ANTHROPOLOGY

Landscape burning facilitated Aboriginal migration into Lutruwita/Tasmania 41,600 years ago

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The establishment of Tasmanian Palawa/Pakana communities ~40 thousand years ago (ka) was achieved by the earliest and farthest human migrations from Africa and necessitated migration into high-latitude Southern Hemisphere environments. The scarcity of high-resolution paleoecological records during this period, however, limits our understanding of the environmental effects of this pivotal event, particularly the importance of using fire as a tool for habitat modification. We use two paleoecological records from the Bass Strait islands to identify the initiation of anthropogenic landscape transformation associated with ancestral Palawa/Pakana land use. People were living on the Tasmanian/Lutruwitan peninsula by ~41.6 ka using fire to penetrate and manipulate forests, an approach possibly used in the first migrations across the last glacial landscape of Sahul.

INTRODUCTION

The establishment of ancestral Tasmanian Palawa/Pakana communities is the earliest evidence of human migrations into temperate latitude regions in the Southern Hemisphere. The oldest archaeological evidence of human occupation in Tasmania (Aboriginal given name: Lutruwita) is from excavated sediment layers in Warreen Cave (*1*) and Parmerpar Meethaner rock shelter (*2*), with the calibrated radiocarbon dates of 39,924 ± 1130 years and 38,680 ± 1400 years, respectively. Lutruwita was isolated from the mainland of Australia by high sea levels for much of the interval between 135 and 43 thousand years ago (ka), with the first sustained land bridge of the last glacial cycle occurring between 43 and 37 ka (*3*). Palawa/Pakana communities were able to traverse the partially exposed eastern Bassian Land Bridge to enter Lutruwita at this time (*1*–*4*). The land bridge became isolated from the Australian mainland as a result of rising sea levels during the early to mid-Holocene (*3*). While early evidence for the occupation of Lutruwita by Palawa/Pakana people is well documented through the archaeological record (*1*, *2*, *5*), the nature of fire use and effects on vegetation and fauna (including megafauna) remains speculative (*2*, *5*) and at times contentious (*6*, *7*). This is partly due to the scarcity of high-resolution paleoecological data that span the period between 50 and 40 ka in the region. Paleoecological records from the Australian mainland suggest that the arrival of Aboriginal peoples on the continent at least ~50 ka (*8*–*13*) was accompanied by changes in the biotic environment, including burning of vegetation and the replacement of closed woody vegetation by open vegetation communities, as well as the decline and extinction in megafaunal population (*6*, *14*–*18*). Landscape management practices using fire are evident in Lutruwita at least after the Last Glacial Maximum (LGM) (*19*) and apparent in paleoenvironmental records from northern and eastern Australia during the past 11,000 years (*20*, *21*). Given existing evidence documenting millennia of burning practices in mainland Australia (*20*–*22*), we would expect landscape burning to accompany the arrival of people in Lutruwita.

Our goal in this study was to use two well-dated deep sedimentary records: Emerald Swamp and laymina paywuta (Palawa meaning: lagoon from a long time ago) situated at the western and eastern extremes of the Bass Strait (Three Hummock Island and Clarke Island/lungtalanana; Figs. 1 and 2) to reconstruct past environmental change and landscape changes associated with human arrival. Three Hummock Island is situated in the presently wet (annual average rainfall, ~939 mm) western side of Bass Strait, and lungtalanana is on the drier (annual average rainfall, ~616 mm) eastern side. These long-term records provide a unique opportunity to understand the interplay of past climates across the Pleistocene land bridge (*23*), including floristic and fire-regime changes associated with the earliest evidence for people within Lutruwita in two contrasting bioclimatic zones of this landscape (dry and wet temperate) with millennia of reversing precipitation gradients (*24*). In the context of previous research from mainland Australia, we expect that Aboriginal arrival in Lutruwita was also accompanied by a shift in fire regimes as a result of an additional source of fire ignitions—namely, people (hypothesis 1). We also expect the greatest plant species turnover (measured by beta diversity) following the first evidence for human arrival to have occurred in the then wetter landscapes where more fire-sensitive plants would have been common compared to the then drier landscapes where plant assemblages were likely more adapted to fires (hypothesis 2). Increased burning by people would differentially disadvantage the fire-sensitive species in wet environments compared to the fire-tolerant species from drier and more naturally fire-prone environments.

Study area climate and vegetation

As with the broader Lutruwita landscape today, the variability in annual rainfall between western and eastern Bass Strait is dominantly controlled by the northward-southward shifts in the position of the Southern Westerlies (SW) known as the Southern Annular Mode (SAM), which creates an east-west rainfall anti-phasing pattern (*25*, *26*). During summer, a positive SAM phase (southward position of the SW) results in higher chances of rainfall over eastern

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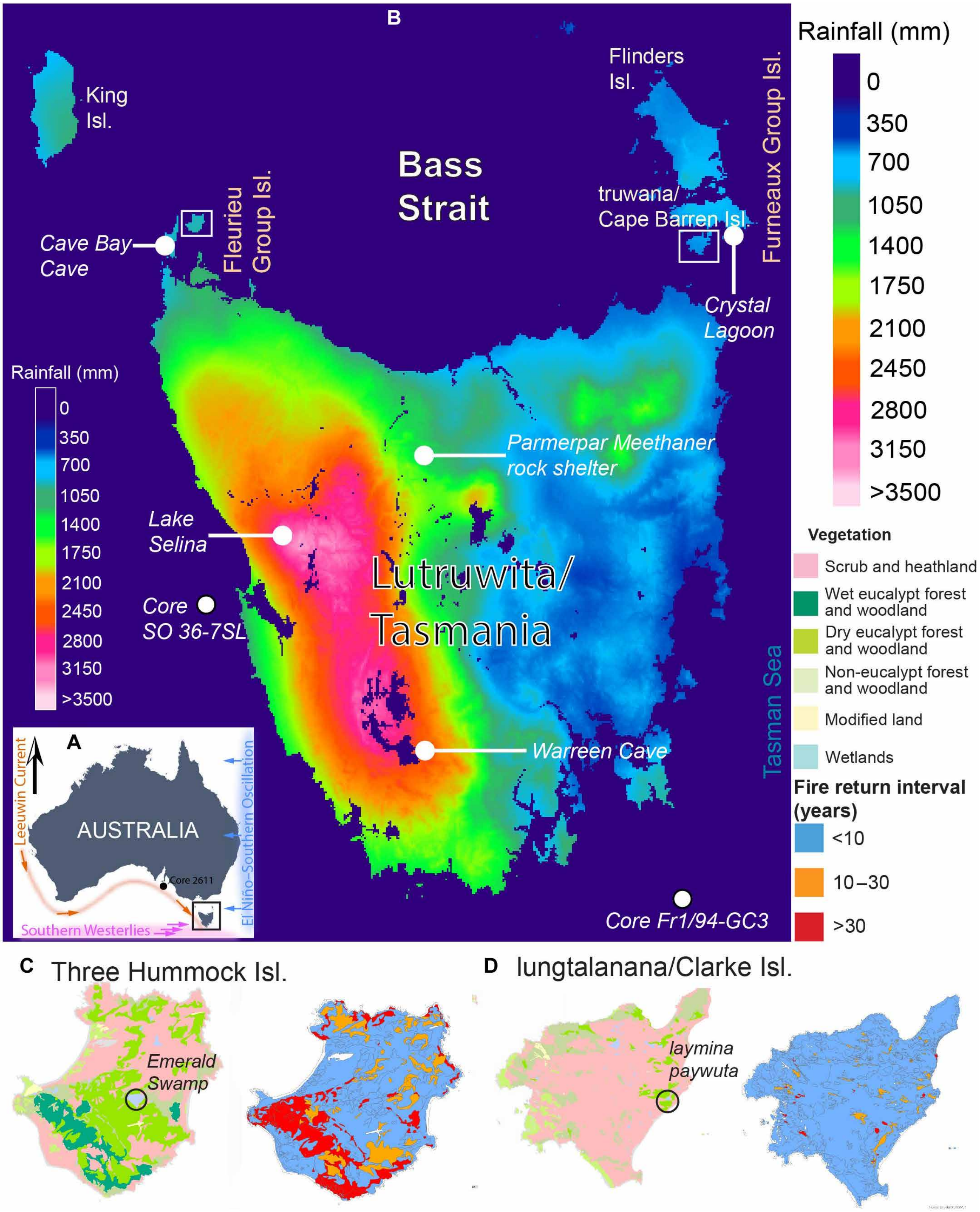

Fig. 1. Climate and vegetation of study area. Key climatic drivers (**A**) and annual rainfall distribution across Lutruwita/Tasmania (**B**), as well as vegetation and fire return interval of study area (*60*) (**C** and **D**)—Three Hummock Island and lungtalanana/Clarke Island in Bass Strait, Lutruwita. Maps [(B) to (D)] were created using LISTmap (*60*). Key sites later mentioned in the text are shown as well, including the site of climatic records (marine core 2611 and Fr1/94-GC3) offshore southern Australia (*33*) and southeast Lutruwita (*28*), existing dated pollen records spanning the past 30,000 to 75,000 years in Lutruwita from Lake Selina (*38*), offshore western Lutruwita—core SO 36-7SL (*34*) and Crystal Lagoon on truwana/Cape Barren Island (*40*), and the two archaeological sites containing the earliest evidence (~40 ka) of human occupation (Warreen Cave and Parmerpar Meethaner rock shelter) in Lutruwita (*1*).

Lutruwita and eastern Bass Strait. Conversely, a negative SAM phase (northward position of the SW) results in greater chances of rainfall in western Lutruwita and western Bass Strait. In winter, a positive SAM phase is associated with reduced chances of rainfall over the entire region and the reverse is the case during a negative SAM phase (*26*). The warm Leeuwin Current (LC) that flows from the coast of Western Australia toward the western side of Lutruwita also contributes moisture to the western Bass Strait today (Fig. 1A) (*27*). Overall, western Lutruwita (including western Bass Strait) currently receives the highest annual rainfall in the region and is characterized by relatively less flammable wetter vegetation communities compared to eastern Lutruwita and eastern Bass Strait (Fig. 1, B to D). Emerald Swamp vegetation on Three Hummock Island, western Bass Strait, is dominated by dense *Melaleuca ericifolia*–*Acacia melanoxylon* swamp forest, while laymina paywuta vegetation on lungtalanana, eastern Bass Strait, is characterized by dry sclerophyll shrub and heathland, dominated by *Eucalyptus*, *Casuarina*, and *Banksia*.

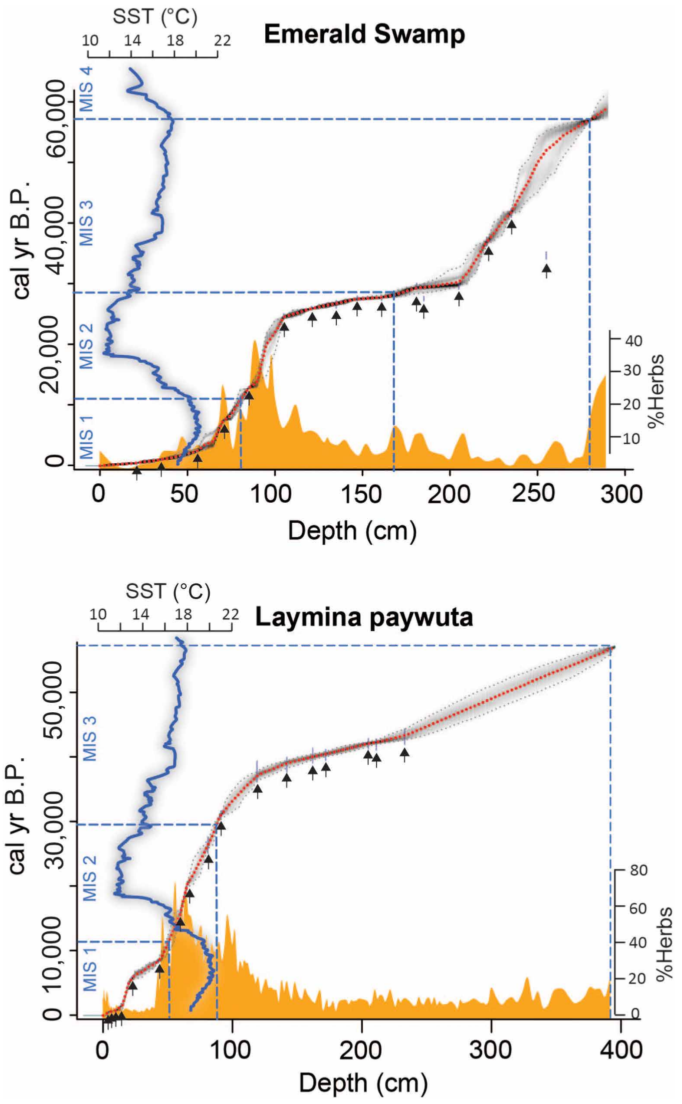

Fig. 2. Site age-depth models. Emerald Swamp and laymina paywuta age-depth model showing calibrated (purple lines/black arrows) radiocarbon dates, 95% confidence intervals of calibrated range (light gray), and single model based on the weighted mean age for each depth (red curve). cal yr B.P., calendar years before the present. See table S1 and fig. S1 for radiocarbon date results and full Bacon age-depth model output. The relative abundance of herbaceous pollen (yellow) for both sites and sea surface temperatures (SSTs; blue) for southern Australia (*33*) used in supporting the identification of the marine isotope stages (MISs) is also shown.

The present-day SAM-driven rainfall anti-phasing over Lutruwita is thought to have also prevailed in the region during the LGM (*23*), the late glacial and early to mid-Holocene, weakening during the past 5000 years as El Niño–Southern Oscillation intensified (*24*). Our pollen records suggest that the climatic anti-phasing may have also prevailed during marine isotope stage 3 (MIS 3), which is discussed below.

RESULTS AND DISCUSSION

Aboriginal arrival accompanied by a shift in fire regime in Lutruwita ~41.6 ka (hypothesis 1)

The co-dominance of drought-tolerant *Callitris* and *Eucalyptus* at the base of the laymina paywuta record indicates possible variable to less-wet conditions in eastern Bass Strait during the beginning of MIS 3, with the latter expansion of wet *Eucalyptus* forest and rainforest marking a wetter phase with potentially easterly moisture flow (+SAM) from ~50 to 35 ka. Rainfall reconstruction for southeast Lutruwita also shows high values during this period (Fig. 3, A and C) (*28*). Aboriginal arrival on the eastern Bassian Land Bridge may have occurred around this wet climatic phase, with perhaps abundant vegetative and potentially freshwater resources for subsistence on the narrow land bridge (Fig. 3, A, C, and F). Fire would have been an important tool used by early Palawa/Pakana communities to penetrate and manage the dense wet forest to promote open vegetation supporting key prey species and to access different raw materials and shelter (*29*–*31*). We expect shifts in fire regime to precede vegetation change in Lutruwita following human arrival, and this is observed in the record from laymina paywuta in eastern Bass Strait. Charcoal accumulation rates (biomass burned: amount of vegetation consumed by fire at the site) (*32*) increased abruptly at the site at ~41.6 ka, and this was followed by a major vegetation change at ~40 ka as identified by pollen zone classification (CONISS; Figs. 3C and 4A). Biomass burned and fire frequency records suggest possible initial forest burns with frequent intense fires within the first two millennia of Aboriginal arrival on the land bridge (Fig. 3A). Given the absence of major climatic shifts in southern Australia during the interval between ~41.6 and 40 ka (Fig. 3A) (*33*), increased charcoal influx, erosional activity (i.e., sediment influx; Fig. 4A), and the transition of closed to open vegetation (vegetation discussed in hypothesis 2) likely indicate landscape changes associated with anthropogenic firing. The environmental impact, however, would have taken time to become observable in archaeological or sedimentary archives. Hence, we interpret the earliest evidence for Palawa/Pakana occupation of Lutruwita to be at ~41.6 ka, followed by a gradual vegetation response by ~40 ka, which is about 2000 years earlier than suggested by the archaeological evidence in the southwest of the island (*2*, *5*).

At Emerald Swamp (hereafter "Emerald"), *Eucalyptus* forest expanded following the termination of the arid MIS 4 and beginning of MIS 3 but quickly declined by ~54 ka and was replaced by shrubland. This suggests a wet start (~57 to 54 ka) of MIS 3 in western Bass Strait, with drying and treeless vegetation expansion after 54 ka. Rainforest also declined in western Lutruwita during MIS 3 (Fig. 3, A and B) (*34*). The corresponding changes in Emerald *Eucalyptus* pollen to LC flow (*33*), which also bring moisture as far as western

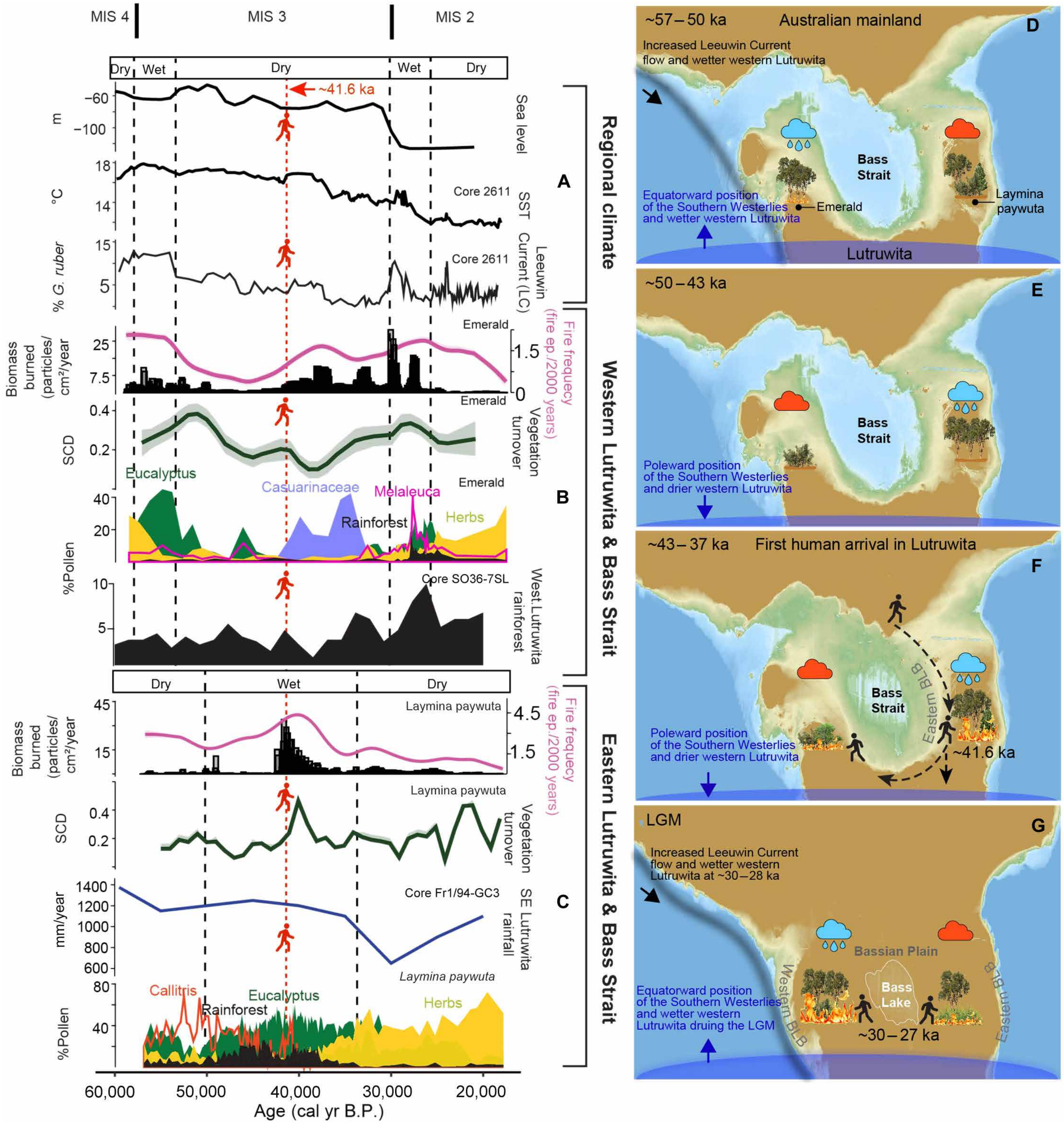

Fig. 3. Late Pleistocene paleoecological and paleoclimatic records from this study and existing ones from the broader Lutruwitan/Tasmanian region. (**A** to **C**) Vegetation and fire activity changes compared to changes in sea level (*3*), alkenone sea surface temperatures, and LC-driven precipitation changes inferred from *G. ruber* planktonic foraminifera in marine core 2611 offshore southern Australia (*33*, *61*). Total percentage pollen of rainforest taxa from core SO 36-7SL offshore western Lutruwita (*34*) and rainfall reconstruction from core Fr1/94-GC3 in southeast Lutruwita (*28*) is also shown. The red dotted line indicates the period of human arrival at ~41.6 ka (see Fig. 4). (**D** to **G**) Summary illustration of vegetation, climate, and development of Bassian Land Bridge from ~50 to 18 ka. Maps were created using the QGIS sea level tool plugin (*62*).

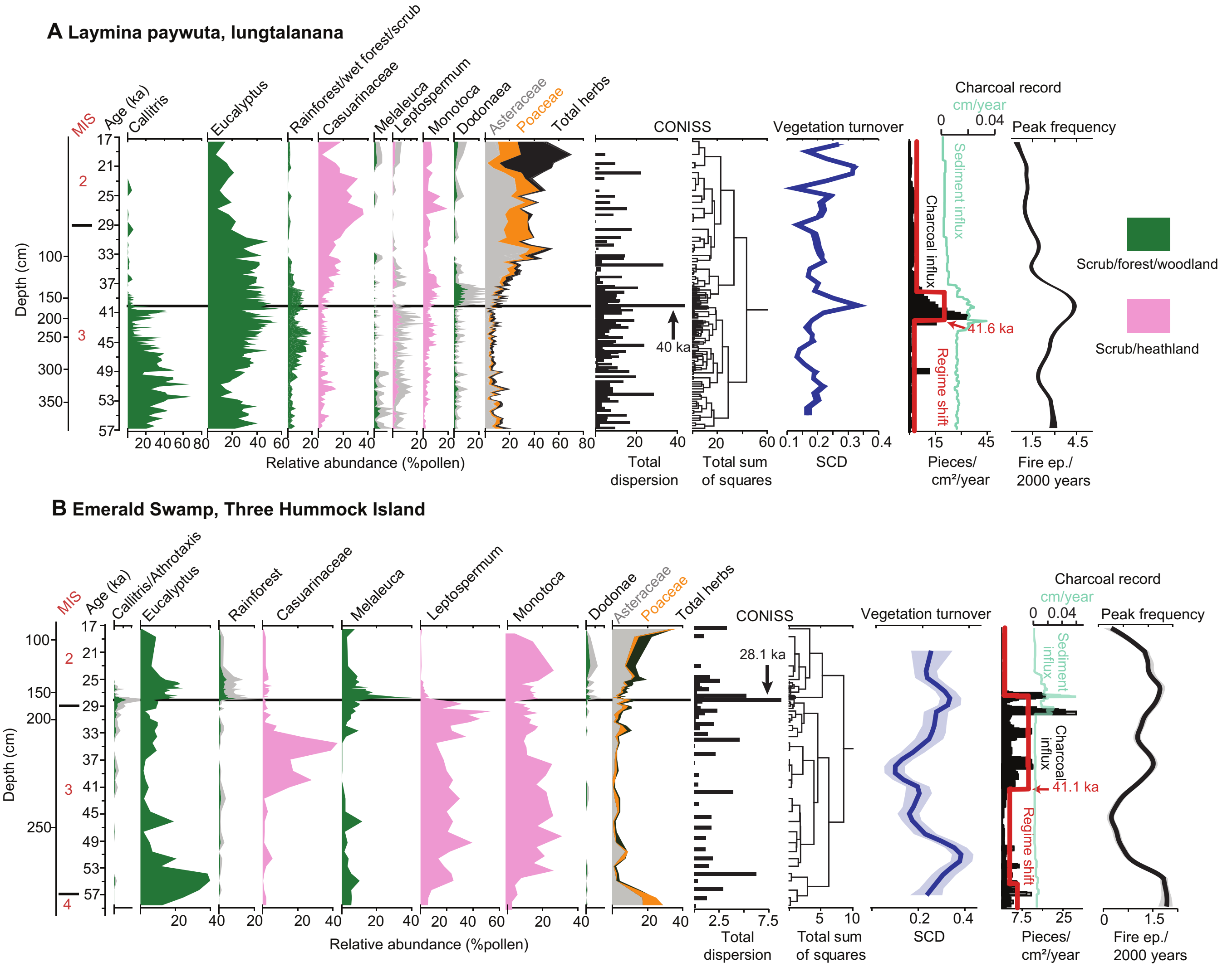

Fig. 4. Pollen and charcoal records. Major terrestrial pollen taxa (>10%), CONISS cluster analysis results, vegetation turnover record, and macrocharcoal record for laymina paywuta (**A**) and Emerald Swamp (**B**). SCD, squared chord distance. Solid black lines indicate the timing of the most significant shift in pollen spectra at both sites identified by the high CONISS cluster dispersion score. The base pollen sum used in calculating pollen percentages is the sum of terrestrial trees, shrubs, and herbs. Note that individual charcoal peaks represent fire episodes (ep.) and not individual fire events. See figs. S2 to S4 for the full pollen record.

Bass Strait today (*27*), suggest that it may have influenced the rainfall pattern in the area as well during MIS 3 (Fig. 3A). LC was also strong at the beginning of MIS 3 and generally became weaker between 54 and 30 ka, as inferred from the declining trend of tropical foraminifera *Globigerinoides ruber* in southern Australia at this time (*33*). Biomass burned increased in the area at ~41.1 ka (500 years after fire-regime shift in laymina paywuta) but was muted compared to that of laymina paywuta, and minor vegetation changes were evident at ~40 ka (Fig. 3, B and C). Western Lutruwita, including Emerald, was likely under a drier climate with less arboreal vegetation when Aboriginal people arrived in Lutruwita. People likely spread to northwest Lutruwita by ~41.1 ka, also frequently burning vegetation (shrubland) but possibly with less-intense fires. The likely explanation for the relatively less landscape firing and minimal vegetation changes at Emerald compared to laymina paywuta is discussed below (hypothesis 2).

Aboriginal burning-drive vegetation turnover across climate gradient following arrival in Lutruwita (hypothesis 2)

Given the abundance of fire-intolerant rainforest communities of western Lutruwita today, we hypothesized greater vegetation turnover in areas under wetter climates in the region following the onset of anthropogenic landscape burning ~41.6 ka. The eastern Bassian Land Bridge was wetter than the western area at this time, with more fire-sensitive plants in the former, including rainforest taxa (Fig. 3, B, C, and F). Of the two study sites, our CONISS and turnover analysis detect the greatest vegetation turnover in laymina paywuta in response to Aboriginal burning following arrival (Figs. 3, B and C, and 5). Notable floristic changes include the marked decline in *Callitris* and the increase in *Dodonaea* by ~40 ka (Fig. 4A). The gradual replacement of preexisting *Callitris*-*Eucalyptus* woodland by wet *Eucalyptus* forest and rainforest at the site was already underway from ~50 ka before the first evidence of people in the landscape (Fig. 4A).

There is a brief increase in *Callitris* ~41 ka, possibly due to infrequent anthropogenic fires suitable for regeneration that was favorable for this long-lived obligate seeder. However, by 40 ka, the permanent establishment of Palawa/Pakana communities occupying the Bassian Land Bridge (*1*) likely caused major increases in fire activity causing *Callitris* to quickly decline while favoring fire-adapted *Eucalyptus*. *Callitris* is both fire dependent and fire sensitive in that infrequent fires reduce competition with shade-tolerant trees, allowing canopy-stored serotinous seeds to establish, yet frequent fires can destroy seed sources and cause local extinction (*35*). Other fire-adapted taxa also became more abundant (~5%), including *Banksia marginata* and the Australian endemic species *Beyeria* (fig. S3). The shift in fire regime at this time likely opened existing forest/woodland canopy, as indicated by increases in understory shrubs, especially *Dodonaea*, given the taxon's preference for light availability under open canopies (Fig. 4A) (*35*, *36*).

There were no notable changes in preexisting vegetation in the Emerald area following human arrival (Figs. 3B and 4B). The already open dry shrubby vegetation in the area perhaps did not require substantial burning for access and use as reflected in the lower charcoal influx (biomass burned) following human arrival compared to laymina paywuta. The marked expansion of fire-adapted and serotinous Casuarinaceae was the key floristic change associated with anthropogenic burning in Emerald. Dense *Monotoca-Leptospermum* scrub (shrubland >2 m tall) and *Melaleuca* swamp forest largely characterized the site before evidence of anthropogenic burning (Fig. 4B). The small presence of native pepper *Tasmannia* (fig. S2) that thrives after disturbance likely also indicates some opening of existing scrub by burning (*36*), with perhaps more heathy vegetation type (shrubland <2 m tall). The Casuarinaceae species is likely *Allocasuarina monilifera*, which is an endemic dwarf heathland species. It is currently the only Casuarinaceae species recorded growing in the Fleurieu Group islands (*37*) but commonly found across the drier eastern Lutruwita (including the Furneaux Group) today in dry substrates (*36*). Dry conditions that prevailed when people arrived in the area, combined with landscape burning, likely drove its successful generation and expansion. It is possible that the recorded Casuarinaceae expansion at Emerald was part of a broader western Lutruwitan vegetation response following human occupation of the area. An existing pollen record from Lake Selina, 100 km to the south in western Lutruwita, spanning the past 30,000 to 52,000 years, also recorded Casuarinaceae pollen increase at ~42 ka, although the chronology is problematic (*38*). While increasing biomass burning intensity and fire frequency from ~35 ka would have resulted in the Casuarinaceae species decline due to fire regime outside species tolerance level (*39*), the onset of wetter conditions may have also reduced the species' niche and outcompeted by wet-tolerant or mesophyllous species (Figs. 3B and 4B). Increased burning was likely driven by the desire to keep the landscape open in response to *Eucalyptus* expansion and vegetation thickening as conditions became wetter toward the end of MIS 3 and beginning of MIS 2. This may also reflect human occupation expansion in northwest Lutruwita, especially between ~30 and 27 ka upon the onset of the LGM when sea level reached minimum and the full extent of the western and eastern Bassian Land Bridge was exposed (Fig. 3G) (*40*). Although the onset of the LGM climate may have contributed to the marked vegetation change in northwest Lutruwita at ~28 ka, frequent Aboriginal burning that kept wet sclerophyll vegetation open at this time likely significantly contributed to a decline in *Leptospermum* in the understory while favoring the more stress/disturbance-tolerant *Monotoca* (Figs. 3G and 4B) (*36*, *37*).

Our results suggest that Aboriginal people markedly burned the landscape when they first entered Lutruwita, a pattern consistent with other evidence from mainland Australia (*14*, *17*). Landscapes characterized by fire-adapted vegetation types were also likely more resilient to anthropogenic burning following Aboriginal arrival in Australia. After comparing vegetation turnover in Lutruwita and sites from moist forest and dry woodland-shrubland biomes from the mainland, the lowest floristic turnover following the earliest evidence for Aboriginal occupation with major burning was observed in southern Australia, followed by Emerald (Fig. 5, A and C). Turnover value distribution was also not significantly different in comparable vegetation types, with similar distributions between southern Australia and Emerald, and between northeast Australia and laymina paywuta (Fig. 5, B and C). In southern Australia, from ~58 ka, people likely used fire to maintain herb-dominated landscapes already created by previous cooling between 75 and 60 ka (*17*, *41*, *42*) and to prevent tree biomass recovery when the climate warmed again between 60 and 45 ka (*17*), stabilizing vegetation composition. A similar pattern of prehuman arrival herbaceous woodland and arid savanna persistence with minimal response to cultural burning after human arrival has also been observed in northwestern and northern Australia, respectively (*20*, *43*). Conversely, high turnover was recorded for tropical wet northeast Australia's vegetation following Aboriginal migration and anthropogenic burning in the area from ~41 ka (Fig. 5) (*14*, *44*). Existing mixed vegetation of sclerophyllous forest and rainforest communities became replaced by sclerophyllous forest at this time (*14*, *44*). The sensitivity of vegetation in northeast Australia to anthropogenic burning may be due to the abundance of fire-intolerant wet forest communities, which is also the case at laymina paywuta, where wet forest also existed at the time of human arrival. Climate would have modulated Aboriginal landscape burning during the late Pleistocene, with people burning wet forested/wooded landscapes with high-intensity fires to promote open landscapes (*19*), and burned already open dry vegetation types with low-intensity fires to maintain desired conditions. The former likely resulted in high vegetation turnover with the decline in fire-intolerant plants, while the latter favored fire-adapted plants with low turnover. It is possible that Aboriginal people were able to modify and use wet forest communities, including rainforests, much more in the past than presently thought (*31*), creating community composition and/or structure very different from today's wet forest communities (*19*).

MATERIALS AND METHODS

Coring sites: Emerald Swamp and laymina paywuta—Lagoon from a long time ago

Emerald Swamp [40°26′23.59″S, 144°54′48.15″E, 35 m above sea level (masl)] sits in the center of Three Hummock Island and is the largest catchment on the granite island at ~1 km^2. The site is characterized by dense *M. ericifolia*–*A. melanoxylon* swamp forest, with sedgy and mossy forest floors. Old tall *Eucalyptus* trees are also present in the forest. *Leptospermum* and *Banksia* form stands in drier substrates away from the swamp forest (*45*). Laymina paywuta (40.542173°S, 148.217650°E, 10 masl) is on the eastern coastal margin of Clarke Island (lungtalanana), bounded by an easterly facing lunette and nestled within a granite catchment. The site is characterized by dry sclerophyll shrub and heathland, with *Eucalyptus*, *Casuarina*, and *Banksia* prominent components of the vegetation. The

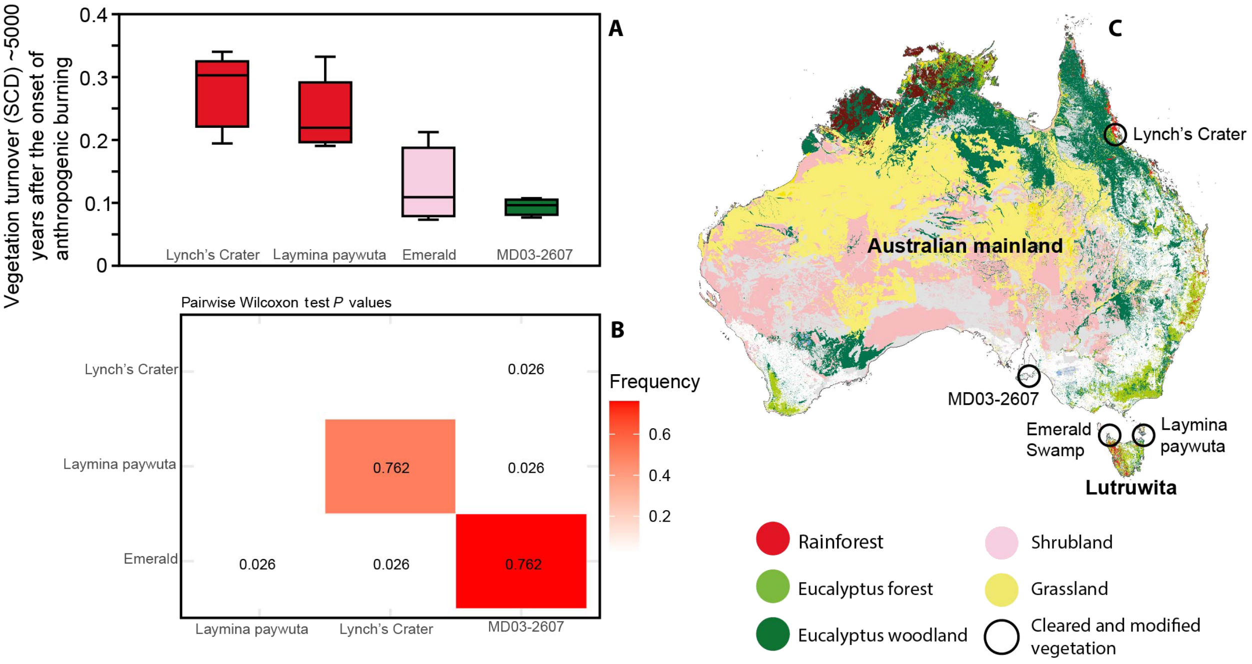

Fig. 5. Vegetation turnover in Lutruwitan/Tasmanian compared to that of the Australian mainland. (**A**) Boxplot of vegetation turnover distribution 5000 years after the onset of anthropogenic burning in Lutruwitan/Tasmanian sites compared to that of the Australian mainland (*44*, *63*) and (**B**) pairwise Wilcoxon test for dissimilarity between sites' turnover distribution. $P < 0.05$ in pairwise Wilcoxon test means significant difference between sites, and $P > 0.05$ means insignificant difference. (**C**) The Australian vegetation map (National Vegetation Information System version 5.1) with site locations is also shown, and boxplot colors match the vegetation map, reflecting prevailing vegetation types around the onset of anthropogenic burning in the sites during the late Pleistocene. See fig. S5 for full turnover plots.

study areas on lungtalanana and Three Hummock Island have a major feature in common. Both catchments have existed in the landscape for a long period without being obliterated by eolian sand sheets, which elsewhere on both islands have both covered any old lagoons as well as forming newer ones.

Sediment core collection and analysis

A 2.9-m core was collected from Emerald Swamp and a 3.94-m sediment core from laymina paywuta (Fig. 1), and accelerator mass spectrometry (AMS) radiocarbon dates were obtained for 28 and 24 bulk sediment sample depths across respective cores. AMS radiocarbon dates were measured at DirectAMS, Washington and Australian Nuclear Science and Technology Organization, Sydney. An age-depth model was then built for the sediment cores based on the resulting AMS dates, using SHCal20 in "rbacon" (*46*, *47*).

Pollen and macrocharcoal were also analyzed from the sediment cores to reconstruct vegetation and fire history, respectively. Pollen analysis follows the standard protocol involving HCl, KOH, and acetolysis treatment (*48*), and at least 300 terrestrial taxa were identified in each pollen sample and presented as percentages. Sediment cores were sampled for pollen at 0.5- to 4-cm intervals and for macrocharcoal at 1-cm interval. To identify major temporal changes in vegetation (pollen spectra), stratigraphically constrained CONISS cluster analysis was performed on terrestrial pollen records and within-cluster scores were used to identify the timing of greatest shifts in pollen assemblages (*49*). Pollen data were further analyzed for turnover using the squared chord dissimilarity (SCD) metric (*50*–*53*) in R "analogue" package (*54*) to further quantify the magnitude of vegetation change. Turnover refers to the amount of compositional change in vegetation (pollen spectra) through time. There are different dissimilarity metrics used in calculating turnover in pollen records, including but not limited to chord distance, SCD, detrended correspondence analysis, and chi-square coefficient; however, these metrics produce similar results (*53*, *55*–*57*). Here, we used the SCD due to its better handling of signal-to-noise effects (*53*). Study sites' turnover results were also compared to sites on the mainland, especially during the first 5000 years of human occupation of landscapes, and pairwise Wilcoxon tests were used to determine the differences in turnover distribution between sites.

Sediment cores were contiguously sampled for macrocharcoal, and samples were bleached overnight (~16 hours) using household bleach, washed through a 125-μm sieve, and manually counted under the stereoscope. Using the CharAnalysis program (*32*), macrocharcoal counts (charcoal particles per cubic centimeter) were converted to influx (charcoal pieces per square centimeter per year) with interpolation to a median time interval, a proxy for past biomass burned at the study sites (*32*). The peak component of charcoal influx, which is the frequency of above-average charcoal influx events, was then used to infer past fire frequency (*58*). Significant charcoal peaks were detected at a minimum count cutoff probability of 0.05, and the frequency of peaks was computed every 2000 years. Given the multi-millennial scale of this study, individual charcoal peaks are taken to represent aggregates of fire events (fire episodes) and not single fire events. Charcoal influx was further subjected to regime shift ($P < 0.01$, cutoff = 50, Huber's weight parameter = 5) analysis to detect the timing of major shift in biomass burned (*59*).

Supplementary Materials

This PDF file includes:

Supplementary Text
Figs. S1 to S5
Table S1

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