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EVIDENCE OF REPEATED WILDFIRES PRIOR TO HUMAN OCCUPATION ON SAN NICOLAS ISLAND, CALIFORNIA

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ABSTRACT.—Understanding how early humans on the California Channel Islands might have changed local fire regimes requires a baseline knowledge of the frequency of natural wildfires on the islands prior to human occupation. A sedimentary sequence that was recently discovered in a small canyon on San Nicolas Island contains evidence of at least 24 burn events that date to between ~37 and 25 ka (thousands of calibrated ^{14}C years before present), well before humans entered North America. The evidence includes abundant macroscopic charcoal, blackened sediments, and discrete packages of oxidized, reddish-brown sediments that are similar in appearance to sedimentary features called "fire areas" on Santa Rosa Island and elsewhere. Massive fine-grained sediments that contain the burn evidence are interpreted as sheetwash deposits and are interbedded with coarse-grained, clast-supported alluvial sediments and matrix-supported sands, pebbles, and cobbles that represent localized debris flows. These sedimentary sequences suggest that the catchment area above our study site underwent multiple cycles of relative quiescence that were interrupted by fire and followed by slope instability and mass wasting events. Our ^{14}C-based chronology dates these cycles to well before the arrival of humans on the Channel Islands and shows that natural wildfires occurred here, at a minimum, every 300–500 years prior to human occupation.

RESUMEN.—Entender cómo los primeros habitantes humanos de las Islas del Canal de California podrían haber cambiado los regímenes de incendios locales, requiere de un conocimiento básico de la frecuencia de incendios forestales naturales en las islas antes de la ocupación humana. Una secuencia de sedimentación que se descubrió recientemente en el pequeño cañón de la Isla de San Nicolás contiene pruebas de al menos 24 incendios que datan de entre ~37 y 25 ka (miles de calibrados ^{14}C años antes del presente), mucho antes de que los humanos llegaran a Norteamérica. Las pruebas incluyen abundantes carbones macroscópicos, sedimentos carbonizados y paquetes discretos de sedimentos oxidados de color rojo-marrón que se parecen a los rasgos sedimentarios llamados "áreas de incendio" de la Isla Santa Rosa y otros lugares. Enormes sedimentos de grano fino que contienen pruebas de incendios se interpretan como depósitos de erosión laminar, y están intercaladas con sedimentos aluviales, apoyados por clastos de grano grueso y con arenas, guijarros y rocas soportados por la matriz, que representan corrientes de sedimentos localizados. Estas secuencias sedimentarias sugieren que el área de captación del sitio de estudio sufrió múltiples ciclos de relativa inactividad interrumpidos por el fuego y seguidos por inestabilidad de la ladera y eventos de remoción en masa. Nuestra cronología basada en ^{14}C, sitúa con certeza estos ciclos mucho antes de la llegada de humanos a las Islas del Canal, y demuestra que ocurrieron incendios forestales naturales, como mínimo, cada 300–500 años antes de la ocupación humana.

Sedimentary charcoal is relatively common in the Quaternary record on the California Channel Islands. Previous researchers have found charcoal in paleosols, eolian and alluvial sequences, and sediment cores dating to the late Pleistocene and Holocene on Santa Rosa, San Miguel, and Santa Cruz islands, among others (Orr 1968, Johnson 1977, Cole and Liu 1994, Anderson et al. 2009, Pinter et al. 2011b, Scott et al. 2011). For decades, researchers have been interested in understanding fire regimes on the Channel Islands and the role early humans might have had in using fire to transform the island landscapes (Orr 1968, Kennett et al. 2008, Pinter et al. 2011a, Erlandson et al. 2012, Rick et al. 2012). However, assessing the role that humans have had in the fire history of the islands is made difficult by the fact that both natural (lightning-induced) and anthropogenic fires leave behind similar evidence in the geologic record, especially during times when human populations are relatively low.

On mainland North America, humans have used fire since at least the late Pleistocene to clear land for cultivation, remove underbrush, drive or trap game, and alter plant communities (Greenlee and Langenheim 1990, Keeley 2002, Bowman et al. 2009). Evidence for such activities goes back even further in time in

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Fig. 1. Reference maps: **a,** location of San Nicolas Island (denoted by red box), off the coast of California; **b,** topography of San Nicolas Island (the catchment area for Chukar Canyon includes a portion of the >250-m area near the center of the island); **c,** site location and local topography for the Chukar Canyon section.

Africa, Europe, Asia, and Australia, where evidence of fire in the geologic record often coincides with the onset of human occupation (Brown et al. 2009, Mooney et al. 2011, Roebroeks and Villa 2011, Archibald et al. 2012, Berna et al. 2012). Thus, in ecosystems that are susceptible to burning but where ignition sources are limited (such as a low-relief island in a Mediterranean climate), the arrival of humans could potentially create a significant change in the local fire regime.

Today, low-lying areas in coastal southern California have one of the lowest lightning-induced fire frequencies in North America due to a general lack of convective storms in the summer and high fuel-moisture content in the winter (Junak et al. 1995, Keeley 2002). In San Diego County, for example, the Bureau of Land Management's Automated Lightning Detection System has recorded, on average, only one lightning strike per square kilometer per decade in areas below ~200-m elevation, with only 2%–5% of those strikes resulting in wildfires (Minnich et al. 1993, Wells and McKinsey 1995). In the recent geologic past, particularly during the late Pleistocene, cooler temperatures and increased moisture would have limited the number of natural fires even more (Heusser 1995, Daniau et al. 2012). Therefore, California's coastal region and the Channel Islands may have been especially sensitive to the introduction of a novel ignition source when humans first arrived. Physical and chronologic evidence from Arlington Canyon on Santa Rosa Island shows that humans have been present on the islands since at least 13 ka (thousands of calibrated ^{14}C years before present; Orr 1968, Johnson et al. 2002, Stafford et al. 2008). Thus, to determine the frequency of natural wildfires on the islands, we must examine evidence of fire in sediments that date to before this time period (Bowman et al. 2011).

Charcoal from the Channel Islands has been recovered from Holocene-age sediment in cores taken on Santa Rosa Island (Cole and Liu 1994, Anderson et al. 2009), and isolated fragments of charcoal dating to the late Pleistocene have been reported from Santa Rosa Island (Orr 1968, Pinter et al. 2011b, Scott et al. 2011) and San Miguel Island (Johnson 1977). Farther afield, charcoal has been recovered from core ODP 893 in the Santa Barbara Basin, although this finding probably reflects burn events on the California mainland more than the islands themselves (Heusser and Sirocko 1997). Thus far, there have not been any published reports of a continuous sequence of late Pleistocene sediments anywhere on California Channel Islands that contains charcoal, spans several centuries or millennia and dates to >13 ka.

In this study, we describe a sedimentary sequence that was recently discovered in a small canyon on the north side of San Nicolas Island. The sequence contains abundant charcoal, spans several millennia, and dates to well before the arrival of humans. It also contains several discrete packages of discolored sediments that are consistent with fire areas that have been documented on Santa Rosa Island, San Miguel Island, Santa Cruz Island, and, to a lesser extent, mainland California (Orr and Berger 1966, Orr 1968). Combined, these features provide an unusual opportunity to quantify the frequency of natural wildfires on San Nicolas Island and establish a baseline for evaluating the impact of anthropogenic fires during the early stages of human occupation on the Channel Islands.

STUDY AREA

San Nicolas Island is a small (~58-km^2), remote island located approximately 100 km from mainland California (Fig. 1a). As one of 8 islands that compose the California Channel Islands, San Nicolas Island is separated from Santa Barbara Island, its nearest neighbor, by 45 km of open ocean. Notably, San Nicolas Island was not connected with the other islands or the mainland during the late Pleistocene, even when sea level was ~90 m lower than modern during the Last Glacial Maximum (Muhs et al. 2012). The island is relatively low and flat (the maximum elevation is only 277 m asl), and bedrock consists primarily of Eocene marine sandstones and siltstones, with minor amounts of interbedded conglomerate and pebbly mudstone (Vedder and Norris 1963). Numerous marine terraces are present between the modern shoreline and the upper reaches of the island, reflecting episodes of tectonic uplift that have occurred for at least the past half million years (Muhs 1985, Muhs et al. 2012).

Deeply incised canyons drain the outer parts of the island, including a canyon on the north side that we refer to informally as "Chukar Canyon" because of the large number of partridges (*Alectoris chukar*) that were present during each of our site visits. The catchment area of Chukar Canyon represents one of the largest drainages on the island and includes a portion of the island's highest mesa-like region: a broad, nearly flat landscape dominated by old marine terraces and located in the central part of the island (Fig. 1b). Vegetation in the catchment area today consists largely of coastal scrub, sparse grassland, and abundant tickseed (*Coreopsis;* Junak et al. 1995).

Chukar Canyon is incised into Eocene bedrock approximately 1 km south of the site before it descends from the mesa's edge, cutting through alluvium and a 100-ka marine terrace just above the study site (Muhs et al. 2012). Adjacent to a U.S. Navy facility outbuilding, resistant bedrock forces the drainage to turn east/southeast at a sharp angle before redirecting northward and ultimately reaching the Pacific Ocean (Fig. 1c). At this bend, a ~5-m thick sedimentary sequence that contains abundant macroscopic charcoal, blackened sediments, and discrete packages of discolored red and dark brown sediments is preserved in the canyon walls (Fig. 2). After working in Chukar Canyon, we surveyed every canyon of significant size on San Nicolas Island (>35 in all) but did not find either a similar package of alluvial sediments or clear evidence of repeated fire events in any of the other canyons.

METHODS

In the field, we set up a 1 × 1-m grid over sediments exposed in Chukar Canyon for description and sampling purposes. Some of the sediments were covered or obviously slumped, but most were well exposed and in their original depositional positions. We identified at least 24 layers that we called "burn zones" based on darkening or discoloration of the

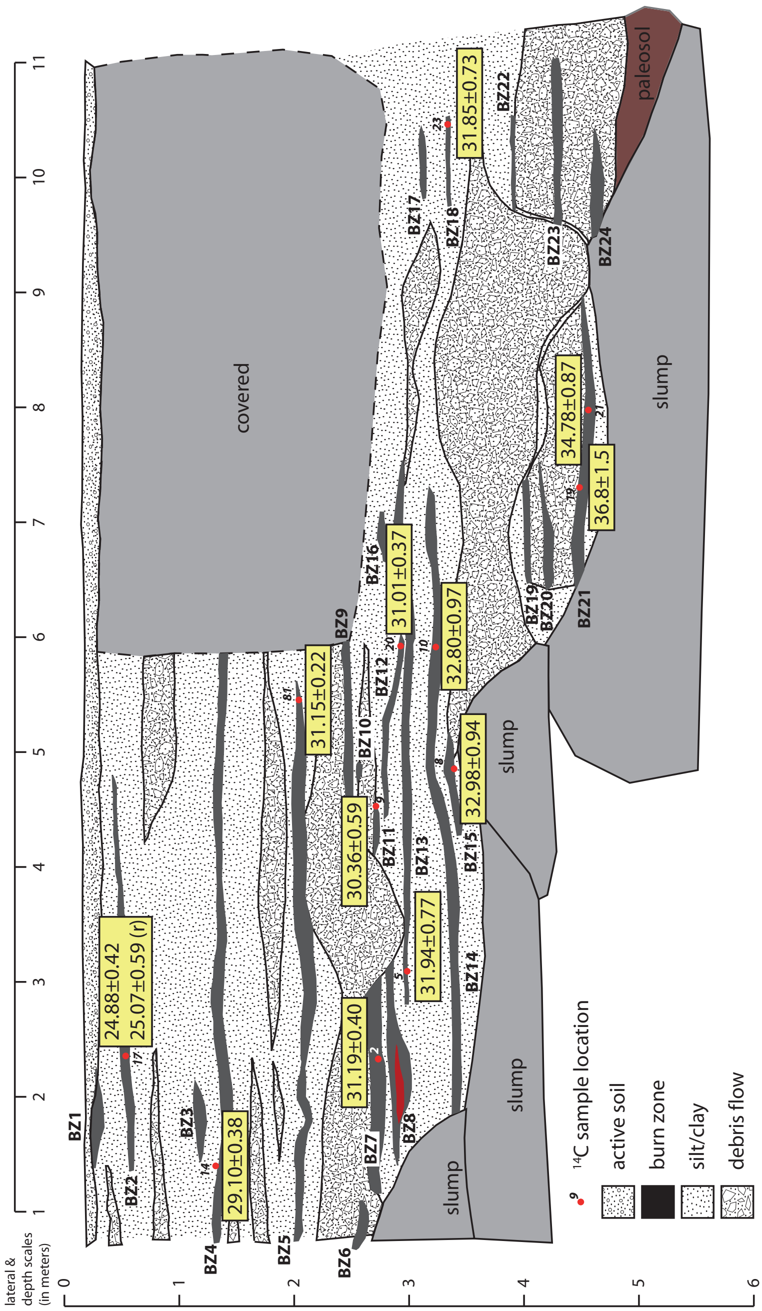

Fig. 2. Stratigraphy of the Chukar Canyon section. Ages in the yellow boxes are given in ka (thousands of calibrated ^{14}C years before present). Burn zone numbers are shown in bold (marked BZ), and sample numbers are shown in italics.

sediments along with macroscopic fragments of charcoal associated with many of the discolored zones. Charcoal was picked from several of the burn zones in the field and was submitted to the U.S. Geological Survey's radiocarbon laboratory in Reston, Virginia, for radiocarbon (^{14}C) dating. There, charcoal samples were subjected to the standard acid-base-acid (ABA) treatment and were combusted to CO_2 under vacuum in the presence of CuO and Ag.

The resulting CO_2 was split into 2 aliquots. One aliquot was converted to graphite by using an iron catalyst and the standard hydrogen reduction process and was submitted to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory for AMS ^{14}C analysis. The second aliquot was submitted for $\delta^{13}C$ analysis to correct the measured ^{14}C activity for isotopic fractionation. All ^{14}C ages were calibrated using the IntCal13 data set and CALIB 7.0 (Stuiver and Reimer 1993, Reimer et al. 2013). Ages are presented in thousands of calibrated ^{14}C years BP (Before Present; 0 yr BP = 1950 AD), and uncertainties are given at the 95% (2σ) confidence level.

We also collected samples of sediment from within and adjacent to the burn zones for clay mineralogy to determine whether these zones were related to fire events. If the sediments sampled were heated by fire during burial, for example, clays that are sensitive to high temperatures (e.g., smectite and kaolinite) would be either absent or present in lower concentrations than in the adjacent, unheated host sediment (Carroll 1970). In the laboratory, clays (<2 μm) were separated by sedimentation, after removal of organic material and carbonates with hydrogen peroxide and 10% HCl, respectively. At least 2 aliquots of each clay sample were then analyzed by X-ray diffraction (XRD) at the U.S. Geological Survey in Denver, Colorado. One aliquot was analyzed successively (1) in an air-dry state, (2) after glycolation, and (3) after heat treatment (550 °C for 1 h). A second aliquot was analyzed after air drying and Mg saturation to determine whether vermiculite was present in any of the samples—it was not. We followed Moore and Reynolds (1989) for identification of clay minerals.

In addition to identifying clay minerals present in the Chukar Canyon sediments, the XRD data were used to conduct a semiquantitative analysis of the clay mineralogy based on a technique developed by H.D. Glass at the Illinois State Geological Survey and later modified by Hallberg et al. (1978). The method uses the difference between the counts per second (CPS) on the X-ray diffractogram and a logarithmic baseline curve. To reduce electronic noise effects and incorporate the maximum possible signal, we used a 5-point running mean on the diffractogram data, which corresponds to a 2θ range of ±0.04°. The CPS data of the glycolated aliquot were taken from the expandable clay (smectite) peak (5.2°, 2θ, 17 Å), the mica/illite peak (8.8°, 2θ, 10 Å), and the kaolinite-plus-chlorite peak (12.4°, 2θ, 7.1 Å) and were calculated as follows:

E (expandables) = CPS at 5.2° 2θ
I (mica/illite) = 3 × CPS at 8.8° 2θ
K (kaolinite plus chlorite) = 2 × CPS at 12.4° 2θ
T (total) = E + I + K

Two lines of evidence indicated that chlorite was absent from the Chukar Canyon sediments: (1) the 12.4° 2θ peak collapsed after heating to 550 °C, and (2) we did not observe a significant peak at 18.7° 2θ. Thus, we interpret the 12.4° 2θ peak to represent only kaolinite in the samples analyzed here.

Finally, clays recovered from 2 samples, BZ8-3 and BZ8-4, were selected for step-heating experiments to determine the highest temperature the sediments were subjected to during burial. We reasoned that if the smectite or kaolinite peaks remained unchanged during a particular temperature step, the sediments could have been heated to that temperature at some time in the past. Clay samples in these experiments were analyzed by XRD after they were glycolated and heated successively at 100 °C increments between 150 °C and 550 °C for 1 h per step. Counts per second (CPS) were measured in 0.02° intervals at all temperature steps.

RESULTS

Observational Data

Fine-grained sediments in the Chukar Canyon sequence are composed predominantly of massive yellowish brown (10YR 5/4 to 5/6) silt and clay, with small amounts of subangular, fine-to-medium sand. These units are, on average, ~25–50 cm thick and contain abundant secondary carbonate and other salts filling small fractures and root voids that are prevalent throughout the section. Secondary carbonate is especially concentrated in the upper third of the exposed sediments. Based on the presence of abundant root voids, the sorting and small grain size of the sediments, and the local surface topography, we interpret the fine-grained units to be sheetwash deposits that formed in vegetated, low-energy systems.

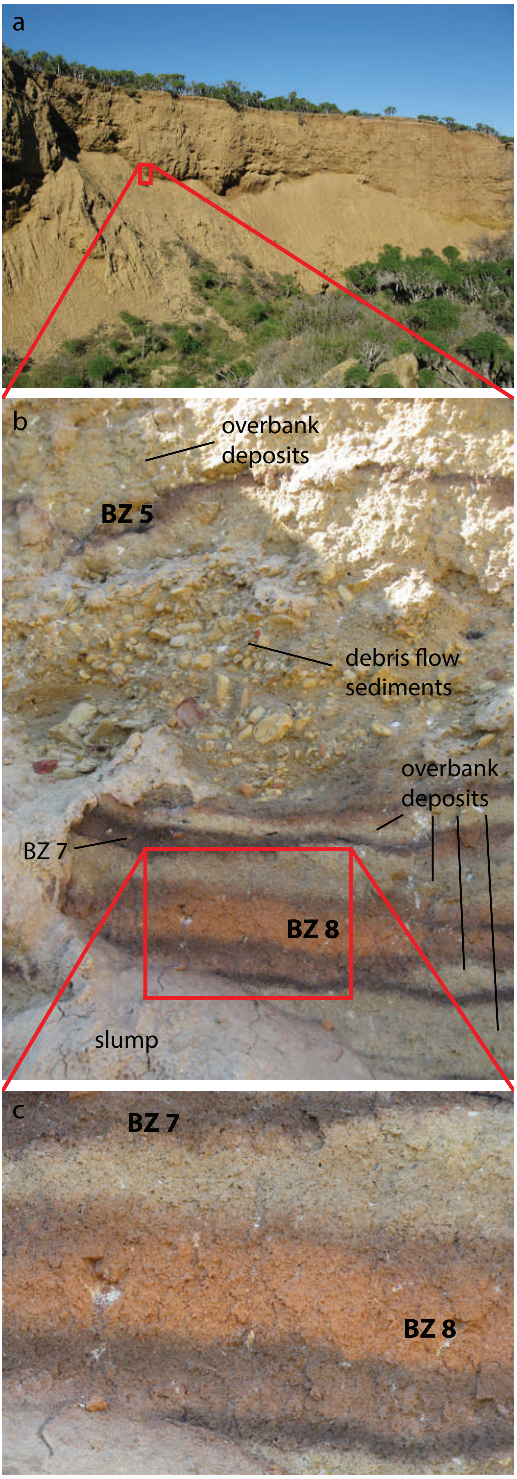

Fig. 3. Photographs of the Chukar Canyon sedimentary sequence: **a,** looking west (cliff face is ~8 m high); **b,** close-up showing different sedimentary facies near the middle of the exposure (field of view is ~1 m high); **c,** extreme close-up of burn zone BZ8 (~10 cm thick). See Fig. 2 for stratigraphic position. Note that the texture, sorting, and grain size of the fine-grained sediments do not change across the color gradient, suggesting the discoloration occurred in situ.

Interbedded with these fine-grained deposits are discrete units up to ~1 m thick that are coarse grained and poorly sorted. Some of the coarse units are clast supported, which we interpret as high-energy alluvial deposits; whereas others are matrix supported, which we interpret as localized debris flows (Fig. 3). In both types of deposits, the large clasts are subangular to subrounded, range up to 3–5 cm in diameter, and are composed of the local Eocene sandstones and siltstones. Both are present in clearly defined channels and exhibit sharp-to-clear contacts with the adjacent fine-grained sediments.

The 24 burn zones that we identified in Chukar Canyon were all contained within the fine-grained facies described above. The zones are lens-shaped or elongated and horizontal to subhorizontal, and they range from ~20 cm to nearly 5 m across. The burn zones exhibited the same field texture and grain size as the adjacent, unmodified sediments. Moreover, the colors of the burn zones were dark reddish brown (5YR3/3) to reddish brown (5YR4/4) near their centers, and graded into lighter, less oxidized colors toward their edges, then transitioned entirely into the yellowish-brown (10YR5/6) host sediment. Combined, these features suggest that the burn zones were formed in situ rather than as a result of processes operating upstream followed by deposition at the site. Burn zone 8 (BZ8) was particularly unusual in that it exhibited a ~5-cm thick lens of yellowish-red (5YR5/8) sediments surrounded by dark-reddish brown (5YR3/3) sediments (Fig. 3c), a combination that is nearly identical in appearance to some of the fire areas described on Santa Rosa Island first by Orr (1968, his Fig. 26) and later by Rick et al. (2012, their Fig. 3c).

Although we did not observe any discrete layers or beds of charcoal, large (5–25-mm) fragments of disseminated charcoal were common in the fine-grained facies (Fig. 4). Nearly all of the charcoal was found in association with burn zones, although a few of the large pieces were found in unmodified host sediment. Notably, we did not observe any microscopic charcoal in the fine-grained sediment. The reason for the presence of macroscopic

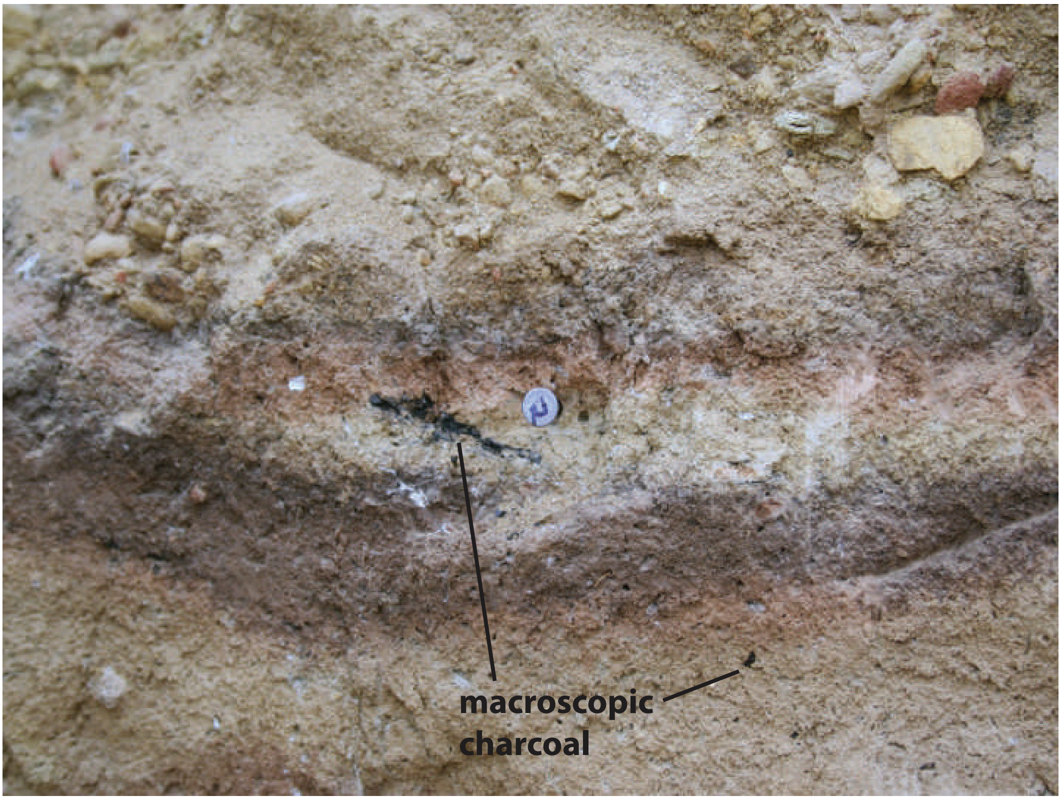

Fig. 4. Photograph showing in situ macroscopic charcoal. Diameter of nail head shown is ~8 mm.

charcoal and absence of microscopic charcoal is unclear but may be due to variable effects of oxidation processes on different sizes of charcoal (large versus small; Cohen-Ofri et al. 2006, Ascough et al. 2010), differences in the preservation potential of the various types of burned vegetation (grass, bushes, trees; Scott 2010, Ascough et al. 2011), or other factors beyond the scope of the current investigation.

^{14}C Analysis

Our calibrated ^{14}C ages (n = 13) range from 24.88 ± 0.42 ka to 36.8 ± 1.5 ka for samples collected at depths of 0.5 and 4.5 m, respectively, and largely maintain correct stratigraphic order (Table 1; Fig. 2). The ages are consistently older with depth even when samples are closely spaced vertically, which occurrence is remarkable considering the disproportionately large effect that small amounts of contamination can have on the measured ^{14}C activities in older samples (Bird et al. 1999, Pigati et al. 2007). As a check of internal consistency, sample SNI1-17 was analyzed twice (in May and September 2010) and yielded ages that are statistically indistinguishable (24.88 ± 0.42 ka and 25.07 ± 0.59 ka). Thus, we are confident that the ages presented here are robust and show little effects of secondary contamination. The calibrated ages show that the section at the base of Chukar Canyon dates to the latter part of marine isotope stage (MIS) 3 and that sedimentation continued into early MIS 2.

Clay Mineralogy

Smectite and kaolinite are known to be sensitive to high temperatures (Carroll 1970) and, therefore, can be used to evaluate whether sediments have been subjected to fire events during burial. Lower concentrations of these clays in suspected burn zones than in the adjacent host sediment would support the hypothesis that the burn zones were indeed a product of fire. In contrast, if smectite and kaolinite concentrations within suspected burn

TABLE 1. Summary of sample information, ^{14}C ages, and calibrated ages.

Sample #	Lab #	AMS #	Material dated	Burn zone	$\delta^{13}C$ (‰ vpdb)	^{14}C age (^{14}C ka BP)	Age (cal ka BP)[a]	P[b]
SNI1-17	WW-7858	CAMS-147418	charcoal	2	–26.0	20.67 ± 0.14	24.88 ± 0.42	1.00
SNI1-17 (rerun)	WW-8061	CAMS-149133	charcoal	2	–25[c]	20.85 ± 0.23	25.07 ± 0.59	1.00
SNI-14	WW-8015	CAMS-148513	charcoal	4	–23.0	25.05 ± 0.16	29.10 ± 0.38	1.00
SNI-81	WW-8161	CAMS-149870	charcoal	5	–23.0	27.19 ± 0.16	31.15 ± 0.22	1.00
SNI1-2	WW-7853	CAMS-147411	charcoal	7	–22.0	27.24 ± 0.30	31.19 ± 0.40	1.00
SNI1-9	WW-7856	CAMS-147416	charcoal	11	–22.6	26.21 ± 0.26	30.36 ± 0.59	1.00
SNI1-20	WW-7860	CAMS-147420	charcoal	12	–22.9	26.95 ± 0.29	31.01 ± 0.37	1.00
SNI1-5	WW-7854	CAMS-147412	charcoal	13	–23.3	27.93 ± 0.33	31.94 ± 0.77	1.00
SNI1-10	WW-7857	CAMS-147417	charcoal	14	–22.7	28.86 ± 0.37	32.80 ± 0.97	1.00
SNI1-8	WW-7855	CAMS-147413	charcoal	15	–21.6	29.03 ± 0.37	32.98 ± 0.94	1.00
SNI1-23	WW-7862	CAMS-147422	charcoal	18	–22.3	27.84 ± 0.32	31.85 ± 0.73	1.00
SNI1-21	WW-7861	CAMS-147421	charcoal	21	–25.6	30.79 ± 0.47	34.78 ± 0.87	1.00
SNI1-19	WW-7859	CAMS-147419	charcoal	21	–24.6	32.55 ± 0.58	36.8 ± 1.5	1.00

[a]Calibrated ages were calculated using CALIB v. 7.0., IntCal13.14C data set; limit 50.0 calendar ka BP. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are calculated as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater (reported at the 95% confidence level; 2σ).
[b]P = probability of the calibrated age falling within the reported range as calculated by CALIB.
[c]$\delta^{13}C$ value not measured.

zones are identical to those in the host sediment, then other processes would have to be considered.

At Chukar Canyon, smectite and kaolinite abundances decrease across the profiles of BZ8 and BZ5 such that the lowest concentrations are found in samples taken from within the burn zones and the highest concentrations are in samples collected in the adjacent host sediment (Fig. 5). The kaolinite abundances show the greatest decrease (~9%) in the yellowish red sediments at BZ8 (sample BZ8-3) compared to the host sediments. The net decrease of smectite and kaolinite is also readily apparent in the concomitant relative increase in mica/illite abundances.

The step-heating results of samples BZ8-3 and BZ8-4 also show patterns that implicate fire as the source of discoloration of the burn zones (Fig. 6a, b). After glycolation and heating, the X-ray diffractogram for sample BZ8-3 shows a clear decrease in the 5.2° 2θ smectite peak after heating to only 150 °C (Fig. 6c), whereas sample BZ8-4 shows a decrease in the smectite peak after heating to 250 °C (Fig. 6d). The diffractogram patterns of both samples show that the 12.4° 2θ kaolinite peak remained stable until the sediments were heated to 450 °C (Fig. 6e, f). Above this temperature, the kaolinite peaks in both samples collapsed entirely.

DISCUSSION

Clay Mineralogy of the Burn Zones

Most researchers initially accepted Orr's hypothesis that the discrete packages of discolored sediments he called fire areas were related to burn events (e.g., Johnson et al. 1980, Wendorf 1982). This hypothsis was eventually challenged by a group invoking a groundwater process to explain the features (Cushing et al. 1986, Cushing 1993). Although the groundwater hypothesis does not appear to have gained much support by researchers working on the islands, it wasn't until recently that Rick et al. (2012) used multiple lines of evidence, including clay mineralogy, to demonstrate that the fire areas were indeed the result of fire and not groundwater processes.

The results of our study further support this conclusion for several reasons. First, the presence of abundant in situ charcoal is a clear indicator of fire. Most of the discrete pieces of

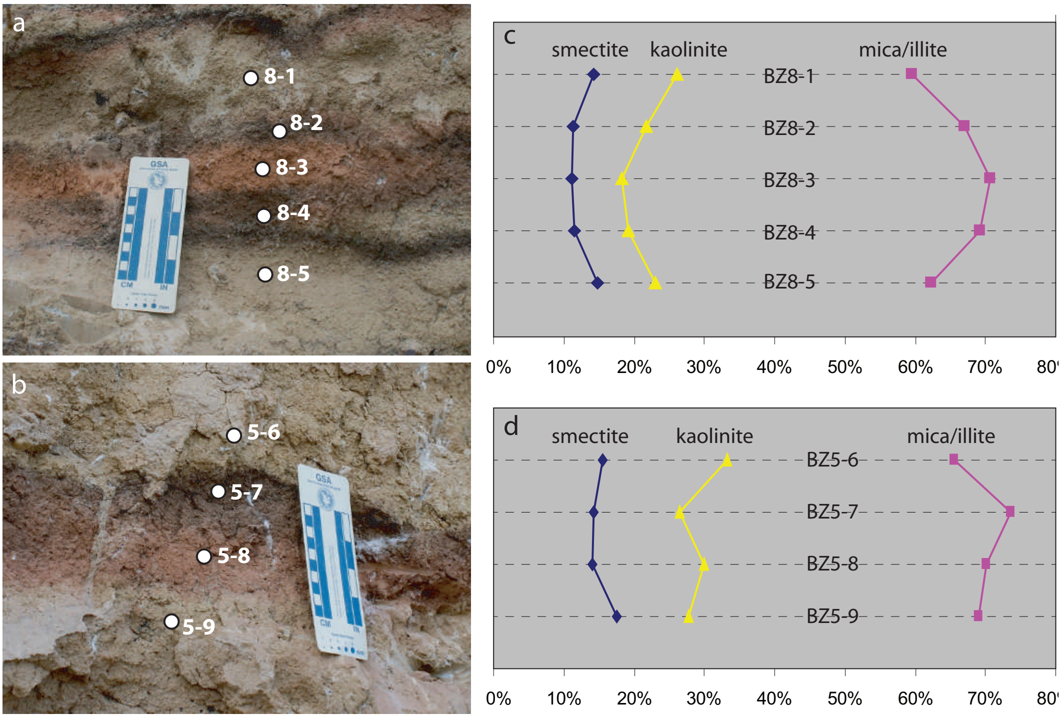

Fig. 5. Photographs and sample locations for 2 burn zones: **a,** BZ8; **b,** BZ5 (see Fig. 2 for stratigraphic positions). Relative percentages of smectite, kaolinite, and mica/illite for samples collected at 2 burn zones: **c,** BZ8; **d,** BZ5.

charcoal observed in the Chukar Canyon sediments were associated with features that we would interpret as burn zones (based on the discoloration of the sediment) even if charcoal was not present. Second, we did not observe any difference in grain size, sorting, or other features that would suggest that groundwater preferentially moved through the burn zones. If these sediments exhibited a higher porosity and permeability than adjacent sediments, for example, then it might be conceivable that groundwater flowed through and preferentially altered some sediments more than others. This was not the case, however, as grain size and porosity did not change across the features. Finally, the results of our step-heating experiments show that the sediments have been heated previously to at least 150–250 °C (based on smectite peaks) and, more likely, to as high as 350–450 °C (based on kaolinite peaks). We favor the higher estimate because the kaolinite peaks were clearer, more stable, and therefore easier to interpret than the smectite peaks at all temperatures (including the unheated, air-dried aliquot). Moreover, smectite is known to be physically smaller than kaolinite, with a typical diameter of 0.01 mm (10 times smaller than kaolinite), and is therefore potentially more physically mobile in the natural environment (Grim 1962, Gibbs 1965). It is possible to envision a scenario in which sediments were heated originally to 350–450 °C during a burn event and buried shortly thereafter, and then some amount of younger (nonheated) smectite was transported from above by pedogenic eluviation/illuviation processes, essentially acting as a contaminant. Regardless, the burn zones at Chukar Canyon are similar in appearance to fire areas on Santa Rosa Island. The burn zone and the physical and mineralogical evidence presented here support the conclusion that these areas were indeed the result of heating or burning rather than groundwater processes.

Frequency of Natural Wildfires on San Nicolas Island

The oldest documented evidence of human occupation on San Nicolas Island is ~8.5 ka (Schwartz and Martz 1992), although evidence

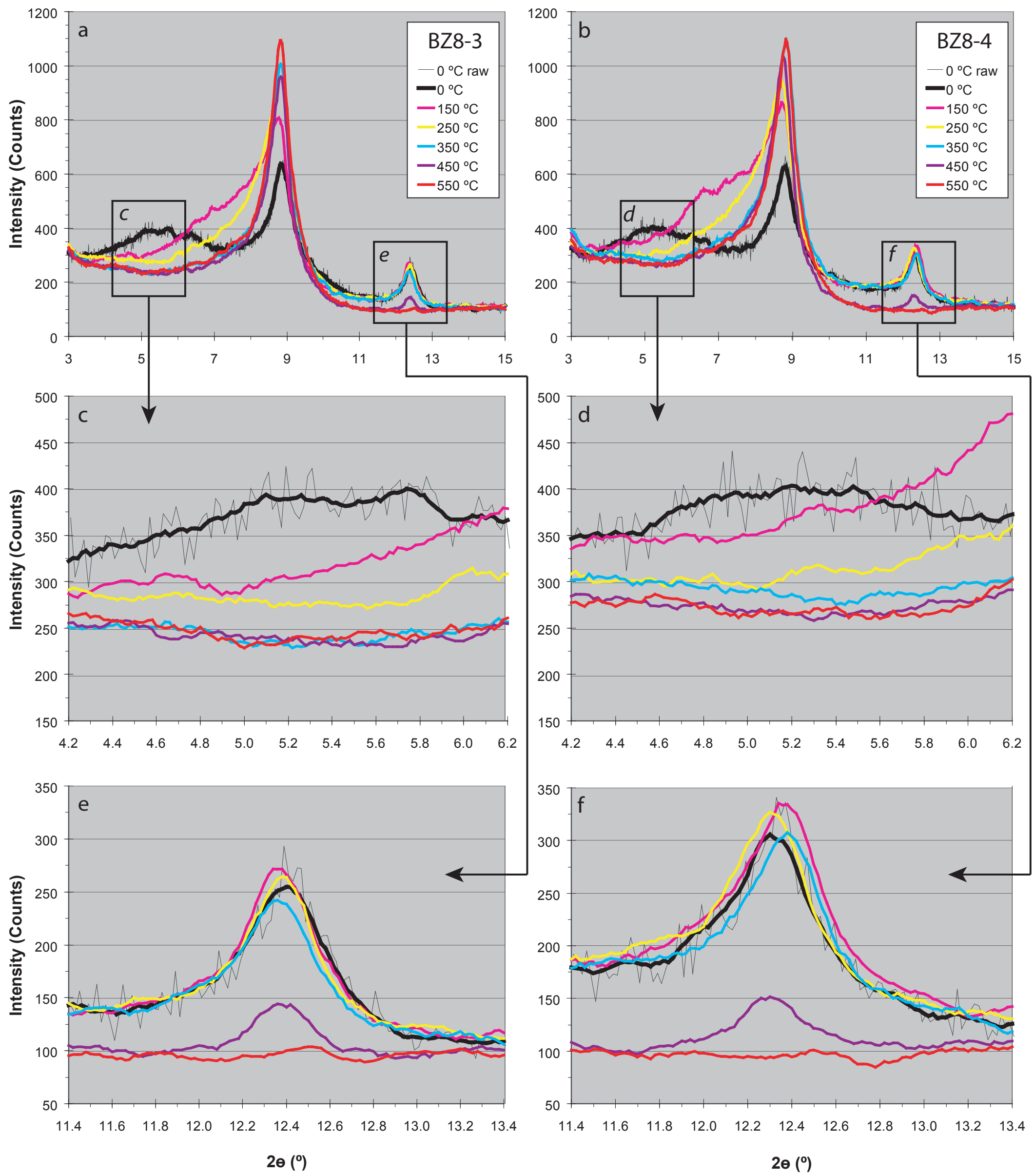

Fig. 6. X-ray diffractograms for samples BZ8-3 (a, c, e) and BZ8-4 (b, d, f), including the full spectrum from 3° to 15° (a, b), the smectite peak centered at 5.2° (c, d), and the kaolinite peak centered at 12.4° (e, f). See Fig. 5 for specific sample locations. Legends shown in the top panels are the same for all panels. The thin black line denotes raw data taken at 0.02° increments. All other lines represent running 5-point mean averages, which correspond to a 2θ uncertainty of 0.04°. Note the clear decrease in the kaolinite peaks (e, f) for both samples when heated to 450 °C, which suggests that the sediments had been heated previously to 350–450 °C.

from Santa Rosa Island suggests that humans were present on the northern Channel Islands by ~13 ka (Orr 1968, Johnson et al. 2002, Stafford et al. 2008). Whether or not humans first arrived on San Nicolas Island in the early Holocene or several millennia earlier is inconsequential as the calibrated ^{14}C ages of the burn zones at Chukar Canyon date to between ~37 and 25 ka, well before the arrival of humans in North America in general (Meltzer 2009) and coastal southern California and the Channel Islands in particular. Thus, we can safely assume the fires that created the burn zones at Chukar Canyon are not anthropogenic.

The mean fire interval (MFI) is a useful metric for quantifying fire regimes and represents the average amount of time between fires at a given location over a specific time period (McBride 1983). Here, calculated MFI values represent the average duration between fire occurrences in the Chukar Canyon drainage basin over the period defined by the calibrated ^{14}C ages. As a whole, the alluvial sequence at Chukar Canyon suggests that as many as 24 different fire events occurred here in a span of ~12 ka, corresponding to an overall MFI of ~500 years. However, burn zones BZ4 through BZ21 apparently occurred in a relatively short amount of time, only ~6 ka, meaning that the MFI was only ~300 years between approximately 29 and 35 ka. Whether examining the record in its entirety or looking only at the peak frequency period, the MFI values presented here should be viewed as *maxima* because it is likely that smaller, less intense burn events that were not captured in the geologic record occurred at our study site during this period. Moreover, considering the relatively low elevation of the Chukar Canyon catchment area, which does not exceed ~275 m asl, the calculated MFIs are likely on the high end for the Channel Islands as a whole if we extrapolate the relation between elevation and the number of lightning-induced fires observed today (Keeley 2002).

The MFI values calculated for the Chukar Canyon catchment area are similar to modern MFI values (200–500 years) observed in the San Diego County–northern Baja California area for an area of similar size (~1 km) and when accounting for only lightning-induced fires (Minnich et al. 1993, Wells and McKinsey 1995). The Chukar Canyon results are also broadly similar to modeled MFI values for preanthropogenic MFIs in the redwood forests of Santa Cruz County, located farther north in central California (MFI = 135 years; Greenlee and Langenheim 1990). However, the validity of such comparisons is limited by differences in vegetation and climate regimes, spatial extent of the areas studied, size of the fires (small fires may not be accounted for in the Chukar Canyon sediments), and the methodologies employed (Marlon et al. 2009, 2012).

Direct comparison of the Chukar Canyon record with other nearby charcoal-based records is not possible because continuous charcoal sequences from other localities in coastal southern California either do not predate the arrival of humans (Cole and Liu 1994, Anderson et al. 2009) or represent an undefined spatial extent (Heusser and Sirocko 1997). Thus, our results provide the first baseline of MFI values against which future studies of fire recurrence intervals on the Channel Islands can be compared directly.

Conclusions

The sedimentary sequence discovered at Chukar Canyon on the north side of San Nicolas Island provides an opportunity to quantify the frequency of fire on the California Channel Islands prior to the arrival of humans. Our ^{14}C-based chronology and the sedimentology of the deposits exposed at Chukar Canyon show that fires that were large enough in both magnitude and intensity to be preserved in the geologic record occurred *at least* every 300–500 years in this catchment area between ~37 and 25 ka, and likely more often than that. These recurrence intervals are similar to both modern observations and modeled preanthropogenic values on the mainland, although the validity of such comparisons is limited because of differences in vegetation types, climate regimes, sedimentary processes, and the methodologies used in the various studies. Nevertheless, our study provides a baseline against which to compare future assessments of fire regimes in this region, as well as studies aimed at determining if and when fire was used by early humans to alter late Pleistocene landscapes on the Channel Islands.

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