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Implications of anomalous relative sea-level rise for the peopling of Remote Oceania

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ABSTRACT

Beginning ~3500–3300 yrs BP humans voyaged into Remote Oceania. Radiocarbon-dated archaeological evidence coupled with cultural, linguistic, and genetic traits indicates two primary migration routes: a Southern Hemisphere and a Northern Hemisphere route. These routes are separated by low-lying, equatorial atolls that were settled during secondary migrations ~1000 years later after their exposure by relative sea-level fall from a mid-Holocene highstand. High volcanic islands in the Federated States of Micronesia (Pohnpei and Kosrae) also lie between the migration routes and settlement is thought to have occurred during the secondary migrations despite having been above sea level during the initial settlement of Remote Oceania. We reconstruct relative sea level at multiple sites on Pohnpei and Kosrae using radiocarbon-dated mangrove sediment and show that, rather than falling, there was a ~4.3-m rise over the past ~5700 yrs. This rise, likely driven by subsidence, implies that evidence for early settlement could lie undiscovered below present sea level. The potential for earlier settlement invites reinterpretation of migration pathways into Remote Oceania and monument building. The UNESCO World Heritage sites of Nan Madol (Pohnpei) and Leluh (Kosrae) were constructed when relative sea level was ~0.94 m (~770–750 yrs BP) and ~0.77 m (~640–560 yrs BP) lower than present, respectively. Therefore, it is unlikely that they were originally constructed as islets separated by canals filled with ocean water, which is their prevailing interpretation. Due to subsidence, we propose that these islands and monuments are more vulnerable to future relative sea-level rise than previously identified.

SIGNIFICANCE STATEMENT

Settlement of Remote Oceania began ~3500–3300 years ago and coincided with falling sea level across the equatorial Pacific Ocean. Archaeological evidence suggests that people arrived on Pohnpei and Kosrae (high islands in Eastern Micronesia) ~1000 years later than on other high islands. We reconstruct sea level on Pohnpei and Kosrae using mangrove sediment and find that rather than falling, sea level rose by ~4.3 meters over the past ~5700 years because of subsidence. This rise likely submerged coastal evidence for the initial settlement and current estimates of when people arrived are therefore biased young. Our results allow reconsideration of the pathways and interactions between voyaging groups across Remote Oceania, and the interpretation of the Nan Madol and Leluh monuments.

Main Text

INTRODUCTION

Settlement of remote Pacific islands began ~3500–3300 years before present (yrs BP) and marked one of the final major phases of pre-modern human migration into uninhabited regions. This migration required formidable long-distance ocean voyaging and the geographic pattern and timing of settlement has long fascinated Western scholars (1). Models for the migration of people into 'Remote Oceania' (2), and the relationship between these voyagers and modern people, are built upon absolute dating of archaeological remains (3, 4), artifact analyses (5), historical linguistics (6), oral histories (7), human genetics (8, 9), computer simulations of voyaging (10, 11), and the history of commensal plants and animals that accompanied humans (12, 13). These data indicate that settlement progressed in two simultaneous, but largely independent, expansions (Figure 1). The Southern Hemisphere route saw migration from Taiwan via New Guinea into island groups south of the equator. This route is marked by a shared Lapita-styled pottery and was foundational to settling of parts of Melanesia, Polynesia, and Eastern Micronesia. The Northern Hemisphere route saw migration out of the Philippines, or other nearby island groups, and was foundational to settlement of islands in Western Micronesia (including Palau and the Mariana Islands).

Separation of the two migrations routes is inferred from the apparent delayed settlement of low-lying, equatorial atolls and high volcanic islands (e.g., Pohnpei and Kosrae) in the region between them. People appear to have arrived in this region at least ~1000 years after settlement of high islands to the west (~3300 yrs BP) and south (~3500 yrs BP) as part of a secondary migration (likely from the south; 14). This interpretation assumes that relative sea level (RSL) fell from a mid-Holocene highstand caused by the spatially-variable response of Earth's crust to the transfer of mass from high-latitude continents to the global ocean through ice melt (15, 16). The occurrence of the mid-Holocene highstand and subsequent RSL fall in the equatorial Pacific

Ocean is a robust feature of Earth-ice model predictions (16) and is supported by proxy evidence such as raised coral reefs and beach sediments (17, 18). RSL fall increases the likelihood that archaeological evidence of initial coastal settlement (19) is preserved and accessible on land. Delayed human settlement of the low-lying equatorial atolls is consistent with their exposure by RSL fall (20–21). The rapid discovery and settlement of low-lying atolls after exposure is sometimes offered as an example of a natural ‘autocatalysis’ (23, 24:13) for exploration of the unoccupied regions: in this case the area between the migration routes. However, the late settlement of the high volcanic islands of Pohnpei and Kosrae is puzzling. Their elevation means they were not just habitable but likely desirable for settlement long before they were inhabited. Thus, while people on the Southern and Northern Hemisphere migration routes possessed the long-distance voyaging capacity to reach the islands (25, 26), the absence of evidence for earlier settlement has been taken as evidence for their settlement as part of the secondary migrations onto equatorial atolls.

We reconstruct RSL on Pohnpei and Kosrae using radiocarbon-dated mangrove sediments. In contrast to other islands in Remote Oceania, RSL at Pohnpei and Kosrae did not fall but rather rose steadily over the past ~5000 years. This sustained rise submerged coastal areas that may hold archaeological evidence for the initial settlement of the islands. The resulting bias in the visibility of the archaeological record may explain the apparent delay in settling these high islands and suggests reconsideration of the degree of separation between the Southern and Northern Hemisphere migration routes. The reconstructed RSL rise also has implications for the interpretation of coastal monumental architecture. We propose that the UNESCO World Heritage Site of Nan Madol (on Pohnpei; Figure 2) and Leluh (on Kosrae) were originally built on land, rather than on islets separated by hallmark canals filled with ocean water.

RESULTS

Mangroves inhabit low-energy coastlines in the (sub)tropics and are widespread on Pohnpei and Kosrae (Figure 1B–C). The elevation range of mangrove environments is intrinsically linked to the tides, which allows RSL to be reconstructed by dating mangrove sediment preserved in the stratigraphic record (27–29). We measured the modern elevation range of mangroves on Pohnpei and Kosrae using field surveys along transects and combined our results with existing survey data (30) to create a regional-scale dataset. Tidal datums were calculated from water-level measurements made by tide gauges (see Materials and Methods). Survey data were linked to the local tidal datums by correlating water-level measurements from loggers deployed during fieldwork to tide-gauge measurements. The elevation of mangroves is 0.12 ± 0.62 m MTL (mean tide level; 95% confidence interval) on Pohnpei (n = 233) and -0.04 ± 0.63 m MTL on Kosrae (n = 31; Figure S2).

RSL rise creates accommodation space that is filled in by *in-situ* accretion of mangrove sediment, which allows the mangrove sediment surface to maintain its elevation in the tidal frame. This process can result in thick sequences of mangrove sediment (31) that record the position of RSL over time. Reports from the literature (32–34) and our own field observations show that Holocene sequences of mangrove sediment up to 6-m thick are preserved on Pohnpei and Kosrae. In the absence of RSL rise, the thickness of mangrove sediment is limited to approximately one half of the tidal range (35, 36). Given (great diurnal) tidal ranges of 0.88 m on Pohnpei and 1.17 m on Kosrae (see Materials and Methods), this stratigraphic observation suggests that sustained and substantial late Holocene RSL rise occurred (37, 38).

We compiled new and existing radiocarbon ages from mangrove sediments on Pohnpei and Kosrae (see Materials and Methods) following recommendations made by the HOLSEA working group (Dataset S3; 39). We used the modern distribution of mangroves on Pohnpei and Kosrae as analogs for interpreting mangrove sediment preserved in the stratigraphic record, which along with the radiocarbon age measurements enabled us to produce 'sea-level index points' that constrain the unique position of RSL in time and space with vertical and chronological uncertainty. In total, we generated 68 sea-level index points from nine sites on Pohnpei and six sites on Kosrae (Figure 1B–C).

Given the similarity of sea-level index points from multiple sites on Pohnpei and Kosrae (Figure 3A), we combined results from all sites and both islands into a single dataset. This decision is supported by Earth-ice models which predict almost indistinguishable Holocene RSL histories for these islands (Figure 2A; 16). To provide a quantitative RSL history with a probabilistic assessment of uncertainties, we used a statistical model (40) that fits 2000, equally-likely RSL histories to the sea-level index points and decadally-averaged tide-gauge observations from Pohnpei for 1970 to 2019 CE (Figure 3A). Reported values are the mean (±1σ) of the 2000 individual members in the model ensemble. RSL rose by 4.3 ± 0.4 m from ~5700 yrs BP to present (Figure 3A), at a mean rate of ~0.7 mm/yr (Figure 3B). The consistency of RSL reconstructions across multiple sites and both islands indicates that sustained RSL rise is not the result of local-scale processes (Figure S3). Comparison of basal (unlikely to be compacted) and non-basal (susceptible to compaction) sea-level index points (Figure S3A) demonstrates that the rise cannot be attributed to post-depositional lowering of the samples used to reconstruct RSL (41).

We also compiled radiocarbon ages on samples that were interpreted (at the time of their publication) to represent human activity on islands throughout Remote Oceania (Datasets S4–5). The median calibrated age for the oldest archaeological samples on Pohnpei and Kosrae is ~2500 yrs BP, and our analysis indicates that RSL rose by 2.5 ± 0.4 m since this time (Figure 3A). RSL rose by 0.94 ± 0.3 m and 0.77 ± 0.3 m since the construction of Nan Madol (770–750 yrs BP; 42) and Leluh (640–560 yrs BP; 43), respectively.

DISCUSSION

Absence of a mid-Holocene highstand

All reasonable combinations of Earth models and ice-melt histories predict a mid-Holocene RSL highstand in the equatorial Pacific Ocean (15, 16), although its timing (approximately 6000–2500 yrs BP) and magnitude (approximately 0.6–2.5 m above present) varies among models. Geological proxies (e.g., elevated coral reefs) across the region record the occurrence of the mid-Holocene highstand (20, 44). In contrast, we reconstruct sustained late Holocene RSL rise on Pohnpei and Kosrae (Figure 3A), which we attribute to ongoing subsidence. Five additional lines of evidence support our interpretation that Holocene RSL did not exceed present on Pohnpei and Kosrae. First, several studies (37, 38, 45) and our own field observations failed to find convincing geomorphic or sedimentary evidence of a RSL highstand despite explicitly searching for it. There is no proposed evidence for a highstand on Pohnpei in the literature. On Kosrae, the proposed evidence is radiocarbon-dated allochthonous coral fragments in beach rock (46, 47). Beach rock can form quickly through transport of allochthonous material during storms and rapid cementation (48). For example, (38) identified cemented beach rock above contemporary sea level in Micronesia during fieldwork in the 1960s and noted that it contained material from World War II alongside older allochthonous coral, which indicates that dating the coral would return unreliable ages of formation. In a wider context, the only proposed evidence for a highstand at Chuuk (a high island archipelago ~700 km west of Pohnpei) is an undated notch cut into resistant basalt (49), that may not be above the influence of present storm surges and sea spray (38). Furthermore, there is no evidence of a Last Interglacial (~125 kyrs BP) shoreline preserved above present sea level, in contrast to other islands in Remote Oceania (50, 51). Second, a GPS CORS (Continuously Operating Reference Station) on Pohnpei measured subsidence of 1.0 ± 0.2 mm/yr since 2003 CE (1σ error; Figure 4). There is no GPS CORS on Kosrae. Although a short time series, this rate is approximately the difference between RSL predicted by Earth-ice models (-0.4 mm/yr, i.e., RSL fall) and reconstructed from mangrove sediments (~0.7 mm/yr; Figure 3B). This subsidence trend is anomalous in the wider context of equatorial Pacific islands that are not on active tectonic margins (52), which suggests that the mechanism of subsidence is unique to the high islands.

Third, analysis of RSL measurements made by the Pohnpei tide-gauge reveals subsidence. Decomposition of the observed trend following (53) estimates the temporally-linear contribution to be 0.59 mm/yr (0.1–1.0 mm/yr; 66% credible interval; 54; Figure S6A). This contribution includes Earth-ice processes and subsidence and is therefore comparable in composition and magnitude to our long-term estimate of RSL rise at ~0.7 mm/yr derived from mangrove sediment. It is notably fast in the context of the equatorial Pacific Ocean outside of islands experiencing active tectonism and/or volcanism (Figure S6A). For example, at Kapingamarangi atoll (~750 km away) where Earth-ice models predict that RSL is almost indistinguishable from that at Pohnpei and Kosrae, there is modest net emergence of -0.1 mm/yr (-0.7–0.5 mm/yr; 66% credible interval). This pattern suggests that subsidence is likely restricted to high islands rather than being regional in scale. The difference between the rate of sea-level change measured at one location by satellite altimetry and a tide gauge is proportional to the rate of vertical land motion (55). The difference (1.7 mm/yr; 56; Figure S6B) at Pohnpei indicates subsidence and is anomalously large for an island in the equatorial Pacific not undergoing active tectonic forcing, although quantifying an absolute rate of subsidence is challenging using this approach (55). For comparison, the difference at Kapingamarangi is 0.2 mm/yr indicating relative stability.

Fourth, the distribution of U/Th ages on coral used to construct mortuary buildings at Leluh is skewed towards younger ages (43). This distribution may support RSL rise because the most accessible construction material is likely young coral in shallow water, while older material is less accessible since it is in deeper water. RSL fall from a highstand would have left relatively old coral on land as accessible construction material resulting in older ages for fill. This interpretation assumes that the people building Leluh consciously chose the most conveniently located material to use as fill. However, the columnar basalts used to construct the outward-facing structures at Nan Madol are evidence of the willingness and ability to move large volumes of heavy material considerable distances (57). The presence of coral fragments from a range of species representative of a complete coral colony, their unweathered condition, and oral histories indicate that coral living in shallow water (rather than dead coral that was, for example, left exposed by

RSL fall) was harvested for construction material at Leluh (43). We propose that the age, type, and condition of construction materials used at Leluh are compatible with RSL rise on Kosrae. Fifth, much of the earliest archaeological evidence on Pohnpei and Kosrae was excavated from intertidal or fully submerged sites (58–60). These diverse and independent lines of evidence support our result that late Holocene RSL rose on Pohnpei and Kosrae due to island-scale subsidence out-pacing the regional-scale RSL fall from a mid-Holocene highstand. As part of the Caroline Seamount Chain, Pohnpei and Kosrae are islands formed by hotspot volcanism (61, 62) that ceased when plate motion moved the islands away from the upwelling mantle reservoir. Subsidence of hotspot volcanic islands is well documented globally, although at many islands — including Pohnpei and Kosrae — observed subsidence rates are greater than would be expected given hotspot swell bathymetry, overriding plate motion, and the age of the lavas (which for Pohnpei and Kosrae are ~5.2 and 1.4 million years, respectively; 61, 62, 63). High subsidence rates specific to Pohnpei and Kosrae may point to localized subsidence processes resulting from, for example, coral loading, or the viscoelastic relaxation of the lithosphere in response to volcanic loading (63, 64), although an exact mechanism has not yet been determined for these islands.

Archaeological evidence for human arrival on Pohnpei and Kosrae

On Pohnpei, the oldest age (median of calibrated range) associated with pottery, a definitive marker of human settlement across Remote Oceania, is 1863 yrs BP (65). The oldest age for ceramic-bearing cultural layers on Kosrae is 1895 yrs BP (58; Beta-30787, Dataset S4). Recent assessment of these earliest ages indicates that Pohnpei and Kosrae were continuously settled since 2000–1800 yrs BP (66). However, on Pohnpei, a charcoal fragment in a sediment core (interpreted to have an anthropogenic origin since the wet climate makes wildfire rare; 58, 67) yielded an age of 2540 yrs BP (Gak-7647; Dataset S4), but the sample was not recovered from an artifact-bearing horizon. On Kosrae, charcoal fragments and changes in pollen assemblages in sediment cores (with an age of 2430 yrs BP; Beta-31733, Dataset S4) are interpreted as evidence of human modification of natural forest including cultivation of breadfruit and use of fire (34). These ages point to settlement of Pohnpei and Kosrae at least 1000 years (and possibly more than 1500 years) after high islands to the west and south (Figure 1A). There are ample radiocarbon ages from archaeological sites on Pohnpei (n = 16) to suggest that these apparent young ages are unlikely caused by insufficient sampling. While there are fewer ages from archaeological sites on Kosrae (n = 5), based on this suite of ages, Pohnpei and Kosrae appear to have been settled at the same time as the atolls between the Southern and Northern Hemisphere migration routes in a secondary pulse of migration within Remote Ocean at ~2000 yrs BP (Figure 1A).

This proposed timing and geographic pattern of settlement of Pohnpei and Kosrae is puzzling. If these high islands were settled at the same time as the equatorial atolls, then atoll emergence was indeed an autocatalysis for the discovery of Pohnpei and Kosrae (23, 24:13) and earlier voyagers did not find (or at least chose not to settle) these islands. However, we argue that it is unlikely that two high volcanic islands (separated by ~500 km) were missed by people on either the Southern or Northern Hemisphere routes during the initial phase of settlement beginning ~3500–3300 yrs BP only to be settled near-simultaneously. People migrating along both routes possessed the long-distance voyaging technologies and skills required to locate Pohnpei and Kosrae (25, 26), although we note that these technologies and strategies changed during the period of migration. Although proximity is not always a good predictor of settlement of small islands in the vastness of the Pacific Ocean, the central location of Pohnpei and Kosrae places them on shortest-voyage trajectories between several island groups and prevailing winds or ocean currents would not make them less likely to be discovered (10, 11), depending on where voyages began from. Equatorial atolls were settled during a later, secondary migration not only because atoll existence relied on RSL fall from a mid-Holocene highstand (68), but because they are less desirable for settlement than high islands. Atolls have poor access to freshwater, poor-quality coralline soils for agriculture, limited building material (in amount and variety), and are vulnerable to storm surges compared to high islands (69). Therefore, the high islands of Pohnpei and Kosrae were desirable targets for settlement.

Implications for human migration into Remote Oceania

On Pohnpei and Kosrae, archaeological deposits bearing ceramics were recovered below present sea level (66), and there are two possibilities to explain the submerged archaeological material. Under an assumption that a mid-Holocene RSL highstand (and subsequent RSL fall) occurred, some researchers proposed that the high islands were settled by people living in houses built on stilts over the shallow coral reef (66, 70). However, there is no direct evidence of stilted houses on Pohnpei or Kosrae. Our results support an alternative explanation, where people lived on the coast as they did elsewhere in Remote Oceania (19, 71), particularly given the steep terrain that characterizes the interior of both islands. Therefore, submerged archaeological evidence is the result of RSL rise (Figure 3A). We argue that evidence of earlier settlements was submerged by this anomalous RSL rise, and that the current estimates of initial settlement are systematically skewed young because of the difficultly accessing submerged and buried evidence, coupled with land above sea level being the target of previous archaeological investigations because of the assumption of RSL fall.

There is another example of local RSL trends obscuring evidence for human settlement in Remote Oceania. In Sāmoa, the earliest evidence for settlement (at ~2750 yrs BP) is a pottery-bearing horizon discovered nearly 2 m below present sea level during construction of a dock (72). Sāmoa's location on an active tectonic boundary makes it prone to vertical land motion, including episodic subsidence during earthquakes (73). Although the mechanism for subsidence is likely different to Pohnpei and Kosrae (which are located far from active plate boundaries and show no evidence for episodic vertical motion), the impact on the archaeological record (submergence of evidence) is similar. Sāmoa also has multiple, independent lines of evidence for anomalous, subsidence-driven RSL rise including direct measurement by a GPS

CORS (52, 74) and the presence of thick sequences of mangrove sediment (75). IPCC AR6 sea-level projections for Sāmoa include 1.3 mm/yr of subsidence estimated from tide-gauge measurements (54).

Evidence of earlier settlement on Pohnpei and Kosrae may yet be uncovered in shallow marine environments (59). The age and nature of such evidence could provide new information on the interactions between Lapita voyagers on the Southern Hemisphere route and their Northern Hemisphere counterparts who settled the Palau and Mariana archipelagos. Ancient DNA of commensal animals, notably pigs (76), dogs (77), and chickens (78), suggest these began as largely independent, parallel migrations into Remote Oceania. At present, the only artifact indicating a direct link between the islands of the Federated States of Micronesia and those settled during the Southern Hemisphere migration is a stone adze uncovered through reef dredging on Pohnpei (59, 79).

Studies of human genetics offer insight into the long-term history of human migration across Remote Oceania (9, 80). Newly reported DNA from people living on Pohnpei and the Chuuk archipelago coupled with ancient DNA from eight burials at Nan Madol defined a ‘Central Micronesian’ population (80). Comparison of this Central Micronesia population to others in Remote Oceania suggests a genetic origin rooted in migration of people from the south, although a genetic contribution from the west cannot be excluded (80). The DNA of individuals buried at the Nan Madol mortuary complex at 500–300 yrs BP may, or may not, be representative of a population that arrived earlier on Pohnpei, but whose remains were submerged along with other archaeological evidence by sustained RSL rise. Thus, it is possible that the high islands in Central Micronesia were part of the earlier initial migration into Remote Oceania from the west, prior to major migration from the south.

More directly dated material evidence (including human remains) is required to parse between competing models of interaction between the Northern Hemisphere and Southern Hemisphere migrations. This evidence may lie submerged around Pohnpei and Kosrae.

Implications for monumental architecture

Nan Madol (sometimes described as the 'Venice of the Pacific') is an administrative and mortuary architectural complex on Pohnpei (Figure 2). It is characterized by artificial islets constructed from columnar basalt, boulders, and corals, and surrounded by narrow 'canals' currently filled with sea water and shallow coral reef (81). Nan Madol's massive sea break walls are interpreted as being constructed to shield the site from storm surges (66). Columnar basalt was sourced from locations across Pohnpei and U-Th ages on coral fill places construction of the tomb of the island's first rulers at ~770–750 yrs BP (42). The prevailing interpretation is that Nan Madol was intentionally constructed in a shallow marine environment to allow the political elite to isolate themselves from mainstream society on Pohnpei (66), and that this isolation was greater at the time of construction than observed today because of subsequent RSL fall. Modern flooding of the lowest-lying buildings at Nan Madol during high tides was thought to indicate that the islets subsided since construction (82). Leluh is a monument on Kosrae that shares many architectural characteristics with Nan Madol. U-Th ages on coral from three mortuary buildings show construction began at ~640–560 yrs BP (43).

Based on our RSL reconstruction, we propose that Nan Madol and Leluh were built on land above the reach of the high tides (and likely most storm surges). We estimate that RSL rose by 0.94 ± 0.3 m and 0.77 ± 0.3 m since the construction of Nan Madol and Leluh, respectively (Figure 3A). We surveyed the bottom of the canal adjacent to one of the main mortuary buildings at Nan Madol (islet H113; 81) to be approximately -0.2 m MTL (-0.68 m relative to mean higher high water, MHHW). Assuming a stationary tidal regime and no sedimentation of canals, this location was at ~0.26 m above MHHW when Nan Madol was constructed. Over the 1983-2001 tidal epoch the 1% inundation level for the Pohnpei tide gauge is 0.23 m above MHHW and the single highest water level was 0.63 m above MHHW. Therefore, the canals at Nan Madol were likely dry when constructed, except during rare and transitory events when water depths of just a few centimeters could have occurred. Due to ongoing RSL rise, low points surrounding buildings at Nan Madol would have become increasingly flooded, leading to the formation of individual buildings as ‘islets’ and the famous ‘canals’ separating them. However, this was a slow process on human timescales. When the rulers of Nan Madol were overthrown at ~350 yrs BP (83), and the site was no longer the primary seat of political power over the island, it is unlikely that the islet we examined would have been surrounded by a permanent canal as it exists today (although sections of it were likely flooded at high tide).

Subsidence-driven RSL rise through the late Holocene indicates that these sites (and modern socio-economic activity on Pohnpei and Kosrae) may be more vulnerable to future rise than previously anticipated (39, 36, 84), since current projections underestimate the contribution from subsidence (54). Thus, our results have implications for both the interpretation and ongoing care of these World Heritage Sites, and more broadly for the island nation of the Federated States of Micronesia.

CONCLUSIONS

Models for human migration into Remote Oceania beginning ~3500–3300 yrs BP assume that the equatorial Pacific Ocean experienced RSL fall from a mid-Holocene highstand. Separation and isolation of Southern and Northern Hemisphere migration routes is inferred from the delayed (by at least ~1000 years) settlement of equatorial atolls and high volcanic islands (including Pohnpei and Kosrae) in the region between them. While emergence of atolls in response to RSL fall made them more habitable through time, the apparent late settlement of high islands is puzzling because they represent desirable, available, and reachable targets for settlement. It is possible that Pohnpei and Kosrae, like more distant targets such as the Hawaiian Islands, were beyond the seafaring strategies and technologies of people during the initial stages of settlement in Remote Oceania. However, given the similar settlement timing for Pohnpei and Kosrae, we suggest that this shared pattern is due to a shared RSL history. Using mangrove sediment, we find that Pohnpei and Kosrae experienced sustained RSL rise of ~4.3 m during the past ~5700 years at a rate of ~0.7 mm/yr because of island-scale subsidence. We suggest that estimates of when these high islands were settled are systematically biased young because RSL rise submerged evidence for the initial occupation of low-lying coastal sites. This finding invites reexamination of the degree of separation between the Southern and Northern Hemisphere migration routes. The new RSL history also has implications for interpreting the long-term socio-political and architectural histories of monuments. In contrast to prevailing interpretations, the administrative centers of Nan Madol and Leluh were originally built on land only to become inundated over subsequent generations due to ongoing RSL rise. Our study highlights the importance of site-specific reconstructions of past environments and relative sea level, as local environmental changes can depart from those predicted by broad-scale models.

MATERIALS AND METHODS

Tide analysis

Pohnpei

We downloaded hourly water-level measurements (expressed relative to station datum) made by the Pohnpei-B tide gauge from the University of Hawaii Sea Level Center (85; last accessed May 12, 2022). From these measurements, we calculated tidal datums following the National Oceanic and Atmospheric Administration definitions and using the national tidal datum epoch (currently 1983–2001). We isolated high and low tides from using the VulnToolKit package (86) for R (Figure S1A, Dataset S1). In this step, each tide was identified as a higher high, lower high, higher low, or lower low and means for these groups provide the elevation of tidal datums (relative to station datum) for the location of the Pohnpei tide gauge (in Kolonia; Figure 1B). To determine if tides vary around Pohnpei, we deployed pressure transducer water loggers at five sites across two field seasons (two sites in 2016 between July 4–8th, and three sites in 2019 between July 19–28th; Figure 1C). Each logger was deployed in open water immediately adjacent to the seaward edge of the mangrove at low tide to ensure that all subsequent low and high tides were measured by the loggers. Water-level measurements at six-minute intervals were corrected for atmospheric pressure changes measured by an additional logger that was simultaneously deployed close by. Comparison of water levels among sites and with those made by the Pohnpei-C tide gauge (hourly measurements) indicates that the timing and magnitude of tides does not vary between them, hence tidal datums established at the tide gauge (Dataset S1) are applicable elsewhere on Pohnpei. By correcting for the difference between water-level measured by the tide gauge (relative to station datum) and each water-level logger (depth), we established the elevation of each water logger relative to tidal datums.

The United States Geological Survey also deployed water-level loggers at two sites on Pohnpei from July 2016 to March 2017 (30). Water-level measurements made by these instruments are reported relative to the EGM2008 geoid. The uncertainty of the EGM2008 geoid is typically ±0.05–0.1 m (87). The two water loggers were deployed at elevations where they could only measure high tides, and alignment of the two time series shows no spatial difference in water level variability and that measurements showed near-identical variability to the Pohnpei tide gauge. This further confirms our conclusion that tides are invariable around Pohnpei, and that the relationship among tidal datums established at the tide gauge are applicable elsewhere. Through differencing these water-level measurements with those made simultaneously by the Pohnpei-C tide gauge, we estimate that EGM2008 lies at -0.92 m MTL (0.18 below station datum for the Pohnpei-B tide gauge).

Kosrae

There are no published and accessible tide-gauge data for Kosrae. However, the National Institute of Water & Atmospheric Research/Taihoro Nukurangi installed a tide gauge at Leluh which collected observations between 2011 and 2016 (88). We used these data from Leluh (which is measured relative to the Kosrae Local Datum) to calculate tidal datums as for Pohnpei, except that 2011–2016 rather than 1983–2001 was used as the tidal epoch out of necessity (Figure S1B; Dataset S1). To determine any spatial variability in tides around Kosrae, we deployed water-level loggers at three mangrove sites around Kosrae (July 8–15th 2019). Water-level measurements were corrected for atmospheric pressure changes measured by an additional logger that was simultaneously deployed close by. We observed no changes in timing and magnitude of tides around Kosrae. Therefore, tidal datums established at the site of the Kosrae tide gauge can be applied at other sites on the island, with the caveat that the 2011-2016 window of measurements is shorter than the 19-year window typically used to calculate datums. We established the elevation of each water logger relative to tidal datums by applying a correction to measured depths to remove the difference to simultaneous water-level measurements made by the tide gauge.

Elevation of the mangrove modern analogue

We used two sources of data to estimate the elevation occupied by mangroves in Micronesia. First, surveys by the United States Geological Survey (30, 36) investigated the elevations of mangroves at seven sites around Pohnpei. Mangrove surfaces were surveyed using several methods and elevations are reported relative to EGM2008 and converted to orthometric elevation. We applied the 0.92 m adjustment (established empirically from water-level logger and tide-gauge measurements; see Tidal Analysis) to each EGM2008 elevation observation to express it relative to MTL (from which correction to other tidal datums is achieved using the relationships determined over the tidal epoch, Dataset S1). Our analysis is limited to observations from 2019 that are noted to have mangrove plant species present at the measurement site (and therefore are measurements of sediment surfaces within a mangrove).
The USGS survey is inherently a conservative dataset to use for estimating the paleo-elevation at which mangrove sediment preserved in the stratigraphic record accumulated. In Micronesian

mangroves (and elsewhere), site geomorphology dictates that a large proportion of the change in elevation between the lower and upper limits occurs in a spatially-narrow band close to the landward edge of the mangrove. Consequently, the majority of mangrove surface area lies within a smaller subset of elevational range (see for example Figure 7 in 30 and Figure 5 in 36) and the probability that a sample of mangrove sediment recovered in a core accumulated within the narrow band at the seaward or most landward edge of the mangrove is low (in the absence of additional proxy evidence to refine the environment of deposition).

Second, we conducted new surveys of modern mangrove distribution at five sites on Pohnpei and two sites on Kosrae (Figure 1B–C). We used an autolevel and staff to measure surface elevation at points located along transect through each site. Transects began inland of the upper limit of mangroves and extended to the seaward edge of the mangrove where shallow, sub-tidal environments occur. The elevation of each point surface station was established relative to tidal datums by autolevel survey to water-loggers or by taking timed water-level measurements using the autolevel and staff, which were compared to simultaneous measurements made by the Pohnpei-C tide gauge.

We combined these two sources of data into a single dataset (n = 233 for Pohnpei and n = 31 for Kosrae). Since tidal range is different on Pohnpei and Kosrae, we expressed elevation as a standardized water level index (SWLI) value:

$$\text{SWLI} = \left(\frac{sample\ elevation\ (m\ MTL)}{MHHW\ elevation\ (m\ MTL)} \times 100\right) + 100$$

Where a value of 100 SWLI is equivalent to local mean tide level (MTL) and a value of 200 SWLI corresponds to local mean higher high water (MHHW). Mangroves on Pohnpei and Kosrae occur at elevations of 7-249 SWLI (95% confidence interval). For Pohnpei this corresponds to elevations of 0.12 ± 0.62 m MTL. For Kosrae, this corresponds to elevations of -0.04 ± 0.63 m MTL (Figure S2).

New mangrove radiocarbon ages

Mangrove sites were selected based on existing literature that describes the coastal stratigraphy around both Pohnpei and Kosrae (e.g., 32). We selected sites that showed the deepest mangrove sequences (to potentially obtain the longest, highest resolution records), as well as those that showed mangrove sediments overlying incompressible substrate (e.g., carbonate reefs) to assess any post-depositional compaction on the sediment sequence. One mangrove sediment core (Pwok) was collected using a Eijelkamp peat sampler, and core top elevations were surveyed using differential levelling from timed water level measurements. Three mangrove sediment cores were collected using a Hiller corer and elevation obtained using a Trimble differential GPS (30, 36). Bulk mangrove sediment samples were prepared for radiocarbon analyses by pre-treatment with acid to remove carbonate and were measured at the U.S. National Ocean Sciences Accelerator Mass Spectrometry Facility and Beta Analytic. Reported radiocarbon ages were calibrated individually using the Intcal20 calibration curve (89) using the BChron package for R (90). Data is available in Dataset S2.

RSL database construction and analysis

To reconstruct RSL, we collated and standardized published radiocarbon ages from coastal sediment samples on Pohnpei and Kosrae into a database following the protocols developed by the HOLSEA program (39), including our new radiocarbon ages. Inclusion in the database required each sample to have: 1) a geographic location; 2) an age (with uncertainty) of sample formation (in this case a radiocarbon age with a unique identifier); 3) an estimate (based on sample type) of tidal elevation at the time of formation with uncertainty (termed the reference water level); and 4) a modern altitude relative to sea level. Samples were excluded from the database if any of these attributes could not be estimated. Radiocarbon ages were individually calibrated using the IntCal20 dataset for terrestrial material (which includes mangrove sediment). The susceptibility of each sample to physical compaction was categorized based on its stratigraphic context (91); base of basal (sample overlies, within 10 cm, an incompressible layer, compaction unlikely), basal (sample is from lower stratigraphic unit, compaction possible), intercalated (sample is from intercalated stratigraphic unit , compaction possible), surface peat (sample is from upper stratigraphic unit, compaction possible), and unknown (no suitable stratigraphic details were available to assign sample a compaction class).

For each sample in the database relative sea level (RSL) is reconstructed as:

$$\text{RSL} = \text{Altitude} - \text{Reference Water Level}$$

Where altitude is measured directly as depth in core, and core top elevation is expressed relative to tidal datums. If the sample had a thickness, we used the mid-point in our calculation of RSL and treated the thickness as a source of uncertainty. Frequently, core-top elevation was not reported, but rather a core top was qualitatively described as being in a mangrove. In those instances, we used the elevation range of modern mangrove environments established from the modern surveys as the core top elevation (with uncertainty). The reference water level for samples determined to have formed in a mangrove is also the range of modern mangroves established from modern surveys (see Elevation of the mangrove modern analogue). The proxies used to confirm that a sample formed in a mangrove environment are principally descriptions of sediment texture, although a small subset of samples present other evidence (e.g., pollen assemblages). The age of each sample in calendar years is from calibration of the radiocarbon age. The result of this approach is the creation of individual sea-level index points which constrain the unique position of RSL in time and space, with vertical and chronological uncertainty. The creation of individual sea-level index points assumes a stationary tidal prism over time. The database and references are available in Dataset S3 and SI References, and the general locality of relative sea-level data is presented in Figure 1B–C.

A RSL history was generated by applying the errors-in-variables integrated Gaussian process (EIV-IGP) model (40) to the database of 68 sea-level index points (Dataset S3). The model was developed specifically to analyze late Holocene RSL reconstructions characterized by vertical and temporal uncertainties, and an uneven distribution of observations through time. Based on the coherence in RSL histories between Pohnpei and Kosrae, among sites on each island, and stratigraphic context (susceptibility to compaction), we analyzed all sea-level index points as a single dataset. In addition, we calculated decadal average RSL from the Pohnpei tide gauge measurements to include in the EIV-IGP model. Hourly tide-gauge measurements were binned into 10-year increments (starting in 1970) and averaged. The temporal position for each 10-year average is the mid-point (e.g., 1975) with an age error of ±5 years. The vertical error is the 95% confidence interval of the measurements. The EIV-IGP model estimated RSL and the rate of RSL change with uncertainty (95% credible intervals) at timesteps of 100 years from ~5730 yrs BP to present.

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Figure Legends

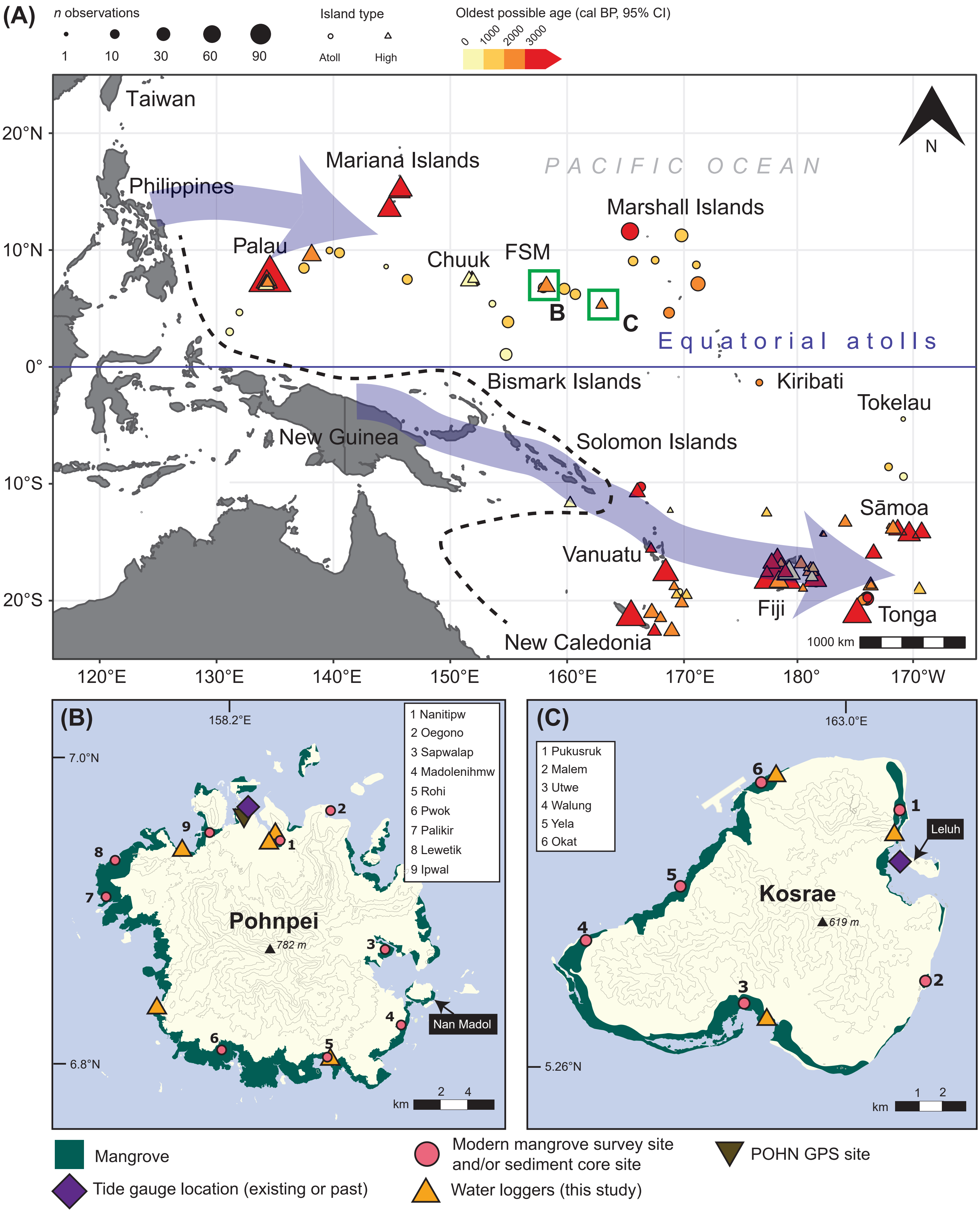
Figure 1. (A) Distribution of calibrated radiocarbon ages on archaeological samples across Remote Oceania (excluding eastern margins; see Dataset S4). Oldest ages and number of observations at an island scale (circles = atolls, triangles = high islands) are represented by color and size. The green squares highlight the high volcanic islands of the Federated States of Micronesia (FSM) (Pohnpei and Kosrae, west to east) of focus in this study. Arrows represent the approximate route taken by the Southern Hemisphere and Northern Hemisphere migrations into Remote Oceania. The black dotted line denotes the boundary between Near Oceania and Remote Oceania. (B, C) Location of modern mangrove surveys (from this study) and sites (numbered) with RSL data compiled in the database of sea-level index points for Pohnpei and Kosrae (Dataset S3).

Figure 2. (A) Satellite imagery of Nan Madol (6.84° N, 158.34° E) with polygons showing the position and shape of building foundations (81). Sometimes called the ‘Venice of the Pacific,’ prevailing interpretation has been that monumental architecture found at this former island capital were built as artificial islets connected by a series of canals. (B) Image of a ‘canal’ next to the tomb of the island’s first rulers a structure called Nandowas, identified as feature #113 in (93, 94). We present new evidence that demonstrates that 800-600 years ago when Nan Madol, and a similar site called Leluh on the neighboring island of Kosrae, were constructed, relative sea level was significantly lower. Both sites were originally built on dry land only to become submerged by rising relative sea levels. The impacts of anomalous sea level rise described in this study, and

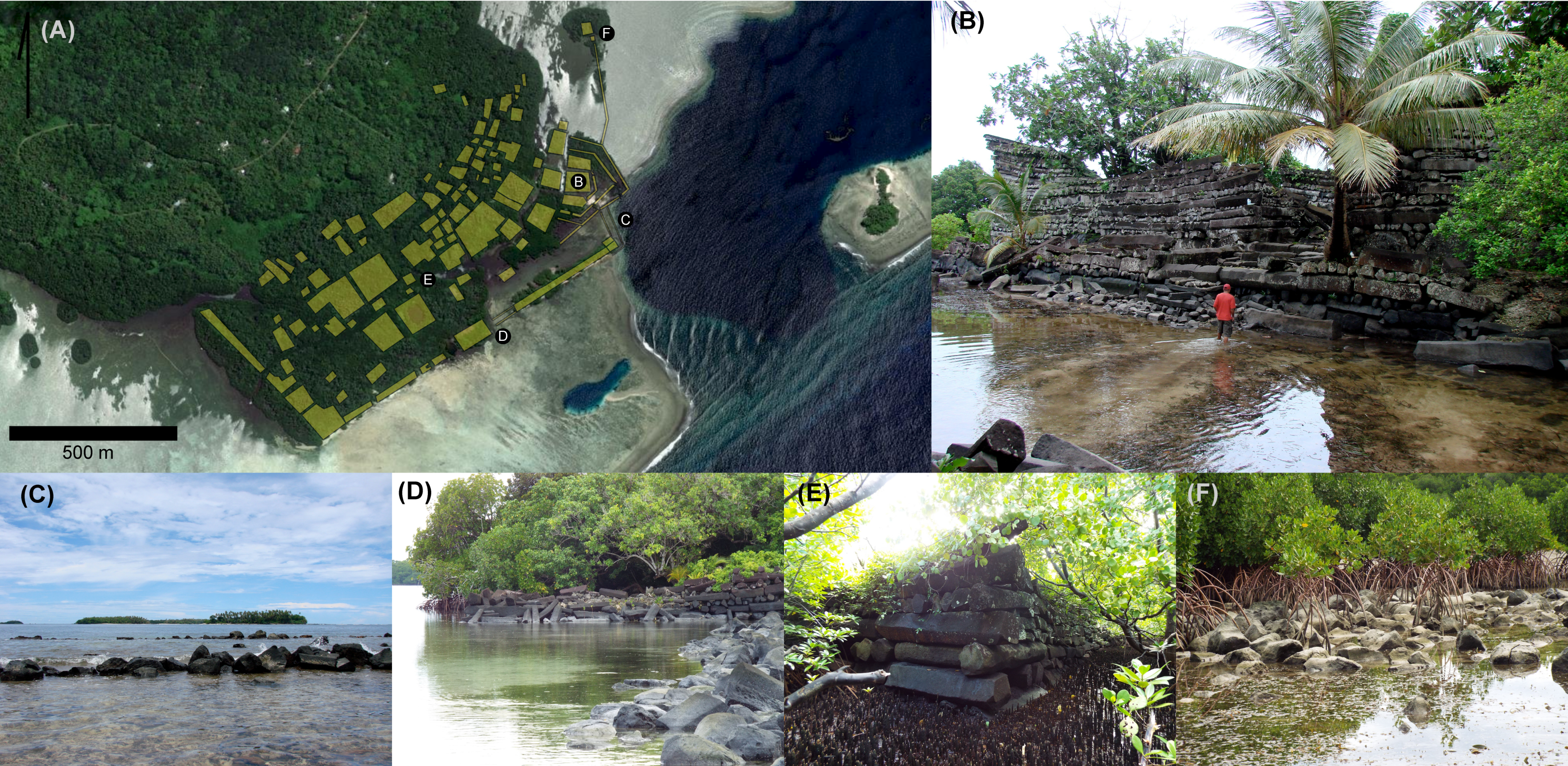
encroaching mangrove, continue to threaten the integrity of architecture across the site, as seen at (C) Lelou (#120), (D) Lemenkau (#129), (E) Peitaup (#44), and (F) Peiniot (#118). Photo credit: © Osamu Kataoka (images reused with attribution).

Figure 3. (A) Relative sea level reconstructed for Pohnpei (purple) and Kosrae (orange) using radiocarbon-dated mangrove sediment. Each of the 68 sea-level index points is presented as a box that captures vertical and chronological uncertainty. Decadally-averaged tide gauge data (green) are also presented as boxes. Application of the errors-in-variables integrated Gaussian process (EIV-IGP) statistical model (40) was applied to this dataset to generate a relative sea-level history (shaded envelope represents the 95% credible interval; CI). The dashed line is relative sea level predicted by the ICE-7G_NA (VM7) Earth-ice model (16) for Pohnpei and Kosrae. For reference, the vertical dashed lines show the approximate timing of the initial settlement on high islands Pohnpei and Kosrae, the construction of Nan Madol (Pohnpei) and Leluh (Kosrae) (B) Rate of RSL change at Pohnpei and Kosrae as calculated by the EIV-IGP model (50^{th} percentile and 95% credible interval).

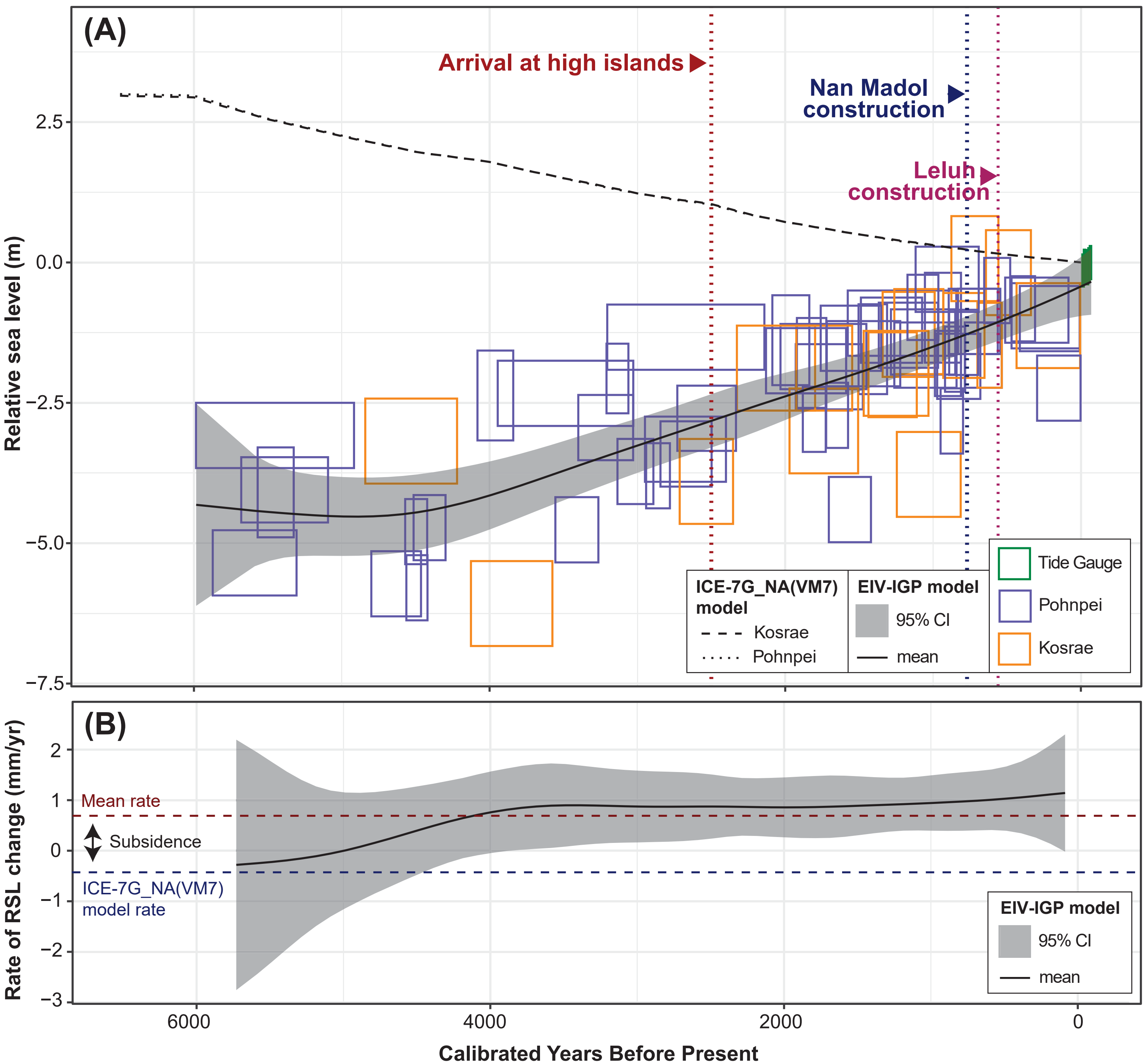
Figure 4. Vertical land motion measured by a GPS Continuously Operating Reference Station (POHN) on Pohnpei. Data points are vertical positions and the red line is a least-squares (LSQ) model fit to the time series. The LSQ rate is -0.9 mm/yr and the MIDAS rate is -1.0 mm/yr (see Supplementary Text for LSQ and MIDAS rates definitions; Dataset S6).



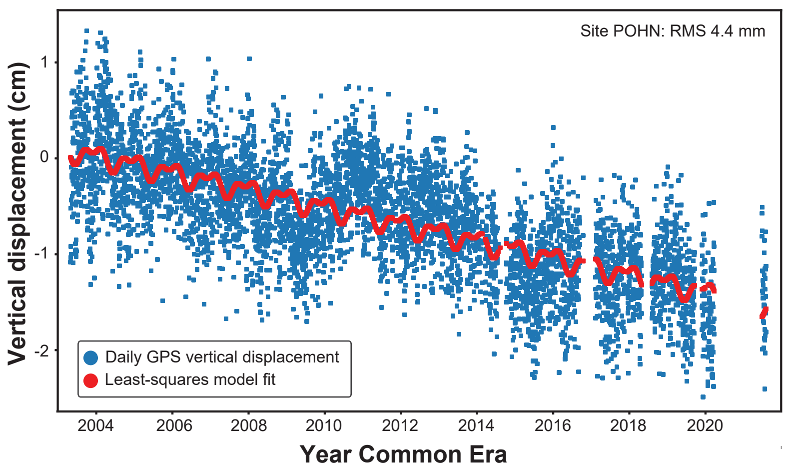
(A)
n observations
1
10
30
60
90
Island type
Atoll
High
Oldest possible age (cal BP, 95% CI)
0
1000
2000
3000
Taiwan
20°N
10°N
0°
10°S
20°S
Philippines
Mariana Islands
PACIFIC OCEAN
Marshall Islands
Palau
Chuuk
FSM
B
C
Equatorial atolls
Bismark Islands
Kiribati
Tokelau
New Guinea
Solomon Islands
Sāmoa
Vanuatu
Fiji
Tonga
New Caledonia
1000 km
N
120°E
130°E
140°E
150°E
160°E
170°E
180°
170°W
(B)
158.2°E
7.0°N
6.8°N
1 Nanitipw
2 Oegono
3 Sapwalap
4 Madolenihmw
5 Rohi
6 Pwok
7 Palikir
8 Lewetik
9 Ipwal
Pohnpei
782 m
Nan Madol
km
2
4
(C)
163.0°E
5.26°N
1 Pukusruk
2 Malem
3 Utwe
4 Walung
5 Yela
6 Okat
Leluh
Kosrae
619 m
km
1
2
Mangrove
Tide gauge location (existing or past)
Modern mangrove survey site and/or sediment core site
Water loggers (this study)
POHN GPS site



(A)
F
B
C
E
D
500 m
(B)
(C)
(D)
(E)
(F)



(A)
Arrival at high islands
Nan Madol construction
Leluh construction
Relative sea level (m)
2.5
0.0
−2.5
−5.0
−7.5
ICE-7G_NA(VM7) model
Kosrae
Pohnpei
EIV-IGP model
95% CI
mean
Tide Gauge
Pohnpei
Kosrae
(B)
Rate of RSL change (mm/yr)
2
1
0
−1
−2
−3
Mean rate
Subsidence
ICE-7G_NA(VM7) model rate
EIV-IGP model
95% CI
mean
6000
4000
2000
0
Calibrated Years Before Present


Site POHN: RMS 4.4 mm
Vertical displacement (cm)
1
0
-1
-2
2004
2006
2008
2010
2012
2014
2016
2018
2020
Year Common Era
Daily GPS vertical displacement
Least-squares model fit