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Earliest direct evidence of monument building at the archaeological site of Nan Madol (Pohnpei, Micronesia) identified using $^{230}Th/U$ coral dating and geochemical sourcing of megalithic architectural stone

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ABSTRACT

Archaeologists commonly use the onset of the construction of large burial monuments as a material indicator of a fundamental shift in authority in prehistoric human societies during the Holocene. High-quality direct evidence of this transition is rare. We report new interdisciplinary research at the archaeological site of Nan Madol that allows us to specify where and when people began to construct monumental architecture in the remote islands of the Pacific. Nan Madol is an ancient administrative and mortuary center and the former capital of the island of Pohnpei. It was constructed over 83 ha of lagoon with artificial islets and other architecture built using columnar basalt and coral. We employed geochemical sourcing of basalt used as architectural stone and high-precision uranium-thorium series dates ($^{230}Th/U$) on coral from the tomb of the first chief of the entire island to identify the beginning of monument building at Nan Madol in AD 1180–1200. Over the next several centuries (AD 1300–1600) monument building began on other islands across Oceania. Future research should be aimed at resolving the causes of these social transformations through higher quality data on monument building.

Archaeology has documented the independent invention of hierarchical societies among Neolithic farmers a number of times during the Holocene (Earle, 2002), frequently through studying the construction of monumental scaled religious architecture (Moore, 1996; Trigger, 2007). The construction of large burial architecture for the political elite is considered especially strong evidence of the authority of powerful leaders. On the remote islands of the Pacific, monumental architecture has proved a valuable metric in documenting chiefdoms and pre-modern states in the era just prior to European contact (Kirch, 1990, 2000, 2010; Kolb, 1994; Hommon, 2013). It has however been much more difficult to use this same line of evidence to examine the origins of hierarchical societies in the region in part due to a lack of well-dated direct evidence of monument building.

The earliest evidence of hierarchical societies and monument building on Pacific Islands come from two culture areas – Western Polynesia and Eastern Micronesia (Fig. 1). Early settlement in both areas began at 1550–1050 BC (3500–3000 cal yr BP) (Burley et al., 2010, 2012; Carson, 2014). The founding populations of these islands did not build large burial architecture out of durable materials. Polynesia's earliest monuments were built in Tonga and are dated by ^{14}C to AD 1320–1390 (630–560 cal yr BP, Wk-33583, coconut endocarp) (Clark and Reepmeyer, 2014), with other ^{14}C dates on unidentified charcoal from tombs associated with the ruling chiefs (Tui Tonga) used to estimate monument building as early as AD 1210–1260 (740–690 cal yr BP, Wk-18773, Wk-18784, Wk-18774, Wk-18775, Lapaha Site, Burial J09) (Clark et al., 2008). In Micronesia, an archaeological proxy for the area's first chiefs – ^{14}C dates on the start of an annual religious ceremony on the island of Pohnpei – date to AD 1200–1300 (relevant ^{14}C dates are on unidentified charcoal, 739–665 cal yr BP, SI-90 and 679–574 cal yr BP, Beta-9688) (Athens, 2007). Newly reported research on the

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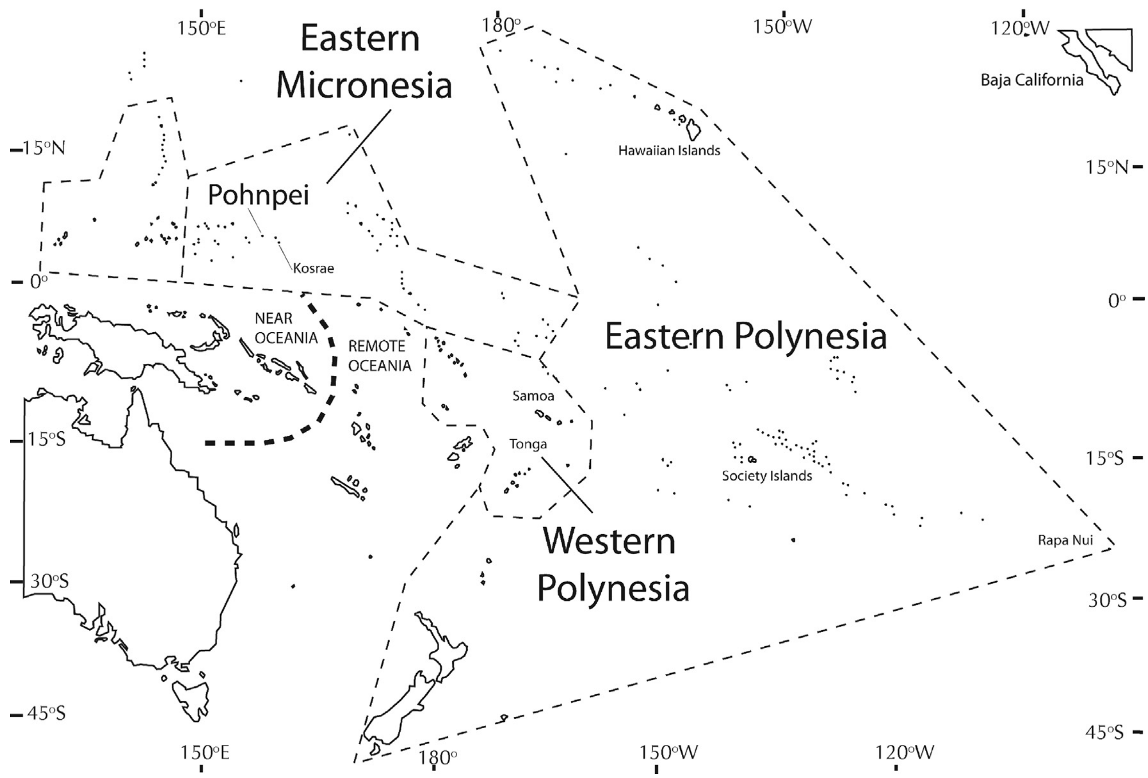

Fig. 1. Pacific Islands with archaeological evidence of monumental architecture. This map shows islands and island groups where archaeological evidence for the construction of monumental architecture in the pre-European contact era has been well documented: Eastern Micronesia (Pohnpei, Kosrae), Western Polynesia (Tonga, Samoa), and Eastern Polynesia (Hawaiian Islands, Society Islands, Rapa Nui). Following on previous studies of monuments (Smith, 2004; Clark and Martinsson-Wallin, 2007), we exclude Pacific Island fortifications, whose chronology has been discussed by Field and Lape (2010).

Micronesian island of Kosrae found mortuary construction as early as AD 1310 (640 ± 6.5 yr, Sample #42, Lelu Site, Burial Insol-1) based on a high-precision ^{230}Th/U date on coral (*Symphyllia* sp.) used as building material (Richards et al., 2015). In sum, our best evidence for the *terminus post quem* for the invention of hierarchical society in Oceania is AD 1300–1400, with less secure evidence for an earlier onset of monument building in AD 1200–1300.

Here we present new interdisciplinary research that pushes our earliest secure evidence of monumental architecture in the islands of the Pacific back more than a century. On the island of Pohnpei in Eastern Micronesia is the well-known site of Nan Madol (Hanlon, 1988); the largest archaeological site in Micronesia (McCoy et al., 2015). Nan Madol is an administrative and mortuary site built on artificial islets that stretches over 83 ha of shallow coral reef and was the center of the Saudeleur polity (Fig. 2). We used a portable x-ray fluorescence (XRF) to geochemically match columnar basalt stones used as architectural building material to their natural sources and ^{230}Th/U dates to determine the construction chronology of a tomb that oral histories identify as the resting place of the first chief to rule the entire island. Our results indicate that by AD 1180 (771 ± 7 yr, *Acropora* sp., Sample C-1) massive stones were being transported from a volcanic plug on the opposite side of the island for the construction of the tomb, and by AD 1200 (747 ± 6 yr, *Acropora* sp., Sample C-13), the burial vault had its first internment. This was followed in the next several centuries (AD 1300–1600) by the onset of monument building on other islands across Oceania (Kirch and Sharp, 2005; Clark and Martinsson-Wallin, 2007; Sharp et al., 2010; Kirch et al., 2015, Martinsson-Wallin et al., 2013). Future research should be aimed at determining the cause of this major turning point in the development of hierarchical societies on Pohnpei and why it was followed by new traditions of monument building over the next several centuries.

Archaeology of Pohnpei Island

Pohnpei is a high volcanic island in the Caroline Islands of Eastern Micronesia (Fig. 1). With a land area of 334 km^2 it is orders of magnitude larger than neighboring atolls and three times the size the next largest high volcanic islands in the group (Truk, 121 km^2; Kosrae, 111 km^2). At the time of regular European contact in the 19th century it is estimated to have had a population of 25,000 (Hanlon, 1988). The local language, Pohnpeian, is classified within the Oceanic language group (Shutler and Marck, 1975) but with a number of documented borrow words from Polynesia (Geraghty, 1994). The island was likely originally settled from the Southeast Solomon or Vanuatu island groups by people who had a Late Lapita ceramic tradition (Athens, 1990). The date of settlement has been estimated at AD 1 (1950 cal yr BP), but the current earliest ^{14}C date of human activity dates to AD 80–200 (1870–1750 cal yr BP) (Athens, 1990). Recent paleoenvironmental coring has highlighted the difficulties in recognizing the true age of settlement (Athens and Stevenson, 2012). Further, we note that although these dates are not in dispute, and fall within the pattern of initial island settlement of Eastern Micronesia, all published radiocarbon dates from archaeological deposits on the island fail to meet one or more of best practices criteria in terms of chronometric hygiene standards (e.g., failure to select short-lived plant taxa, not reporting the taxonomic identity of charcoal, greater than 10% error on ^{14}C dates, poor laboratory quality, and inadequate information on context especially in the case of unpublished gray literature reports) (Spriggs and Anderson, 1993; Rieth and Athens, 2013).

Pohnpeian oral traditions describe two major turning points in the island's political history. The first is the unification of the island's three districts and dozens of clans in to a single polity under a new ruler called the *saudeleur*, meaning the Lord of Deleur,

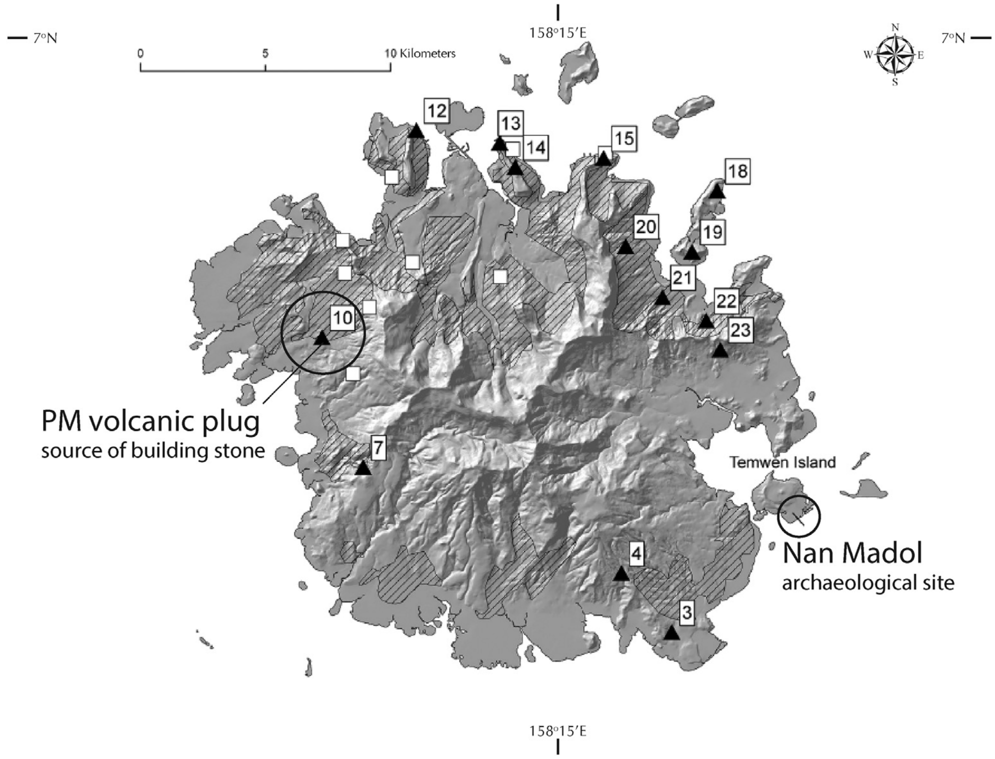

Fig. 2. Potential sources of raw material for the construction of the site of Nan Madol. While most of the island's surface geology is post-shield basalt, there is a band of main shield stage basalt (marked with lines) exposed at mid elevations that includes notable topographic features such as Sokens Island. For full list of locations of natural sources of columnar basalt (triangles), see Ayres et al. (1997: Fig. 4.2). Relevant for this study are 10 = Pwusen Malek, 12 = Sokens, 13 = Nett Point, 14 = Nett; and 22 = Oa. Locations of published data on chemistry of main shield basalt shown as squares (after Spengler et al., 1994).

a title that references the small nearshore islands around Nan Madol, the administrative center of the polity (Hanlon, 1988). The dynasty ruled for generations until another major turning point in Pohnpei's history came when the Saudeleur were replaced by localized district level rule and a political system that endures in the modern day in the form of traditional titles (Keating, 1998).

Oral traditions on Pohnpei say the island was settled by seven voyages with the most recent voyage bringing two brothers who founded the Saudeleur Dynasty (Bernart, 1977; Hadley, 1981). The last two of the seven voyages are said to have come from “Katau Peidi,” which has been translated as referring to a foreign land downwind, west of the island. There is no consensus on where the founding members of the Saudeleur Dynasty were from or how much migration there was from other islands in the past. Ethnographer Ward Goodenough noted the term Katau (or Kachaw) appears in a number of different Micronesian languages in different contexts and traditions (Goodenough, 1986). In the case of Pohnpei, he argued it likely referred to a mythic spirit place in the sky, thus adding to the prestige of the Saudeleur as well as other historical figures.

The political center of Nan Madol, is made up of 98 artificial islets and 12 seawalls built on a lagoon (McCoy et al., 2015) (Fig. 3). Islets are arranged in a formal layout with canals left in between, which has led to comparisons with the city of Venice, Italy. On top of islets are the stone foundations of buildings and other stone architecture. Archaeology and oral histories agree that the site was occupied both before and after the Saudeleur ruled the island. Currently, our best estimate for when the Saudeleur began their rule comes from dating a ceremony on an islet named Idehd in Nan Madol's administrative precinct (Athens, 2007). The ceremony, called Pwung en Sapw, involved sacrificing a sea turtle to a sacred eel in a fashion that re-enforced the new social hierarchy (Bernart, 1977; Hadley, 1981). Radiocarbon dates bracket the earliest signs of the Pwung en Sapw ceremony, also sometimes referred to as the Great Ceremony, to AD 1200–1300 (Athens, 2007). This is consistent with excavations from the islet of Pahnkedira that have been interpreted as indicating two building phases. While not directly tied to the Saudeleur in the same way as the Pwung en Sapw ceremony, the earliest construction at AD 900–1100 may not have included megalithic architecture, but the second phase at AD 1300–1500 would appear to indicate large architecture in place (Ayres, 1993).

The largest and most elaborate architecture at Nan Madol is located within the religious precinct on an islet called Nandauwas (Fig. 3). The primary purpose of these imposing structures was to serve as the tomb for the first Saudeleur (for an overview, see Hambruch, 1936; Hadley, 1981). The islet itself is one of the largest (80 × 60 m), with the exterior held in place by boulder and columnar basalt framing stones and coral fill raising the islet over a meter above the waterline. On the islet's surface there are two four-sided enclosing walls. The exterior wall is +8 m high in places with a main entry on the west side. It was constructed with massive boulders, found mainly along the lower courses, and a façade of carefully stacked columnar basalt placed in alternating header-and-stretcher orientations. Within the wall's core is building fill almost entirely made of coral rubble. The lower half is ca. 3–2 m thick and the upper half is thinner but with a seamless continuation of the exterior façade, leaving a walkway around the interior face.

At the center of the islet of Nandauwas within the interior wall is the tomb of the first Saudeleur (Fig. 4). Built upon a low platform of coral within the larger outer wall, the second, inner wall is identical in form to the massive exterior wall, but at a smaller scale. At the center of the enclosure we find the burial vault of the Saudeleur. The vault itself is also built in the header-stretched style. The top of

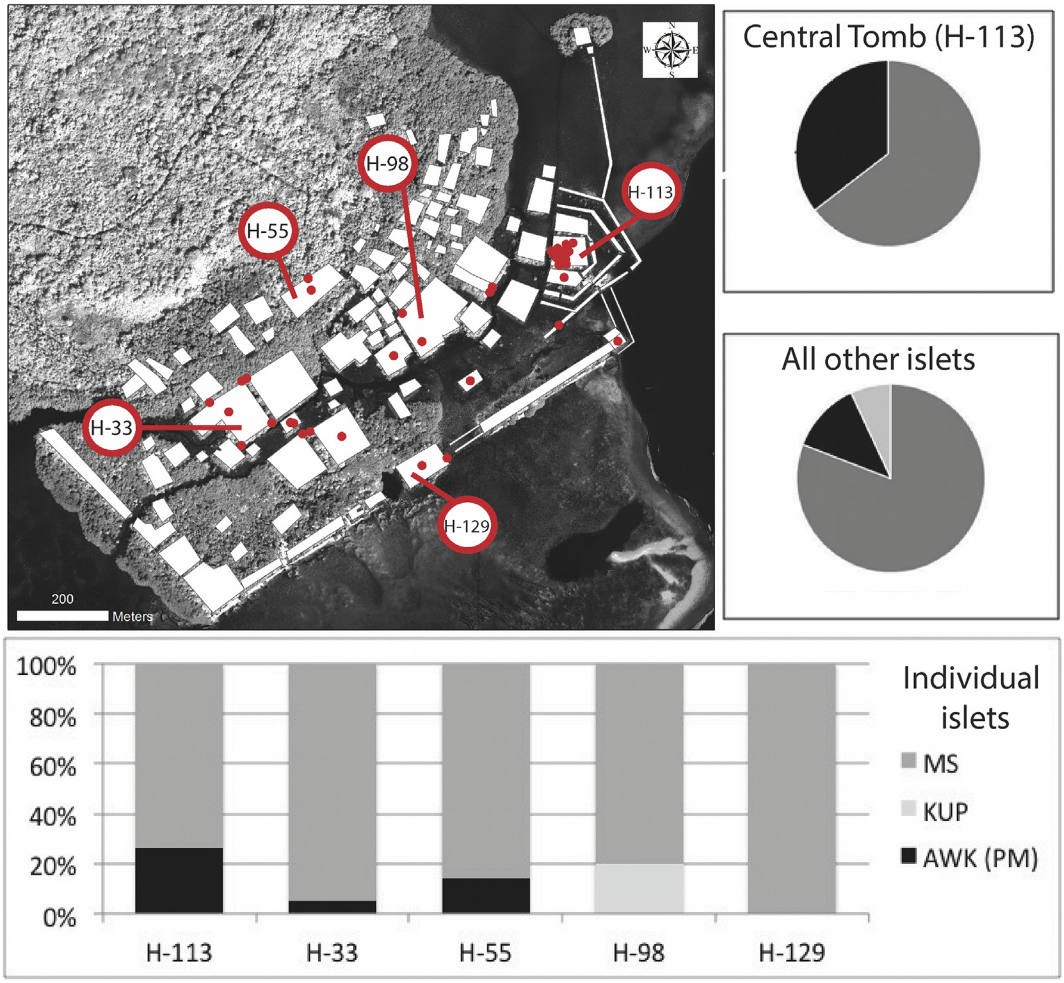

Fig. 3. Locations of Portable XRF assays of architectural stones at the site of Nan Madol. Outlines represent artificial islets and sea breaks recorded on a recent survey of the site (McCoy et al., 2015). Note the greatest proportion of stone from the PM source was found on the islet of Nandauwas, with the highest concentration within the islet's central tomb complex. The commonplace use of stone from the opposite side of the island speaks to the size of the polity at the time the first rulers were buried here. MS – Main shield volcanics (dark gray); AWK (PM) – Awak volcanics (black), PM source; KUP – Kupwuriso volcanics (light gray).

the central vault is capped by columnar basalt notable for length (+2 m) and relative uniform size. There are two other burial vaults on either side of the central wall-and-vault complex that were built in a similar style but are lacking an enclosing wall.

Geology of Pohnpei Island

The distinctive columnar basalt used as architectural stone to construct tombs on the islet of Nandauwas and elsewhere across the site of Nan Madol was originally formed from the horizontal contraction of cooling lava flows resulting in long, column-shaped boulders and cobbles (Spengler et al., 1994). While rare, columnar basalt is well-documented around the globe. On Pohnpei, the geologically oldest examples are from flows that belong to the first phase of volcanic shield building on the island. The Main Shield basalts (8.5–7.5 Ma) were followed by younger post-shield flows from what is called the Awak stage (7–3 Ma). The most notable example of an Awak stage volcanic feature is Pwisehn Malek, a volcanic plug on the border of Kitti and Sokehs municipalities. The island's most recent flows belong to the Kupwuriso stage (1–2 Ma).

Columnar basalt and other boulders used in architecture have been matched to Pohnpei volcanics based on petrography and geochemistry (Ayres et al., 1997; McCoy and Athens, 2012). However, archaeologists have yet to match architectural stone to a specific location where it was quarried. A number of possible quarry locations have been identified (Ayres et al., 1997). At these locations, some pieces of columnar basalt were likely already detached from flows due to weathering. If people also detached and removed stone from flows they did so in a matter that did not leave any clear evidence of human activity behind. Therefore, definitively identifying any one location as a quarry based on archaeology alone is inherently difficult. Building on a geochemical pilot study (McCoy and Athens, 2012), here we report a method of sourcing of megalithic stone using portable X-ray fluorescence (pXRF) to discern the three geochemically distinct stages (Main Shield, Awak, and Kupwuriso volcanics), and identify stone from the Awak stage volcanic plug called Pwisehn Malek (hereafter abbreviated as PM).

Methods

Our research design called for three datasets: 1) a field survey of monumental architecture, especially the stone used as building materials; 2) the determination of the absolute age of the burial architecture of the island's first chief; and 3) geochemical assays of architectural stones (columnar basalt) to match them to their natural source.

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Fig. 4. Burial architecture on the islet of Nandauwas. Clockwise from upper left, west entry of exterior wall, example of header-and-stretcher oriented columnar basalt of central tomb wall, columnar basalt used as roof stones for crypt; and the central tomb's crypt. Photo credits: Adam Thompson, Helen Alderson.

High-definition documentation of architecture by 3D laser scanning

Terrestrial laser scanning has been rapidly adopted by archaeologists working with ancient architecture especially alongside other methods of investigation (e.g., Ercoli et al., 2016). At the site of Nan Madol, a Trimble GeoXT 6000 Series GPS was used to record sample locations where architectural stone was described and geochemically assayed, and to map the exterior outline of artificial islets (McCoy et al., 2015). On the islet of Nandauwas, where we intensively sampled the chemistry of architectural stone, additional survey was aimed at high-definition recording of architecture using a Faro Focus 3D Laser Scanner (Fig. 5). In total, 56 individual scans were necessary, 24 on the exterior wall and 32 on the interior tombs, over 4 days. The Faro Focus scanner was set to 1/4 (or 6 mm in 10 m) for almost all scans primarily in consideration of the scan and image collecting time, which was typically 8 min. The completed digital model allows one to view in cross-section details that are difficult to represent in other survey methods. The immediate value of the 3D model is that it helped confirm the assignment of individual architectural stones to the construction history of the islet of Nandauwas (see Supplemental Material). The long-term value of the dataset is it provides a complete and high-quality model that can be compared with other architecture.

Uranium series dating (^{230}Th/U)

Richards et al.'s (2015) recent work at the site of Lelu (Leluh) on the island of Kosrae has demonstrated that when coral is used as a building material, a great deal of fossil coral is mined along with freshly harvested corals. For this study, field sampling of coral used as building material on the islet of Nandauwas focused on branch coral (*Acropora* sp.) with little or no signs of weathering or wear on the surface to try and avoid dating fossil coral. Small portions of five samples from key locations around the islet were dated by uranium series (^{230}Th/U) method at the Xi'an Jiaotong University lab. Complete lab protocols, standardization and half-lives are described in Cheng et al. (2013). When samples were crushed ahead of analysis a high amount of detritus was discovered for two samples (C-19, C-24). The best, cleanest pieces were hand selected for dating. At the time it was unknown if the apparent detritus would have an adverse impact on the results. We discovered these high detritus coral samples produced ^{230}Th/U dating results with a great deal of error at 2σ (±275, ±43 yr) compared with the clean samples (±8 to ±6 yr).

Geochemical sourcing of architecture by portable XRF (pXRF)

Non-destructive assessment of the geochemistry of geological samples and basalt used in architecture was conducted using a Bruker AXS™ portable x-ray fluorescence spectrometer (Fig. 6). To quantify (ppm) Fe, Sr, Y, Zr, and Nb each architectural stone was shot three times, in different non-overlapping locations, for 300 s each time, at 40 kv, 8–25 microamps, through a filter (12 mil Al + 1 mil Ti + 6 mil Cu). These elements were targeted for sourcing architectural stone due to their natural variability as reported in previous geological survey of the island (Spengler et al., 1994). Results were calibrated by first applying Speakman's (2012) OB40 method and then a lab specific calibration derived from international standards (AGV-2, B.C.R-2, BHVO-2, BIR-1a, DNC-1a, GSP-2, QLO-1, SRM-278, W-2a). A pressed pellet standard (BHVO-2) was shot during field and lab use of the pXRF as a quality control.

For this project we re-examined 48 samples of architectural basalt originally collected in 1984 and reported on by McCoy and Athens (2012) (identification numbers NM-). Experiments

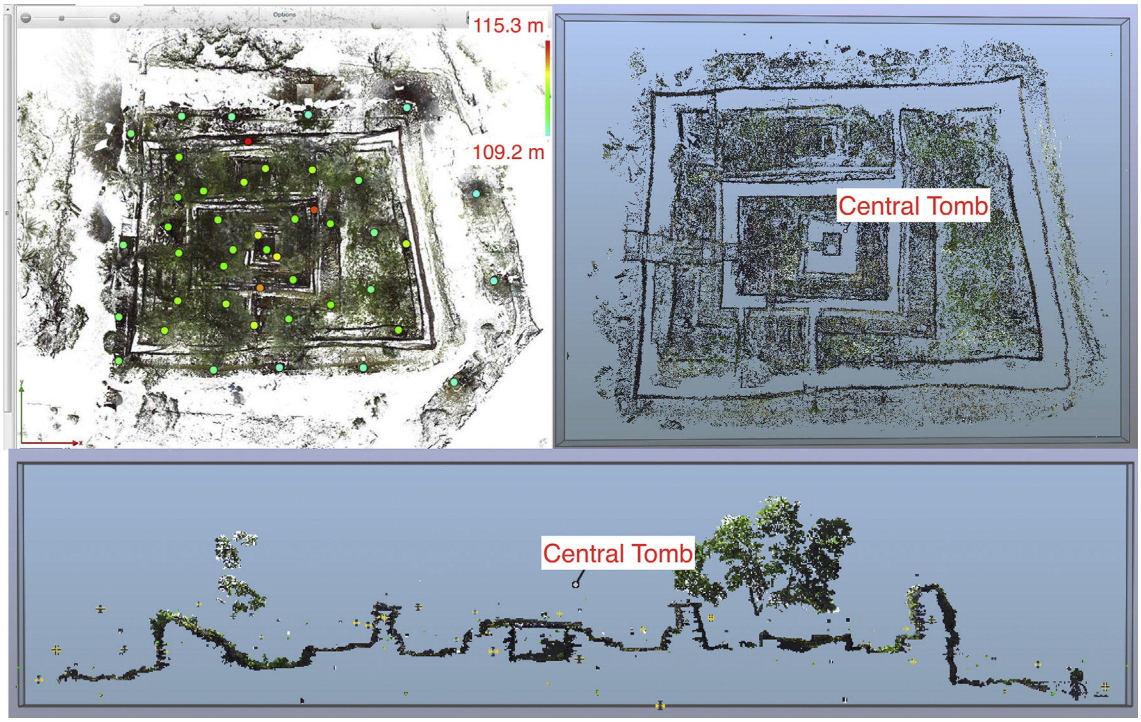

Fig. 5. Point clouds generated from a 3D scan of architecture on the islet of Nandauwas. Spheres represent scan locations (upper left). A horizontal cross-section of scanned points (from near ground level) shows in plan view burial architecture including thick exterior wall surrounding wall around the central tomb (upper right). A vertical cross-section shows the relative position of interior tomb (bottom) as well as portions of trees growing between the exterior and interior walls. See Fig. S10 for locations of coral samples. Source: SCENE LT, Faro.

described in Supplemental material allowed us to achieve better accuracy on basalt (Potts et al., 1997), and the effect of weathering processes on chemical composition has on precision (Potts et al., 2006). The new analysis confirmed most architectural samples were correctly assigned by McCoy and Athens (2012) to their geological age (88%, 42 out of 48). More importantly, it helped us identify PM as the source of all Awak aged basalt through a principle components analysis of Awak geological samples and architectural stones.

We assayed a further 173 pieces of architectural basalt at the site of Nan Madol in 2012, many of these on the islet of Nandauwas. Each stone was given a unique identification number (S-), photographed, described in terms of its position within a piece of architecture (Course 1, Course 2, etc.), measured, and sample locations were recorded by GPS (Fig. S3). Supplement datasets include geochemistry, locations of samples, and descriptions of the form of architectural basalt ($n = 206$ columns, $n = 15$ boulders). A fuller description of the survey methods and results is given in Alderson (2013).

Fig. 6. Portable XRF assaying columnar basalt in the field. The pXRF was used on islets across the site of Nan Madol and intensively on the islet of Nandauwas. Photo credit: Mark McCoy.

Results

Prior to this study, a small number of Nan Madol's architectural stones ($n = 48$) had been geochemically assigned to their likely geological age (McCoy and Athens, 2012) and none had been matched to a specific source. The geochemical survey of 221 examples of architectural stone from Nan Madol by pXRF showed that most belong to the Main Shield stage ($n = 168$), with less from post-shield stage sources (Awak, $n = 40$; Kupwuriso, $n = 13$). Based on the proportions of material from different geological stages, it is likely that columnar basalt and boulders were selected from different sets of sources (columnar vs. boulder; chi-square, 107.8, p value < 0.0001, significant at $p < 0.01$ level).

We discovered that the post-shield volcanic plug Pwisehn Malek (PM), located on the opposite side of the island, is the likely source of all Awak stage stones and is only found among columnar basalt. When we looked more closely at PM sourced columnar basalt we found evidence to suggest it was an especially popular source of building material in select locations of Nan Madol (Fig. 3). Specifically, while columnar basalt from PM was identified on half of the 18 islets tested it is twice as frequent on Nandauwas (H113), the burial islet of the first chief of the island (Fig. 3); a significant difference when compared to all other islets (H113 vs. all other islets, chi square 8.349, p value 0.15383, significant at $p < 0.05$ level). An islet-by-islet comparison for all 18 islets is not appropriate given the small sample sizes on many islets. On the four islets

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with larger sample sizes (10 or more), three showed proportions of sources statistically distinct from Nandauwas (H113 vs. H33, 4.36, 0.036714, <0.05 level; H113 vs. H98, 22.3, 0.000014, <0.05 level; H113 vs. H129, 3.49, 0.061581, <0.1 level). The only exception is the islet of Pein Kitel (H55) where no statistical difference with Nandauwas was found (H113 vs. H55, 0.98, 0.3223, no difference).

The high transport cost of transporting PM columnar basalt to Nan Madol makes it a good metric for the authority of the island's first chiefs. On the burial islet of Nandauwas we found that the highest concentration of PM building material is within in the central tomb complex where an estimated 40% of the basalt used in the enclosing wall and central vault were transported from this source. Since the appearance and size of the PM basalt found at the tomb is indistinct from others examined in our field study (Alderson, 2013), we suggest it is unlikely to have been sought after by the site's builders for its aesthetic qualities, and in that sense makes it ideal as a metric the geographic scale of quarrying rather than reflecting a particular stylistic choice. The natural erosion of the exposed volcanic plug may have made it an easier, and thus preferred, target for stone for building. The location of the plug, however, makes transportation cost the highest of any potential quarry and so in our view its use is better thought of as a materialization of the power of the Saudeleur over the entire island. While more survey is required determine how common PM columnar basalt is at Pein Kitel, an islet associated with the end of the rule of the Saudeleur, previous archaeological studies have suggested that the islet was constructed using stones robbed from existing structures (Ayres, 1993:28).

High-precision dates on branch coral (*Acropora* sp.) used as building fill indicate that the central burial vault on the islet of Nandauwas was in use by AD 1180–1200 (770–750 yr) (Table S4). We find excellent precision for two examples of coral building fill from the central vault and inner enclosing wall where the laboratory procedure produced clean, white, solid pieces for testing (C-1, C-13). If construction fill was harvested live from the reef, and we suggest that was the case, then the central vault's enclosing wall was built no earlier than AD 1172 (778 yr) and no later than AD 1186 (764 yr). The vault's coral rubble fill post-dates the construction of the enclosing wall having been harvested no earlier than AD 1197 (753 yr) and no later than AD 1209 (741 yr). The gap between these two events could have been as short as 11 years, but no more than 37 years.

Two samples that remained a brown-black color and/or loose composition after lab cleaning produced poor precision (C-19, C-24), likely due to high detritus content, and are disregarded from our analyses. The only date on clean coral fill used to construct the islet of Nandauwas itself falls between AD 59 (1891 yr) and AD 73 (1877 yr), which is immediately prior to the current earliest secure date of human occupation of the island and likely represents fossil coral. In a recent study on coral used as building material at the site of Leluh (Lelu), Richards et al. (2015) report also high error ranges on 3 out of 24 samples, possibly due to detritus, and most samples are considered fossil corals. We believe the much lower ratio of fossil-to-fresh coral that we found compared to Richards et al. (2015) reflects our effort to specifically selected samples that showed the least signs of wear for dating.

Discussion

Through the application of geochemical sourcing of megalithic stone and high-precision dating we have identified when the Saudeleur Dynasty gained control over Pohnpei and marshaled labor to construct monumental mortuary architecture at Nan Madol. By AD 1180 (771 $\pm$ 7 yr), massive stones were being transported from a volcanic plug on the opposite side of Pohnpei Island to the site of Nan Madol for the construction of the enclosing wall around the Saudelur's tomb, and by AD 1200 (747 $\pm$ 6 yr), the burial vault had its first internment. This is consistent with an estimate of AD 1160 (generation counting) for the date of the unification of the island based on the number of generations from the founding of the Saudeleur Dynasty forward to more recent island leaders (Mauricio, 1993). It is further supported by the ^{14}C dates around AD 1200–1300 (750–650 cal yr BP; Athens, 2007) for start of the Pwung en Sapw ceremony derived from excavations in another islet at Nan Madol. Given the 11–37 yr gap between coral dates on the wall and vault architecture, it is plausible that, like so many powerful heads of polities, the Saudeleur may have directed the construction of the monumental tomb where they were later buried, and began instituting new religious traditions immediately following their rise to power.

It remains to be seen what precisely led to the successful establishment of an island-wide chiefdom by the Saudeleur. The most developed model for the transformation of Pohnpeian society to a hierarchical chiefdom *sui genris* is a hypothesis called the 'breadfruit revolution' (Petersen, 2006). In brief, it argues that the founding populations of Pohnpei, and its immediate neighboring high volcanic islands in Eastern Micronesia (Kosrae, Truk), brought with them a domesticated variety of the breadfruit tree (*Artocarpus altilis*), which was hybridized with a wild taxa (*Artocarpus mariannesis*) brought in from where it naturally occurs in Western Micronesia. These new hybrid varieties were by comparison more productive, produced crops year-round, were more resilient to natural disaster, drought, and sea salt, and required little labor. This was followed by a "prehistoric sociocultural efflorescence" underwritten by an increase in population and the availability of surplus labor. Ethnographic and linguistic evidence supporting this scenario includes the spread of matrilineal clans and religious traditions across Micronesia. Archaeological evidence cited in support of the hypothesis includes phenomenon broadly bracketed by ^{14}C to the period between AD 800 (1150 cal yr BP) and AD 1400 (550 cal yr BP), specifically an increase in the construction of stone architecture, the onset of the use of shell peelers, the creation of breadfruit paste storage pits, and the occupation of small atolls (Parker and King, 1981; Bath and Athens, 1990; Cordy, 1993; Athens, 1995). At present, we have cannot say if a widespread change in arboriculture or agroforestry preceded monument construction in AD 1180–1200 (770–750 yr), but if it did that would be strong evidence in favor of the breadfruit revolution hypothesis.

Looking more broadly across Oceania, it is currently impossible to determine how the onset of construction in Pohnpei may, or may not, have influenced later monument construction due to a lack of high-quality data on ancient architecture. For example, the most likely case for the direct influence of Nan Madol is the site of Leluh (also spelled Lelu) on Kosrae, a high volcanic island east of Pohnpei, where columnar basalt in a header-and-stretcher style. New research has reported early examples of burial mounds made of coral dated by $^{230}Th/U$ to AD 1300 (640 $\pm$ 6.5 yr) (Richards et al., 2015). Our discovery of monument construction 100 years earlier is strong circumstantial evidence for the apparent influence of Nan Madol on other communities within Eastern Micronesia, however, a lack of quality survey data means any argument for, or against, these sites being part of the same architectural tradition is based on an *ad hoc* set of criteria. The quality of published survey data is better for Polynesia, including examples of high-definition documentation of ritual sites (Mulrooney et al., 2005; Clark et al., 2008), but again identifying architectural traditions spanning the region is difficult (for a recent in-depth assessment of current archaeological data, see Cochrane, 2015). In our view, future inter-disciplinary research on monumental architecture should, when possible, apply high-precision dating, geochemical sourcing of architectural

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stone, and high-definition survey in order to create better historical models for the origins and spread of hierarchical society beyond studies of single sites.

Conclusion

We report the earliest secure dates on the construction of monumental architecture in the remote islands of the Pacific located at the site of Nan Madol on Pohnpei Island in Eastern Micronesia. High-precision uranium series dating of coral from the tomb of the Saudeleur Dynasty indicate political control over the entire island was established by AD 1180–1200 (770–750 yr). The power of this new type of chiefdom was materialized in the choice of megalithic stone used in the construction of its leader's tomb, a notable portion of which was sourced using geochemistry to a distant volcanic plug. The construction of the monumental tomb at Nan Madol was followed by the onset of monumental architecture construction across the remote islands of the Pacific in the period from AD 1300–1600 (650–350 cal yr BP). Future research should be aimed at determining the cause of this major turning point in the development of hierarchical societies in Pohnpei and more widely in the region.

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Author contributions

MDM conceived the project, secured funding and permissions, and wrote the draft manuscript. MDM and HA conducted XRF field and lab research. HA and HC contributed to the manuscript. RH conducted laser scanning of architecture. HC and RLE conducted ^{230}Th/U dating.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.yqres.2016.08.002.

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