. However, large regions of the country remain largely unexplored by archaeologists and many sites have very limited or no absolute dates (Mansyur 2007; Prasetyo 2014; Kealy *et al*. 2018a). More recent attempts in cataloguing archaeological dating records in Indonesia have tended to focus on just a single island and/or temporal period, such as the list made by Bulbeck (2018) on Holocene sites in Sulawesi. He compiled 73 known sites in Sulawesi with compatible radiometric determinations. By using the dating records, he was able to analyze the level of site use at 500 year intervals (Bulbeck 2018).

Here, we review published archaeological dates from Indonesia, focusing on the dating records of initial occupation by *Homo sapiens* of cave and rockshelter sites. We focus on cave-sand rockshelters not only because they represent a reliable source of shelter for prehistoric communities, but they also have a good chance for preserving archaeological materials. While cave stratigraphies are often complex (see Sutikna *et al*. 2016; O'Connor *et al*. 2017), overhangs and chambers offer greater protection to archaeological deposits, and enable a greater degree of sediment build-up and maintenance of stratigraphic layers, than do open sites. Similarly, dating of burial and shell midden sites often only captures a brief moment in time and is at even greater risk of stratigraphic disturbances or redeposited materials than most cave sites (Attenbrow 1992; Bedford *et al*. 2011). This 'time capsule' capacity makes cave and rockshelter sites ideal for prehistoric archaeological research and dating. As some Indonesian sites have recovered upwards of 50 dates from a single excavation (e.g., Kealy *et al*. 2020), reproducing this data here is excessive. Instead we provide a single, initial occupation date, indicating that dating has been successfully conducted at the site and providing some estimate as to the temporal range of the preserved archaeological deposit.

The collection of absolute dates for this study drew to a close in August 2020 when the revised manuscript was accepted for publication.

Development of radiocarbon dating methods in archaeology

As noted above, there are two different types of dating methods in archaeology; relative and absolute dating. Since at least the 19th century, relative dating has been used by antiquarians to interpret their findings. Relative dating often depends on the Law of Superposition and contextual components such as stratigraphy or biostratigraphy to produce a more precise sequential order of events (Lyman *et al*. 1998). The Law of Superposition is a fundamental part of the principles of geochronology coined by Nicolaus Steno (1669) which states that in any undisturbed stratigraphic formation, the deeper the layer, the older it is; thus, the topmost layer will be the youngest and the bottom layer the oldest. Other related principles include the Principle of Original Horizontality, which refers to the horizontal deposition of sedimentary layers through gravity; the Principle of Lateral Continuity, which describes original sedimentary beds as continuous layers that extend laterally in all directions; and lastly, the Principle of Cross-cutting Relationships, which states that a sedimentary feature which cuts across another must be younger than the sediment it cuts across (Kravitz 2014). All four of these laws of stratigraphy have been adapted to interpret stratigraphic sequences in archaeology.

In the early 1950s, the radiocarbon revolution brought a new wave of dating methods into archaeology. Absolute (also known as chronometric) quantitative measurement is now the favored method to estimate the age of archaeological data. The moment Arnold and Libby (1949) published their ground-breaking paper on radiocarbon age determination, numerous archaeological samples were sent in for dating (Arnold and Libby 1951). Without a doubt, radiocarbon has become the fundamental component for building our understanding of the earth's chronological events for the last 50 thousand years. Today, this dating methodology is usually conducted in the following steps: collection, pre-treatment, measurement, calibration, and sometimes the application of Bayesian statistical models (Wood 2015). Pre-treatment in particular is critical for the removal of contaminants which can result in erroneous results if present during the dating process (Bird *et al*. 2014; Wood 2015). Two main methods for charcoal pre-treatment exist, the more common or standard acid–base–acid (ABA) method, and the Acid Base Oxidation – Stepped Combustion (ABOx-SC) method developed by Bird *et al*. (1999). ABOx-SC is increasing in global use (Scott *et al*. 2018) and considered the "most reliable pre-treatment for sample decontamination prior to radiocarbon dating" (Bird *et al*. 2014:31). Unfortunately, for samples in the humid tropics such as Indonesia, ABOx-SC often proves too intense, resulting in oxidation and loss of the sample (Bird *et al*. 2014; Wood 2015).

While radiocarbon is the most prominent method that has been applied to archaeological sites, it has its own limitations. Due to the poor preservation of organic remains encountered in the tropics (Louys *et al*. 2017; Morley 2017), the oldest (i.e., Pleistocene) radiocarbon dates in Indonesia are rarely obtained from charcoal; instead relying on shell (see Table 1). Radiocarbon dating of marine shell is however considered more problematic than terrestrial plant carbons such as charcoal, due to a greater number of uncertainties affecting the results. In particular, local marine reservoir (ΔR) effects, the "hard-water effect" for shells from limestone rich areas, and effects of recrystallization (Douka *et al*. 2010), all detract from the accuracy of the final calibrated date. While taxonomic identification of shells and the use of staining with Feigl's solution minimize errors associated with hard water and recrystallization (Dickson 1966; Douka *et al*. 2010), there has been very limited research investigating local reservoir effects across the Island Southeast Asia region (Southon *et al*. 2002).

Dating beyond the radiocarbon limit

Despite continued improvements in radiocarbon techniques, the limit of the calibration curve remains at ca. 55 ka (Reimer *et al*. 2020). Additionally, it is understood that the older the sample, the harder it becomes to get a precise date using radiocarbon dating due to unstable ^{14}C isotopes (Jones 1999), while the risk of contamination increases exponentially as the age approaches 50 ka (Price *et al*. 2011; Wood 2015). Moreover, not every site recovers a high abundance of materials that can be used for radiocarbon analysis. Fortunately, radiocarbon is not the only absolute dating method available to researchers today (Walker 2005).

In the early 1990s, Roberts and colleagues published their research at Madjedbebe (back then called Malakunanja II) claiming that the site had been occupied since 50 ka based on thermoluminescence (TL) dating techniques (Roberts *et al*. 1990). This site is located on the Arnhem Land escarpment, Northern Territory of Australia (Figure 1), and had previously been dated to 18 ka using radiocarbon (Kamminga and Allen 1973). TL was developed in the 1970s and had received some application in archaeology for dating quartz grains in pottery (Zimmerman 1971; Mejdahl 1979; Wintle and Huntley 1982); however, its use at Madjedbebe by Roberts *et al*. (1990) was the first instance where TL was used to date archaeological sediments for determining initial occupation. Unsurprisingly, this claim by Roberts *et al*. (1990) received numerous protests and scepticism from the archaeological community (e.g., Hiscock 1990; David 1993; Lourandos 1993).

Roberts *et al*. (1998a) then suggested that Optically Stimulated Luminesence (OSL) dating was a more suitable and reliable dating technique than TL, as it is less susceptible to exposure inconsistencies and any such inconsistencies can also be better detected in OSL samples. TL dating has since been largely abandoned for dating in Australasian archaeology and Roberts *et al*. (1998b) subsequently re-dated Madjebebe using OSL. The new OSL study recovered dates of 44.2 ± 4.7 ka and 55.5 ± 8.2 ka which continued to support the >50 ka colonisation date for Australia (Roberts *et al*. 1990; Roberts *et al*. 1998b). Thus, the debate continues (see O'Connell and Allen 2004; Allen and O'Connell 2014).

In particular, O'Connell *et al*. (2018) conducted a thorough critique of the various post-depositional influences at Madjedbebe, which they consider responsible for an erroneously older date of occupation at the site. As luminescence dating concerns the age on the sediments and cannot therefore be directly connected with human occupation (unlike radiocarbon, e.g., charcoal from hearths, shells from middens, etc.), a sound understanding of site formation processes, stratigraphic integrity and confidence in the association between sediment and cultural materials is essential. Extensive investigations into the chronology and stratigraphy at Madjedbebe over the last few years by Clarkson *et al*. (2015, 2017, 2018), have however, provided strong support for the stratigraphic integrity of this site.

One argument against OSL dating is a potential lack of comparability with radiocarbon dates (compounded by the obvious lack of available radiocarbon dates beyond 50 ka). Recent work at Madjedbebe (Clarkson *et al*. 2015, 2017) and another northern Australian site, Riwi (Wood *et* *al*. 2016), recovered strong support for correspondence between radiocarbon and OSL dates obtained from the <50 ka levels of these deposits, supporting the validity of deeper >50 ka OSL dates. The few other Australian sites where multi-dating techniques have been applied (e.g., Ngarrabullgan, Jinmium, Devil's Lair) have generally recovered good agreement between the radiocarbon and OSL dates, supporting the reliability and accuracy of both dating techniques (David *et al*. 1997; Roberts *et al*. 1998a; Turney *et al*. 2001; Wood *et al*. 2016).

Examples of dual (radiocarbon and OSL) dating of a site are rare, particularly in Indonesia where Liang Bua (Table 1:69) on Flores remains the only cave/rockshelter site combining radiocarbon with other absolute dating techniques to date human occupation layers (Sutikna *et al*. 2016). Recent re-excavations at the site of Asiatu Kuru (previously Jerimalai) on nearby Timor-Leste recovered the first OSL dates for the site (Shipton *et al*. 2019). Shipton *et al*. (2019) also recovered good agreement between their OSL determinations and radiocarbon dates on charcoal but did identify a lack of this agreement with dates on shell. It is clear that much greater efforts to apply multi-dating techniques to archaeological investigations are required across the region to improve our understanding of the correspondence between these methods and develop a comparable dataset of their results. Additionally, work on inter-laboratory comparisons for OSL analysis needs to be expanded to meet similar quality control and consistency protocols that exist for radiocarbon (Scott *et al*. 2007, 2018; Murray *et al*. 2015).

A major criticism of the Madjedbebe OSL dates is the complete absence of any other sites across Sahul (Australia-New Guinea) which have recovered dates of similar antiquity (see O'Connell *et al*. 2018). However, the number of sites recovering initial occupation date ranges which include 50 ka, have increased significantly in recent years (e.g., Wood *et al*. 2016; Delannoy *et al*. 2017; Veth *et al*. 2017; Maloney *et al*. 2018; McDonald *et al*. 2018; David *et al*. 2019). Also, a number of re-dating efforts of previously >50 ka sites have resulted in their revision to substantially younger occupation dates (e.g., Jinmium, Roberts *et al*. 1998a; see also O'Connell *et al*. 2018). This proliferation of initial occupation dates around 50 ka, in addition to similar molecular clock estimates from studies of Aboriginal mitochondrial DNA (Tobler *et al*. 2017) and Y chromosomes (Bergström *et al*. 2016), led O'Connell *et al*. (2018) and Allen and O'Connell (2020) to suggest that Australia was colonized at 50 ka, but no earlier. However, it should be noted that the vast majority of these dates are from radiocarbon samples, bringing their ages right up against the radiocarbon barrier (see above) and raising the possibility that these sites may have been occupied earlier but require an alternative dating method to investigate.

Another dating method which extends beyond the radiocarbon limit is Uranium series (U-Series). U-series dating commonly uses concentrations of inorganically precipitated calcium carbonate usually found in caves, open air carbonate deposits, or fossil soils (Schwarcz 1980). As with OSL techniques, U-series does not *directly* date human occupation, but rather associated materials, recovering 'maximum' and/or 'minimum' ages which bracket the 'true' dates for occupation (see Aubert *et al*. 2014). This method has recently seen increased applications in Indonesia, most famously by Aubert *et al*. (2014, 2018, 2019) to date the rock art of Sulawesi and Kalimantan. Additionally, at the site of Lida Ajer (Table 1:5) in Sumatra (Figure 1), Westaway *et al*. (2017) applied OSL and U-series dating techniques to bone-bearing sediments and speleothems, and combined U-series with electron spin resonance (ESR) dating techniques on human and faunal teeth recovered from the site. The combined dating effort produced a range between 73–63 ka (Westaway *et al*. 2017), considered by the authors as consistent with the estimated time of *Homo sapiens* arrival in Island Southeast Asia.

While speleothems are rich in Uranium (U) which is co-precipitated with the calcium carbonate at the time of formation, bones and teeth typically contain little or no U when fresh. Archaeological bones and teeth on the other hand commonly have high concentrations of U as they are a well-known ‘open systems’; meaning that U from the surrounding environment is taken up by these biological tissues following burial, with the radioactive decay chain beginning thereafter (Pike *et al*. 2002; Eggins *et al*. 2005). However, being open systems means that not only is U taken up by bones and teeth but it can also be subsequently lost; due to leaching by flowing water, mineral alteration, or mineralogical transformation, leading to age overestimation, a particularly common scenario in cave environments (Pike *et al*. 2002; Pons-Branchu *et al*. 2014, 2020). While the possibility for leaching can be recognized and tested for (e.g., Price *et al*. 2013), and different models applied to account for perceived ‘open’ or ‘closed’ system scenarios (Pike *et al*. 2002; Eggins *et al*. 2005), this known issue of U-series dating of biological items has led many to question the reliability of such dates (e.g., O’Connell *et al*. 2018).

History of dating human occupation in Indonesia

Interest in Indonesian prehistory can be traced back to its colonial occupation, to the likes of G. E. Rumphius—an 18th century antiquarian, and Eugène Dubois—famously known for his discovery of *Homo erectus* at Trinil during his 1891–1892 exploration (Dubois 1894). Later in 1907–1908 Dubois carried out larger excavations to recover more hominin remains, but only found faunal material. Research on ‘Java Man’ was further pursued by von Koenigswald in 1931–1933. He found more hominin and primate fossils in Java (von Koenigswald and Weidenreich 1938, 1939; Tobias and von Koenigswald 1964) including the famous *Meganthropus palaeojavanicus* (since thought to be *H. erectus* but recently resurrected as a distinct species; Zanolli *et al*. 2019), which have inspired discussion among palaeoanthropologists ever since.

The earliest recorded archaeological cave exploration in Indonesia was made by P. and F. Sarasin in 1902. Both naturalists visited Sulawesi between 1902 and 1903, discovering the Toalian culture which triggered a later influx of researchers to the region (Soejono 1969). Nevertheless, it was not until the late 1960s–early 1970s that absolute dating samples were first collected and published from Indonesian sites (Jacob 1967; Mulvaney and Soejono 1971; Glover 1976). One of the earliest dating efforts in Indonesia arose from the collaborative Australian-Indonesia research team led by Raden Panji Soejono and Derek John Mulvaney (Mulvaney and Soejono 1970).

Soejono, later considered “the father of Indonesian prehistory”, and Mulvaney, later “the father of Australian archaeology”, conducted research together on Sulawesi, and dated several sites. From their joint research they concluded that “Typological comparison of artefacts too often degenerates into diffusionist conjecture, but we hope that our final report will be based on quantitative data.” (Mulvaney and Soejono 1970:176). Archaeological research and collaboration between Indonesia and international counterparts became more common into the later 1970s and 1980s, producing further dating results (e.g., Bronson and Asmar 1975; Bellwood 1976; Glover 1976, 1981).

Mulvaney was one of the earliest archaeologists to apply radiocarbon in archaeological research (Mulvaney 1960), discovering the first stratigraphic proof that Aboriginal people had been in Australia during the last glacial period (Mulvaney and Joyce 1965:183). This research also had subsequent implications for Indonesian prehistory, precipitating further questions about the ancestors of Australia’s indigenous peoples and the timing and pattern of their dispersal through the islands of Indonesia (Birdsell 1977). As mentioned above, current dates from Madjedbebe in Northern Australia support occupation of Sahul prior to 50 ka (Clarkson *et al*. 2017; Allen and O’Connell 2020). Based on models of early human movements through the region (e.g., Birdsell 1977; Kealy *et al*. 2018a), this indicates occupation of numerous Indonesian islands well before 50 ka. This is supported by the >60 ka dates for occupation from Lida Ajer in Sumatra (Westaway *et al*. 2017), then part of continental Sunda.

The island nation of Indonesia shares land borders with Papua New Guinea (New Guinea), Malaysia (the island of Borneo), and Timor-Leste (Timor), from which a number of notable early occupation dates for the region have been recovered (Figure 1). In particular, the Papua New Guinea (PNG) site of Vilakuav provides good support for a >50 ka colonisation of Sahul (Summerhayes *et al*. 2010), with other notable Pleistocene sites including Latichu, Nombe, Kiowa, and Kosipe (Gaffney *et al*. 2015; O'Connor and Chappell 2003). In neighboring Malaysian Borneo, the well-known site of Niah cave was one of the earliest discoveries to promote occupation of the region back to 50 ka (Harrisson 1970; Higham *et al*. 2009). Meanwhile, archaeological research in the country of Timor-Leste has recovered a number of Pleistocene dates from sites such as Lene Hara, Laili, Matja Kuru 2, Bui Ceri Uato, and Uai Bobo 2 (Kealy *et al*. 2016; Hawkins *et al*. 2017), with the most notable being Asitau Kuru with an occupation date extending back to 46.5 ka (Shipton *et al*. 2019).

Caves and rockshelters are not the only type of prehistoric site that has been dated in Indonesia. Researchers have also worked to date megalithic, shell midden, burial, and open sites. Most non-cave and rockshelter prehistoric sites are dated from the middle to late Holocene, with the exception of early Holocene shell middens such as Pangkalan (Wiradnyana 2016) and Pleistocene limestone-fissure sites such as Punung and Wajak (Westaway *et al*. 2007; Storm *et al*. 2013). Yet caves and rockshelters represent an easily identified locality with a good likelihood for preserving evidence of prehistoric occupation, making them a favorite of archaeologists when conducting surveys of novel regions (Kealy *et al*. 2018b).

METHODS

Revision of the literature

We conducted an extensive revision of the published literature pertaining to archaeological research within the country of Indonesia. In particular, we worked to include papers written in languages other than English (i.e., Bahasa Indonesia), as well as those in earlier publications not readily available online. The focus of this study was on cave and rockshelter sites with published absolute dates.

Once sites were recognized, we identified the earliest date representing initial occupation of the site and catalogued these with the associated dating method. In the case of U-series dates the published calibrated range was recorded without modification. For radiocarbon results the radiocarbon date, error, laboratory code, and material type, were all documented where available.

All identified site localities were plotted on a map of the region with the best available accuracy, dependent on the detail of published descriptions and GPS coordinates. In addition, we distinguished sites based on their initial occupation period as either Pleistocene, Holocene, or Transitionary between the two geological epochs. According to the ICS International Chronostratigraphic Chart v. 2020/01, the Holocene epoch began 11,700 years ago (Cohen *et al*. 2013 updated). Here we allow for a transitionary period of 1000 years (i.e. 12,200–11,200), and any site with an initial occupation calibrated date range which overlaps with this transitionary range was marked on our maps as occurring during the Pleistocene–Holocene transition.

Calibration of radiocarbon dates

In the name of consistency, all radiocarbon dates regardless of how recently they were published, were re-calibrated here. For calibration we used the online platform OxCal v.4.4 (Bronk Ramsey 2009), and applied the recently released International calibration curve—IntCal20 (Reimer *et al*. 2020) for samples of terrestrial carbon (e.g., charcoal and tooth enamel). IntCal20 is considered to provide a more reliable estimate than SHCal20 (the Southern Hemisphere calibration curve; Hogg *et al*. 2020) for equatorial regions, thus we elected to use this curve for all our calibrations, including those from sites located south of the equator. For marine shell samples we applied the Marine20 calibration curve (Heaton *et al*. 2020).

A single study by Southon *et al*. (2002) has reported marine reservoir data for Indonesia, with five ΔR values applicable to Indonesian waters; one from northern Australia, one from southwest Java, one from southwest Kalimantan, and two from Singapore. Their values range from -80ΔR to +74ΔR with an average of -2.4ΔR, suggesting that the effect is minimal in the region (Southon *et al*. 2002). Considering our focus here on early dates, such low values for ΔR have a neglectable effect on the final calibrated dates. Minimal local reservoir effects, in addition to a complete lack of ΔR data from central and eastern Indonesia, led to our decision to calibrate all our marine shell dates without a ΔR offset (e.g. O'Connor *et al*. 2018; Samper Carro *et al*. 2019). Temporal errors can also occur in charcoal samples due to the 'old wood' effect (Kennett *et a*l. 2002); however, in the tropical environment of Indonesia this error range is unlikely to reach, and certainly not exceed, the local reservoir effect for shells (Kennett *et al*. 2002; Petchey *et al*. 2012). With our focus here on prehistoric dates, the majority of which are older than 1000 years, errors of ~100 to 200 years are unlikely to have a substantial impact on the overall calibrated result (Petchey *et al*. 2012).

As calibration of radiocarbon dates uses either an atmospheric calibration curve (e.g. IntCal20; Reimer *et al*. 2020) or a marine curve (e.g., Marine20; Heaton *et al*. 2020), freshwater shell dates are particularly problematic (e.g., Glover 1981) as freshwater systems are known to experience substantial variability in their ^{14}C reservoir effects (Fernandes *et al*. 2012). Unless the freshwater shells can be taxonomically identified, directly associated with a specific locality, and a corresponding ^{14}C reservoir correction calculated (e.g. Berger and Meek 1992), any calibration attempt will be subject to substantial uncertainty (Culleton 2006; Fernandes *et al*. 2012). For dates obtained on freshwater shells we therefore combined the calibration ranges produced using both IntCal20 (i.e., atmospheric) and Marine20 (i.e., marine) curves. This was done to obtain a broad age estimate accounting for the range of possible ecological zones (e.g. intertidal – mostly marine, to inland – freshwater) from where the samples may have originated, and the variability in their ^{14}C reservoir effects. Similarly, we applied the same procedure to dates where published information on the material sampled was unavailable or unclear (e.g., they could be either shell or charcoal). Unfortunately, one published date also lacked information on the associated error with the radiocarbon date. For this we applied an error of ±500 to the calibration as a rough estimate based on the general average error across sites (see Table 1).

We are aware that the methods applied to the freshwater shells, unknown samples, and those missing error information, have likely under- or over-estimated the ages of these sites. Nevertheless, we consider these calibrations as useful estimates to aid archaeologists with general site interpretation, perhaps inspiring their reinvestigation in the future.

RESULTS

A total of 99 cave and rockshelter sites with published absolute dates were catalogued for Indonesia (Table 1, Figure 1). Eight dates are available only from publications in Bahasa Indonesia, and yet of particular significance as they concern key sites such as Gua Pawon (Table 1:9), the only dated cave site in West Java (Yondri 2010); Gua Toroan (Table 1:20) and Delubang (Table 1:21), the only two records for cave occupation on the island of Madura (Muda 2017); and Gua Gede (Table 1:23) the only known site on Nusa Penida (Hidayah 2017). As Figures 2–8 illustrate, the most common sites are dated to the Holocene, with Transitionary sites understandably few in number. The majority of sites are located on the island of Sulawesi with 23 sites (Figure 5), followed by Java (Figure 3) with 13 sites. With the exception of the Nusa Tenggara islands (Figure 6), the rest of Indonesian's smaller, more easterly islands (i.e., Figures 7 and 8) record a notable reduction in relative numbers of known Pleistocene-aged sites.

Based on our calibrations, Indonesia preserves 44 Pleistocene archaeological records for initial *Homo sapiens* occupation in caves and rockshelters, 46 Holocene records, and nine sites which record initial occupation over the Pleistocene–Holocene transition. Of the 81 radiocarbon dates we catalogued, at least 30 are calibrated here for the first time (Table 1).

Of the more than 18,000 islands in Indonesia, about 6000 are inhabited in the country today

(Rigg 1996; Cribb and Ford 2009); however, only 28 have known, dated archaeological sites (Table 1, Figures 1–8). The most commonly dated material is terrestrial carbons (e.g., charcoal and bone), utilizing radiocarbon methods. Eleven of these dates lack information on the material sampled, and one date is missing the associated radiocarbon error.

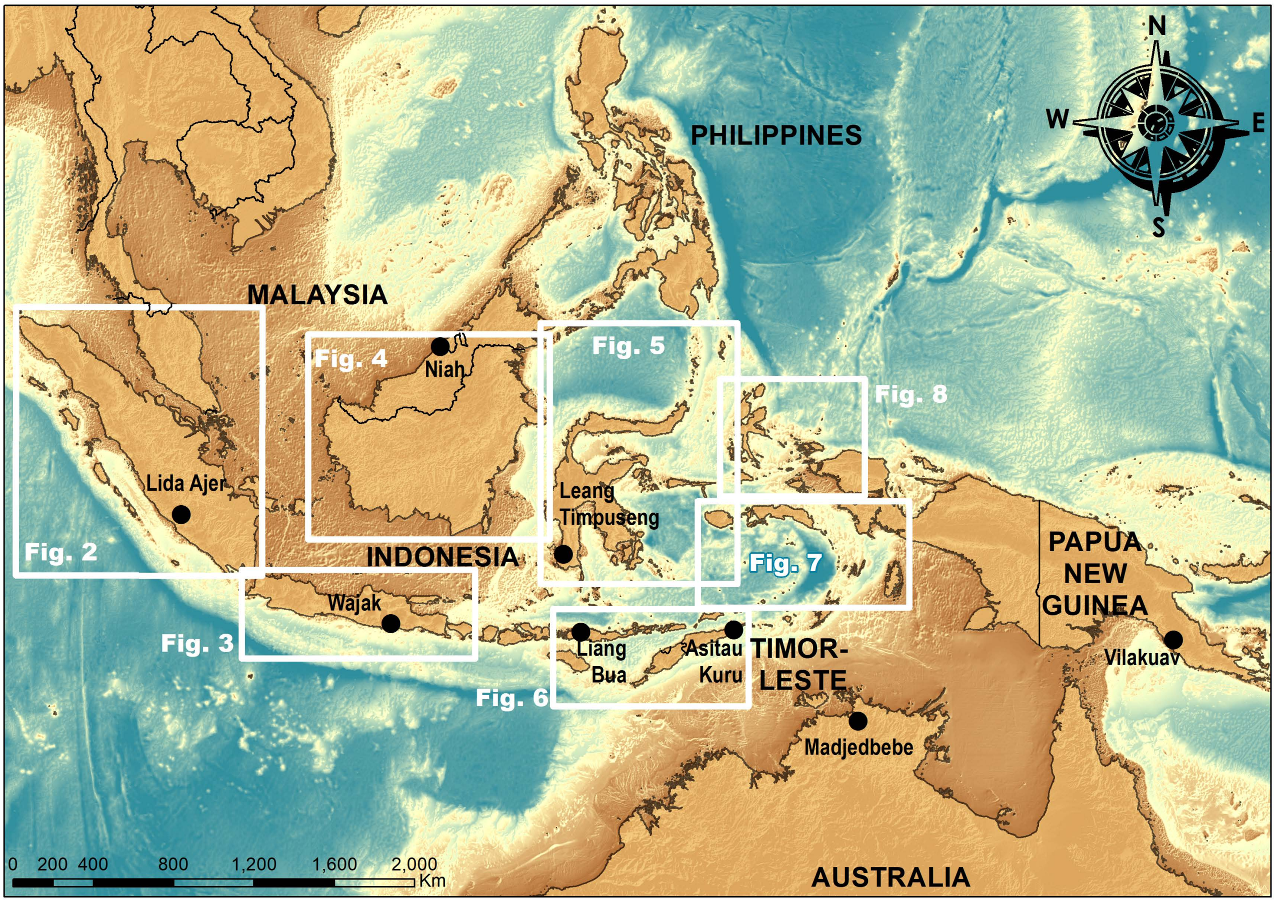

Figure 1: Map of Indonesia and its neighbouring countries. Regional archaeological sites of interest are indicated by black circles. The extent of the continental shelves delineating Sunda and Sahul is shown in grey. Boxes correspond to Figures 2–8 in the Results. Bathymetric basemap from the General Bathymetric Chart of the Oceans (GEBCO_19) dataset (Smith and Sandwell 1997). Figure designed by Kaharudin and Kealy.

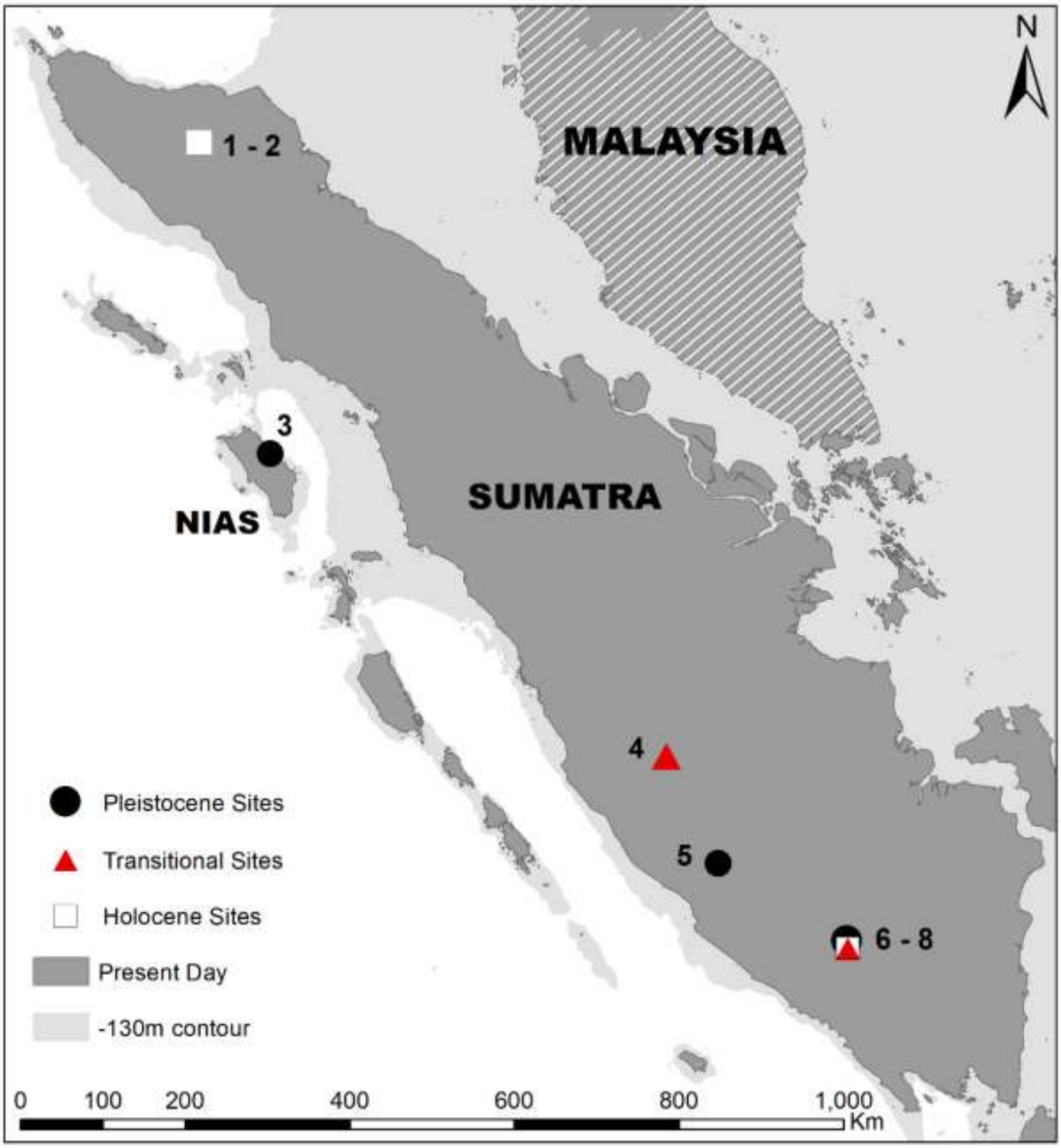

Figure 2: Map of Sumatra showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles), Transitionary period (red triangles), and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin.

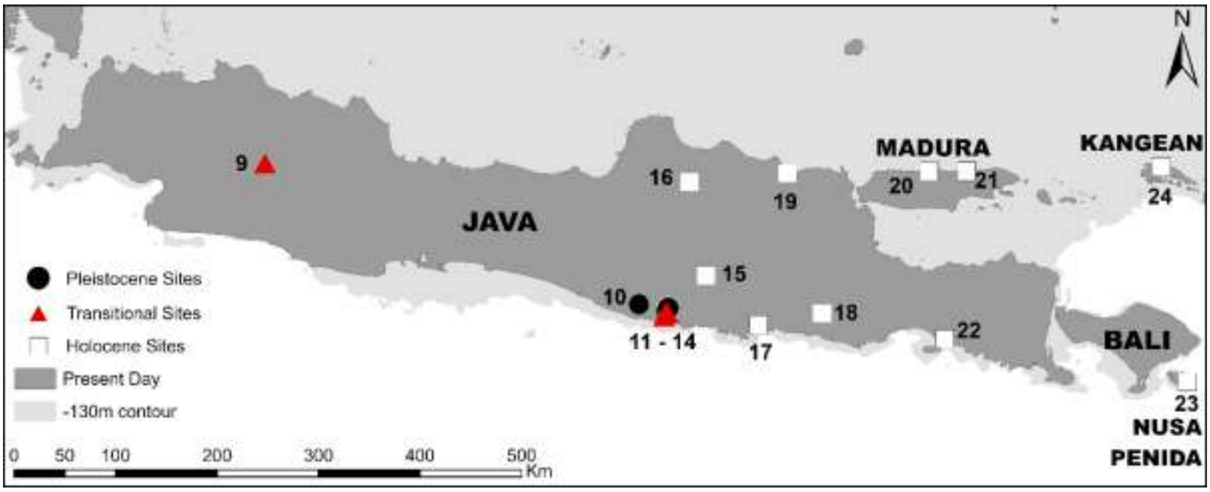

Figure 3: Map of Java and Bali showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles), Transitionary period (red triangles), and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin .

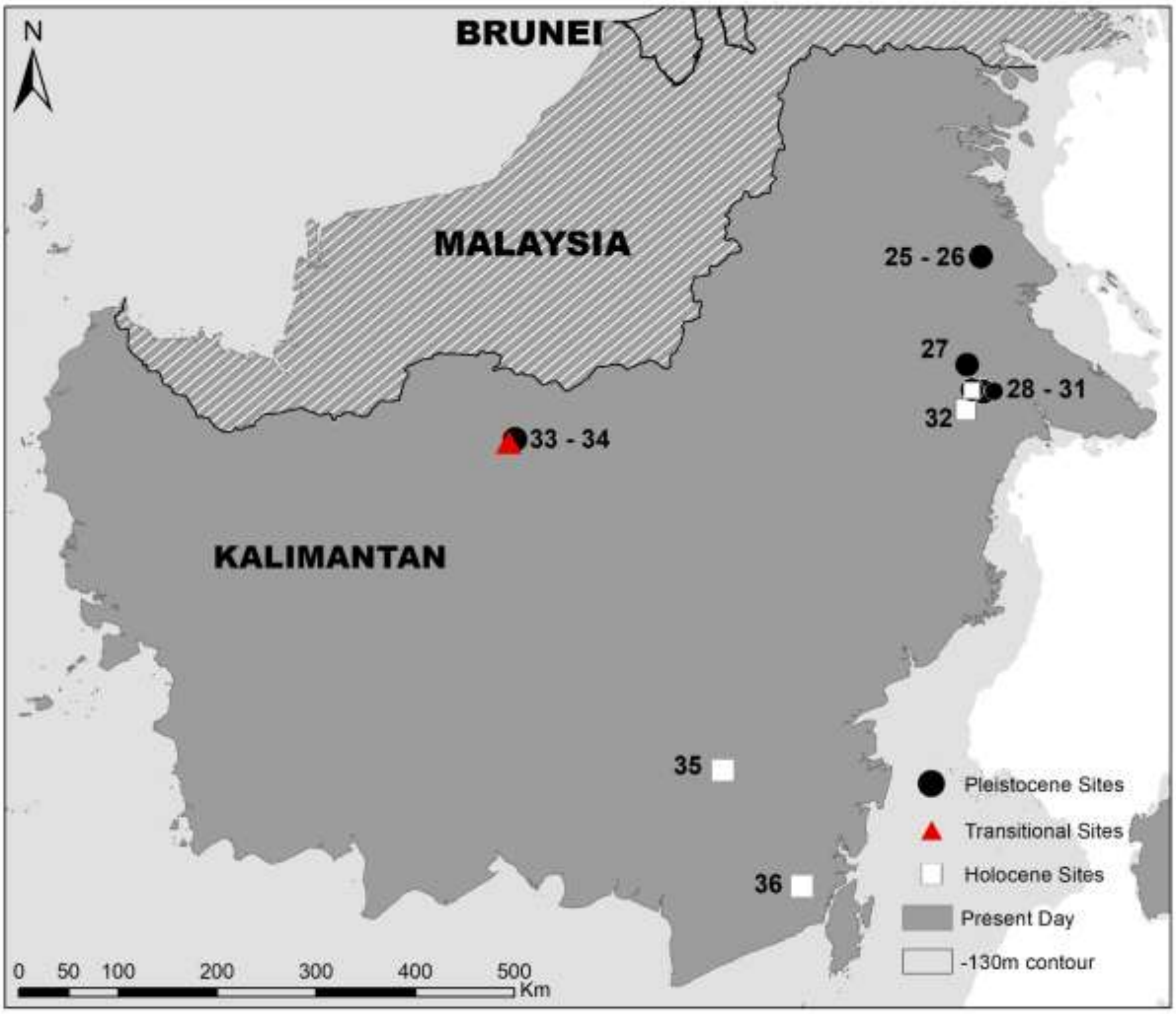

Figure 4: Map of Kalimantan showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles), Transitionary period (red triangles), and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin.

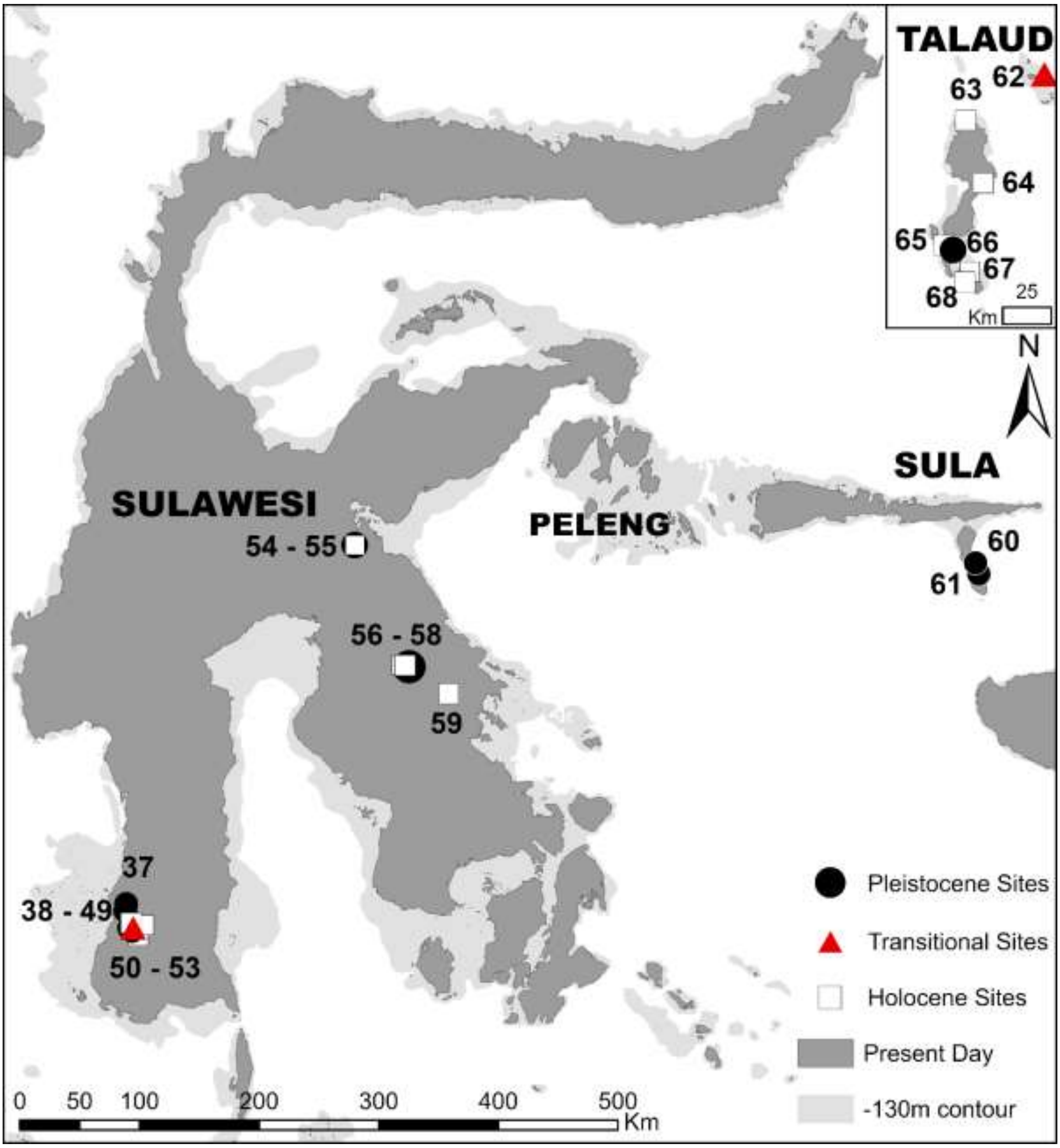

Figure 5: Map of Sulawesi, the Sula islands, and the Talauds (inset), showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles), Transitionary period (red triangles), and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin.

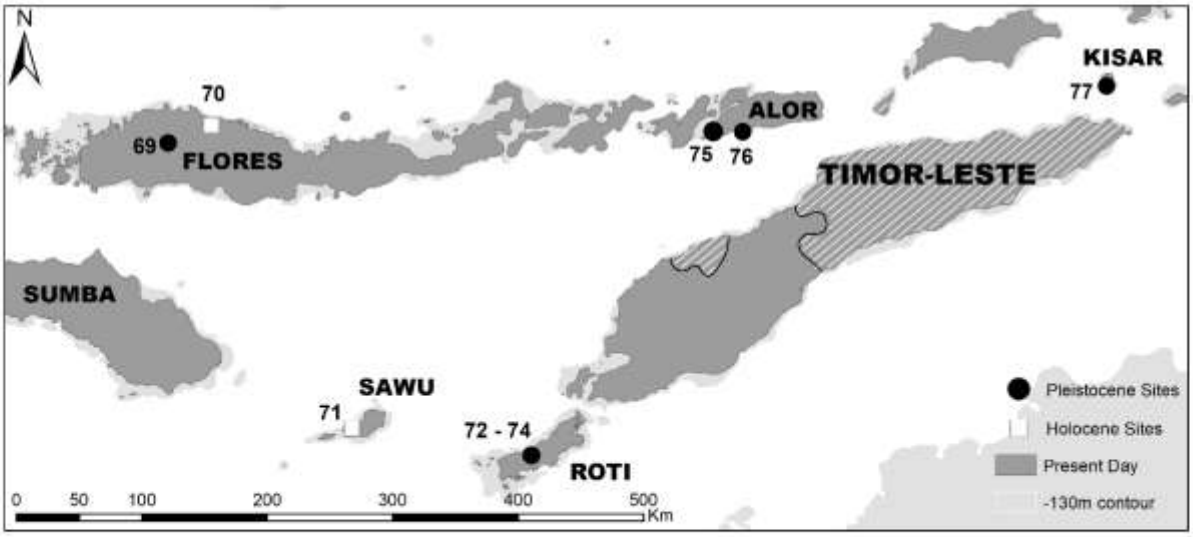

Figure 6: Map of Nusa Tenggara Timur and Kisar island showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles) and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin .

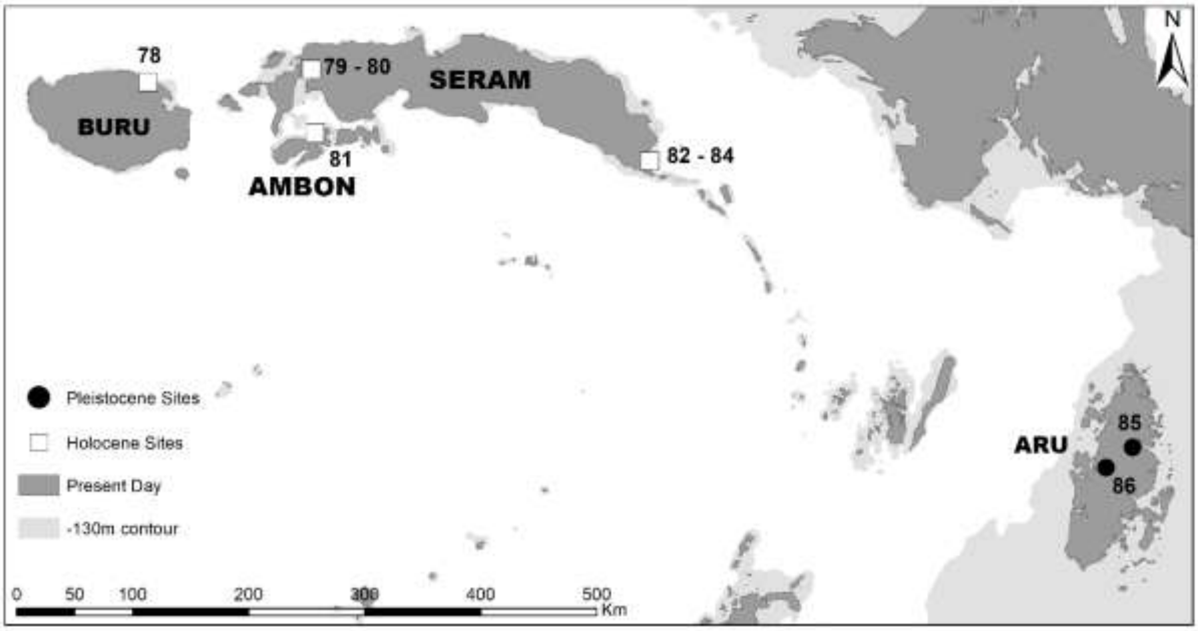

Figure 7: Map of Maluku showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles) and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin .

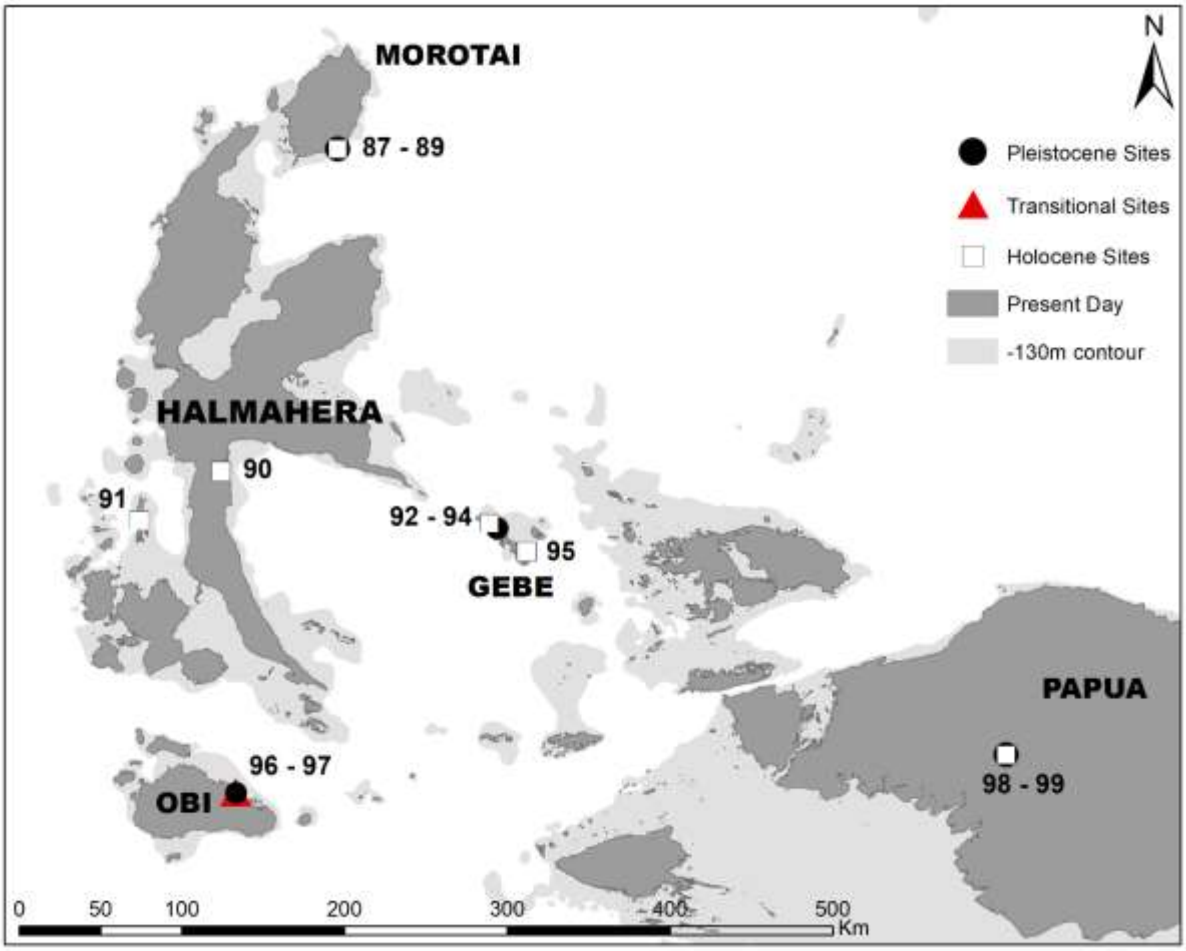

Figure 8: Map of Maluku Utara and Papua Barat showing location of cave and rockshelter sites with absolute dates. Numbers correspond to Table 1. Sites documenting initial occupation during the Pleistocene (black circles), Transitionary period (red triangles), and the Holocene (white squares), are indicated. Figure by Kealy and Kaharudin.

Table 1: Cave and rockshelter sites in Indonesia preserving archaeological records for which absolute dates have been obtained, detailing site location, dating methods, and earliest date for occupation. Radiocarbon dates were calibrated in OxCal Online v.4.4 (Bronk Ramsey 2009) following the methodology detailed above. Calibration ranges are shown for a 2-sigma error (i.e., 95.4% probability). U-series dates are reported here according to their published calibrations—please refer to the individual sources for methodological details.

Sumatra

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source[a]
1	Loyang Ujung Karang	Sumatra	Radiocarbon	–	Burn ashes	5080	120	6176–5589	1
2	Loyang Mendale	Sumatra	Radiocarbon	–	–	8430	80	9545–8547 [b]	1
3	Gua Togi Ndrawa	Nias	Radiocarbon	–	–	12,170	400	15,529–12,736 [b]	1
4	Tianko Panjang	Sumatra	Radiocarbon	P-2250	Charcoal	10,250	140	12,593 – 11,401	2
5	Lida Ajer	Sumatra	U-Series/ ESR	modeled composite	Breccia/teeth	–	–	73,000–63,000	3
6	Gua Harimau	Sumatra	Radiocarbon	–	Charcoal	13,055	120	15,995–15,276	4
7	Gua Pondok Selabe I	Sumatra	Radiocarbon	–	–	4520	290	5895–4425 [b]	5
8	Gua Pandan	Sumatra	Radiocarbon	–	–	9270	380	11,690–8987 [b]	5

Java and Bali

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source
9	Gua Pawon	Java	Radiocarbon	–	Human bone	9525	200	11,311–10,248	6
10	Gua Braholo	Java	Radiocarbon	–	Bone	33,100	1260	40,970–35,400	7
11	Song Keplek	Java	Radiocarbon	–	Bone	24,420	1000	31,020–27,085	7
12	Song Gupuh	Java	Radiocarbon	Wk-14650	Charcoal	9961	60	11,699–11,241	8
13	Song Terus	Java	U-Series	ST9901	Bone	–	–	11,800–10,600	9
14	Gua Tabuhan	Java	U-Series	–	Bovid enamel	–	–	56,000–50,000	9
15	Gua Lawa	Java	Radiocarbon	–	–	8190	170	9524–8127 [b]	7
16	Gua Kidang	Java	Radiocarbon	–	Marine shell	9600	160	10,815–9825	10
17	Song Gentong	Java	Radiocarbon	ANU-10584	–	8760	190	10,275–8690 [b]	11
18	Gua Perahu	Java	Radiocarbon	–	–	6971	–	9010–6224 [c]	12
19	Gua Peturon	Java	Radiocarbon	–	–	7670	120	8850–7668 [b]	7

20	Gua Toroan	Madura	Radiocarbon	–	Marine shell	3750	30	3671–3365	13
21	Gua Delubang	Madura	Radiocarbon	–	Marine shell	4470	30	4635–4270	13
22	Gua Macan	Java	Radiocarbon	–	–	2490	90	2745–1717 [b]	11
23	Gua Gede	Nusa Penida	Radiocarbon	GGD-U11-D7sp22pg	Tooth	8800	50	10,147–9562	14
24	Gua Arca	Kangean	Radiocarbon	Wk-49954	Marine shell	5850	44	6241–5905	15

Kalimantan

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source
25	Lubang Payau	Kalimantan	Radiocarbon	ANU-11261	Freshwater shell	17,730	250	22,165–19,863 [b]	16
26	Kimanis	Kalimantan	Radiocarbon	ANU-11259	Freshwater shell	23,630	480	28,979–25,969 [b]	16
27	Liang Abu	Kalimantan	Radiocarbon	UBA-20842	Charcoal	12,660	58	15,284–14,914	17
28	Lubang Jeriji Saléh	Kalimantan	U-Series	LJS1.3	CaCO3 over rock art	–	–	41,720–40,040	18
29	Lubang Ham	Kalimantan	U-Series	LH2.3	CaCO3 over rock art	–	–	9670–9310	18
30	Liang Sara	Kalimantan	U-Series	LSR2.3	CaCO3 over rock art	–	–	15,260–14,570	18
31	Liang Banteng	Kalimantan	U-Series	LBT1.3	CaCO3 over rock art	–	–	19,920–19,680	18
32	Liang Jon	Kalimantan	Radiocarbon	SacA-19317	Charcoal	2665	35	2849–2740	17
33	Diang Kaung	Kalimantan	Radiocarbon	ANU-12131	Charcoal	9700	35	11,222–10,875	19
34	Diang Balu	Kalimantan	Radiocarbon	ANU-43333	Charcoal	12,475	40	14,979–14,336	19
35	Gua Babi	Kalimantan	Radiocarbon	–	–	6620	110	7679–6627 [b]	20
36	Gua Payung	Kalimantan	Radiocarbon	–	Freshwater shell	3070	130	3564–2335 [b]	21

Sulawesi, Sula, and Talauds

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source
37	Leang Bulu Sipong 4	Sulawesi	U-Series	BSP4.3.5	CaCO3 over rock art	–	–	44,900–43,920	22
38	Leang Timpuseng	Sulawesi	U-Series	LT2.3	CaCO3 over rock art	–	–	41,570–39,860	23
39	Leang Jarie	Sulawesi	U-Series	LJ1	CaCO3 over rock art	–	–	39,990–39,350	23
40	Leang Sampeang	Sulawesi	U-Series	LS1.2	CaCO3 over rock art	–	–	33,360–31,840	23
41	Gua Jing	Sulawesi	U-Series	GJ1.3	CaCO3 over rock art	–	–	32,600–29,100	23
42	Leang Lompoa	Sulawesi	U-Series	LL2.2	CaCO3 over rock art	–	–	30,500–28,200	23
43	Leang Barugayya 1	Sulawesi	U-Series	LB1.2	CaCO3 over rock art	–	–	32,300–26,000	23
44	Leang Barugayya 2	Sulawesi	U-Series	LB4.2	CaCO3 over rock art	–	–	53,100–35,700	23
45	Leang Sakapao 1	Sulawesi	U-Series	Wk-3821	Freshwater shell	31,280	570	36,867–33,906 [b]	24
46	Leang Burung 1	Sulawesi	Radiocarbon	ANU-6175	Apatite	4610	220	5893–4655	25
47	Leang Burung 2	Sulawesi	Radiocarbon	GRN-8649	Freshwater shell	32,160	330	37,354–35,113 [b]	26
48	Leang Bulu Bettue	Sulawesi	U-Series	–	Anoa tooth	–	–	40,000–39,600	27
49	Batu Ejaya 1	Sulawesi	Radiocarbon	Wk-5464	Marine shell	4430	50	4608–4186	25
50	Leang Karassak	Sulawesi	Radiocarbon	Wk-3823	Charcoal	2690	60	2933–2727	25
51	Gua Pasaung	Sulawesi	Radiocarbon	Wk-20381	Charcoal	6026	70	7155–6674	28
52	Ulu Leang 1	Sulawesi	Radiocarbon	GRN-8648	Freshwater shell	10,740	50	12,763–11,700 [b]	25
53	Gua Batti	Sulawesi	Radiocarbon	Wk-30264	Charcoal	2928	26	3167–2968	29
54	Topogaro 1	Sulawesi	Radiocarbon	TMNA1-2	Charcoal	8742	31	9890–9555	30
55	Topogaro 2	Sulawesi	Radiocarbon	TMNA2-5	Charcoal	25,424	83	29,983–29,314	30

56	Gua Mo'o Hono	Sulawesi	Radiocarbon	D-AMS-001620	Freshwater shell	6855	32	7779–6999 [b]	31
57	Gua Talimbue	Sulawesi	Radiocarbon	D-AMS-004043	Charcoal	15,863	69	19,375–18,947	32
58	Gua Sambangoala	Sulawesi	Radiocarbon	D-AMS-001993	Charcoal	4923	30	5718–5591	33
59	Gua Tengkorak	Sulawesi	Radiocarbon	D-AMS-009676	Charcoal	7239	36	8170–7971	34
60	Gua Fatiba	Sanana (Sula)	Radiocarbon	ANU-10502	Marine shell	14,200	150	16,815–15,910	35
61	Gua Manaf	Sanana (Sula)	Radiocarbon	ANU-10500	Marine shell	14,090	140	16,635–15,770	35
62	Leang Tahuna	Merampit (Talauds)	Radiocarbon	ANU-10207	Marine shell	10,610	100	12,117–11,340	35
63	Leang Tuwo Mane'e	Karakelong (Talauds)	Radiocarbon	ANU-1717	Marine Shell	4860	130	5112–4355	36
64	Leang Balangingi	Karakelong (Talauds)	Radiocarbon	ANU-393	Charcoal	950	130	1176–663	36
65	Leang Buidane	Salebabu (Talauds)	Radiocarbon	ANU-1516	Charcoal	510	80	662–327	36
66	Leang Sarru	Salebabu (Talauds)	Radiocarbon	ANU-10499	Marine shell	30,750	720	36,085–32,960	35
67	Leang Arandangana	Kabaruan (Talauds)	Radiocarbon	ANU-10202	Marine shell	1130	70	712–396	35
68	Leang Buida	Kabaruan (Talauds)	Radiocarbon	TERRA-070407a06	Marine shell	1358	31	893–631	37

Nusa Tenggara Timur and Kisar

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source
69	Liang Bua	Flores	Radiocarbon	OxA-X-2648-13	Charcoal	42,500 [d]	900	47,276–43,846	38
70	Liang Toge	Flores	Radiocarbon	GX-209	Bone	3550	525	5451–2725	39
71	Lie Madira	Sawu	Radiocarbon	ANU-10916	Marine shell	5800	90	6260–5770	40

72	Lua Meko	Rote	Radiocarbon	ANU-10908	Marine shell	24,420	250	28,346–27,240	40
73	Lua Manggetek	Rote	Radiocarbon	ANU-10915	Charcoal	13,390	430	17,465–14,844	40
74	Pia Hudale	Rote	Radiocarbon	ANU-10912	Marine shell	11,290	150	12,992–12,266	41
75	Makpan	Alor	Radiocarbon	ANU-53609	Marine shell	35,232	427	40,360–38,585	42
76	Tron Bon Lei	Alor	Radiocarbon	ANU-40130	Marine shell	17,630	70	20,661–20,109	43
77	Here Sorot Entapa	Kisar	Radiocarbon	Wk-43368	Marine shell	13,395	33	15,525–15,080	44

Maluku

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source
78	Labarisi	Buru	Radiocarbon	–	Marine shell	6600	90	7150–6644	45
79	Hatuhuran	Seram	Radiocarbon	Beta-181924	Charcoal	1180	40	1243–972	45
80	Hatusua	Seram	Radiocarbon	D-AMS-013933	Marine shell	1092	24	641–417	46
81	Batususu	Ambon	Radiocarbon	Beta-73693	–	780	60	898–44 [b]	45
82	Liang Watu Tewa	Seram	Radiocarbon	D-AMS-013930	Marine shell	4086	28	4118–3775	46
83	Liang Fanga 2	Seram	Radiocarbon	D-AMS-013929	Marine shell	4850	28	5135–4780	46
84	Liang Kilbidi	Seram	Radiocarbon	D-AMS-013931	Marine shell	3607	27	3479–3186	46
85	Liang Nabulei Lisa	Kobroor (Aru)	Radiocarbon	OZF518	Eggshell	13,130	80	16,014–15,501	47
86	Liang Lemdubu	Kobroor (Aru)	U-Series	LC28	Flowstone	–	–	27,310–26,730	48

Maluku Utara and Papua

No.	Site name	Island	Dating method	Dating code	Dating material	14C Date	± error	Calibrated Date (2σ) BP	Source
87	Daeo 2	Morotai	Radiocarbon	ANU-9450	Marine shell	13,930	140	16,417–15,571	49
88	Tanjung Pinang	Morotai	Radiocarbon	ANU-7782	Marine shell	8860	110	9622–9028	49
89	Sambiki Tua	Morotai	Radiocarbon	ANU-7784	Charcoal	720	180	1055–326	49
90	Gua Siti Nafisah	Halmahera	Radiocarbon	ANU-7789	Marine shell	5120	100	5548–4971	49
91	Gua Uattamdi	Kayoa	Radiocarbon	ANU-7776	Marine shell	3440	110	3432–2835	49
92	Golo	Gebe	Radiocarbon	ANU-9447	Marine shell	32,490	1070	39,137–34,305	49
93	Wetef	Gebe	Radiocarbon	Wk-4627	Marine shell	25,540	420	29,855–28,002	49
94	Buwawansi	Gebe	Radiocarbon	Wk-4628	Marine shell	8550	70	9245–8720	49
95	Um Kapat Papo	Gebe	Radiocarbon	ANU 9318	Marine shell	6670	60	7165–6755	49
96	Kelo 2	Obi	Radiocarbon	Wk-49406	Marine shell	10,447	29	11,694–11,269	50
97	Kelo 6	Obi	Radiocarbon	Wk-49410	Marine shell	14,974	39	17,552–17,035	50
98	Gua Toe'	Papua	Radiocarbon	OZG-063	Eggshell	25,940	180	30,739–29,948	51
99	Gua Kria	Papua	Radiocarbon	OxA-6043	Charcoal	6900	80	7927–7590	51

a Sources: 1) Wiradnyana 2016. 2) Bronson and Asmar 1975. 3) Westaway et al. *2017. 4) Matsumura* et al. *2018. 5) Forestier* et al. *2006. 6) Yondri 2010. 7) Simanjuntak and Asikin 2004. 8) Morwood* et al. *2008. 9) Sémah* et al. *2004. 10) Nurani and Murti 2017. 11) Simanjuntak 2001. 12) Lahagu* et al. *1991. 13) Muda 2017. 14) Hidayah 2017. 15) Alifah, 2020. 16) Arifin 2017. 17) Plutniak* et al. *2014. 18) Aubert* et al. *2018. 19) Kusmartono* et al. *2017. 20) Widianto 1997. 21) Fajari and Kusmartono 2013. 22) Aubert* et al. *2019. 23) Aubert* et al. *2014. 24) Bulbeck* et al. *2004. 25) Bulbeck* et al. *2000. 26) Glover 1981. 27) Li* et al. *2016. 28) Hakim* et al. *2009. 29) Oktaviana* et al. *2016. 30) Ono* et al. *2020. 31) O'Connor* et al. *2018. 32) Bulbeck* et al. *2019. 33) Fakhri 2018. 34) Bulbeck 2018. 35) Tanudirjo 2001. 36) Bellwood 1976. 37) Ono* et al. *2018. 38) Sutikna* et al. *2018. 39) Jacob 1967. 40) Mahirta 2003. 41) Mahirta* et al. *2004. 42) Kealy* et al. *2020. 43) Samper Carro* et al. *2016. 44) O'Connor* et al. *2019. 45) Latinis and Stark 2005. 46) Lape* et al. *2017. 47) O'Connor* et al. *2005a. 48) O'Connor* et al. *2005b. 49) Bellwood 2019. 50) Shipton* et al. *2020b. 51) Pasveer 2004.*

b Where there is no known dating material the calibration ranges from both IntCal20 and Marine20 were combined.

c Where there is no known error we applied an average estimate error of ±500.

d Here we list the start of Homo sapiens *occupation in Liang Bua, not the earlier arrival of other members of the genus (i.e.,* H. floresiensis*).*

DISCUSSION

Here we present a catalogue of archaeological sites and their corresponding dates for initial occupation, compiled for the first time in over 35 years for the entirety of Indonesia. Our study demonstrates the rapid growth seen in the field of Indonesian archaeology over the last few decades. Where Bronson and Glover documented just 15 dated sites (ten of them caves and rockshelters) across the country in 1984, here, despite limiting our catalogue to only caves and rockshelters, we list 99 sites (an increase of almost 3 sites per year).

An unequal distribution of sites

Sulawesi, Java, and Kalimantan are the regions with the greatest abundance of absolute dating records. This is not to suggest however that other regions of Indonesia have not preserved evidence of prehistoric occupation. As the recent wealth of archaeological discoveries on the island of Kisar demonstrates, a previous lack of sites is more likely an indicator of a lack of research than a lack of preservation (see O'Connor *et al*. 2019, this volume). Even comparatively better-known regions such as Sulawesi still have large areas unexplored and likely a large number of prehistoric sites yet to be discovered (see Figure 5).

So far, accessibility seems to be a dominant factor in the number of sites recorded for a region. For instance, it is much easier to conduct an excavation near a village in Java compared to somewhere in the middle of the jungle of Kalimantan or Papua. Both the availability of settlements and transport networks, as well as physical distance from key centers of infrastructure and administration (Jakarta in particular), appear to have had a substantial impact on the intensity of both initial exploratory research as well as more extensive excavation and dating efforts in Indonesia. This situation is highlighted in the islands and regions missing or poorly represented here in our catalogue. In particular we highlight the regions of Maluku Utara, Nusa Tenggara Barat, and central and northern Sulawesi as key areas for future archaeological research to fill in the geographic gaps.

While a number of open sites, caves, and rock art have been reported from Papua (Fairyo 2010, 2016; Suroto 2012), to date, only two cave sites have produced dating records (Gua Toe', Table 1:98 and Gua Kria, Table 1:99; Pasveer 2004). This situation highlights another factor affecting the distribution of dating efforts across Indonesia—international research collaboration. International collaboration is one of the main driving factors for the increase in dating records in Indonesia that we see over the last few decades (about 65% of the dates catalogued here are the result of international collaboration). Indonesia has its own radiocarbon dating laboratories (the geology research center; P3G in Bandung, and two labs associated with the national nuclear facility-BATAN, one in Yogyakarta: PTAPB and one in Jakarta: PATIR; Faisal 2009), and there are good examples of independent research efforts using these facilities (e.g., Simanjuntak and Asikin 2004).

Several explanations may describe the lack of chronological narrative in some sites. Many cave and rockshelter sites identified in Indonesia as having prehistoric archaeological potential have yet to be excavated, or have not yet had their excavations completed. Of the sites that have been excavated, not all have been dated using absolute methods (our reading of the literature would suggest at least 30 excavated prehistoric sites in Indonesia remain undated). Furthermore, even those sites for which absolute dates have been recovered, not all are well reported in the literature, making it difficult for later investigations of their chronology.

A wrinkle in the oldest age

Radiocarbon dating is the most common technique applied in archaeological sites, including in Indonesia. Although some of the earlier publications provide limited information on their dating methods and results, a number of them were published before publications of conventions in radiocarbon terminology and reporting (see Stuiver and Polach 1977; Mook and van der Plicht 1999). These publications often lack detailed information on dating materials, laboratory sample numbers, as well as the margin of error, which can negatively impact future revisions and research of the sites. We encourage future dating efforts by both technicians and archaeologists involved, to work to produce, obtain, and clearly publish all relevant dating information in accordance with current radiocarbon conventions.

The calibration of radiocarbon dates significantly improves the accuracy of the estimated age of a sample; converting from a radiocarbon determination to an estimated 'true age' (ORAU 2020). However, a calibration curve spaning the last 55 thousand years (i.e., IntCal20; Reimer *et al*. 2020) has not always been available. Archaeological research prior to 2009 was limited to calibrations of ages of less than 26 ka (Reimer *et al*. 2004, 2009). For example, Pasveer (2004) reported 26,000 years of rainforest exploitation in Papua based on the raw date she obtained from Gua Toe' (Table 1:98). She calibrated the majority of her samples but was unable calibrate the oldest two (OZF-847: 23,140±150 and OZG-063: 25,940±180; Pasveer 2004:69). Our current calibrated date (30,739–29,948 cal BP) indicates a clearly older record, pushing back the story of rainforest exploitation by at least another 4 ka. This example demonstrates the significance of continued improvements in calibration curves and calibration techniques, in addition to the importance of re-calibration of previously published dates.

In addition to re-calibration, some sites may be worth revisiting for either their archived collections or physically for re-excavation, in order to increase their dating record. Improvements in the techniques of radiocarbon analysis and laboratory methods mean earlier excavated sites such as Liang Toge (Table 1:70) in particular could benefit from a modern re-dating effort. Liang Toge (Jacob 1967) was dated well before Bird *et al*. (1999) developed the improved ABOx-SC pre-treatment method, while laboratory techniques more generally have improved substantially for all materials, and bone in particular (Wood 2015). Similarly, advancements in excavation techniques and the possibilities of combining dating techniques such as OSL with radiocarbon makes re-excavation of certain sites particularly attractive. The success of such efforts by Clarkson *et al*. (2015, 2017) at Madjedbebe in northern Australia is an inspiration for similar actions to be taken in Indonesia. Furthermore, the increase in international collaborations and funding, and relative decline in dating costs, have somewhat reduced the financial constraints on the numbers of dates possible for archaeological sites in Indonesia.

A higher volume of dates from a single site also provides researchers with the capacity for detailed Bayesian modeling which further improves the accuracy of age estimates (Wood 2015). The success of this technique at the north Australian site of Riwi is a testament to the usefulness of Bayesian modelling in dating archaeological sites, although it also highlights the high number of individual dates required (Wood *et al*. 2016). Recently, work by O'Connor *et al*. (2019) on the island of Kisar produced 21 radiocarbon determinations from two 1 x 1 m square excavations. They successfully used these dates to produce a Bayesian model for occupation across the site, one of the very few such attempts in Indonesian archaeology so far.

CONCLUSION

Thirty-five years after Libby (Arnold and Libby 1949) developed radiocarbon dating, Bronson and Glover (1984) catalogued ten dated cave and rockshelter sites in Indonesia. Another 35 years on and the number of dated archaeological sites in Indonesia has increased substantially. Further aided by improvements in absolute dating techniques, methodologies, and calibration, today there are 99 cave and rockshelter sites across the country with published dates. While this study is restricted to cave and rockshelter sites, we acknowledge that these assemblages comprise just a part of Indonesia's archaeological record. The increase in research generally and dating in particular has not been restricted to Indonesia alone, such efforts have continued throughout the wider Southeast Asian region (e.g., Habu *et al*. 2017; Piper *et al*. 2017); however, Indonesia is remarkable for the number and significance of its new discoveries since 1984. This massive improvement in the chronological record for Indonesian prehistory further enables researchers to interpret the archaeological assemblages, patterns of occupation, and broader cultural narratives of this archipelago.

This review clearly documents improvement in dating efforts across Indonesia, while also highlighting both geographical and temporal gaps in our record. Indonesia, with its fossil records of various archaic hominins (e.g., *Homo erectus*, *H. floresiensis*), and prehistory of multi-cultural turnover, holds a wealth of research potential in these under- and un-explored areas. Further improvements in both the dating records and methodologies across Indonesia have the capacity to inform on more regional and global questions of early hominin admixtures, trade and migration, and pose new questions for Indonesia's prehistoric story.

We are looking at the bright future of Indonesian archaeology. In doing so, improvements in dating technology and their applications should be encouraged. Similarly, international collaboration has proven a key boost to the research milieu, and so should continue to be supported in the future. Investing in Indonesia's dating capability will provide a key contribution on the development of archaeological theory, models, and framework in Indonesia.

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