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Fire history on the California Channel Islands spanning human arrival in the Americas

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Recent studies have suggested that the first arrival of humans in the Americas during the end of the last Ice Age is associated with marked anthropogenic influences on landscape; in particular, with the use of fire which, would have given even small populations the ability to have broad impacts on the landscape. Understanding the impact of these early people is complicated by the dramatic changes in climate occurring with the shift from glacial to interglacial conditions. Despite these difficulties, we here attempt to test the extent of anthropogenic influence using the California Channel Islands as a smaller, landscape-scale test bed. These islands are famous for the discovery of the 'Arlington Springs Man', which are some of the earliest human remains in the Americas. A unifying sedimentary charcoal record is presented from Arlington Canyon, Santa Rosa Island, based on over 20 detailed sedimentary sections from eight key localities. Radiocarbon dating was based on thin, fragile, long fragments of charcoal in order to avoid the 'inbuilt' age problem. Radiocarbon dating of 49 such fragments has allowed inferences regarding the fire and landscape history of the Canyon *ca* 19–11 ka BP. A significant period of charcoal deposition is identified approximately 14–12.5 ka BP and bears remarkable closeness to an estimated age range of the first human arrival on the islands.

This article is part of the themed issue 'The interaction of fire and mankind'.

1. Detecting anthropogenic fire signals in the geological record

Significant evidence exists for human use of fire dating as far back as 0.8–1.0 Myr from sites in South Africa, where burnt bone with butchery marks has been discovered [1,2]. By *ca* 400 ka BP, similar evidence of hearths is found at sites across Europe, including Beeches Pit in eastern England, which also includes the suggestion of fireside stone tool production [3,4]. Such evidence of direct human interaction with fire (see also [5]) is rare in the archaeological record, particularly at open, rather than cave or more sheltered, sites [6]. Whereas modern hunter–gatherer communities globally use fire at the landscape scale [7–11], understanding how fire was used as a tool by past human populations is a complex task, particularly in geographical regions with abundant natural ignition sources, including Mediterranean climates.

One increasingly important approach is to investigate very long Quaternary records to improve existing knowledge of fire history over long timescales, including over multiple glacial–interglacial cycles. These types of investigation usually attempt to detect anomalous levels of charcoal content and other products from

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the ‘combustion continuum’, such as black carbon [12,13], and relate this to corresponding spatial and temporal patterns in the archaeological record (e.g. [14–16]). This approach allows detailed comparison between climatically similar periods (e.g. interglacials) where people are known to have been present and periods where they were probably absent (e.g. [17]). However, long terrestrial records are often limited geographically, particularly in areas that have undergone repeated Quaternary glaciation.

Alternatively, marine records are increasingly used to identify potential anthropogenic burning in the past (e.g. [18]). Marine records typically have more straightforward depositional histories (i.e. are often isotaphanomic), allowing for easy calculation of charcoal concentrations, which are typically reported as number, area or volume. Although marine records are undeniably valuable, they also have limitations, such as complex or undefined charcoal source areas. Such limitations can make reliable interpretation difficult, particularly as it is often micro-charcoal, less than 125 µm [19], which is the charcoal size fraction present at sites distal from terrestrial source areas. There are many challenges of interpreting microcharcoal fragments in palaeorecords [20]; studies in pollen source areas are also informative, with some suggesting that marine pollen records are heavily biased towards pollen from higher mountain areas and river outflows [21,22]. Another issue is that pollen source areas may change significantly over time in marine records [23]. Thus, it is always desirable to combine these data with fire records from proximal terrestrial sequences.

For the Late Quaternary, the spatial coverage of terrestrial palaeorecords improves markedly and, during the last approximately 50 kyr, radiocarbon dating allows reasonable chronologies to be formed. The majority of Quaternary charcoal records covering this time come from lacustrine or peat bog sequences, mostly with relatively straightforward depositional histories, allowing the construction of charcoal statistics such as charcoal accumulation rates (CHAR) [24]. Because these records minimize local variations, they contribute to regional and global syntheses of charcoal patterns over time (e.g. [25–27]). For example, in New Zealand (which was colonized approx. 1280 AD), anthropogenic fire detected in terrestrial archives comes as asynchronous increases in charcoal contemporaneous with a wave of human arrival across the country [28,29]. Detecting the clear arrival of people and the associated shift in fire regime in this region was helped by (i) New Zealand’s low background of natural wildfire and (ii) the relatively stable climate during this period.

Less attention has been focused on understanding fire regimes over millennial timescales recorded in more complex sedimentary environments, such as fluvial deposits, probably because depositional heterogeneity precludes simple age models and generation of statistical indices such as CHAR. This is unfortunate as these settings have long been recognized as rich sources of archaeological information (e.g. [30]) and are excellent records of longer-term landscape evolution [31]. Often, secondary geomorphic effects associated with wildfire, such as post-fire erosion, are preserved in this part of the landscape sedimentary system [32–35].

Within this investigation, we look to use these more complex sedimentary environments, specifically a fluvial fill sequence, attempting to answer questions surrounding the potential presence or absence of anthropogenic fire signals. Our case study is the northern California Channel Islands during the last glacial–interglacial transition (LGIT), *ca* 15–10 ka BP. Before outlining our work in detail, first the North American context is introduced, in terms of the key environmental and archaeological evidence and also the complexities of investigating human–fire interactions during this timeframe.

2. Fire and the arrival of people in North America

It is well understood that intentional landscape burning has been practiced by humans in North America over much or all of the Holocene [36–40]. More controversial is the suggestion that the first arrival of humans in the Americas during the end of the last ice age can be associated with non-trivial anthropogenic influences on landscape, in particular with the use of fire [41,42]. Proponents of this idea suggest that even small transient human populations could have had broad impacts on ignition-limited portions of the landscape [41].

The Late Pleistocene Clovis culture is the oldest well-defined archaeological techno-complex of North America and is thought to have appeared *ca* 13.4 ka BP and disappeared around approximately 12.7 ka BP [43–49]. Despite the fairly short interval, Clovis technology is found over a large spatial range [49]. Less-secure evidence of a human presence in the Americas during the two millennia before Clovis (approx. 15.5 until approx. 13.8 ka BP) has also been suggested (e.g. [50–52]) and hotly debated [53–57]. The exact timing of human arrival in the Americas remains uncertain.

Understanding the impact of the human vanguard into North America is further complicated by the contemporaneous changes in climate during the LGIT [58–62]. In particular, the Younger Dryas cold event (*ca* 12.9 ka BP) [63–66] contributed to rapid environmental shifts at a key time during human arrival in, and/or migration through, the Americas. Against the backdrop of these broad-scale climatic events, diachronous changes in vegetation types, burning patterns and megafauna populations have been suggested as evidence of human impacts from Alaska to southern parts of North America (see [41] for full discussion). An example of this is a sharp vegetation shift from herb tundra to shrub tundra associated with a sharp increase in burning occurring 14–13 ka cal BP [67]. Other authors have also noted charcoal spikes following reductions in megaherbivore populations and resultant effects on fuel-load changes, and suggest that these may be fire-regime shifts indirectly related to human activity [68,69].

A synthesis of 35 palaeofire records from over North America identified a general increasing charcoal influx trend throughout the LGIT, which halted during the Younger Dryas [70]. These two steps in the continental-scale climate record mostly track with the known climatic shifts of this period. These authors do, however, note a steep increase in charcoal influx around 13.2 ka BP which, although widespread, is not represented continent-wide. This coincides with the appearance of Clovis people; however, it is suggested that the range of sites and the high elevation of some of those sites make a causal link to humans unlikely [70].

In summary, detecting the use of fire by the first populations entering North America is complicated by (i) the nature of wildfire, which is sporadic and difficult to predict on short timescales; (ii) the wide range of Pleistocene environments and mosaic landscapes present over North America; and (iii) uncertainties in the precise timing of human arrival in different regions. This uncertainty relates to both chronological uncertainties (usually related to radiocarbon dating) as well as the accidental nature of the archaeological record, which includes variable and often significant lag times between first arrival and first evidence [71].

3. The Northern California Channel Islands

The Northern Channel Islands are located off the coast of southern California and are formed of four islands (ranging in size from *ca* 3 to 250 km^2; figure 1). From largest to smallest, the islands are Santa Cruz, Santa Rosa, San Miguel and Anacapa. During the last glacial period, glacioeustatic sea level merged these islands into one large landmass known as ‘Santa Rosae’ Island (shown in figure 1*c*) [72]. At the Last Glacial Maximum, Santa Rosae was approximately four times larger than the combined area of the present-day islands, but was still separated from mainland California by 2–4 km at the closest point [73].

The Northern Channel Islands contain extensive thick and extensive Quaternary deposits as well as evidence of human occupation fully spanning the Holocene. Among the abundant archaeological materials on Santa Rosa Island, Phil C. Orr discovered two human femora deposited in fluvial sediments at the mouth of Arlington Springs Canyon. These human remains have become known as ‘Arlington Springs Man’ [74]. Collagen from these and other associated materials, such as charcoal, have since been radiocarbon dated. The most recent direct date comes from [75] (10 960 ± 80 radiocarbon years BP) and is recalibrated here using the most recent international calibration curve, IntCal13 [76,77], equivalent to 13 020–12 700 cal yrs BP (2σ range). Archaeological material is widespread and abundant on the Northern Channel Islands, including evidence early in the record from Daisy Cave and Cardwell Bluffs on San Miguel Island and sites 512 and 706 from the northwest side of Santa Rosa Island (shown in figure 1) [78–82]. In summary, the archaeological record of California’s Channel Islands has become an important source of information for understanding these earliest coastal peoples [82]. The chronological data from these sites have been used within this study (see Material and methods).

The palaeoenvironmental record of the Northern Channel Islands around the LGIT mostly comes from sedimentary, macrobotanical and palynological records. The Sauces Canyon palaeobotanical site on Santa Cruz Island includes specimens of Douglas fir (*Pseudotsuga menziesii*), Santa Cruz Island pine (*Pinus muricata* f. *remorata*), Bishop pine (*Pinus muricata*) and Gowen cypress (*Cupressus goveniana*) [83] species radiocarbon dated from around 17 cal ka BP and younger [84]. Evidence for diverse woodland communities also comes from pollen records from Daisy Cave on San Miguel Island, Cañada de los Sauces on Santa Cruz Island and from Soldedad Pond on Santa Rosa Island. These pollen assemblages document widespread conifer forests during the Late Pleistocene, probably existing until *ca* 12 cal ka BP, when the predominant conifer cover was replaced by mixed grassland and scrub communities [78,85,86]. The exact nature of this ecosystem transition, between forested to largely open conditions, remains unclear because no continuous high-resolution pollen record has yet been studied which crosses this boundary. This has precluded a detailed understanding of this shift and its interplay with climate change, human arrival and changing fire regimes through the onset of the Holocene. The endemic Channel Islands pygmy mammoth (*Mammuthus exilis*) also became extinct during this interval, with the last dated evidence of mammoths overlapping the radiocarbon ranges proposed for Arlington Man (approx. 13 ka BP) [87,88].

Several workers have noted charcoal fragments present in the extensive fluvial and alluvial fill sequences of the Northern Channel Islands, but this palaeofire record has been only minimally studied [89–93]. Pinter & Anderson noted high abundances of macrocharcoal fragments from sites across the Channel Islands and suggested that they could have been the result of large wildfires, perhaps triggered by the first human colonizers [94]. More recently, Kennett *et al.* working from the basis of one sedimentary section from Arlington Canyon on Santa Rosa Island proposed a single wildfire event relating to an extra-terrestrial impact [95], although this has been hotly debated [91,92].

The Northern Channel Islands currently experience fairly low levels of natural wildfire, with few events recognized in the recent past [96]. The Western Transverse Ranges region of coastal California, of which these islands are a part, experiences few convective storms during the summer and relatively moist winters, which results in some of the lowest lighting-induced fire frequency in North America [36,97]. The Mediterranean climate of the islands does, however, promote ecosystems which are susceptible to burning even if they lack natural ignition sources [93,98].

The climate of the Northern Channel Islands during the LGIT was moister and cooler than the present day [78,85,86], which promoted the mosaic woodland systems observed in the pollen and palaeobotanical record, and probably further reduced the potential for wildfire events compared with the present [98,99]. A recent study by Pigati *et al.* [100] on San Nicolas Island does, however, record evidence of natural wildfire between 25 and 37 ka BP, which suggest a similar fire return interval to the present.

Island settings have long been thought to be particularly sensitive to environmental changes, particularly to invasive species (including humans). This sensitivity is due to resource limitations and because endemic flora and fauna have been isolated from natural competition for long periods of time. Indeed islands are often viewed by scientists as ‘natural laboratories’ that allow ecological and other theories to be formed or tested [93]. The much-studied archaeological record and rich sedimentary record of the Northern Channel Islands make for an excellent test bed for considering the impacts of the first human arrival upon fire regimes.

4. Approach and research rationale

Here, we investigate the Arlington Canyon sedimentary sequence on Santa Rosa Island because (i) it is the canyon from which the Arlington Springs Man remains were recovered [74], and it is thus closely associated with the earliest evidence of human presence on the islands; (ii) sedimentary charcoal in Arlington Canyon has been noted by several research groups [92,95]; and (iii) although much attention has been focused on single isolated sites (Arlington Springs by Johnson *et al.* [75]; and the Younger Dryas purported impact horizon [95,101,102]), surprisingly little research has been done on a unifying analysis of the many kilometres of exposed sedimentary stratigraphy in Arlington Canyon. This

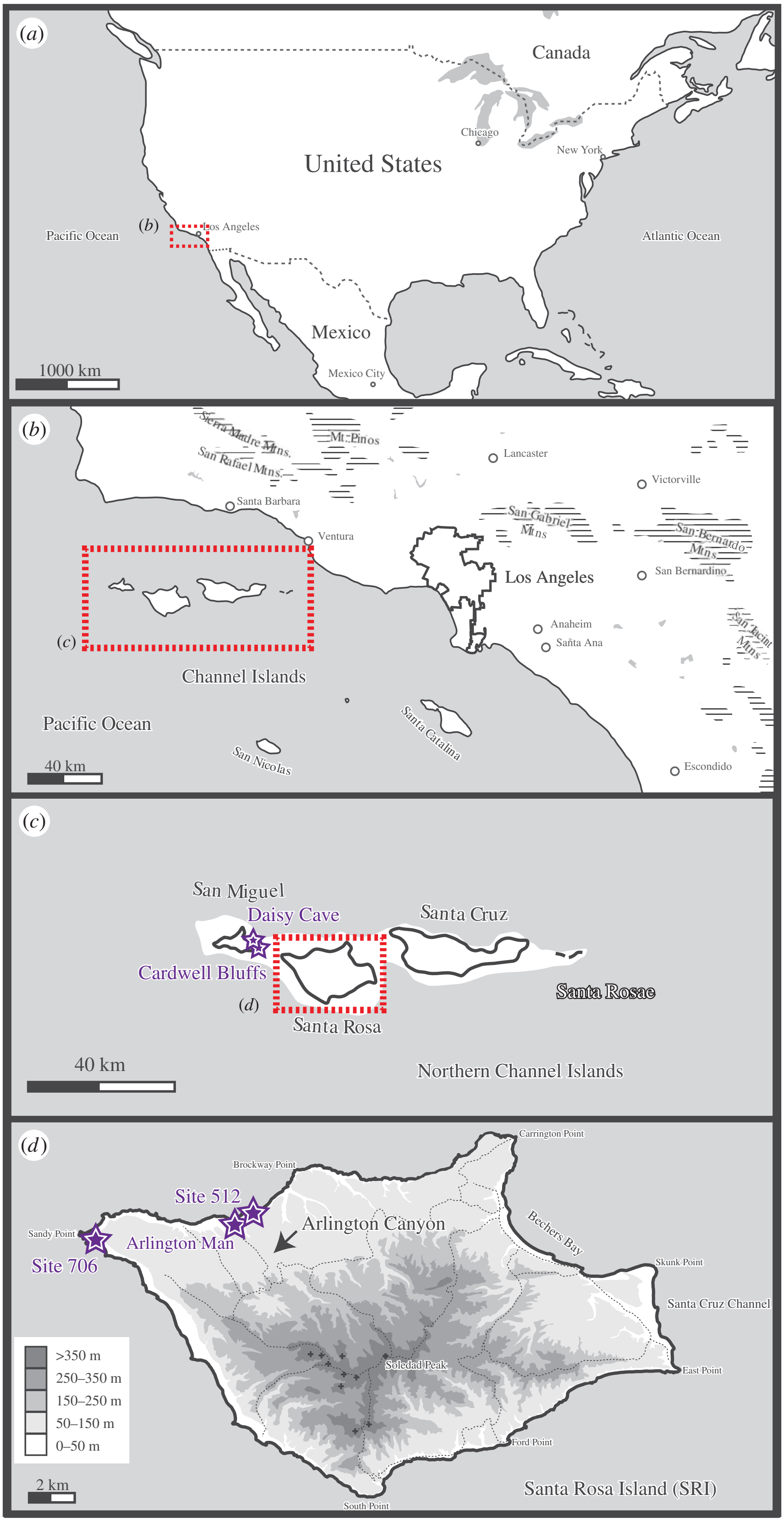

Figure 1. Map of the California Channel Islands, including (*a*) the position of the Islands in relation to mainland USA, (*b*) the position of the islands in relation to the US West Coast, (*c*) the Northern Channel Islands including an outline of the Santa Rosae palaeocoastline at *ca* 16 ka BP [72], and (*d*) Santa Rosa Island, including key archaeological sites and the position of Arlington Canyon. (Online version in colour.)

is absolutely necessary because of the complexity of the various depositional environments present in the canyon, in particular in understanding its fluvial facies and architecture. Here, we present radiocarbon results which refine the temporal understanding of these sediments, an important goal on the way to building a more robust stratigraphy [103], as well as providing insights to the temporal extent of wildfire on the Northern Channel Islands of California.

Late glacial fire histories are most often based upon sequences where sediments were deposited in a largely uniform manner, such as in lakes, with constant sediment accumulation rates and charcoal that are calculated against volume and time (e.g. influx/yr). Charcoal in fluvial sediments cannot be interpreted in this way, as both deposition rates and sediment textures may vary significantly. Despite these challenges, reconstructing fire history from these environments has advantages, in particular being able to directly connect the charcoal record to geomorphic responses to fire [32–35,104–106]. Streams and floodplains are also landscape systems that humans would have regularly used (and indeed often also contain archaeological materials).

5. Material and methods

The area of interest in this study is Arlington Canyon (figure 1) which lies on the NNW side of Santa Rosa Island, with nearly continuous Late Quaternary fluvial deposits stretching 4 km from the mouth of the canyon. Arlington Canyon itself is incised into a sequence of uplifted Quaternary coastal terraces [107]. The Late Pleistocene to Holocene sedimentary deposits form a fluvial fill terrace that was subsequently incised, exposing vertical to near-vertical cliff sections, often approximately 20–30 m in height [92]. These outcrops are widespread through the canyon, allowing detailed sampling and analysis. Over four field seasons, eight key localities have been identified, systematically described and sampled for palaeoenvironmental analysis (see figure 2 for key dated sections and the electronic supplementary material for more information). Because of the lateral sedimentary variability, we described multiple sections at most localities in order to fully characterize the sedimentary architecture. At all sections, the occurrence of visible charcoal fragments was carefully recorded and sampled. Charcoal-bearing units were categorized in the field as either (i) large charcoal fragments present, (ii) small charcoal present, or (iii) charcoal fragments rare. Sediment samples were also analysed in the laboratory for macro- and microcharcoal content.

Radiocarbon dating on charcoal does not capture the date of the burning event, but rather the date at which the plant or woody material ceased to fixate atmospheric CO_2 via photosynthesis [13]. Gavin for example, found that charcoal dates on a fire from Vancouver Island were 0–670 years older than the known age of the fire; this is due to the 'inbuilt' age of the wood prior to burning [108]. In addition, radiocarbon ages in sedimentary sequences do not necessarily represent the age of deposition of the sediment, but rather the age of the material being dated, which in some cases may be older. Because charcoal is chemically inert and sometimes mechanically robust, it can sometimes survive erosion from an older deposit, transport through the fluvial system and redeposition, yielding the well-known challenge of 'old' charcoal dates (i.e. [109]). For this reason, we relied solely on fragile charcoal fragments such as thin charred twigs or pieces with small axes or other material that exists in the litter layer and can be charred by wildfire (such as seeds, carbonaceous spherules and coprolites; see [92] for definitions of these forms) for dating. Thin twigs or pieces with axes measuring only a few millimetres are less likely to survive subsequent reworking without fragmenting.

Charcoal pieces were radiocarbon dated by two different laboratories: the Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at University of California Irvine and the Oxford Radiocarbon Accelerator Unit, RLAHA, at the University of Oxford. Samples processed at the University of Oxford used the methods outlined by Brock *et al*. [110]. All radiocarbon ages (14C yBP) were corrected for isotopic fractionation prior to reporting following the conventions of [111]. The new radiocarbon dates here are presented in the electronic supplementary material.

Because terrestrial plants exchange with atmospheric CO_2, there is no reservoir effect, and charcoal ages from terrestrial vegetation may be calibrated to calendar years using the atmospheric IntCal13 radiocarbon calibration curve [13,76], as can the archaeological (bone) samples of the terrestrial species (*M. exilis*, human and goose). The marine samples (shells) required calibration using the Marine13 radiocarbon calibration curve [76], with an additional local marine reservoir correction ('*Delta_R*') of 225 ± 35 years [81]. The Bayesian statistical software OxCal v. 4.2 [74] was used and, for the archaeological samples, a simple single 'Phase' model was applied for each of the individual human occupation sites, thus providing a 'Start' *Boundary* for the human occupation at each individual site. A subsequent Phase was applied, cross-referencing the Start *Boundaries* of each of the human-occupied sites, as well as adding in the single 14C dates from SRI-706 and of Arlington Springs Man. The Start *Boundary* of this latter Phase therefore estimates the first human appearance date on Santa Rosae.

6. Results and interpretations

(a) Nature of the sedimentary charcoal record

Figure 2 shows the sedimentary context and the associated charcoal record for Arlington Canyon. Charcoal fragments were preserved over a large range of depositional energies, including pebbly matrix-supported sediments to fine silts; coarser gravels tended not to contain charcoal. The lower portions of the Arlington Canyon sequence include a range of depositional facies, from coarse channel lags to low-energy overbank deposits. The upper portions of the sequence are nearly uniformly fine-grained, with multiple dark palaeosol horizons dated to the Holocene [91]. Because of this variability, many sections across Arlington Canyon were sampled and analysed in order to fully characterize the fluvial architecture and complex depositional and erosional history of this sequence.

Most of the charcoal present within these sequences was transported and deposited by water. If we use modern systems as a guide, it appears that most charcoal was moved from burned areas via overland flow; usually, the first rainstorm after a fire event is the most important for transferring this newly formed charred material through the sedimentary system [112–114]. Charcoal fragments display complex sedimentation and transport characteristics which can be affected by: (i) the wide variety of sizes, (ii) the type of material that was charred, and (iii) the temperature at which the charcoal formed [112,115,116]. These factors all influence the lag time between charring and deposition. The distribution of charcoal in fluvial sediments is also strongly influenced by taphonomic processes (e.g. [35,117]). Fluvial processes transport charcoal by both suspended and bed load, and often, during deposition, charcoal fragments can be concentrated into lenses, cross-bedding structures, or more broadly dispersed in sediments [116]. These types have all been observed in the Arlington Canyon record.

Given the charcoal size distribution and depositional context, the large majority of sedimentary charcoal in Arlington Canyon was transported by water and is thus related to fire events within the catchment, although incorporation of minor amounts of wind-borne charcoal cannot be ruled out. Many studies have shown that charcoal fragments larger than 125 μm can be transported significant distances by aeolian processes (approx. 1–25 km; [19,118–120]). We examined the

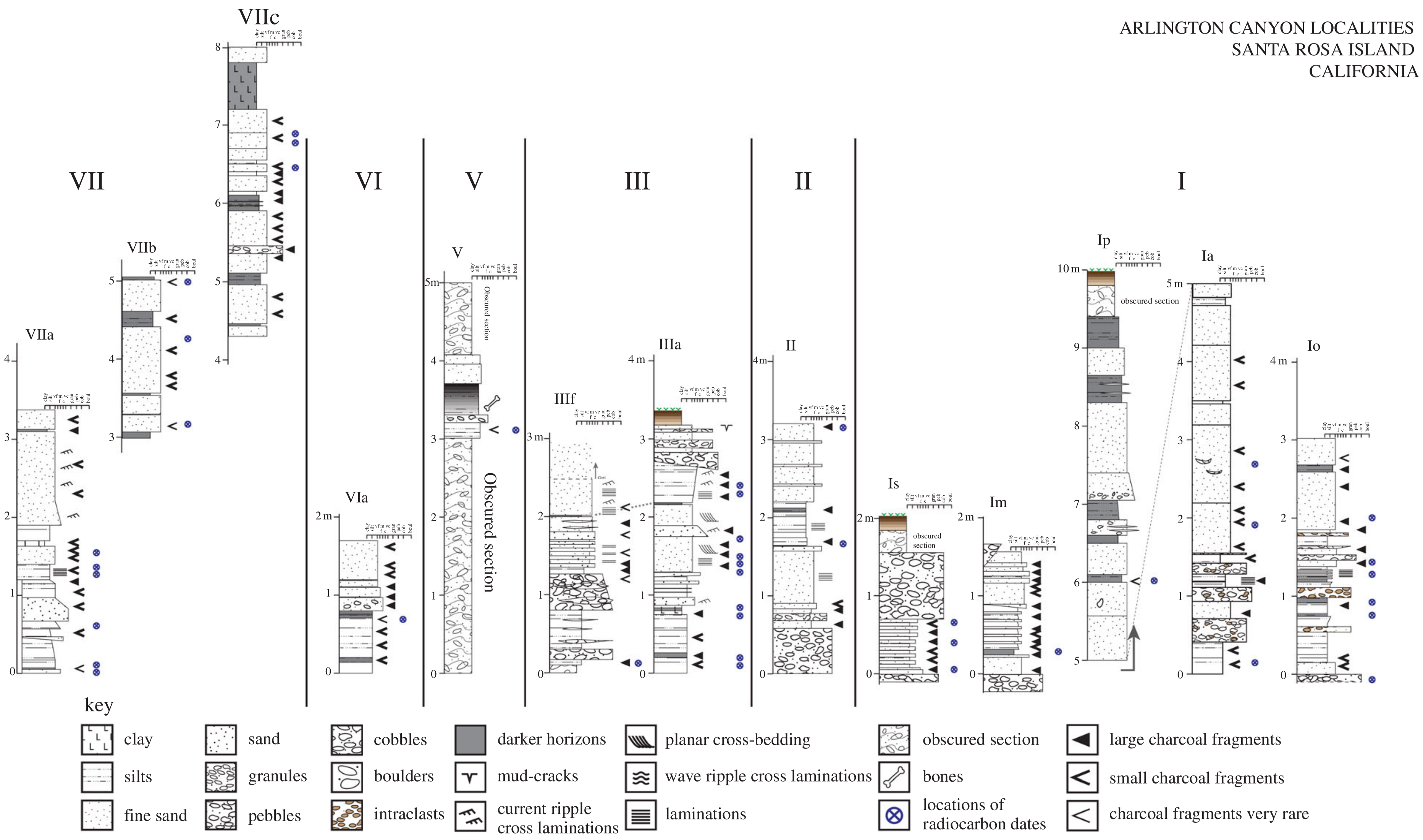

Figure 2. The Arlington Canyon sedimentary sequences described and dated within this study, including the sedimentary characteristics, location of visible charcoal fragments and the dating sample points (see the electronic supplementary material, table S2 for precise grid reference for each site). Note depths given are measured from the ground (0 m) up and do not represent comparable elevations between localities. (Online version in colour.)

detailed distribution of charcoal, noting not only its size distribution, but also the plant organs preserved. What was clear was that the charcoal varied considerably through the sequences representing multiple wildfire events over a considerable period of time rather than being reworked from a single fire event. We noted particularly the number of less than 1 mm diameter charred axes present in some samples that would have probably fragmented during reworking. We therefore selected small axes of herbaceous plants or small-diameter twigs for radiocarbon dating to eliminate the problem of 'old wood'.

Multiple dark-coloured palaeosol horizons are superimposed upon the finer-grained sediments that generally comprise the uppermost half of the Arlington Canyon fill sequence (see sites Ip, V, VIIb and VIIc; figure 2) and locally deeper in the stratigraphy. These palaeosol horizons occur along depositional and erosional contacts, draping over the palaeo-land surface. These palaeosols contain very little or no charcoal, and their dark colours are the result of translocation and concentration of dark minerals and pedogenic clay, typical of mollisolic soil formation.

The distribution of charcoal through Arlington Canyon makes clear that this is a record of more than one fire event (e.g. SI figure 1). Unlike Kennett *et al.* [95], we find no evidence for one high-intensity fire. Indeed scanning electron microscopy (SEM) and reflectance analysis carried out by Scott *et al.* [92] document only low-temperature surface fires. While it is always possible that higher-temperature fires (e.g. crown fires) occurred on the Northern Channel Islands during the latest Pleistocene, no sedimentary or charcoal evidence currently exist to confirm such fire behaviour.

(b) Dating the charcoal sedimentary record

Here, we present 49 radiocarbon dates from Arlington Canyon. Other charcoal dates are available, in particular from Kennett *et al.* [95], but we have not included these because we have sampled Kennett's AC003 site using our own methods and sediment characterization. Unlike in lacustrine and peat records, fluvial records cannot be used to generate fire return interval via charcoal concentrations and accumulation rates. Direct dating of charcoal may reveal discrete wildfire events. However, during the LGIT, chronological precision can preclude separation of fire events occurring within 200–300 years of each other (for example, in many pine forests the fire return interval is often less than 100 years [35]).

For each locality, we attempted to date the full stratigraphic range of charcoal-bearing units in order to gain knowledge of the age of the first and last wildfire event. Radiocarbon samples were also taken from intermediate charcoal layers where discrete or significant charcoal was present. Figure 2 shows the sections that were dated and the distribution of dated horizons. Age reversals are sometimes present within the sequences, a well-known problem within fluvial systems. However, for the purposes of this study, these dates are still included as they still represent chronological evidence of fire (just not contained in sediment of contemporaneous age).

Figure 3 shows the distribution of calibrated ages from Arlington Canyon (presented at 95.4% confidence limits). The large majority of age determinations from Arlington Canyon range between 14 and 12.5 ka BP, with a small number of earlier dates, from 19 to 14 ka BP; and only one charcoal date is present after 12.5 ka BP. The lack of charcoal after 12.5 ka BP is unlikely to be due to a lack of sediment of this age in Arlington Canyon but rather to a lack of datable (i.e. large enough) charcoal being found (e.g. figure 2, section Ip).

The preponderance of ages between 14 and 12.5 ka BP cannot be used as evidence of increased wildfire frequency, only that deposition and/or preservation of charcoal in the Arlington Canyon sedimentary record appears to become more common during this time interval. Such shifts in charcoal abundance can be explained by a number of mechanisms, the most likely being: (i) a change in fluvial dynamics, sedimentology or palaeo-environment leading to increased deposition and/or preservation; (ii) an increase in the production of charcoal, perhaps related to ecosystem changes in the contributing watershed; or finally (iii) a shift in fire regime. This is also true of the lack of charcoal after 12.5 ka BP, which could relate to a change in fuel source. Based upon existing pollen records, we suggest that the sharp drop-off in sedimentary charcoal after 12.5 ka BP results primarily from the transition from conifer forests that were widespread on the Northern Channel Islands through the Late Pleistocene to the grassland cover that has dominated the islands through the Holocene [78,85,86].

In summary, charcoal occurrence in the fluvial aggradational sequences of Santa Rosa Island, and elsewhere, reflect a complex mosaic of causal mechanisms and overlapping palaeoenvironmental changes over time. Combined with other proxies, the Arlington Canyon sequence does track broad, landscape-level changes through the terminal Pleistocene and into the Holocene. Now that these shifts have been recognized, future research should aim to examine pre- and post-14 ka BP fire regimes on the islands. This could include the following lines of examination: (i) what material and which species were burning; and (ii) the systematic measurement of charcoal reflectance, which records the minimum burn temperature.

(c) Wider significance

A number of significant events occurred on the Northern Channel Islands during the LGIT that are worth exploring is some detail in relation to the 'landscape shifts' identified above. Megafauna are important herbivores and can have significant impacts on vegetation composition, fuel loads and the resulting fire regimes [69]. On the Channel Islands, the endemic pygmy mammoth (*M. exilis*) would have been an important component of the landscape. Radiocarbon dating evidence of the presence of this species has been calibrated here using the new IntCal13 calibration curve in figure 3 and shows the last occurrence of *M. exilis* is around 12.9 ka BP, thus post-dating the landscape shift documented here at approximately 14 ka BP. Two ages of mammoths, one directly dated bone and the other associated charcoal [87,88,121], also coincide with current age estimates for 'Arlington Springs Man' [75]. Recalibration of these dates using IntCal13 strengthens the case made by Agenbroad *et al.* [88] that the island pygmy mammoth and humans were contemporaries on Santa Rosa Island (figure 2).

These dates both post-date the landscape shift seen at 14 ka BP by approximately 1 ka. A closer correspondence is, however, seen between the estimated first appearance of humans on Santa Rosae (figure 3), which has been calculated by cross-referencing the Start *Boundaries* calculated for the dated archaeological evidence and the age range where a large number of charcoal radiocarbon dates are returned (approx. 14–12.5 ka BP). This is particularly compelling considering

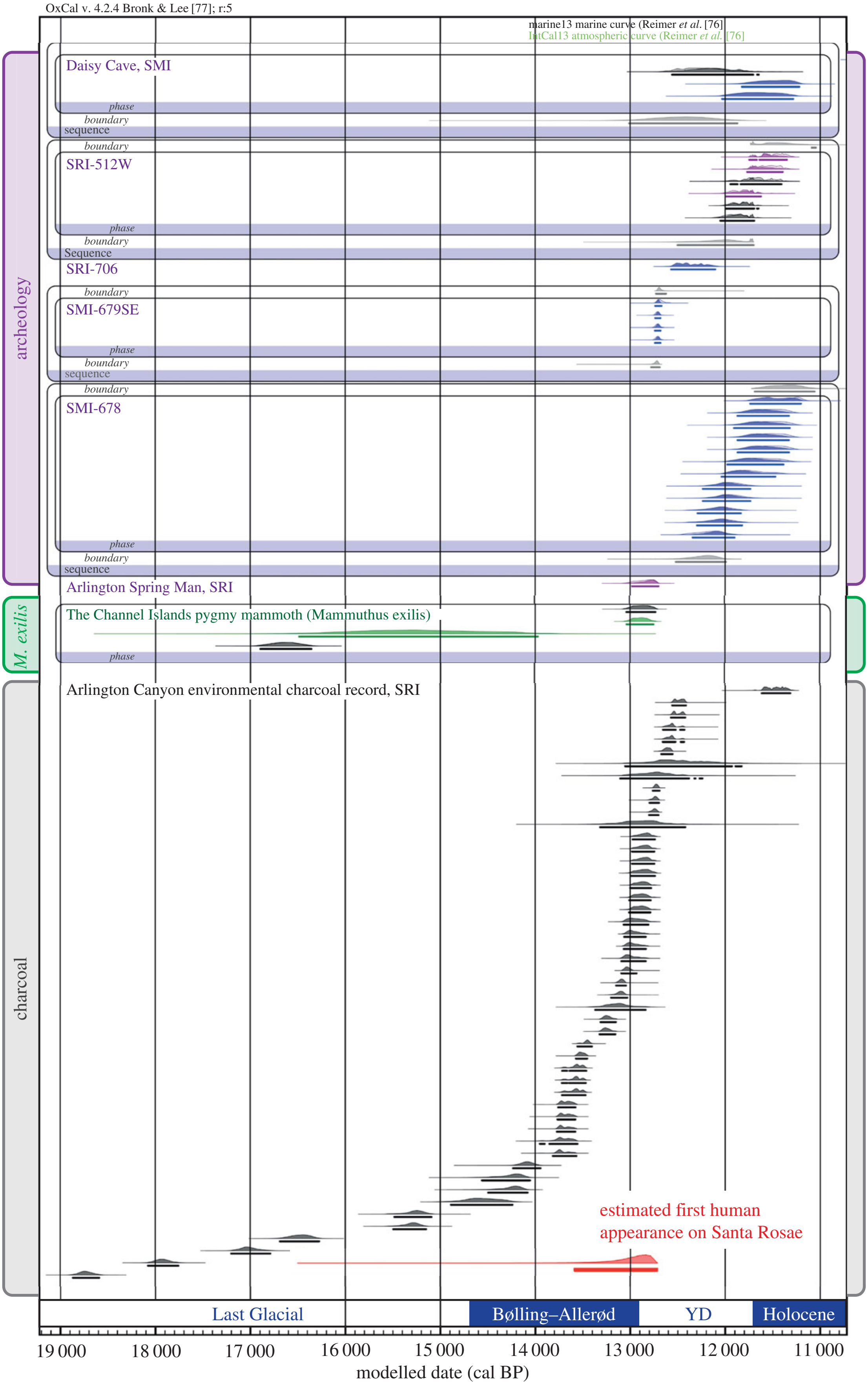

Figure 3. Calibrated age ranges from all charcoal radiocarbon dates from our research, dates of *M. exilis* [87,88,121], and dates from archaeological sites from the northern California Channel Islands [75,78–81]. All dates based on charcoal are in dark grey. All ages have been calibrated with IntCal13 (age ranges in purple, green or dark grey) or Marine13 with a local marine reservoir correction applied (samples in blue) where appropriate [76]. Archaeological sites Daisy Cave, 512 W, SRI-706, SMI-679SE and SMI-678 are presented within sequence models [77]. Also shown in red is the estimate of the first human appearance date on Santa Rosae. All ages are given at 95.4% confidence limits; see the Material and methods section for more information. (Online version in colour.)

that this timeframe appears to cross multiple climatic shifts (i.e. the onset and end of the Younger Dryas, for example). We also note that the estimated first appearance of humans on Santa Rosae, 13 590–12 720 years BP (at 95.4% confidence limits) bears a closeness to the onset and disappearance of the Clovis Culture as dated from mainland North America (approx. 13.4 to approximately 12.7 ka BP; [49]), although it must be stated that no evidence of the Clovis culture has ever been found on the California Channel Islands.

This time period also coincides with global climate events as well as with local vegetation shifts. Both onshore pollen records and nearby offshore marine cores document a large shift from *Pinus*-dominated to *Quercus*-dominated pollen assemblages and an increase in herbaceous taxa at approximately 14 ka BP [98], which may relate to the Bølling–Allerød interstadial (*ca* 14.7–12.9 ka BP [122–124]). Improving the current comparisons between the Channel Islands and the Santa Barbara Basin palaeorecords in more chronologically robust way (e.g. denser dating of this vegetation transition, calculation of age errors and use of updated radiocarbon calibration curves) may shed more light on these questions.

Another way to test the question of climatic versus human impacts on wildfire may be to study fluvial sediments from the Islands dating to previous interstadial events, thought to have a similar climatic signature to the Bølling–Allerød (a.k.a., Greenland Interstadial (GI) 1; [125]), e.g. GI8 and GI12, with onsets of approximately 38.2 and approximately 46.8 ka BP, respectively [122,126,127]. Currently, it is unclear if such aged sequences are preserved in alluvial Island sediments. However, a recent study by Pigati *et al.* on San Nicolas Island, 80 km to the south of the Northern Channel Islands, documented several 'burn events' in sediments dating to 25–37 ka BP, which overlaps with several known interstadial events. Pigati *et al.* [100] found that wildfires were significant enough to be preserved in the geological record at least every 300–500 years; this is broadly comparable to modern pre-anthropogenic values. Unfortunately, the nature of the sedimentary archive, as well as difference in modern climate between Santa Rosa and San Nicolas Island, means these data are not suitable for comparison but does perhaps point a way forward to disentangling natural wildfire systems with ones that have been altered by humans.

7. Key findings

- Fire was part of the Arlington Canyon landscape long before the arrival of humans (to at least 18.5 ka BP in the deposits studied here). Similar fluvial fill sequences elsewhere on Santa Rosa and Santa Cruz Islands contain charcoal dating back to 26.5 ka BP, and charcoal on San Nicolas Island, 80 km to the south, date back to approximately 37 ka.
- Complex sedimentary sequences can record important fire history information, yet this source has been underused within Quaternary palaeofire research.
- Charcoal dating results suggest two significant landscape shifts within Arlington Canyon: (i) an increase in sedimentary charcoal at approximately 14 ka BP, followed by (ii) a decline at approximately 12.5 ka BP. In the first case, it is not possible to say whether the frequency of wildfire events increased during this transition, or changes in sedimentary processes prevailed. Potential explanations include enhanced fluvial activity/deposition, an increase in flammable fuels available on the landscape, or a shift in fire regime. Similarly, the reduction in charcoal deposition at approximately 12.5 ka BP cannot necessarily be interpreted as a reduction in wildfire but probably relates to a reduction in trees as a fuel source as noted from pollen records covering this period [78,85,86].
- Sedimentary charcoal (i.e. evidence of burning) is most abundant within the Arlington Canyon record between approximately 14 and approximately 12.5 ka BP. This is chronologically offset from any single climate event during the LGIT, such as the Bølling–Allerød interstadial (*ca* 14.7–12.9 ka BP), the Younger Dryas climatic deterioration (*ca* 12.9 ka), and the Holocene onset (*ca* 11.7 ka BP; [122–124]). This does not preclude a causal link between burning and climatic change, as there may be leads and lags in terrestrial response. However, we note that the transition at 14 ka BP does correspond with an estimated age of the first human appearance on the islands, calculated via a synthesis of the pre-existing archaeological evidence.

Data accessibility. The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. M.H. wrote the paper with contributions from all the other authors. All authors (except R.A.S.) collected material and were involved in description and analysis in the field. R.A.S. assisted with analysis and interpretation of geochronological data.

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