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Re-evaluating the origins of late Pleistocene fire areas on Santa Rosa Island, California, USA

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ABSTRACT

At the close of the Pleistocene, fire regimes in North America changed significantly in response to climate change, megafaunal extinctions, anthropogenic burning and, possibly, even an extraterrestrial impact. On California's Channel Islands, researchers have long debated the nature of late Pleistocene "fire areas," discrete red zones in sedimentary deposits, interpreted by some as prehistoric mammoth-roasting pits created by humans. Further research found no evidence that these red zones were cultural in origin, and two hypotheses were advanced to explain their origin: natural fires and groundwater processes. Radiocarbon dating, X-ray diffraction analysis, and identification of charcoal from six red zones on Santa Rosa Island suggest that the studied features date between ~27,500 and 11,400 cal yr BP and resulted from burning or heating, not from groundwater processes. Our results show that fire was a component of late Pleistocene Channel Island ecology prior to and after human colonization of the islands, with no clear evidence for increased fire frequency coincident with Paleoindian settlement, extinction of pygmy mammoths, or a proposed Younger Dryas impact event.

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Introduction

Human use and control of fire during the past 1.6 Ma was a major milestone in human evolution that allowed people to live in colder environments (e.g., northern Eurasia), create new technologies, have a source of light, and cook and process food (Brown et al., 2009; Roebroeks and Villa, 2011). Research from around the world suggests that fire also was an important tool used by ancient peoples to clear undergrowth, increase wild-plant productivity, promote grazing land for game, and to help clear land for cultivation and provide soil nutrients (Smith, 2007; Bleige Bird et al., 2008; Archibald et al., 2012). In North America, recent studies have suggested that fire regimes changed significantly around 14,800–12,900 yr ago, with explanations ranging from the extinction of megafauna and changing vegetation communities to anthropogenic burning by Paleoindians, climate change, or even an extraterrestrial impact (Kennett et al., 2008; Gill et al., 2009; Marlon et al., 2009; Pinter et al., 2011).

On California's Channel Islands, researchers have long been interested in understanding fire history and anthropogenic burning during the Pleistocene and Holocene (Orr, 1968; Johnson, 1980; Anderson et al., 2010; Scott et al., 2011). Orr and Berger (Berger and Orr, 1966; Orr and Berger, 1966; Orr, 1968; Berger, 1980) argued that many "fire areas" or reddish features (red zones hereafter) found in Pleistocene alluvium on Santa Rosa Island were the remains of mammoth (*Mammuthus exilis*) roasting pits used by prehistoric hunting peoples between >37,000 (infinite ^{14}C age) and 12,760 cal yr BP. Because of their antiquity and dubious associations of bones and artifacts with the red zones, few scholars have accepted Orr and Berger's claims for a cultural origin of the Channel Island red zones, or similar features found in Pleistocene alluvium along the adjacent mainland (Erlandson, 1994:183; Glassow, 1996; Reeder et al., 2008). Two hypotheses emerged to explain the red zones: (1) that they were caused by natural fires and burning of stumps and roots that stained sediments red and often left behind charcoal (Johnson et al., 1980; Wendorf, 1982); and (2) that "the vast majority or all" of the features were the result of groundwater processes and had nothing to do with fire (Cushing et al., 1986; Cushing, 1993).

Prompted by recent interest in late Pleistocene fire history, we investigated six red zones near Radio Point, Santa Rosa Island (Fig. 1). Located in the same part of the island as Orr and Berger's research and three nearby archaeological sites with evidence for Paleoindian settlement on the Channel Islands (Arlington Springs [CA-SRI-173], CA-SRI-512, and CA-SRI-26) at ~13,000–11,500 cal yr BP (Johnson et al., 2002; Erlandson et al., 2011a, 2011b), these red zones present an opportunity to re-evaluate the origins of the Channel Island red zones and to provide context for late Pleistocene fire history and ecology of the Channel Islands (Anderson et al., 2010; Scott et al., 2011). Radiocarbon dating, macrobotanical analysis, and X-ray diffraction

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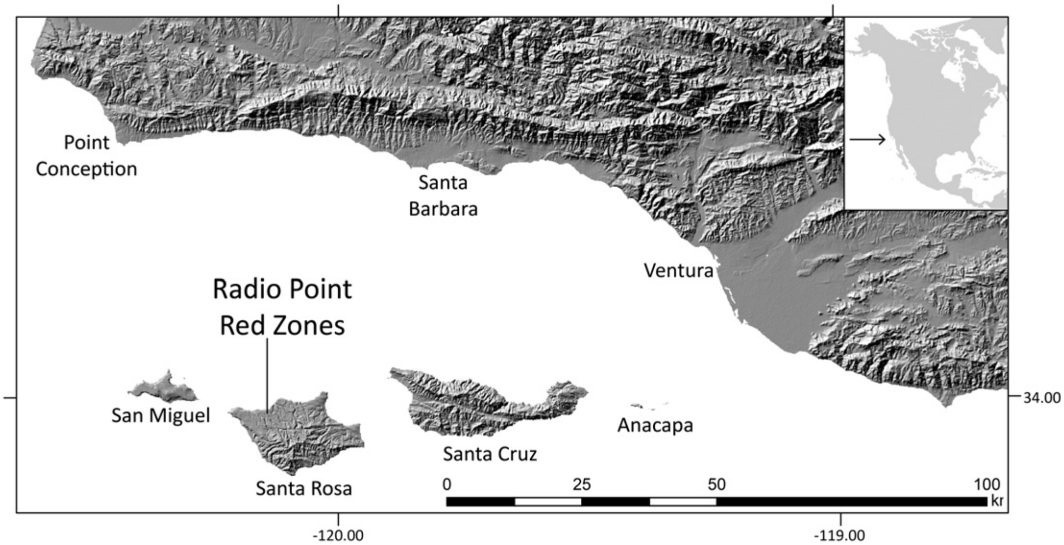

Figure 1. The northern Channel Islands, Santa Barbara Channel region, and location of Radio Point red zones.

(XRD) analysis of clay minerals and iron oxides from samples at the six red zones are presented below.

Context and background

Environmental and cultural overview

The Channel Islands, located off the southern California Coast, are divided into northern (Anacapa, Santa Cruz, Santa Rosa, and San Miguel) and southern (San Clemente, Santa Catalina, San Nicolas, and Santa Barbara) groups. During Pleistocene glacial periods when sea levels were lower, the four northern islands coalesced into a single larger island known as Santarosae, which began to separate ~11,500 cal yr BP (Kennett et al., 2008). Today the islands range in size from about 2.6 to 249 km^2 and are between about 20 and 98 km from the mainland. All the islands have a Mediterranean climate, with mild summers and cool, wet winters (Schoenherr et al., 1999).

The Channel Islands contain a limited terrestrial fauna and flora, lacking many animals and plants common on the mainland (Schoenherr et al., 1999). Other than humans and domesticated dogs, the largest land mammals on the islands during the Holocene were the island fox (*Urocyon littoralis*) and island spotted skunk (*Spilogale gracilis*). During the Pleistocene, both full-size and pygmy mammoths (*Mammuthus columbi and M. exilis*) lived on the northern Channel Islands until ~13,000 cal yr BP (Agenbroad et al., 2005), but until historical introductions of livestock the islands lacked most of the terrestrial herbivores, carnivores, and omnivores that were common on the adjacent mainland.

Vegetation communities on the islands are also distinct, including a number of endemic and relict species. Several vegetation communities are found on the islands, including coastal sage scrub, oak and pine woodlands, riparian, grasslands, and chaparral, and a variety of invasive grasses and other plants (Junak et al., 1995). Ravaged by more than a century of historical overgrazing, island soils have periodically been exposed causing widespread deflation, gullying, and scouring of the landscape (Johnson, 1972, 1980).

Although ancient vegetation records from the Channel Islands are limited (Chaney and Mason, 1930; Axelrod, 1967; Cole and Liu, 1994; West and Erlandson, 1994; Kennett et al., 2008), Anderson et al. (2010) recently provided a detailed vegetation and fire history for the terminal Pleistocene and Holocene on Santa Rosa Island. During the last glacial period, conifers were present on the northern Channel Islands, including Douglas fir (*Pseudotsuga*), cypress (*Cupressus*), and pine (*Pinus*), suggesting a forested environment more typical of the central California Coast than the Channel Islands today (Chaney and Mason, 1930; West and Erlandson, 1994; Erlandson et al., 1996; Anderson et al., 2010). This is consistent with the nearby Santa Barbara Basin pollen record that indicates a dominance of coniferous forest at this time (Heusser and Sirocko, 1997). By ~11,800 cal yr BP, coastal sage scrub, relict stands of pine, and native grassland replaced the late Pleistocene forests (Anderson et al., 2010).

Terminal Pleistocene and Holocene charcoal records from Santa Rosa Island suggest high charcoal influx during the terminal Pleistocene as the vegetation shifted from forested to non-forested conditions (Anderson et al., 2010). Fire frequency may have decreased during the early Holocene and then increased after 7000 cal yr BP (Anderson et al., 2010). Historical occurrences of lightning-caused fires in coastal California are rare (Anderson et al., 2010). This and ethnographic evidence for Chumash burning on the mainland (Timbrook et al., 1982) led Anderson et al. (2010) to suggest that the increase in fire during the middle Holocene and even greater increase during the late Holocene may have resulted from Native American burning. Based on analysis of a sedimentary sequence on San Miguel Island and radiocarbon dating, Johnson (1972, 1980) argued that natural fires from lightning strikes were an important component of Channel Island ecology for the last 40,000 yr, well prior to the human era. This is supported by radiocarbon ages of eolianite paleosols from San Miguel Island that range in age from the last glacial to greater than 40 ka (Johnson, 1977). A charcoal record from Arlington Canyon, Santa Rosa Island also demonstrates that fire was important from at least 24,000 yr ago, with no evidence for an increase in fire frequency around 12,900 cal yr BP (Scott et al., 2011). In contrast, charcoal from an ocean core in the Santa Barbara Basin and a different sedimentary record on Santa Rosa Island suggest increased burning at ~12,900 cal yr BP, hypothesized to coincide with a YD impact (Kennett et al., 2008). Because they receive much of their sediments from mainland sources, the Santa Barbara Basin records are not specific to the northern Channel Islands.

Native American settlement on the northern Channel Islands spans roughly the past 13,000 cal yr BP, one of the longest records of coastal human occupation in North America (Johnson et al., 2002; Erlandson et al., 2011a). The number of sites on the islands increases considerably after about 10,000 cal yr BP, with the densest human occupation occurring during the late Holocene, especially after

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about 1500 cal yr BP (Rick et al., 2005). Marine food remains, including shellfish, finfish, marine mammals, and birds, are common in Channel Island archaeological sites throughout the terminal Pleistocene and Holocene. Channel Islanders also used a variety of terrestrial plants since at least the early Holocene (Reddy and Erlandson, 2012).

Characteristics and origins of the red zones

Along a 3 km stretch of coastline on Santa Rosa Island's north shore, Orr and Berger (1966) identified over 100 red zones that were visible in sea cliffs up to 30 m high, with a few also noted on Santa Cruz Island and the southern California mainland. Orr and Berger (1966:1409) characterized the red zones by their "brilliant to dull brick-red appearance" and occurrence as U-shaped pits about 60 cm in diameter or saucers about 3.5 to 5 m in diameter. Often containing charcoal bands, some of the red zones were associated with pygmy mammoth and bird bones, and radiocarbon dates suggested ages from >37,000 to 12,760 cal yr BP (Berger and Orr, 1966; Orr and Berger, 1966). Wendorf (1982:174) added to these descriptions noting that: "fire areas vary in size and shape from small marks 4 or 5 cm wide to elongated lenses several meters in length and as much as a meter in depth." Cushing et al. (1986) suggested that some of the red zones could be the remnants of once continuous bands extending several meters to over 1 km. We have observed some thin lenses of reddened sediment extending more or less continuously for tens of meters, but most of the fire areas we have examined are generally more localized.

Because many of the red zones were considerably older than initial human colonization of the Channel Islands (~13,000 cal yr BP) and the reported association of mammoth and other bones with the red zones was problematic (Wendorf, 1982; Cushing et al., 1986), researchers explored alternative hypotheses that were unrelated to human activities. Two hypotheses remain the dominant explanations for the origins of the red zones: natural fires and groundwater processes. The natural fire hypothesis contends that most of the red zones were the result of natural fires that burned tree stumps and roots, some of which may have overturned and later been exposed by erosion (Wendorf, 1982). This hypothesis is supported by discussions with fire fighters and examination of recently burned stumps, which suggested that natural fires could result in reddening of soils, charcoal concentrations, and similar manifestations as the ancient red zones on the Channel Islands and elsewhere in California (Wendorf, 1982). Johnson et al. (1980) also suggested that the red zones were from natural fires.

Cushing et al. (1986) presented an analysis of sediments, bones, and carbonized plant remains from red zones to test their hypothesis that the red zones were actually "ochreous areas" caused by groundwater processes that resulted in carbonization of plant materials, reddening of soils through iron oxidation, and discoloration of bones. Critical to their argument was the contention that the clay mineral smectite is irreversibly transformed to illite when heated to 200°C or higher. If smectite was present in the red zones, they concluded that they could not be caused by fire (Cushing et al., 1986:210). Cushing (1993) later tried to determine if carbonization of plant materials formed by groundwater or burning were macroscopically different, but this study was inconclusive. Based on XRD analysis of sediments which showed the presence of smectite, along with analysis of bones and charcoal, Cushing et al. (1986:216) concluded that: "many (if not all) of the fire areas of the Channel Islands were formed by microbial and geological processes taking place in groundwater, rather than by thermal events."

Clay mineralogy and the red zones

Our review of the influence of heating on sediment mineralogy suggests that smectite and other clay minerals are affected by exposure to increased temperatures. As Cushing et al. (1986) noted, interlayer water is lost from low- charge phyllosilicates at relatively low temperatures (Grim and Bradley, 1948; Grim, 1953; Harward et al., 1969; Bray et al., 1998; Kolarikova et al., 2005; Ouhadi et al., 2010), but the contention that smectite is irreversibly transformed to illite at 200°C is problematic. The temperature at which smectite structures persist and retain the ability to rehydrate is dependent upon the type and amount of substitution in the crystal lattice. Grim's (1953) review of smectite dehydration demonstrates that Li montmorillonite loses the ability to rehydrate after heating to 105° to 125°C and H or Ca montmorillonite after 300° to 390°C. Na montmorillonite is able to regain some interlayer water after heating to 600°C and "the structure of many montmorillonites persists to temperatures of the order of 800° to 900°C" (Grim, 1953:223). Ouhadi et al. (2010) found that the apparent transformation of smectite to illite upon heating to 200°C was in fact only the loss of interlayer water from the smectite and with rehydration the 10 Å XRD illite peak disappeared and the smectite peak reformed.

In experimental heating of hydroxy-interlayered vermiculites (HIV), Harris et al. (1992) found that irreversible crystal structure collapse from dehydroxylation occurred between 400° and 420°C and that decreases in d-spacing resulting from moderate elevations in temperature were essentially irreversible. The temperature and time necessary for kaolinite dehydration is dependent on crystallinity and particle size (Grim, 1953). Ulery et al. (1996) noted kaolin collapse above 420°C while differential thermal analysis has shown dehydration beginning around 400°C (Ross and Kerr, 1931; Grim, 1953) and DeKeyser (1939) found that kaolinite could be dehydrated completely at 350°C with prolonged heating times. Thermogravimetry indicated HIV dehydroxylation between 400° and 420°C (Harris et al., 1992).

In XRD analysis, structural reorganization of smectites and HIV resulting from heating that does not entirely destroy the mineral structure is expressed as a decrease in d-spacing (peak shift), broadening of XRD peaks, and a loss of peak intensity (Harris et al., 1992; Bray et al., 1998). Ouhadi et al. (2010) noted a marked decrease in smectite peak intensity after heating and rehydration that reflected the temperature to which the sample was heated. Samples heated to 200°C, for instance, showed a greater loss of peak intensity than those heated to 100°C. Their X-ray diffractograms also showed a peak shift that increased with increased temperature (Ouhadi et al., 2010). HIV peak shifts are slight but peak broadening is considerable (Harris et al., 1992). Examining soils from California sites subject to prescribed burns or recent natural fires, Ulery et al. (1996) found that kaolin, HIV, vermiculite, and chlorite were all collapsed or decomposed by the increased temperatures. In burned areas in New Jersey decreases in illite/smectite d-spacing and intensity were the result of loss of interlayer water from phyllosilicates (Reynard-Callanan et al., 2010).

Iron oxides are similarly affected by fire. Transformations through oxidation or dehydroxylation of magnetite, goethite, and ferrihydrite to form maghemite and hematite are common (Schwertmann and Taylor, 1989; Nornberg et al., 2004, 2009). Moore and Reynolds (1997) also noted the alteration of lepidocrocite to maghemite as a result of heating. In experimental fires Nornberg et al. (2009) found that goethite and ferrihydrite were converted to hematite at temperatures higher than 230°C while Dionisio et al. (2009) determined that goethite was still present in samples heated to 250°C and that the transformation takes place at 300°C. Moore and Reynolds (1997) noted the alteration of lepidocrocite to form maghemite between 230 and 280°C while Schwertmann and Taylor (1989) identified heating of pedogenic iron oxides to 300–425°C as a pathway to maghemite formation.

If the Santa Rosa Island red zones are the result of burning, XRD data should show alteration of the phyllosilicate minerals, including: 1) loss of smectite peak intensity and a shift in the smectite peak, 2) an absence

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of kaolinite, and 3) broadening of the HIV peak and decreased peak intensity relative to a control sample. An absence of these changes would suggest that thermal alteration was not responsible for the red zones, and that groundwater processes or another factor are more plausible explanations. These criteria can be evaluated by comparing a control sample from deposits not obviously altered with samples from the red zones.

Materials and methods

Red zones and sediment samples

During fieldwork in 2010 at CA-SRI-512, an archaeological site dated between ~12,300 and 11,500 cal yr BP, we analyzed and sampled six Pleistocene red zones in the vicinity. The first of these, found within the remnants of a paleosol located on the eroding slope below the site, was a roughly 1.5 m wide red zone with a large concentration of charcoal (Fig. 2). Although located within the boundary of CA-SRI-512, this feature exhibited no obvious signs of being created or modified by humans. A 20 × 40 cm wide probe excavated through the red zone to a depth of 50 cm, exposed a 2–4 cm thick red (2.5YR 5/6) layer, a dense 2–3 cm thick charcoal/carbonized plant concentration, and yellowish brown (10YR 5/6) sediments surrounding and below the reddish layer. This excavation also produced numerous bones of the extinct mouse, *Peromyscus nesodytes*, that appeared to come largely from an area that was not as red or obviously altered as other parts of the feature.

We sampled five additional red zones located in the Radio Point area about 100–150 m west of CA-SRI-512. These localities, called RPF1–RPF5 are described in Table 2. RPF1–RPF4 were located across a 50 m exposure in terrestrial sediments that overly marine terrace deposits in roughly the same stratigraphic position, while RPF5 was located in the same terrace but ~4 m above RPF 4 in a stratigraphically younger deposit about 2 m from the top of the terrace.

These five red zones range in size from small (50 × 20 cm), vertically exposed areas like RPF5 to round horizontal exposures like RPF1 to a large (100 × 120 cm) vertical exposure at RPF4 that had been bisected by erosion and gullying (Figs. 3 and 4).

Soils near Radio Point have been mapped as Petrocalcic Palexeralfs by the USDA-NRCS. All of the red zones contained charcoal and were associated with paleosols formed in predominately silt (0.002–0.05 mm) and very fine sand (0.05–0.1 mm) sediments with textures of very fine sandy loam, silt loam, and silty clay loam. These sediments ranged in color from red (2.5YR 5/6) to yellowish brown (10YR 5/6). No animal remains or artifacts were found associated with RPF1–RPF5.

To test the fire versus groundwater origins for these red zones and provide context for our understanding of the terminal Pleistocene human occupation of CA-SRI-512, we collected sediment and carbonized plant samples from the red features and from immediately adjacent areas within the larger feature that were brownish in color (Table 3). Adjacent to RPF3, from the same stratigraphic layer but in an area well outside the red zones, we also collected a control sample of sediments that appeared not to have been thermally altered or modified by groundwater/microbial processes. Carbonized plant remains in the features generally occurred as large clusters (Figs. 2 and 4), but the smaller RPF4 and RPF5 features produced more limited and scattered charcoal.

Macrobotanical analysis and radiocarbon dating

Fragments of charcoal from CA-SRI-512 and each of the other red zones were identified by PaleoResearch Institute, Colorado (Puseman, 2010, 2011; Table 1). Charcoal fragments were broken to expose fresh cross sections of the charcoal. They were then compared to modern and archaeological reference specimens under magnification (320–800 ×).

Charcoal from adjacent to the macrobotanical samples was also selected for radiocarbon dating (Table 2). Seven samples from the six features, including one sample each from RPF1–RPF5 and two samples from CA-SRI-512 were ^{14}C-dated via AMS. One sample from CA-SRI-512 was analyzed by Beta Analytic, Inc. and the other was analyzed by the National Ocean Sciences AMS (NOSAMS) Facility at the Woods Hole Oceanographic Institute. The other five samples were pretreated by Kennett and Culleton at the University of Oregon and then dated at the UC Irvine AMS Facility.

X-ray diffraction analysis

A qualitative analysis of clay mineralogy and iron oxides by XRD was performed on sediment samples from the six features and the control sample. Samples for analysis were pretreated with 30% H_2O_2 to remove organic matter, a sodium hexametaphosphate-sodium carbonate solution was used as a dispersant, and the clay-sized (<2 μm) fraction was separated by repeated centrifuging. Samples to be used for clay mineralogical analysis were divided into two subsets with one saturated with 0.1 M KCl and the other with 0.1 M $MgCl_2$. Oriented mounts for XRD analysis were made using a vacuum filter apparatus (Drever, 1973; Reynolds and Moore, 1997). $MgCl_2$ saturated samples were further treated with 25% ethylene glycol. Clay mineralogical analysis was performed using a Cu tube ($\lambda = 0.154$ nm) from 2° to 30° 2θ. Scans were performed at 25°C on the $MgCl_2$ saturated

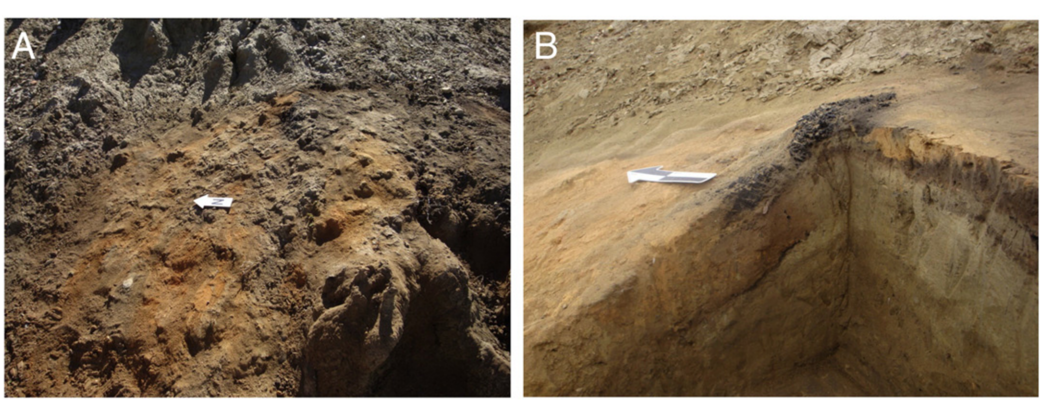

Figure 2. CA-SRI-512 Fire Area: A) Overhead view prior to excavation showing large red zone with 20 cm north arrow for scale (charcoal is in middle top of photo). B) Sidewall view of same red zone after excavation showing charcoal concentration, red zone, and surrounding brownish areas with 20 cm north arrow for scale (photos by T. Rick).

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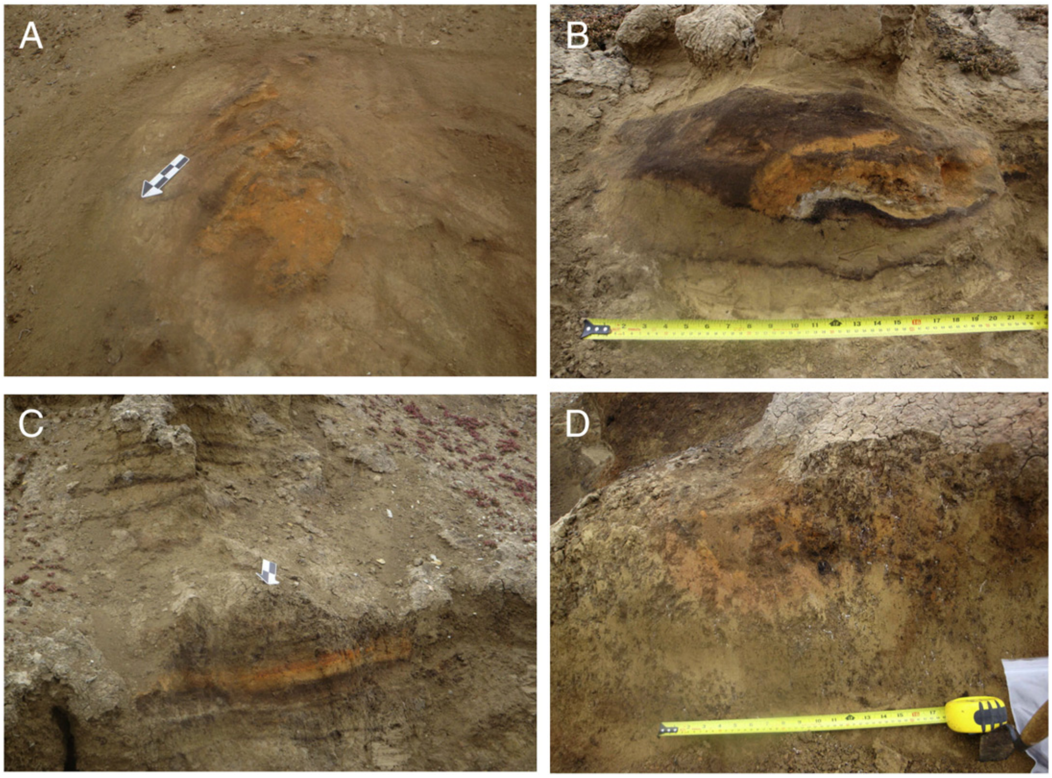

Figure 3. Photographs of four red zones analyzed in this study: A) RPF1 with 20 cm north arrow; B) RPF2 (measuring tape is set to 58 cm); C) RPF4 with 20 cm north arrow; and D) RPF5 (measuring tape is set to 45 cm) (photos by T. Rick).

and ethylene glycol solvated samples and at 25°C, 300°C, and 550°C on the KCl saturated samples.

High-gradient magnetic separation (HGMS) (Schulze and Dixon, 1979) was used to concentrate iron oxides for analysis. The <2 μm fraction to be used for iron oxide analysis was passed through an electromagnetic filter with the power source set to 9v 2.04 amp generating a magnetic field of approximately 2.3 Tesla. The collected magnetic fraction was saturated with 0.1 M $MgCl_2$ and solvated with 25% ethylene glycol. XRD scans were performed from 4° to 60° 2θ.

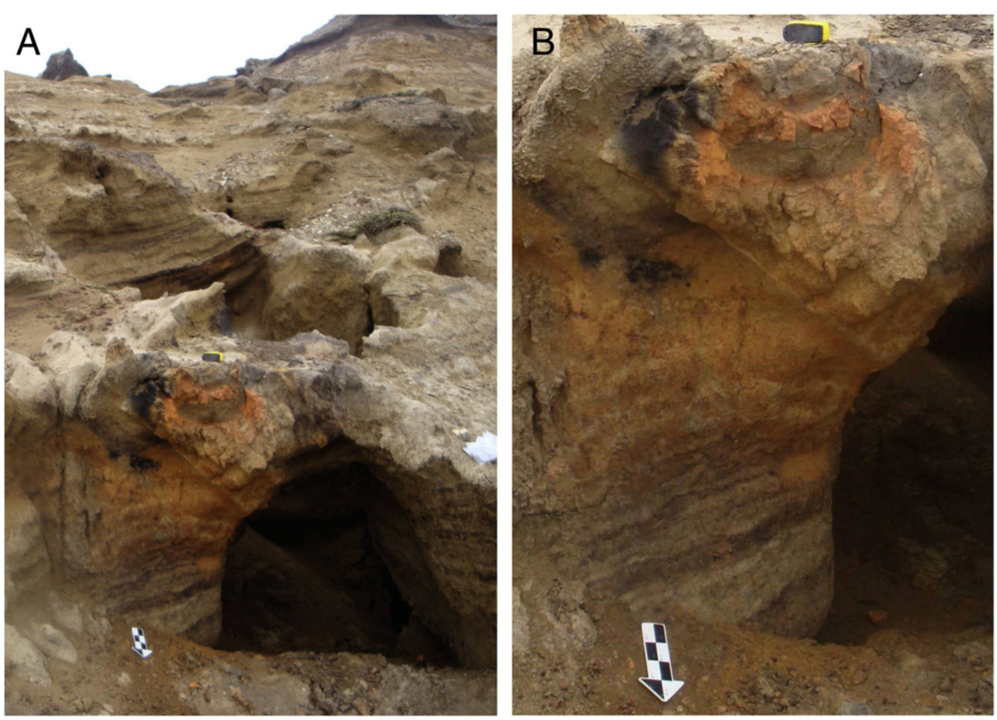

Figure 4. Two different views of the large vertically exposed red zone, RPF3 with 20 cm north arrow for scale. This red zone has one of the larger charcoal concentrations and reddish soil areas. Charcoal identified from this feature was vitrified, suggesting it had been thermally altered (photos by T. Rick).

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Table 1
Descriptions of red zones and macrobotanical remains.

Locality	Dimensions (length × width)	Depth from top of terrace	Macrobotanical remains	Red zone sediment color (dry)	Comments
CA-SRI-512	165 × 150 cm	–	*Ceanothus*	2.5YR5/6	Feature exposed horizontally; *Peromyscus nesodytes* bone concentration at 35 cm just below reddish stain
RPF1	90 × 52 cm	~5 m	*Abies*	2.5YR5/8	Feature exposed horizontally
RPF2	82 × 28 cm	~6–7 m	Cupressaceae	5YR5/8	Exposed vertically with well-defined reddish bands and bands of charcoal
RPF3	110 × 125 cm	~6–7 m	Conifer-vitrified	5YR5/8	Large feature exposed vertically on three sides, charcoal concentrations and reddish area
RPF4	102 × 20 cm	~6–7 m	Unidentified	2.5YR5/8	Vertical exposure with a banded cross section
RPF5	50 × 25 cm	~2 m	Periderm-vitrified	5YR5/6	Small vertical fire feature located in a higher stratigraphic unit than RPF1-4

Results and discussion

Macrobotanical analysis

Macrobotanical analysis of carbonized plant remains from the six Santa Rosa Island red zones suggests that they all result from fire and burning. Although Cushing (1993) noted that few studies examined the differences between groundwater carbonized plant material and charcoal from fire, all the plant remains from the Santa Rosa Island red zones analyzed in this study were identified, compared, and consistent with charcoal. Samples from six late Pleistocene red zones were identified as coming from at least three different trees or shrubs. The sample from CA-SRI-512 was identified as *Ceanothus* (cf. *Ceanothus arboreus*, California lilac) (Puseman, 2010), in part, because spiral or helical thickenings and simple perforation plates found in *C. arboreus* were noted in the radial section of this specimen. *Ceanothus arboreus* is an evergreen shrub or small tree that can grow from 1 to 7 m tall, with a short straight trunk and many spreading branches. It grows today on island ridgetops, rocky slopes, floodplains, chaparral, and in pine forests (Junak et al., 1995). Based on the absence of resin canals, the presence of a distinct growth ring and taxodioid cross field pitting, and comparison to other specimens (e.g., Douglas fir), the sample from RPF1 was identified as the genus *Abies*, a conifer, but the species cannot be determined based on wood anatomy (Puseman, 2011). A sample from RPF2 was identified to the Cupressaceae family of conifers because it had cupressoid cross field pitting and uniseriate or occasionally biseriate rays one to sixteen cells in height, with most of the rays four to eight cells high. The specimen from RPF3 was also identified as a conifer, but this specimen was vitrified, which results in a shiny, glassy appearance that is a result of fusion from heat (Puseman, 2011). The specimen from RPF4 was not identifiable and the specimen from RPF5 consisted of periderm or bark, but was too vitrified for further identification. Researchers agree that vitrification of charcoal is the result of fire, although questions remain about whether it results from fires of high versus low heat or burning old versus green wood (Marguerie and Hunot, 2007; McParland et al., 2010).

Table 2
Radiocarbon data from Radio Point red zones.

Site/ locality	Provenience	Material[1]	Lab #	Age (^{14}C yr BP)	Calendar age (cal yr BP, 1 sigma)
SRI-512	Fire feature on slope below A6, 0–5 cmbs	*Ceanothus* charcoal	Beta-261353	10,090 ± 50	11,820–11,410
SRI-512	Fire feature on slope below A6, 0–5 cmbs	*Ceanothus* charcoal	OS-75147	10,200 ± 45	12,010–11,820
RPF1	10 cmbs removed from horizontally exposed feature	*Abies* charcoal	UCI-84271	17,950 ± 60	21,520–21,330
RPF2	Upper level, 5 cm below surface	Cupressaceae charcoal	UCI-84272	18,390 ± 60	22,180–21,760
RPF3	10 cmbs in dense charcoal concentration	Conifer-vitrified	UCI-84273	19,740 ± 70	23,760–23,460
RPF4	22–25 cmbs, adjacent to sediment sample	Charcoal	UCI-84274	22,480 ± 100	27,560–26,880
RPF5	6 cmbs in upper stratigraphic layer	Periderm-vitrified	UCI-84275	12,820 ± 40	15,480–15,060

1. Beta = Beta Analytic Inc., OS = NOSAMS Lab, Woods Hole Oceanographic Institute, UCI = Keck Carbon Cycle AMS Lab, University of California, Irvine.
2. All dates calibrated using Calib 6.0 (Stuiver and Reimer, 1993; Reimer et al., 2009).

Table 3
Description of XRD samples from the Radio Point red zones.

Sample #	Locality	Field Provenience	Munsell color (moist)[a]	Note
1	RPF5	Upper fire area	7.5YR3/4-10YR3/4	5YR4/6 and charcoal mixed
2	SRI-512	"Brick red" layer: 0-5 cm below surface	7.5YR4/4 5YR4/6	Charcoal
3	RPF3	Next to charcoal concentration, 40–55 cm below surface (cmbs)	7.5YR4/6	
4	SRI-512	Light brownish lens, 10–20 cmbs	10YR3/4	
5	SRI-512	Least amount of possible burning in brownish lens below reddish area, 10–20 cm	10YR3/1	10YR4/6 concentrations of Fe
6	RPF2	Light brown soil with charcoal flecks	10YR4/3	Faint concentrations and depletions of Fe
7	RPF2	Burned reddish feature, 0–7 cm	10YR3/2	10YR4/6 concentrations of Fe
8	RPF2	Reddish soil from below sample 7, 10–18 cmbs	5YR4/6	
9	RPF4	Red soil feature 4–32 cmbs	2.5YR5/8	
10	RPF1	Reddish soil feature	7.5YR4/6	Small pockets of clay
11	Control Sample	Same soil as others but 2.5 m away from RPF3 in clean brownish soil	10YR4/3	

[a] Colors were taken in the lab on moist samples.

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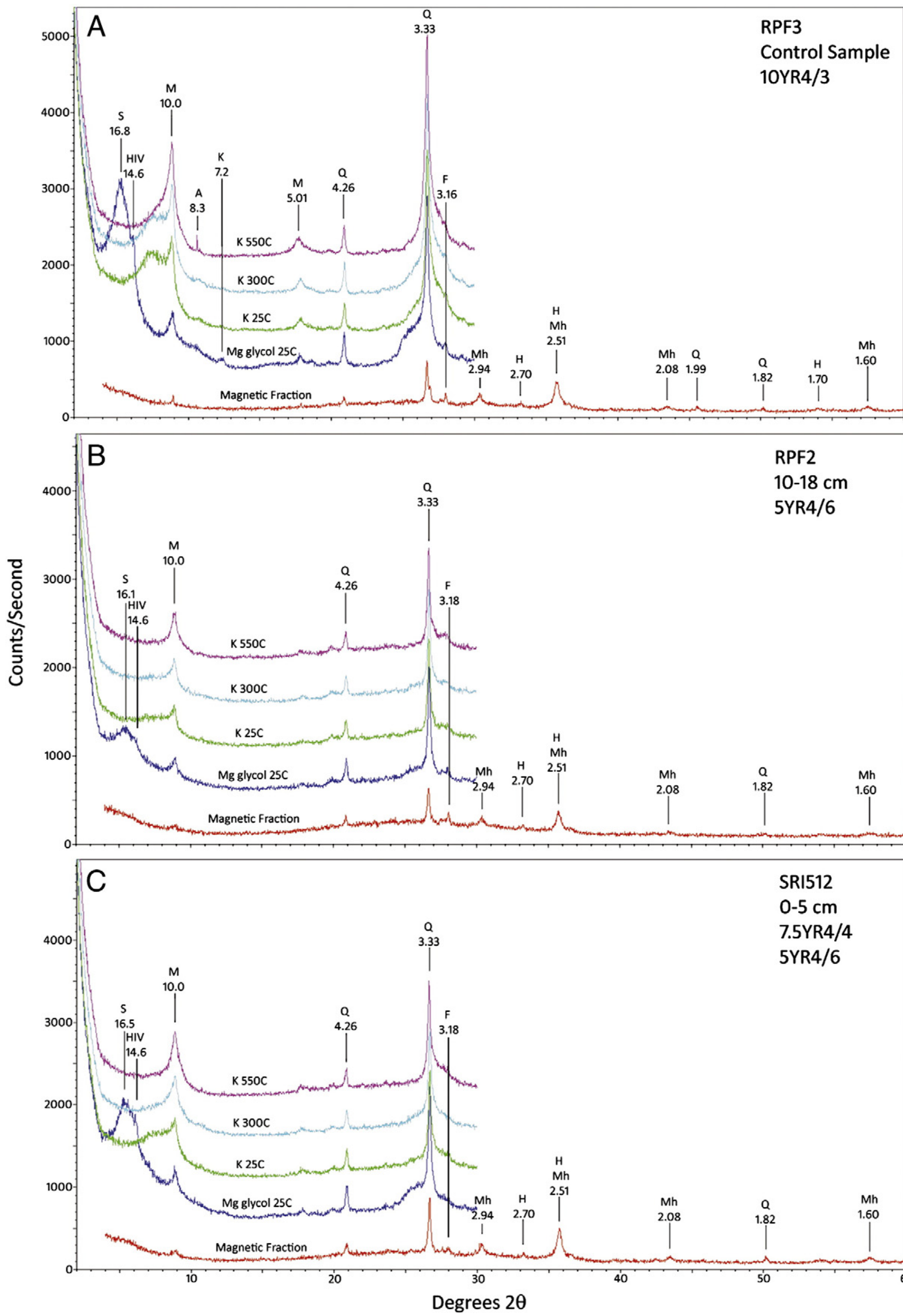

Figure 5. X-ray diffraction scans of <2 μm particles and the Fe oxides concentrated in the magnetic fraction from three soil samples: A. Control sample (sample 11) representing the unburned group of samples; B. RPF2 (sample 8) representing the strongly burned group; and C. CA-SRI-512 (sample 2) representing the burned at a lower temperature or for shorter duration group. S — smectite, HIV — hydroxy-interlatered vermiculite, M — mica, A — amphibole, K — kaolinite, Q — quartz, F — feldspar, Mh — maghemite, H — hematite. B. and C. show decreased smectite d-spacing (peak shift), a decreased peak intensity and broadening, HIV loss of peak intensity and broadening, and loss of kaolinite, relative to A.

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Clay mineralogy and iron oxides

Samples belonging to the first group were those with little or no indication of heating. These included the control sample collected from adjacent to RPF3 (sample 11), and samples from the brownish areas of CA-SRI-512 (samples 4 and 5) and RPF2 (sample 6). Minerals present in samples from this group included smectite, HIV, kaolinite, mica, quartz, and feldspar with trace amounts of amphibole. Figure 5A shows the XRD pattern from the control sample near RPF3. Of this group, the A horizon from CA-SRI-512 (sample 5) had a slightly decreased smectite peak intensity which may result from slight heating or may be a function of the amount of smectite present in the soil.

Samples belonging to the second group were strongly heated. These included those taken from the red areas of RPF1 (sample 10), RPF2 (sample 8), RPF3 (sample 3), and RPF4 (sample 9). Minerals present in this group included smectite, HIV (except for Sample 3), mica, quartz, and feldspar with trace amounts of amphibole. Figure 5B shows the XRD pattern for sample 8. In this group of samples, the smectite peak (Mg saturated and ethylene glycol solvated) had shifted to 15.3–16.2 Å from the 16.8 Å smectite peak in the control (sample 11). Peak intensities for smectite (Mg glycol) and HIV (Mg glycol and K saturated, 25°C, 300°C) decreased markedly, and peaks broadened relative to the control (sample 11). No kaolinite was present in samples from this group. Loss of smectite peak intensity, the shift in the smectite peak, and the broadening of the HIV peak were consistent with heating of soils and partial reorganization of the mineral structures. The absence of kaolinite and greatly decreased (or absent in the RPF3 sample) HIV suggest that sediments in the features were subjected to temperatures in the range of 400°C (Ross and Kerr, 1931; DeKeyser, 1939; Grim, 1953; Harris et al., 1992; Ulery et al., 1996.

Samples in the third group showed evidence of heating but less so than those in the second group, suggesting these may have been heated at lower temperatures or for shorter duration. Samples from RPF2 (sample 7), RPF5 (sample 1), and CA-SRI-512 (sample 2) had smectite peaks shifted to 16.5 Å (Mg glycol) with broadening and decreased intensity. These samples had HIV peaks that were broadened with decreased intensity compared to the control (Fig. 5C). Unlike the samples from the second group, small amounts of kaolinite were present in samples in this group. The presence of kaolinite and less pronounced shift in the smectite peak suggest that heating of these samples was to lower maximum temperatures and/or for shorter durations than samples from the second group. The three samples in this group were either smaller and less well-defined (samples 1 and 7) or from reddish deposits (sample 2).

Iron oxides were less useful than phyllosilicates in addressing the genesis of the fire features. Only hematite and maghemite were present in samples. While the presence of ferrihydrite, lepidocrocite, or goethite—iron oxides and oxyhydroxides favored in low temperature environments—in reddened samples would have indicated formation processes other than heating (Nornberg et al., 2004, 2009), their absence in the control and other 'unburned' samples prevents iron oxide analysis from supporting the hypothesis that reddened features were the result of burning. It is possible, even likely, based on phyllosilicate assemblages, that hematite and maghemite in samples from reddened areas were a function of burning, but the reason for the absence of goethite, lepidocrocite, and ferrihydrite in samples from brownish areas is unclear.

Peromyscus nesodytes *bones*

A few of the *Peromyscus nesodytes* (giant island deer mouse) bones recovered from the CA-SRI-512 fire feature are whitish to gray-black in color, similar to calcination that results from burning (Lyman, 1994:384–392). Other mouse bones from this feature were stained brown to black, but it is unclear if these were burned since staining of bone can result from a variety of processes (Cushing et al., 1986) and other archaeological *P. nesodytes* bones we have observed are often stained dark brown to black and do not appear to be burned.

Chronology

Seven radiocarbon dates provide a chronology for the six red zones from ca. 27,500 to 11,400 cal yr BP (Table 2). RPF1–RPF 4 are the oldest with ages ranging from 27,560 to 21,330 cal yr BP. Other red zones visible in even older deposits exposed in sheer sea cliffs and gullies in the Radio Point area suggest even older fire events. RPF5 is in a deposit 2 m above RPF1–RPF4 and is younger, dating to ~15,480–15,060 cal yr BP. The two CA-SRI-512 radiocarbon samples overlap at 1 sigma and suggest an age of ~12,010–11,410 cal yr BP. The CA-SRI-512 fire area is the only one that dates to within the known era of human occupation on the Northern Channel Islands (Johnson et al., 2002; Erlandson et al., 2011a). The age of the CA-SRI-512 red zone also corresponds with the calibrated age range of several ^{14}C dates from the terminal Pleistocene archaeological deposits at the site (Erlandson et al., 2011a, 2011b), but no hearths or clear evidence of an anthropogenic origin for this fire feature were present. With a substantial and roughly contemporary human campsite located on the terrace immediately above the fire feature, however, it is conceivable that the fire was of cultural origin and represented either an intentional or accidental burning of the surrounding landscape.

Conclusions

Analysis of sediments and macrobotanical remains from six Pleistocene red zones on Santa Rosa Island supports the hypothesis that these features were the result of thermal alteration, presumably from natural fires, rather than from groundwater processes. XRD data from eleven samples, including some from the red zones, adjacent yellowish brown paleosols, and a control sample, illustrate that some of the reddened features and a few adjacent soils were burned, possibly at temperatures near 400°C. Other paleosols located away from the reddish areas, including our control sample do not appear to have been thermally altered. Macrobotanical analysis of charcoal also supports the natural fire origin for these features since the charcoal was comparable to modern, burned specimens and two of the remains were vitrified, a process that results from thermal alteration (Marguerie and Hunot, 2007).

Our research supports the contention of other scholars that many of the Channel Island red zones are combustion features related to fire and thermal alteration. These include radiocarbon dating and stratigraphic observations by Johnson et al. (1980), Wendorf's (1982) investigation of modern natural fires and the effects of this thermal alteration on soils, and Orr and Berger's (1966) pit-fire experiments. Our study adds to this earlier research by providing XRD data and macrobotanical analysis that support the natural fire origins of these red zones. While it is possible that other red zones, especially those located near springs and other water sources, may result from microbial activities operating in groundwater (Wendorf, 1982; Cushing et al., 1986), the majority of the red zones on Santa Rosa Island we have observed are consistent in appearance and structure with the six Radio Point features, suggesting that they result primarily from exposure to natural fires.

The presence of fire events between 27,500 and 11,400 cal yr BP are consistent with Scott et al.'s (2011) fire record for Arlington Canyon, Santa Rosa Island, which suggests there were surface fires through coniferous woodlands beginning at least 24,000 cal yr BP that may have burned at temperatures less than 500°C. This is supported by ~40,000-yr-old fire events on San Miguel Island (Johnson, 1980) and the original chronology of >37,000 yr for the Santa Rosa Island fire features (Orr and Berger, 1966). Since only one of the red zones, the ~12,000-yr-old feature at CA-SRI-512,

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occurred during the era of human occupation, the earlier fires were likely the result of lightning strikes.

Throughout North America vegetation communities and fire regimes changed dramatically at the close of the Pleistocene and were perhaps influenced by climate change, megafaunal extinction, human activities, and possibly a YDB extraterrestrial impact (Kennett et al., 2008; Gill et al., 2009; Marlon et al., 2009; Pinter et al., 2011). The age of our six red zones and stratigraphic observations in the Radio Point area do not show a strong increase in fire at the YDB or a clear association with the extinction of island mammoths about 13,000 cal yr BP (Agenbroad et al., 2005). We caution that additional dating and analysis of island red zones is necessary to better evaluate any potential increases in fire between ~14,000 and 12,900 cal yr BP. It remains possible that the fire feature at CA-SRI-512 was created by a human-started fire since it is located at an archaeological site where the age of the human occupation and the fire feature overlap. The presence of fire features well prior to human colonization, however, suggests that natural fires were an important component of late Pleistocene Channel Island ecology long before the arrival of humans. Future XRD analysis of soils and radiocarbon dating of red zones should prove fruitful in enhancing our understanding of island fire history and possible changes associated with the extinction of island pygmy mammoths and the arrival of humans.

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