Wildfire and abrupt ecosystem disruption on California's Northern Channel Islands at the Ållerød–Younger Dryas boundary (13.0–12.9 ka)

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ABSTRACT

Sedimentary records from California's Northern Channel Islands and the adjacent Santa Barbara Basin (SBB) indicate intense regional biomass burning (wildfire) at the Ållerød–Younger Dryas boundary (∼13.0–12.9 ka) (All age ranges in this paper are expressed in thousands of calendar years before present [ka]. Radiocarbon ages will be identified and clearly marked "^{14}C years".). Multiproxy records in SBB Ocean Drilling Project (ODP) Site 893 indicate that these wildfires coincided with the onset of regional cooling and an abrupt vegetational shift from closed montane forest to more open habitats. Abrupt ecosystem disruption is evident on the Northern Channel Islands at the Ållerød–Younger Dryas boundary with the onset of biomass burning and resulting mass sediment wasting of the landscape. These wildfires coincide with the extinction of *Mammuthus exilis* [pygmy mammoth]. The earliest evidence for human presence on these islands at 13.1–12.9 ka (∼11,000–10,900 ^{14}C years) is followed by an apparent 600–800 year gap in the archaeological record, which is followed by indications of a larger-scale colonization after 12.2 ka. Although a number of processes could have contributed to a post 18 ka decline in *M. exilis* populations (e.g., reduction of habitat due to sea-level rise and human exploitation of limited insular populations), we argue that the ultimate demise of *M. exilis* was more likely a result of continental scale ecosystem disruption that registered across North America at the onset of the Younger Dryas cooling episode, contemporaneous with the extinction of other megafaunal taxa. Evidence for ecosystem disruption at 13–12.9 ka on these offshore islands is consistent with the Younger Dryas boundary cosmic impact hypothesis [Firestone, R.B., West, A., Kennett, J.P., Becker, L., Bunch, T.E., Revay, Z.S., Schultz, P.H., Belgya, T., Kennett, D.J., Erlandson, J.M., Dickenson, O.J., Goodyear, A.A., Harris, R.S., Howard, G.A., Kloosterman, J.B., Lechler, P., Mayewski, P.A., Montgomery, J., Poreda, R., Darrah, T., Que Hee, S.S., Smith, A.R., Stich, A., Topping, W., Wittke, J.H. Wolbach, W.S., 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and Younger Dryas cooling. Proceedings of the National Academy of Sciences 104, 16016–16021.].

1. Introduction

Abrupt and massive environmental and biotic changes are evident at the Ållerød–Younger Dryas Boundary (YDB, 13.0–12.9 ka) in the archaeological and paleontological records of North America. It appears that at least 16 of 35 extinct Late Pleistocene animal genera have abrupt, terminal occurrences at, or close to, this boundary (Firestone et al., 2007; Grayson, 2007; Haynes, 2008). The remaining genera are rare in the Pleistocene record and the available chronological information is generally insufficient to evaluate their extinction histories. This is also the case for 19 extinct Late Pleistocene bird genera (Grayson, 2007). Grayson and Meltzer (2002) hypothesized that these extinctions were gradual during the Late Pleistocene and that processes causing the massive extinction

were temporally and regionally complex and related to the changing environmental conditions associated with deglaciation. Animal extinction histories should be complex during such significant environmental shifts, but the abrupt extinction of significant numbers of genera/species at ∼13–12.9 ka occurred during a time of more gradual ecosystem processes associated with the last deglacial episode. A continental scale AMS ^{14}C dating campaign is required to test the hypothesis that posits an abrupt environmental and biotic event. Relatively comprehensive extra-regional data are in strong support of an abrupt extinction of several Rancholabrean mammalian taxa including *Equus* [Horse], *Camelops* [Camel], and *Mammuthus* [Mammoth] (Haynes, 2008), with the best dataset from *Mammuthus* indicating that this genus abruptly disappeared over much of the continent at ∼12.9 ka (Haynes, 2008). By this time most of North American megafauna were extinct, with *Bison* spp. a rare survivor that experienced a significant population bottleneck at ∼12.9 ka (Drummond et al., 2005). This appears to have stimulated genetic change that ultimately led to the appearance of the modern Bison [*Bison bison*] during the Holocene (McDonald, 1981). The abrupt termination of multiple genera and the bottleneck in bison populations at or close to 12.9 ka demands explanation.

The rapid extinction of many Rancholabrean animals is closely timed to the Clovis cultural assemblage that abruptly appeared and disappeared across North America between 13.1 and 12.9 ka (Waters and Stafford, 2007) and immediately preceded the Younger Dryas (YD) cooling (Broecker, 2006). Our opinion is that Martin's (1967, 2005) long-standing hypothesis that human hunting was responsible for this extinction (overkill) event is not supported by the available data. The reasons are that there is a near-absence of kill sites for many of these genera, including camels and sloths (Grayson and Meltzer, 2002; Grayson, 2007), the event was rapid, encompassed numerous animal taxa, and had a large geographic extent. In addition, increasing evidence for pre-Clovis human occupations negates an explosive occurrence of people rapidly expanding throughout the Americas (Dillehay, 1989, 1997; Waters and Stafford, 2007; Gilbert et al., 2008). The rapid onset of YD cooling is recorded throughout the Northern Hemisphere, in equatorial climate records (Haug et al., 2001; Hendy et al., 2002; Yancheva et al., 2007), and provides another potential explanation for the abrupt extinction event. The timing of YD cooling is out of phase with the chronology of Milankovitch forcing mechanisms, but its severity and rate of onset is comparable to many such cooling events during the Late Quaternary (Hendy et al., 2002) and hence by itself does not provide an adequate explanation for ecosystem disruption and massive extinction. More complex ecological explanations involving a combination of climate change and human predation are the most viable (Barnosky et al., 2004) in the absence of alternative mechanisms, however, based on 97 geoarchaeological sequences across North America, Haynes (2008) argues for a dramatic environmental event at ∼12.9 ka (10,900 ^{14}C years). He argued that the base on a physically distinctive YD black layer at 70 of these localities dates to ∼12.9 ka and serves as a stratigraphic marker horizon (Fig. 1)—a thin stratum where Clovis artifacts and select Rancholabrean fauna occur below, but never within or above this unique bed (Haynes, 2005, 2008; see also Firestone et al., 2007).

Magnetic microspherules are concentrated at the base of the best dated of these distinctive black layers at Murray Springs, AZ (Haynes, 2008) and in association with an assemblage of numerous other exotic materials identified in many other terminal Clovis-age deposits (Firestone et al., 2007). Many of these exotic materials are found in sediments associated with documented extraterrestrial impact events (e.g., Cretaceous–Tertiary [K/T] boundary [Köeberl, 2007]; Tunguska [Longo et al., 1994]). Although much remains to be learned about this boundary layer,

the co-occurrence of these exotic materials forms the basis of the Younger Dryas Boundary (YDB) cosmic impact hypothesis (Firestone et al., 2007). Large cosmic impacts can have major effects on Earth systems and are known to trigger abrupt climatic shifts, widespread biomass burning, and animal extinctions (Alvarez et al., 1980; Wolbach et al., 1985). The recognition of mass extinction at the K/T boundary attributed to a major cosmic impact, along with the presence of a significant number of similar cosmic impact markers identified at the YDB, provide an empirical basis for hypothesizing that North American animal extinctions at the end of the Pleistocene had a similar origin. These extinctions may have been caused, at least in part, by the direct effects of an cosmic impact (shockwave and heat) and subsequent major and cascading ecological changes (e.g., regional wildfires, climate change, vegetation disturbance and shifts). Much of the existing archaeological, paleontological, and paleoenvironmental data in North America are not adequate to test the YDB cosmic impact hypothesis due to sparse geographic occurrences and insufficient chronological resolution in available records. The apparent suddenness of the event that occurred at the onset of the YD requires investigations of very high chronological resolution to test the hypothesis. A first step in evaluating the YDB cosmic impact hypothesis is the further analysis of existing stratigraphic and chronological datasets, removing erroneous radiocarbon dates that have large error margins (Spriggs, 1989; also see Pettitt et al., 2003; Waters and Stafford, 2007; contra the approach of Buchanan et al. 2008) or other problems (e.g., the 'old wood effect'; Schiffer, 1986; Kennett et al., 2002). Unless the objects of interest are dated directly (e.g., Pleistocene animal bones, dung, or other biological remains) stratigraphic context is essential with all sites with questionable radiocarbon dates or associations removed until confirmed with modern techniques. Calibration with careful attention to ^{14}C reservoir problems is essential (Ingram and Southon, 1996; Kennett et al., 1997), as is careful consideration of radiocarbon production plateaus and uncertainties in the calibration curve known to exist during this interval (Muscheler et al., 2008). The same rigorous criteria expected for defining pre-Clovis occupations are now required for all terminal Pleistocene stratigraphic sequences.

It is in this context that we present evidence for the co-occurrence of massive wildfire, abrupt vegetation change, *Mammuthus exilis* extinction and disruption in human use of California's Channel Islands at ∼13–12.9 ka. These islands were never connected to the mainland during the Quaternary and thus provide a unique and detailed record of Proboscidean colonization, biogeography, dwarfism, and extinction in an insular maritime environment (Agenbroad, 2002a, 2005). They also provide a long and well-preserved sequence of human occupation spanning the last 13,000 years (Erlandson et al., 1996, in press; Johnson et al., 2002; Kennett, 2005; Rick et al., 2005). These records are coupled with high-resolution climate and environmental records from the adjacent Santa Barbara Basin (Kennett et al., 1995, 2007; Heusser and Sirocko, 1997; Kennett and Kennett, 2000; Hendy et al., 2002, 2004). High quality SBB records result from a combination of rapid sedimentation rates, general lack of bioturbation, a relatively continuous abundance of climatic/environmental proxies and proximity to continental influences. The paleontological, archaeological, and paleoenvironmental records on these islands provide a unique opportunity to examine *M. exilis* extinction in the context of climatically induced environmental change and the arrival of humans on these islands. We now turn to the existing Late Quaternary paleoenvironmental sequences for the region and the archaeological and paleontological records from the Northern Channel Islands. We then examine the evidence for regional wildfires at 13–12.9 ka and discuss this within the context of existing records and the YDB extraterrestrial impact hypothesis.
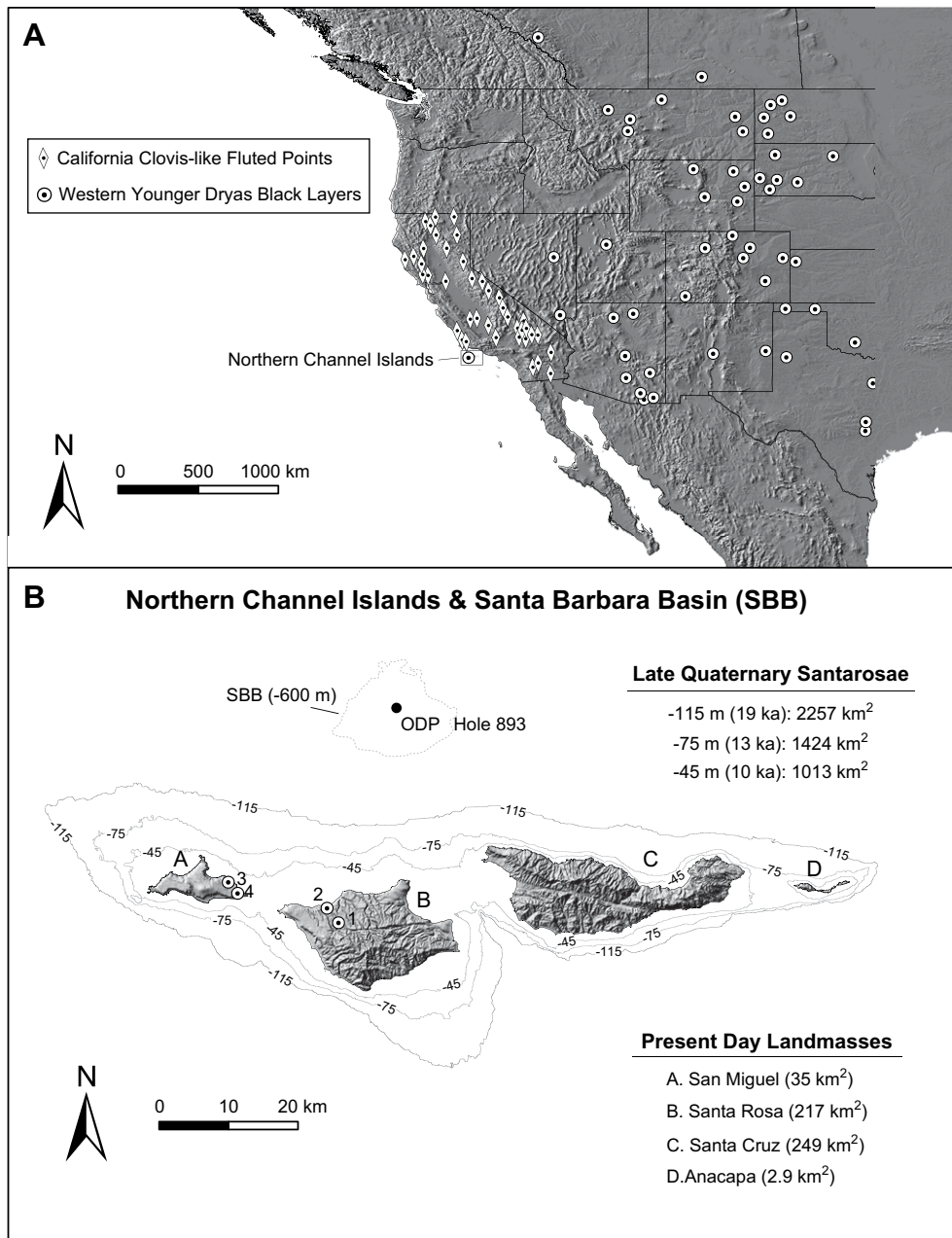
Fig. 1. Maps of [A] Western North America [B] Northern Channel Islands showing localities discussed in the text. The general distribution of black sedimentary layers in Western North America is based on Haynes (2008). The general distribution of Clovis-like fluted points in California comes from Rondeau et al. (2007). Bathymetry surrounding the Northern Channel Islands was established using the same procedure as Kinlan et al. (2005), but temporal assignments for Late Quaternary Santarosae shorelines were made based on more modern sea-level records (Fairbanks, 1989; Bard et al., 1990, 1996; Hanebuth et al., 2000). Localities identified on the Northern Channel Islands are: 1 = AC-003; 2 = Arlington human locality [CA-SRI-173]; 3 = Daisy Cave [CA-SMI-261]; and 4 = Cardwell Bluffs (maps by Jacob Bartruff).

2. Late Quaternary paleoenvironmental change

High-resolution Late Pleistocene environmental sequences are limited on the Northern Channel Islands, but the adjacent Santa Barbara Basin (SBB) offers extraordinarily sensitive records of global climate change and associated regional environmental responses on interannual through glacial/interglacial timescales (Kennett et al., 1995, 2007; Behl and Kennett, 1996; Heusser and Sirocko, 1997; Heusser, 1998; Cannariato et al., 1999; Hendy and Kennett, 1999; Kennett and Kennett, 2000; Hendy et al., 2002, 2004; Nederbragt and Thurow, 2005; Graham et al., 2007; Sarnthein et al., 2007; Nederbragt et al., 2008). Well-preserved sediments in the center of this basin record climatic variability closely correlated with Northern Hemisphere and broader climate history as documented in the Greenland ice core (e.g., GISP2 δ^{18}O; Hendy et al., 2002). Decreased ventilation leading to varved sediments occurs during warm episodes (Bølling [14.7–14.1 ka], Ållerød [14–12.9 ka], and earliest Holocene [11.6–10.5 ka]) while increased ventilation and resulting non-laminated (bioturbated) ocean sediments typify cool intervals (e.g., Last glacial Maximum [LGM; 18 ka], Older Dryas [14.1–14 ka], Younger Dryas [YD] [12.9–11.6 ka]; Behl and Kennett, 1996). Planktonic foraminiferal δ^{18}O values accord well with these glacial–interglacial cycles and also record multiple, abrupt sub-millennial-scale cool and warm excursions throughout the Late Quaternary (Hendy et al., 2002), often of similar magnitudes or more extreme than the abrupt cooling that marks the onset of the YD.

The Late Quaternary age model for ODP Site 893 was established based on a new suite of AMS ^{14}C dates (Sarnthein et al., 2007; Fig. 2). Radiocarbon dating was performed on mixed planktonic foraminifera. A regional reservoir correction (ΔR) of 233 ± 60 years has been assumed (Ingram and Southon, 1996). From the 51 ^{14}C dates between 9.5 and 20 ka, 36 dates were averaged, and 12 dates (including, dates within radiocarbon plateaus) were excluded from the age model. The remaining dates were used to generate 21 calibrated calendar year ages (including 11 that represent average dates). Calibrated calendar year ages were obtained using the full probability method of calendar age calibration (Telford et al., 2004). Reservoir-corrected ^{14}C dates younger than 22 ^{14}C ka were calibrated using CALIB 4.0 (Stuiver et al., 2004) and the ^{14}C calibration dataset MARINE04 (Hughen et al., 2004).

Sedimentary, faunal, and $\delta^{18}O$ records in SBB generally show cohesive warm–cool–warm cycles during the Ållerød, YD and Early Holocene, respectively (Fig. 3). The Ållerød–YD transition is marked by a sharp change from laminated to bioturbated sediments (Behl and Kennett, 1996) with non-laminated sediments persisting through the YD, estimated to be ~1300 years in duration based on an AMS ^{14}C chronology, varve counting, and correlation with the GISP2 ice core record (Kennett and Ingram, 1995a,b; Hendy et al., 2002; Nederbragt and Thurow, 2005). Planktonic foraminiferal $\delta^{18}O$ isotope and faunal assemblages clearly show: 1) Bølling and Ållerød warm episodes (separated by the Older Dryas); 2) the YD cool episode, and 3) the Early Holocene (Hendy et al., 2002). Planktonic foraminiferal $\delta^{18}O$ records of thermoclinal (*Neogloboquadrina pachyderma*) and surface (*Globigerina bulloides*) water forms are consistent with this hypothesis and indicate abrupt cooling at the onset of the YD. The Bølling–Ållerød warm episode registers in both planktonic foraminiferal species. The onset of the YD is represented by a 1‰ increase in $\delta^{18}O$ (Hendy et al., 2002).

Marine faunal assemblages also indicate cooler sea surface temperatures (SST) during the YD. The ratio of sinistral (left coiling) to dextral (right coiling) in *N. pachyderma* is highly sensitive to SSTs (summarized in Fisler and Hendy, 2008). Sinistral *N. pachyderma* forms are favored with a poorly developed thermocline (high-upwelling) and SST < 10 °C. The high abundance of the dextral

coiled morphospecies through much of the Bølling–Ållerød indicates SST > 10 °C, a well-developed thermocline, and intensive upwelling of nutrient-rich water. The Bølling is widely recognized as an interval of unusually high marine productivity in the North Pacific (Hendy et al., 2004). Dextral/sinistral ratios are high in Bølling–Ållerød and Early Holocene assemblages and the YD is marked by an abrupt decrease in this ratio indicating SST < 10 °C. This is consistent with the $\delta^{18}O$ records for this thermoclinal species indicating cold SSTs during the YD. Planktonic foraminiferal abundance decreased during the YD. *Globigerina quinqueloba* dominated the assemblage during the YD (40–80%), while *G. bulloides* is rare in comparison to Ållerød and Early Holocene assemblages. These species are surface dwellers that thrive in nutrient-rich water, however, *G. bulloides* does not host photosynthetic endosymbionts and consequently has a higher prey requirement (Ortiz et al., 1996). Low foraminiferal abundance and high *G. quinqueloba* frequencies during the YD indicate a decrease in size and/or frequency of prey perhaps as a result of reduced upwelling (Fisler and Hendy, 2008). Dinoflagellate cyst production increased during the Bølling/Ållerød and diminished during the YD, and is also consistent with reduced upwelling during the cool event (Pospelova et al., 2006). Coccolith assemblages change more gradually across the Ållerød–YD boundary and during the YD they are most similar to the LGM (MIS2). This observation is consistent with other proxies suggesting cool YD SSTs (Nederbragt et al., 2008). An increase in *Florisphaera profunda* in YD assemblages (much higher than LGM) suggests that coccolithophorid production occurred during seasonal chlorophyll maxima associated with stratification of the water column (Nederbragt et al., 2008, p. 10).

Late Quaternary changes in sea level altered the size and configuration of the Northern Channel Islands between 19.5 and 10 ka (and after), increasing the width of the channel separating these islands from the mainland (Junger and Johnson, 1980). The distribution of highly productive reef habitat and associated kelp forests also changed during this interval (Kinlan et al., 2005), where tectonic influences on eustacy (uplift or subsidence) are relatively minor compared to glacio-eustatic effects during this interval. The Northern Channel Island platform is tilting, subsiding in some locations and uplifting in others (Sorlien, 1994). Fault slip and warping on Santa Rosa and Santa Cruz Islands are similar; both faults are oriented east–west and dipping steeply to the north (Pinter et al., 2001, 2003). Late Quaternary uplift has occurred north of these faults with left slip rates between 0.75 and 1 mm/year and vertical uplift of 0.1–0.2 mm/year (<2m in 13,000 years; Pinter et al., 2001, p. 9). During the LGM, sea level was ~120 m below the current high-level stand (Fairbanks, 1989; Siddall et al., 2003). The four Northern Channel Islands were amalgamated to form one large landmass known as Santarosae (Orr, 1968; Fig. 1b). A land bridge between the mainland and Santarosae did not exist during the Quaternary; however, the distance from the eastern end of the island to the mainland was reduced to ~7 km at the LGM. Eustatic rises in sea level are not well constrained between 19.5 and 14.5 ka, but a gradual rise of ~25 m is suggested by records in the Indo-Pacific (Bard et al., 1990; Fig. 3f, Table 1). This would have caused a ~17% (391 km^2) reduction in the size of Santarosae, affecting the coastal lowlands that may have been the most productive habitat for animal populations (Agenbroad, 2002b). A more rapid rise of 15 m is evident between 14.5 and 13.4 ka. Sea level was ~75 m below the current high stand at the beginning of the YD (~13–12.9 ka) and gradual increases (~30 m) are evident through the YD and Early Holocene (~12.9–10 ka) resulting in another reduction in land area of roughly 16% (304 km^2). In general, these data are evidence for step-like decrease in island size and increased isolation from the mainland superimposed on more gradual trends between 19.5 and 10 ka. Potential reef area surrounding the islands expanded between 19.5 and 13.5 ka, and contracted gradually
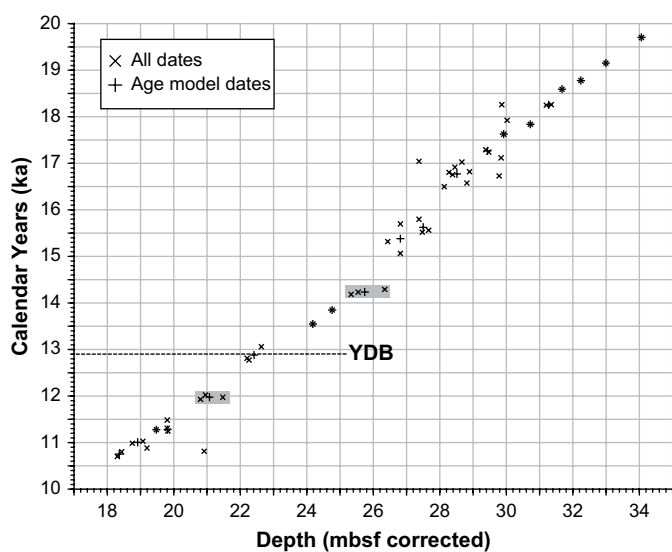

Fig. 2. Age in calendar years BP (ka) versus core depth (corrected cm BSF) for ODP Site 893. Dates were generated using planktonic foraminiferal carbonate (×'s) (Roark et al., 2003; Sarnthein et al., 2007). Dates for the age were also generated using the average of multiple dates (crosses). Dates that were used in the linear interpolation of the age model are shown as crosses. Shaded areas highlight globally recognized ^{14}C age plateaus (Sarnthein et al., 2007).
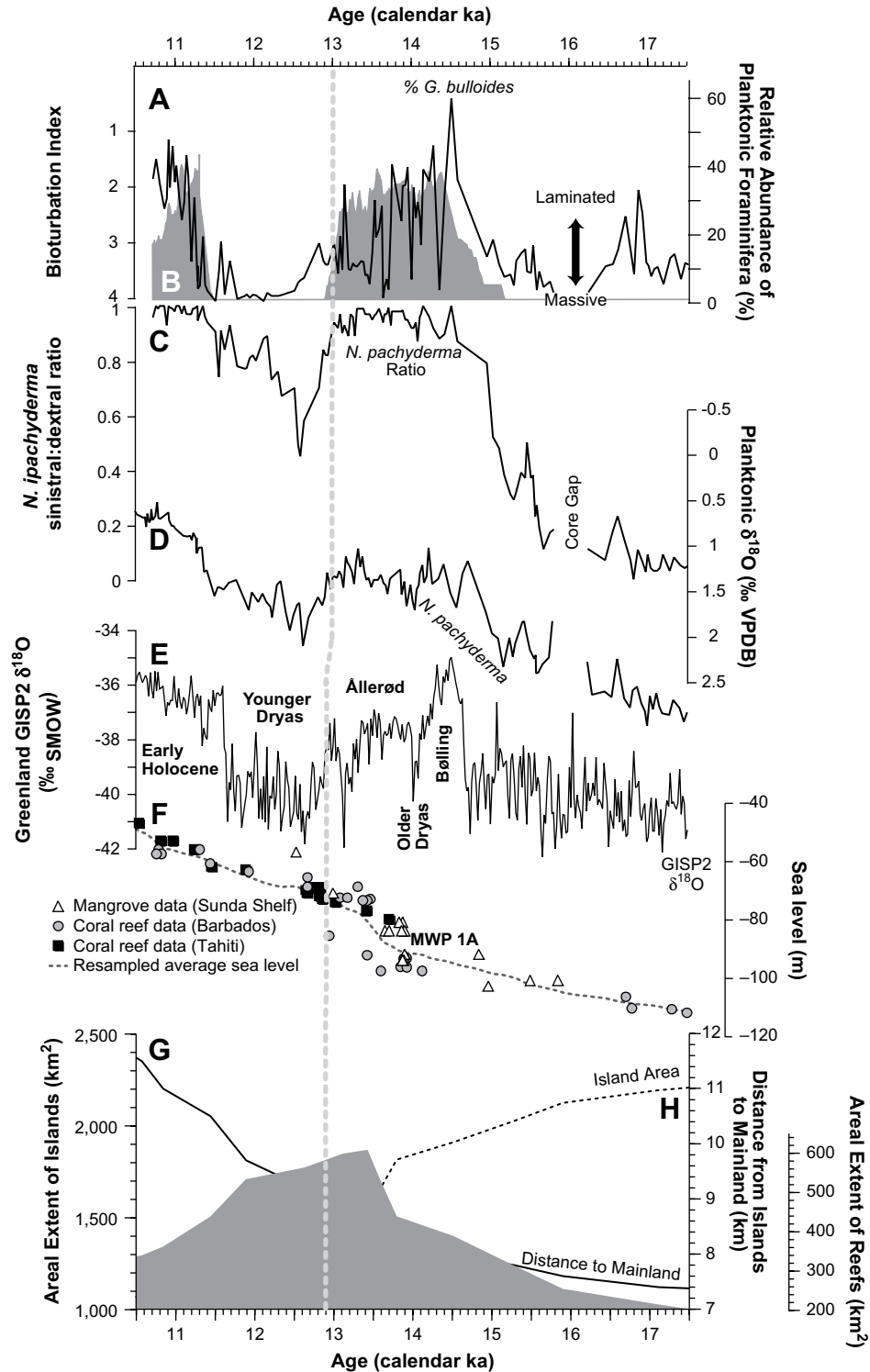
Fig. 3. Comparison of marine records in Santa Barbara Basin with the Greenland Ice Sheet. [A] The relative abundance of the planktonic foraminifera *G. bulloides* (Hendy et al., 2002), [B] the Bioturbation Index (Behl and Kennett, 1996), [C] the ratio of the planktonic foraminifera dextral to sinistral coiled *N. pachyderma*, and [D] the δ^18O record of *N. pachyderma* (Hendy et al., 2002). [E] The Greenland Ice Sheet (GISP2) δ^18O record (Stuiver and Grootes, 2000) and [F] sea-level records from the Sunda Shelf (open triangles; Hanebuth et al., 2000), Barbados (gray circles; Fairbanks, 1989; Bard et al., 1990) and Tahiti (black squares; Bard et al., 1996) with the average sea-level change of these locations resampled every 100 years (dashed gray line). The distance to the mainland from the islands (solid line), [H] the areal extent of the islands (dashed line) and [I] the areal extent of reefs (gray shaded area) through time. Gray dashed line marks the initiation of the Younger Dryas cooling event in Greenland and Santa Barbara Basin, an event that is considered to be synchronous.

during the late Ållerød and YD (13.5–12 ka). The Northern Channel Islands separated sequentially at ∼10.9 ka (Anacapa), ∼9.3 ka (Santa Cruz) and ∼9 ka (Santa Rosa–San Miguel); these estimates differ from those of Kinlan et al. (2005; also see Porcasi et al., 1999) due to the use of more recent estimates of sea-level change.

3. Late Quaternary archaeological records

A human presence on Santarosae at ∼13 ka is indicated by skeletal remains—two partial femora and a patella—at the Arlington Springs site on Santa Rosa Island (CA-SRI-173, Johnson

Table 1
Estimated areal extent of the Northern Channel Islands during the Late Quaternary and related changes in reef size and distance to mainland.

Age (ka)	Bathymetry (m)	Area (km²)	Reef area (km²)	Mainland (km)[a]
9.02	−30	819.13	327.33	13.00
9.35	−35	893.25	313.72	12.00
9.72	−40	951.01	322.95	12.00
10.22	−45	1013.01	328.68	11.80
10.57	−50	1083.15	339.82	11.50
10.84	−55	1149.07	362.14	11.00
11.44	−60	1208.42	438.86	10.50
11.89	−65	1276.62	533.89	9.70
12.63	−70	1345.78	563.65	9.20
13.12	−75	1424.08	599.10	9.00
13.43	−80	1512.00	608.67	8.70
13.58	−85	1649.72	537.11	8.50
13.80	−90	1816.69	439.34	8.20
14.51	−95	1910.44	390.04	8.00
15.28	−100	2026.16	314.66	7.80
15.90	−105	2125.05	254.99	7.60
17.11	−110	2194.44	215.22	7.40
18.85	−115	2256.79	178.88	7.30
19.50	−120	2301.36	157.16	7.30

[a] Estimated distance from eastern Anacapa to adjacent mainland.

et al., 2002; Fig. 4). Orr (1968) discovered the skeletal remains in 1959, buried 11 m below the modern ground surface in a filled arroyo sequence now bisected by the main Arlington Canyon drainage. Several direct dates are available for this skeletal material (Johnson et al., 2002), the most reliable of which is an AMS ^{14}C date on XAD-purified collagen (CAMS-16810, 10,960 ± 50 ^{14}C years or 13–12.9 ka; Table 2). A detailed stratigraphic analysis of the sediments surrounding these bones is consistent with this chronology and confirms an age of 13–12.9 ka (Johnson et al., 2002, 2007; Agenbroad et al., 2005). These data are evidence that humans were present on the Northern Channel Islands when contemporary Paleoindian peoples were well distributed throughout North America and used a wide diversity of available resources including the hunting of large game animals with Clovis spear points (Haynes, 2005; Waters and Stafford, 2007). Clovis points and related technology, although found on the adjacent mainland and throughout much of North America (Anderson and Faught, 2000; Erlandson et al., 2007; Rondeau et al., 2007), have not been found on the Northern Channel Islands, but the potential overlap between the most recently dated *M. exilis* skeleton and the Arlington skeletal material suggests that humans may well have encountered these

animals at this early date. Regardless, early human presence on these islands provides unequivocal evidence for seaworthy boats and sufficient skill to safely navigate the Santa Barbara Channel (Erlandson et al., 2007).

An apparent 600–800 year gap exists between the age of the Arlington Springs locality and the next evidence for human occupation at ∼12.2 ka (Fig. 4). Evidence for human occupation at 12.2 ka occurs at Daisy Cave and Cardwell Bluffs near the east end of modern San Miguel Island. The recently discovered Cardwell Bluffs locality contains several large quarry/workshop sites that have produced hundreds of chipped stone bifaces, including numerous crescents and stemmed projectile points associated with red abalone shells and other well-preserved shellfish remains dating between 12.2 and 11.6 ka (Erlandson et al., in press). The earliest unequivocal evidence for human occupation at Daisy Cave (12.2–11.6 ka) consists of a handful of Monterey chert and siliceous shale artifacts associated with red abalone and other marine shell fragments from the adjacent rocky intertidal zone (Stratum G; Erlandson et al., 1996; Erlandson, 2007). This short-duration deposit, likely representing a single visit, occurs at the base of a well-stratified sequence that shows consistent and repeated use of the cave starting in the terminal Pleistocene. Early Holocene deposits contain a diverse tool assemblage including projectile points, bone fish gorges, shell beads (*Olivella biplicata*), sea grass cordage, and chipped stone debris mixed with the remains of fish, sea mammals, birds, and shellfish (Erlandson, 2007; Erlandson et al., 2007). Increased use of Daisy Cave coincides with the occurrence of many other San Miguel and Santa Rosa sites that contain evidence for early maritime adaptations (Rick et al., 2005).

4. Island mammoth extinction

Paleoenvironmental trends and the human colonization history provide the ecological context for the extinction of *M. exilis* on Santarosae. Pleistocene faunas on this island were of low diversity compared with the diverse fauna documented at Rancho La Brea just across the Santa Barbara Channel on the California mainland (Marcus and Berger, 1984; Coltrain et al., 2004). Mammoths (*Mammuthus columbi*) colonized these islands during the Late Quaternary, probably well before 47 ka, and perhaps during one of the low sea-level stands prior to this time when the swimming distance was relatively short. A more diminutive *Mammuthus* species (*M. exilis*), about the size of a large bison and endemic to

Table 2
Late Quaternary paleontological and archaeological sites from the Northern Channel Islands.

Lab #	Material dated	Provenance	[14]C	±←	Reference
Beta-92053	Charcoal w/*M. exilis*	Southwest Coast, Santa Rosa Island	18,130	70	Agenbroad, 2002b, p. 523
Beta-96610	Charcoal w/*M. exilis*	Southeast Coast, Santa Rosa Island	13,770	60	Agenbroad, 2002b, p. 523
CAMS-71697	*M. exilis* (Collagen)[b]	Northwest Coast of Santa Rosa Island	11,030	50	Agenbroad et al., 2005, p. 5
Beta-133594	Charcoal w/*M. exilis*	Northwest Coast of Santa Rosa Island	11,010	70	Agenbroad et al., 2005, p. 5
CAMS-16810	Human Skeleton[b]	SRI-173, Arlington Springs, 11 m below surface	10,960	80	Johnson et al., 2002, p. 543
Beta-52360[a]	*Tegula*	SMI-261, E-6: Stratum G	10,600	70	Erlandson et al., 1996
Beta-14660[a]	*Haliotis rufescens*	SMI-261, E-6, Stratum G	10,700	90	Erlandson et al., 1996
CAMS-33369	Charred twig	SMI-261, 94-E6, Stratum G	9580	60	Erlandson et al., 1996
CAMS-14366	Charred twig	SMI-261, Cave A, 26–30 cm	9180	60	Erlandson et al., 1996
CAMS-33375	Marine Shell	SMI-261, Col. E-6, F-G transition	9620	70	Erlandson et al., 1996
OS-27943	*Mytilus californianus*	SMI-522, Base of midden	9450	70	Erlandson and Rick, 2002
OS-31684	*Mytilus*	SMI-548, Area A: 0–5 cm	9070	55	Erlandson et al., 2004
OS-34804	*M. californianus*	SMI-604, Probe: 25	9440	50	Rick et al., 2001
Beta-145308	*M. californianus*	East Locus	8920	90	Erlandson et al., 2007
OS-44638	*M. californianus*	SMI-608	9200	50	Erlandson et al., 2005
OS-28282	*M. californianus*	SMI-610, Sea Cliff: 0–10	9080	60	Erlandson et al., 2007
Beta-47625[a]	*Haliotis rufescens*	SRI-6, Component 1	8800	80	Erlandson et al., 1999

[a] Standard radiocarbon—[13]C/^{12}C adjusted.
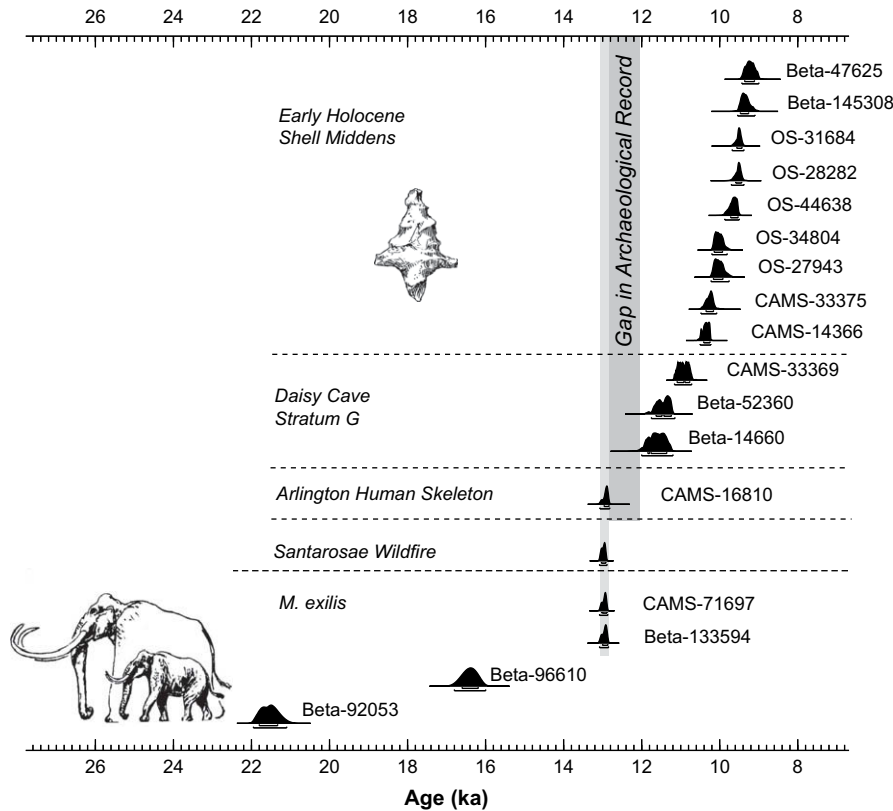[b] XAD-purified collagen.

Fig. 4. Available chronological information for *M. exilis* and archaeological datasets from the Northern Channel Islands. Uncalibrated radiocarbon dates and provenience information are provided in Table 2. All radiocarbon dates were calibrated in OxCal v3.10 (Bronk Ramsey, 1995, 2001) using the IntCal04 calibration curve for terrestrial samples (Reimer et al., 2004). A regional reservoir correction (ΔR) of 233 ± 60 years was applied to all marine shell dates (Ingram and Southon, 1996). Reservoir-corrected ^{14}C dates calibrated using the MARINE04 dataset (Hughen et al., 2004). Five dates from the lowest dark layer were used to establish the Santarosae wildfire $11,060 \pm 40$ [14]C years (illustration by Rusty Van Rossman).

Santarosae, was favored by natural selection due to isolation, apparent lack of predators, lower carrying capacity and reduced food supply (Agenbroad, 2002a) and appears to have been the dominant species by the end of the Pleistocene.

Hundreds of *M. exilis* bones have been collected and curated during the last century, and at least 140 new fossil localities were identified on Santa Cruz, San Miguel, and Santa Rosa during a recent comprehensive study (Agenbroad, 2002b). The majority of these bones were found out of primary context and within alluvial deposits. Radiocarbon dates on associated charcoal range to the limits of the ^{14}C dating technique at ~47 ka. One nearly complete *M. exilis* skeleton found on the north coast of Santa Rosa was directly dated to ~16.3–13.9 ka (Agenbroad, 1998). Finally, a thoracic vertebra (*M. exilis*) from the northwest coast of Santa Rosa Island was directly dated with modern techniques $11,030 \pm 50$ [14]C (CAMS-71697, XAD-purified collagen; Fig. 4, Table 2). The vertebra was found in the upper marine terrace and is associated with a charcoal date of $11,010 \pm 70$ [14]C (Beta-133594). Therefore, a calibrated age of 13–12.9 ka is presently considered to be a terminal age for *M. exilis* on the island (Agenbroad et al., 2005)—the onset of the YD.

5. Wildfire and abrupt ecosystem disruption

Sedimentary records from the Northern Channel Islands and SBB (ODP Site 893) indicate intense regional wildfires and abrupt ecosystem disruption at the Ållerød–YD transition (~13–12.9 ka). This time interval coincides with a last possible occurrence of *M. exilis* and marks the beginning of an apparent 600–800-year gap in the archaeological record, both of which may be indications of

ecosystem disruption on Santarosae. Evidence for periodic fires during the LGM is evident in sedimentary records from San Miguel Island (Johnson, 1972, 1977) and charcoal records from Soledad Pond and Abalone Rocks Marsh, both on Santa Rosa Island, indicate that small scale grass/brush fires were part of island ecology throughout the Holocene with increasing intensity in the Late Holocene and Historic Periods (Anderson, 2002). Here we present evidence for intense biomass burning of conifers and subsequent mass wasting of the landscape at 13–12.9 ka in Arlington Canyon (Santa Rosa Island, AC-003). This expands and complements preliminary evidence for ~13 ka wildfires discovered on San Miguel Island, the next island west of Santa Rosa (Firestone et al., 2007). Evidence for these wildfires is from the well-dated paleontological sediments at Daisy Cave (Stratum I, CA-SMI-261), which underlie the archaeological deposits that began accumulating at ~12.2 ka (Erlandson et al., 1996). Pinter and Anderson (2006) also have proposed Santarosae Island-wide "mega-fires" and landscape transformation at ~13 ka.

The AC-003 section (UTM: 10S 0762524/3764532, Fig. 1) is located ~1.35 km from the modern coastline and 1.2 km upstream from the Clovis-age Arlington locality. Arlington Canyon cuts through a series of uplifted Quaternary terraces that dominate the landscape north of the Santa Rosa Island fault and are well known for containing *M. exilis* remains (Orr, 1968; Agenbroad, 2002b). Holocene alluvial and colluvial deposits are exposed throughout Arlington Canyon, but AC-003 was selected because preliminary work by G. James West indicated that the basal deposits in the exposed sequence dated to the Ållerød–YD transition and appeared similar in character to the dark sedimentary layers described by Haynes (2008) across much of North America (Johnson et al., 2007).
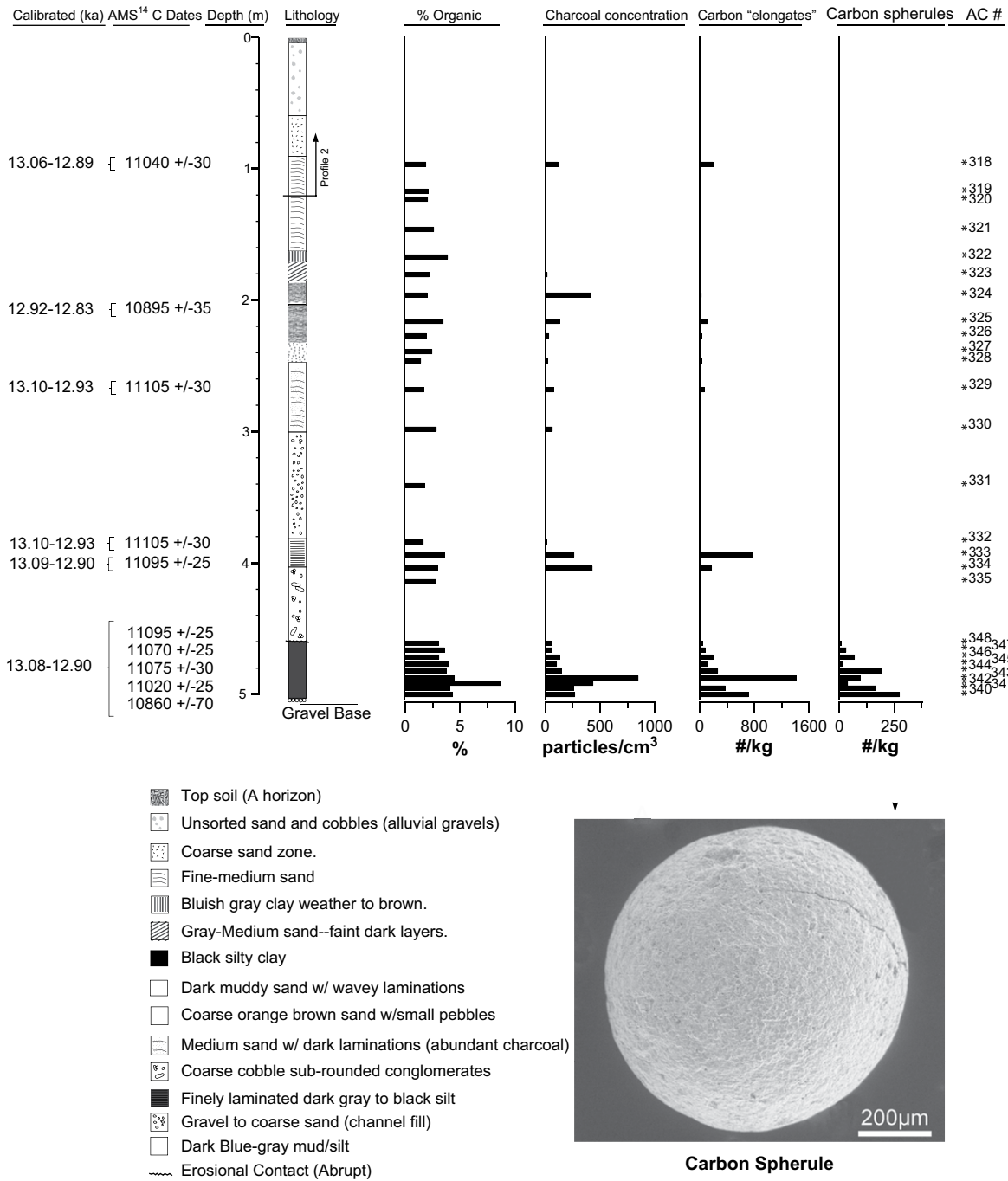
Fig. 5. Stratigraphic section of AC-003 profile showing lithology, calibrated and uncalibrated radiocarbon dates, % organic carbon, and detrital carbon. These data are presented in Table 3 along with additional information (e.g., inorganic carbon, glass-like carbon). Charcoal samples of 1 cm^3 were taken from each level using water displacement and placed in plastic cups. Ten milliliters of sodium hexametaphosphate were added to each sample to disaggregate the sediment and samples were left to soak for 24 h at room temperature. Samples were gently washed through a mesh sieve of 125 μm and the residue was transferred to a gridded Petri dish. All charcoal particles in the samples were identified and tallied under a stereomicroscope at 30× magnification. Samples for loss-on-ignition were approximately 1 g and were taken from each level, placed in ceramic crucibles, and dried at 80 °C for 24 h. Samples and containers were weighed and combusted at 550 °C for 1 h and at 900 °C for 2 h. Weight loss after the 550 °C combustion was used to calculate the percent organic carbon content of the samples; weight loss after 900 °C combustion was used to calculate the percent carbonate content of the samples. Other forms of detrital carbon (e.g., carbon spherules and "elongates") were extracted using methods outlined in Firestone et al. (2007). ESEM images of a carbon spherule from the lower dark sedimentary layer (Lorry I. Lokey Nanoscience Laboratories, University of Oregon).

The section is exposed on the western side of the canyon at the base of a steep incline extending down from the Quaternary terrace above.

Fig. 5 shows the lithostratigraphy of the AC-003 section in addition to chronological information, % organic and inorganic carbon, charcoal concentration, and detrital carbon morphological data (also see Table 3). The basal deposits of this section were exposed in 2001, but largely covered with modern alluvium in 2007, when we exposed and sampled the profile. The exposed 5 m thick sequence rests upon a basal gravel that is at modern stream level and is largely covered with alluvial sands and gravels. A distinctive organic carbon rich, dark blue-gray silty mud (44 cm thick) directly overlays the basal gravel. The gleyed silty mud is capped with a coarse cobble channel lag deposit (~60 cm thick)

Table 3
Organic, inorganic, and other detrital carbon from AC-003.

Sample #	cmbs	% Organic	Charcoal #/cm³	Herbaceous (%)	Detrital carbon		
					Spherules (#/kg)	Elongate (#/kg)	Glass-like (g/kg)
AC318	95–99[a]	1.870	115	7.83	0	192	0.000
AC319	115–120[a]	2.080	2	0.00	0	0	0.000
AC320	122–125	2.044	0	0.00	0	0	0.000
AC321	145–148	2.601	0	0.00	0	0	0.000
AC322	166–169	3.870	0	0.00	0	0	0.000
AC323	179–183	2.175	18	0.00	0	0	0.000
AC324	195–198	1.991	413	8.72	0	23	0.001
AC325	215–217	3.459	131	0.00	0	112	0.001
AC326	226–229	1.920	31	0.00	0	30	0.001
AC327	238–241	2.437	2	0.00	0	0	0.000
AC328	245–248	1.416	22	0.00	0	31	0.001
AC329	267–270	1.688	76	1.32	0	66	0.000
AC330	297–300	2.838	65	0.00	0	0	0.001
AC331	340–343	1.769	5	0.00	0	0	0.000
AC332	383–386	1.648	13	0.00	0	18	0.000
AC333	392–396	3.583	261	0.00	0	767	0.001
AC334	403–406	2.959	430	0.23	0	173	0.001
AC335	413–416	2.785	0	0.00	0	0	0.000
AC348	459–464	3.025	51	0.00	8	42	0.001
AC347	464–469	3.577	58	0.00	31	81	0.001
AC346	469–475	3.075	132	0.00	68	193	0.001
AC345	475–480	3.929	102	0.00	13	113	0.001
AC344	480–485	3.720	148	0.00	190	264	0.001
AC343	485–491	4.472	849	0.24	85	1412	0.001
AC342	491–493	8.719	435	6.90	38	0	0.000
AC341	493–498	4.069	258	1.55	166	373	0.001
AC340	498–503	4.310	268	0.37	274	714	0.001

[a] Profile 2.

and a second dark layer (20 cm thick) consisting of finely laminated dark gray to black sandy silt. The upper dark layer is also organic carbon rich and contains charcoal and charred tree branches up to 5 cm in diameter. Intense wildfire evidence is also indicated by the presence of carbon spherules (400–1500 μm) in the lowest dark layer (see Fig. 5). These spherules occur widely in the YDB layer in North America and have also been found in surficial sediments associated with intense coniferous forest crown fires (Firestone et al., 2007). Elongated carbon forms found in a number of levels in the sequence have similar surface features to the carbon spherules. Both carbon forms have (1) the appearance of melted and charred organic matter, (2) a moderately glossy shell unlike that of charcoal, and (3) interior vesicles that are typically a few micrometers in diameter. However, there are at least three important differences between the two carbon types. Carbon elongates are not spherical, but are approximately 2–3 times longer than they are wide, they have a much coarser spongy interior cellular structure, and they are found throughout the sequence whereas carbon spherules occur only in the lowest black layer. The remainder of the sequence consists of alluvial sands and gravels and includes additional charcoal-rich layers. Charcoal layers in the upper section are thinner and dispersed and do not form a distinctive black layer as with the lowest deposits.

AMS ^{14}C dates for the lower black organic carbon-rich layers suggest that they accumulated rapidly at ~13.0–12.9 ka (Table 4). Five of the AMS ^{14}C dates for the lower black layer are slightly older,

Table 4
Radiocarbon dates from the AC-003 stratigraphic section.

Lab #	Depth (cm)	Lithological unit[a]	Material dated	^{14}C	±←	Cal.[c] age (BP)
UCIAMS-47235	95–99	Unsorted sand and cobbles (alluvial gravels)	Charcoal	11,040	30	13,060–12,890
UCIAMS-47236	179–183	Gray-medium sand-faint dark layers	Charcoal	12,095	40	14,060–13,820[e]
UCIAMS-47237	215–217	Black silty clay	Charcoal	10,895	35	12,915–12,830
UCIAMS-47238	267–270	Gray sand w/laminations (abundant charcoal)	Charcoal	11,105	30	13,100–12,930
UCIAMS-47239	392–396	Finely laminated dark gray to black silt	Charcoal	11,105	30	13,100–12,930
UCIAMS-42816	403–406	Finely laminated dark gray to black silt	Wood[b]	11,095	25	13,090–12,930
UCIAMS-36308	464–469	Blue-gray mud/silt	Wood	11,095	25	13,090–12,930
UCIAMS-36307	469–475	Blue-gray mud/silt	Wood	11,070	25	13,070–12,910
UCIAMS-36306	485–491	Blue-gray mud/silt	Wood	11,375	25	13,310–13,180[f]
UCIAMS-36959	480–485	Blue-gray mud/silt	Charcoal	11,075	30	13,080–12,910
UCIAMS-36960	480–485	Blue-gray mud/silt	Glassy carbon	11,185	30	13,190–12,980[f]
UCIAMS-36961	480–485	Blue-gray mud/silt	Carbon sphere	11,440	90	13,470–13,120[f]
UCIAMS-36962	480–485	Blue-gray mud/silt	Carbon Brecchia "elongate"	11,110	35	13,110–12,930[f]
Beta-161032	480–485	Blue-gray mud/silt	Wood (yellow pine-Diploxylon)[d]	10,860	70	12,940–12,780
UCIAMS-36305	493–498	Blue-gray mud/silt	Wood	11,235	25	13,220–13,080[f]
UCIAMS-36304	498–503	Blue-gray mud/silt	Wood	11,020	25	13,040–12,880

[a] See Fig. 4 for stratigraphic position.
[b] Large log in stratum (outer portion sampled).
[c] 2 sigma, IntCal04.
[d] Original sample collected by G. James West.
[e] Rejected-out of stratigraphic sequence.
[f] Not included in average age of lowest stratigraphic unit due to "old wood" effect.

Table 5
Raw, percent and pollen concentration values for AC-003 sediments.

Depth (cmbs) %	245	%	394	%	401	%	445.5	%	447.5	%	458	%	460	%
Pinus	11	15	43	37	98	38	65	41	37	29	62	38	49	26
TCT[a]	38	51	45	39	130	50	53	33	73	57	80	49	120	64
Quercus	13	17	12	10	12	5	6	4	4	3	2	1	0	0
Juglans	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Rhus	1	1	2	2	0	0	2	1	0	0	2	1	1	1
Rhamnaceae	1	1	3	3	0	0	5	3	2	2	3	2	0	0
Rosaceae	4	5	0	0	2	1	10	6	3	2	1	1	2	1
Artemisia	1	1	0	0	1	c	2	1	0	0	0	0	1	1
Aster Hi	0	0	0	0	2	1	13	8	0	0	2	1	0	0
Aster Low	1	1	4	3	4	2	0	0	1	1	5	3	5	3
Liguliflorae	0	0	1	1	0	0	1	1	0	0	1	1	0	0
Poaceae	5	7	3	3	5	2	0	0	1	1	2	1	5	3
Chenopodiaceae	0	0	0	0	6	2	3	2	3	2	3	2	1	1
Polygonaceae	0	0	1	1	0	0	0	0	2	2	0	0	2	1
Eriogonum	0	0	1	1	1	c	0	0	0	0	0	0	1	1
Apiaceae	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Salix	0	0	2	2	2	2	0	0	0	0	1	1	1	1
Cyperaceae[b]	7	6	0	0	2	1	0	0	0	0	0	0	1	1
Juncus[b]	28	25	0	0	6	0	3	2	4	3	0	0	0	0
Isoetes	0	0	0	0	0	0	0	0	0	0	1	1	2	1
Unkn/undiff	119	52	105	47	131	33	74	31	73	36	63	28	129	40
Grains/cc	5155		26,530		29,480		26,676		10,393		172,626		86,313	

[a] Juniperus–Cupressus.
[b] Outside pollen sum.
[c] Present <1%.

but there is no stratigraphic correlation and they all fall within the expected range if the pith wood of old trees burned in a wildfire. Conifer forest (*Pinus* and *Juniperus–Cupressus*) partly covered the landscape in the latest Ållerød (13–12.9 ka) according to the pollen evidence (Table 5), an observation consistent with pollen and macrobotanical evidence from Santa Cruz and San Miguel Islands (Chaney and Mason, 1930; Fergusson and Libby, 1964; Johnson, 1977; West, 1994; Anderson, 2002). Biomass burning at 13–12.9 ka was followed by erosion with sediments containing charcoal, wood, and detrital carbon filling the channel. This organic carbon-rich dark layer was then rapidly buried and preserved by a series of mass sediment wasting events of a denuded early YD landscape. Pollen grains are poorly preserved, highly eroded and corroded, and have been reworked in the upper deposits in this section. The upper 4 m of the deposit also date to between 13 and 12.9 ka indicating periodic fires and mass sediment wasting of the landscape in close succession in the early YD or rapid redeposition of material from the lowest burn layer in subsequent mass wasting events. If the latter, then the upper diffuse charcoal layers are not a proxy for fire activity, but a marker of sediment input from parts of the watershed burned at the YDB and deposited soon after this event during wet conditions promoting erosion. If the former, then the fires were clearly less intense and derived from already dead materials on the landscape. Regardless, it is clear that sediments accumulated rapidly during the early YD at this location after 12.9 ka and then stopped. This indicates that the channel incised soon after this catastrophic event, trapping the stream in the canyon for much of the YD and Holocene. The stratigraphic and chronological evidence from AC-003 clearly suggest mass sediment sediment wasting of the landscape in the wake of intense biomass burning. Only modest evidence for fire during the YD is evident in the nearby Soledad Pond sequence, a record that begins at ∼12.5 ka and is notable for the virtual absence of conifer pollen and the dominance of non-arboreal plant taxa (e.g., sunflower [*Asteraceae*], coyote brush [*Baccharis*]), suggesting that the transition to non-arboreal vegetation on Santarosae was rapid (Anderson, 2002, p. 10)

Evidence for intense wildfire and abrupt ecological disruption on the Northern Channel Islands is consistent with the vegetation and charcoal records from SBB ODP Site 893 (Heusser, 1995, 1998; Heusser and Sirocko, 1997), the longest and most continuous available for the Santa Barbara Channel region (Fig. 6). Pollen assemblages reflect vegetation changes on the adjacent coasts. These pollen records accumulated in Santa Barbara Basin sediments via eolian and water transport. This pollen spectrum is dominated by pine (*Pinus*) and juniper–cypress (*Juniperus–Cupressus*) during the LGM, and these conifers persisted in the region throughout the Bølling–Ållerød. Oak [*Quercus*] woodlands gradually expanded in the region after 16 ka suggesting increasingly warm, seasonally dry conditions during the Ållerød. The onset of the YD closely correlates with a major abrupt decline in the abundance of *Juniperus–Cupressus* pollen suggesting that these trees were abundant regionally before, but not after, ∼13–12.9 ka. Spikes in *Pinus* pollen during the early YD, after major reductions in *Juniperus–Cupressus*, suggest that it played a successional role in southern California coniferous forests (Heusser and Sirocko, 1997, pp. 243) and soon also diminished. This major reduction in the montane forest vegetation corresponded with a distinct increase in grass and herbs (mainly from the Asteraceae family), suggesting a regional shift to more open habitats dominated by grasslands, coastal sage, and chaparral communities with dispersed stands of oak; vegetation that dominates in the region throughout the YD and Holocene (Heusser, 1998). Range restrictions in *Juniperus–Cupressus* are unlikely a product of YD cooling given the abundance and extent of these taxa during the LGM. The YD is generally considered to be a dry interval in western North America relative to the Ållerød wet period (Allen and Anderson, 1993; Broecker, 1994; Benson et al., 1996). Gradual increases in oak pollen starting at 16 ka suggest that seasonally dry conditions were developing and were in place by the YD. *Pinus* events evident in the early YD indicate strong winter monsoon rains and dry, hot summers (Heusser and Sirocko, 1997, pp. 244). This is consistent with other western North American evidence that conditions at the Ållerød–YD boundary were seasonally wet (Haynes, 2008), at least during the early YD.

The abrupt reduction in conifers and the shift to more open habitats regionally correlates with the most extreme pollen minima and charcoal maxima of the last 25,000 years in ODP Site
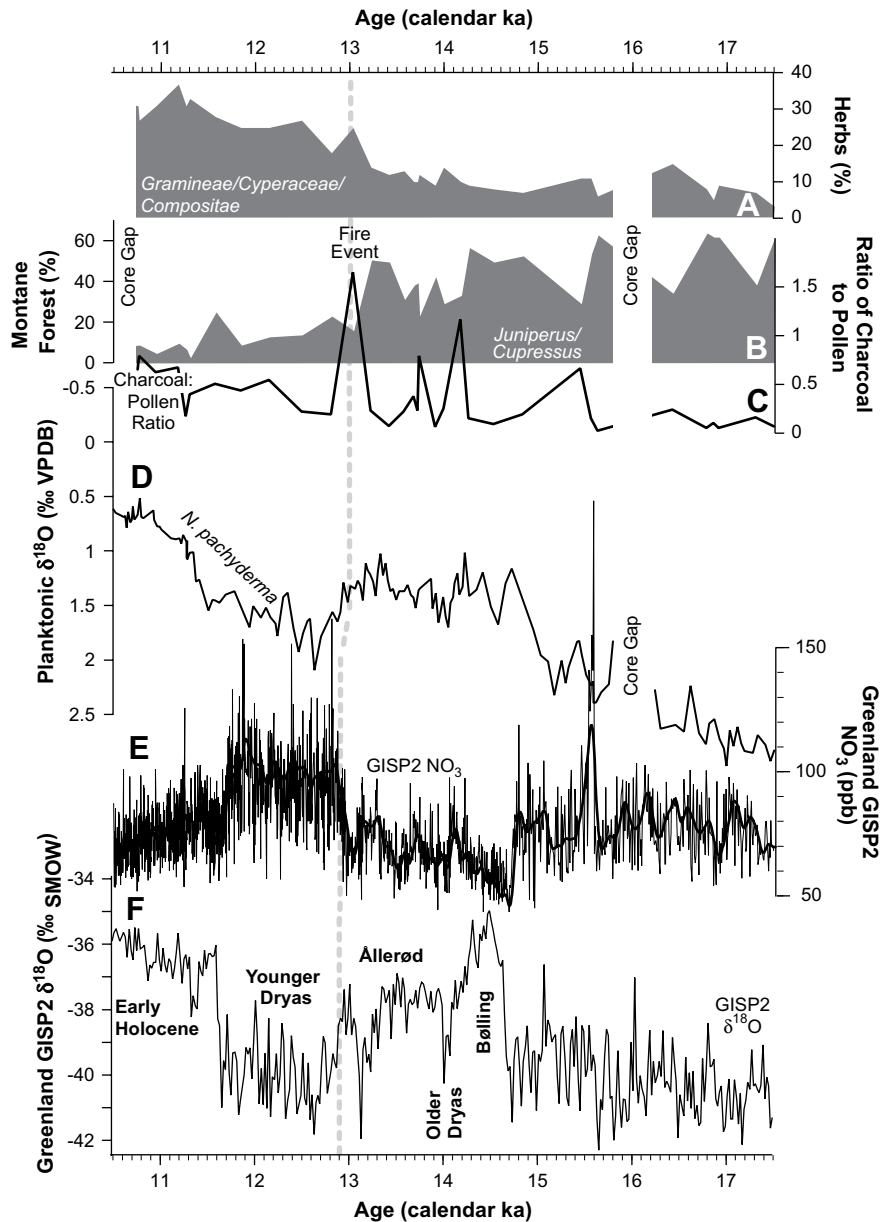
Fig. 6. Comparison of pollen records from Santa Barbara Basin with climate records from the Greenland Ice Core. [A] Percent abundance of Herbs (Gramineae, Cyperceae, and Compositae including *Artemisia* or sage), [B] percent abundance of montane forest Cedar types (*Juniperus–Cupressus*) and [C] the ratio of pollen to charcoal concentration [solid line] (Heusser, 1995). [D] The $\delta^{18}O$ record of *N. pachyderma* (Hendy et al., 2002), [E] the NO_3 concentration of the GISP2 ice core with the spline fit in a heavy black line (Mayewski et al., 1993) and [F] the GISP2 $\delta^{18}O$ record (Stuiver and Grootes, 2000). Gray dashed line marks the initiation of the Younger Dryas cooling event.

893, interpreted as a wildfire indicator (Heusser and Sirocko, 1997). This suggests rapid ecosystemic change in the wake of major regional wildfires and associated landscape disturbance. These changes are consistent with the record of wildfire from the upper Arlington Canyon section and evidence for abrupt change in island vegetation during the YD. Fuel build-up from Late Pleistocene conifer forests and gradual drying through the Bølling/Ållerød are indicated by the expansion of oak starting at 16 ka (Heusser and Sirocko, 1997) and would have contributed to the intense nature of this conflagration. The deeply buried dark layer (a sapropel) evident in the AC-003 section accumulated under wet conditions that contributed to the anoxia necessary to preserve the organic matter. Rapid deposition of sediments in the early YD is also consistent with increased precipitation transferring sediment from the surrounding denuded landscape. When the AC-003 sequence is considered within the context of existing Late

Quaternary vegetation and fire records for the islands (Anderson, 2002; Pinter and Anderson, 2006; Firestone et al., 2007), it appears that biomass burning at 13–12.9 ka was island-wide and marks a major shift in vegetation and fire regime. The SBB record extends the distribution of the biomass burning and associated shift in vegetation regionally. Organic carbon burial rates in Santa Barbara Basin increase at the beginning of the YD, a process linked to increase in ballast minerals and higher sedimentation rates (Nederbragt et al., 2008). Gradual increase in organic carbon deposition may be related to sea-level rise as the margins of SBB have been implicated as temporary storage areas (+200 years) for sediments without significant ballast. However, the large increase in organic carbon burial rates at the onset of the YD is also consistent with mass sediment wasting of the landscape in the wake of extensive biomass burning on the adjacent islands and mainland.

6. Discussion

Biological communities on islands are inherently fragile and animal populations are vulnerable to extinction. This is because breeding populations are small and isolated from mainland populations. Ecological perturbations, whether through natural environmental change, human-induced environmental catastrophes, or direct hunting, will have far greater effects on island ecosystems than on nearby, contemporaneous mainland faunas. Late Pleistocene biological communities on Santarosae were no exception. *M. columbi* was the only member of the mainland's diverse Rancholabrean fauna to colonize these offshore islands, probably significantly before 47 ka (Agenbroad, 1998). *M. exilis* resulted from evolution by natural selection in this insular environment and in the absence of predators (Agenbroad, 2002b). This species was highly adapted to this depauperate terrestrial environment as evidenced by its survival and persistence during the multiple abrupt warming and cooling episodes that marked the Late Quaternary (Hendy and Kennett, 1999).

The available data are support for a *M. exilis* extinction at ~13–12.9 ka (Agenbroad et al., 2005). Gradual changes in sea-level between 17.5 and 13 ka reduced island area by ~32%. The most rapid landmass decrease is evident during the Bølling/Ållerød, between 14.5 and 13.4 ka. If *M. exilis* populations were adapted to the coastal lowlands of Santarosae then this would have had a significant impact on the population (Agenbroad, 1998, 2002a). However, only modest sea-level rise occurred across the Ållerød–YD boundary and fragmentation of island habitats through formation of the four separate islands commenced later after 10.8 ka. Reductions in foraging range associated with sea-level rise between 17.5 and 13 ka certainly would have reduced *M. exilis* populations and increased their vulnerability to extinction. However, the modest habitat loss across the Ållerød–YD boundary cannot explain the seemingly abrupt extinction at 13–12.9 ka. Abrupt cooling evident in SBB ODP Site 893 is also an unlikely explanation for *M. exilis* extinction at 13–12.9 ka because previous cooling and warming episodes during the Late Quaternary were equally abrupt.

The earliest evidence presently known for a human occupation of Santarosae (at Arlington Springs) closely coincides with the last evidence for *M. exilis*. This coincidence forms the basis for the hypothesis that the extirpation of *M. exilis* was human induced (Agenbroad et al., 2005). Human-induced extinction of the largest, ecologically vulnerable, prey is well documented in similar island settings and occurs with clear evidence for human colonization, population increases, and dietary expansion (Anderson, 1989; Steadman, 1995; Patton, 1996). In these cases the bones of target species (e.g., Moa in New Zealand, Anderson, 1989) are found in early colonization sites and several hundred years pass before these animals were completely extirpated. This often occurs with clear evidence for expanding agricultural populations.

The skill and technology needed to hunt large animals was clearly present on the adjacent mainland between ~13.3 and 12.9 ka (Erlandson et al., 2007; Rondeau et al., 2007). Behavioral ecological theory predicts that these large animals would have been targeted when humans colonized these islands (Kennett, 2005, p. 220), but there is yet no direct evidence that these animals were hunted. Orr (1968) argued for the coeval existence of *M. exilis* and humans on Santarosae as early as 40,000 years ago. In a series of controversial articles, Orr and Berger argued that the close physical association of mammoth bones, crude stone tools and "hearths" indicated a clear Pleistocene occupation of the island by humans (Orr and Berger, 1966; Berger and Orr, 1966; Berger, 1980, 1982). Subsequent work suggested that the associations of flaked tools and bones could have easily resulted from natural processes, and some of the fire areas (hearths) may have been a product of chemical weathering (Johnson, 1972). In fact, close to a century of paleontological and archaeological work has failed to locate a single *M. exilis* kill locality. Of the 140 *Mammuthus* localities identified in a recent comprehensive survey of these islands (Agenbroad, 2002b), there are no reported bones with cut marks or human artifacts associated with them. No early colonization sites containing the bones of these animals have been identified. However, because none of these localities has direct ^{14}C dates the 140 mammoth localities recorded theoretically span a long period of time (13 ka to >50 ka). If humans were recent occupants of the Santarosae (13.1 ka), only a small number of *Mammuthus* specimens would overlap with human presence. The taphonomy of deposition is also against discovering kill sites. Bones in upland kill sites would disintegrate rapidly unless they were rapidly redeposited, and if so, this would scatter artifact evidence widely. However, the Clovis-like spear point technology present on the California mainland has not been found on these islands. Even with the problems associated with site burial or loss related to sea-level rise (Kennett, 2005), the complete absence of evidence that these animals were hunted is puzzling and currently inconsistent with the human overkill hypothesis.

At present, the Arlington human skeletal material provides the only direct evidence for human presence on Santarosae at ~13.1–12.9 ka. The partial remains of this individual occur in a small arroyo that filled with sediment during the YD then was later exposed near the mouth of the modern Arlington drainage. Although it is possible that Santarosae was permanently occupied by this time there is currently no evidence for other archaeological sites that would suggest a large population. The presence of humans on this offshore island is unequivocal evidence that peoples living along the mainland coast of western North America possessed boats and advanced maritime technologies. If primary settlements were located along the coast of Santarosae and were submerged or destroyed during sea-level rise, this would suggest a maritime adaptation rather than one focused on the hunting of large game animals. The current absence of interior kill sites seems consistent with this interpretation.

A possible gap in the record during much of the YD ends at ~12.2 ka with evidence for Paleoindian occupations of Cardwell Bluffs and Daisy Cave on western Santarosae (San Miguel Island; see Erlandson, 2007; Erlandson et al., in press). This time gap is partly explained by fluctuations in the radiocarbon calibration curve in the early YD, including a plateau of ~200 years (Muscheler et al., 2008). These fluctuations can make events and gaps in the record look more or less abrupt and calibrating radiocarbon dates is essential (Bartlein et al., 1995). Regardless, more extensive evidence for human occupation of Santarosae is only seen in the proliferation of terminal Pleistocene and Early Holocene shell middens between 10.2 and 9 ka—sites associated with evidence for a maritime adaptation (Rick et al., 2005; Erlandson et al., 2007). Solid evidence for human occupation of the islands preceded the stabilization of sea-level and loss of coastal habitat by ~4000 years, with numerous early sites found in caves, near fresh water springs, and around toolstone sources that drew maritime peoples away from now submerged shorelines. This suggests that the evidence for earlier human occupation is not entirely lost to Late Quaternary sea-level rise and coastal erosion. Data from ODP Site 893 indicate that marine productivity remained at least seasonally high along the California margin during the YD and terrestrial climate records from North America suggest that the early part of this interval was likewise seasonally moist. The absence of evidence for a human presence on Santarosae is therefore unlikely to be a product of climate-driven decreases in marine or terrestrial productivity.

Beyond Santarosae there is currently little evidence for a substantial population in California during the YD (Jones et al.,

2002; Erlandson et al., 2007). Clovis-like fluted points have been identified at 51 locations (see Fig. 1a), representing nearly every type of environmental setting—except the Channel Islands (Dillon, 2002; Rondeau et al., 2007). There remains some uncertainty about the chronology of Clovis-like points in California. Only two sites, Borax Lake (LAK-36; Meighan and Haynes, 1970) and Skyrocket (CAL-629/630; Bieling et al., 1996) have produced Clovis-like points stratigraphically below Early Holocene occupation levels. In both cases, radiometric dating of these deposits is uncertain, but they clearly pre-date Early Holocene materials based on superposition (Skyrocket) and obsidian hydration measurements (Borax Lake). No archaeological sites in mainland California have been convincingly radiocarbon-dated between 12.9 and 12 ka and only a few date between 12 and 11 ka. In contrast, more than 38 sites have produced radiocarbon evidence for occupation between 10.5 and 9 ka (see Erlandson et al., 2007). The vast majority of these sites provide no evidence for earlier Pleistocene occupation. The earliest archaeological record from California is therefore marked by a possible gap between the Late Pleistocene and the Early Holocene. If the age of fluted projectile points in California equates with the recently revised age for Clovis over North America (Waters and Stafford, 2007, p. 1123) of ∼13.3–12.9 ka, then this could represent a depression in mainland human occupation that extends between ∼12.9 and 10.5 ka. While the chronology of this hiatus remains poorly defined, the time gap between the Clovis-like fluted point tradition and Early Holocene records is widespread and remarkable (Jones, 2007). Much more work is needed in California. We simply point out that there is currently an absence of archaeological sites dating to much of the YD and the millennium following it, which is potentially consistent with broader-scale ecosystem disruption at 13–12.9 ka.

Wildfire, mass wasting, and reduction in forage at 13–12.9 ka are possible mechanisms for abrupt *M. exilis* extinction on Santarosae, a scenario in which human hunters could still have played some 'coup de grace' role. These intense wildfires occurred after a substantial build-up of fuel from Late Pleistocene conifer forests and in the context of regional drying that started ∼16 ka. Human-induced fires and associated habitat loss are among several inter-linked mechanisms proposed for large herbivore extinction in Madagascar (Burney, 1993; Burney et al., 2003). These extinctions occurred in the Late Holocene (after 1.7 ka) in association with expanding agricultural populations and clear human trans-formation of the landscape. The purposeful use of fire for land clearing is well known in agricultural societies (Posey, 1985; Piperno et al., 1991; Smith, 2001; Kennett et al., 2006a,b). Hunter–gatherers are known to use fire to alter landscapes for economic purposes (Yen, 1989) and this was well documented historically in California (Anderson, 2005). However, the apparent low human population levels on Santarosae at ∼13.1–12.9 ka and major conflagrations are generally inconsistent with resource manage-ment and the hypothesis that these fires were of anthropogenic origin (*contra* Pinter and Anderson, 2006).

The organic carbon-rich sediments at the base of the AC-003 sequence containing wildfire proxies co-occur with regional evidence for wildfire and ecosystem disruption in the form of major vegetation shifts and animal extinction on the islands and possibly more broadly in southern California (Marcus and Berger, 1984). The age of this deposit is equivalent (∼13.0–12.9 ka) to the base of a distinctive black layer (YDB) found broadly across North America at 70 localities (Haynes, 2005, 2008). Dark sedimentary layers can develop locally for a variety of natural and anthropogenic reasons (see Quade et al., 1998), but this dark, geographically extensive layer occurs directly above extinct Pleistocene animal remains (Haynes, 2005, 2008). Clovis artifacts associated with the remains of select fauna occur in terminal Pleistocene alluvial or spring deposits and are also capped by this distinctive black sedimentary

layer at Blackwater Draw, NM, Murray Springs, AZ, Lehner, AZ, UP Mammoth, Colby, and Domebo (Holiday, 1985; Taylor et al., 1996; Haynes, 2005, 2007, 2008) and other Clovis-age sites (Lubbock Lake, TX; Holiday, 1985). The base of this dark stratum at Murray Springs (AZ, Clanton Ranch member—Stratum F1): is well dated to between 13 and 12.9 ka; it marks a major and continent-wide biostratigraphic change; and it serves as a major boundary with Pleistocene fauna occurring directly below and never above this easily discernable bed (Haynes, 2005). This black stratum (termed the Black Mat) contains organic matter derived from oxidized plant material and algae suggesting a shallow pond or marshy environ-ment (Haynes, 2007, p. 45). Petrographic work indicates the pres-ence of charcoal, vitreous carbon, vitrinite, and spores. Pyrolysis-GC/MS analysis suggests that the organic matter was derived from aromatic biomolecules typical of mature coals or burned wood fragments (Haynes, 2007, p. 245, report by Stankiewicz and Tege-laar). These characteristics are consistent with intense wildfires indicated by the presence of soot in this same stratum (Firestone et al., 2007). Hemispheric biomass burning is also indicated at the onset of the YD by large increases in ammonium and nitrate values in the Greenland GISP2 ice core (Mayewski et al., 1993, 1997; see Fig. 6).

Two independent research groups have now identified peaks in metallic microspherules at the base of this distinctive black layer (YDB) at Murray Springs (Firestone et al., 2007; Haynes, 2008). Preliminary work indicates that the abundance of microspherules at Murray Springs and at many other localities in North America co-occur with other apparent cosmic impact markers (e.g., above background concentrations of iridium; Firestone et al., 2007). Elevated iridium levels correlate with extensive wildfire at the K/T boundary (Köeberl, 2007, p. 33; Wolbach et al., 1985). The recog-nition of mass extinction at the K/T boundary attributed to a major extraterrestrial impact along with the presence of a significant number of the same cosmic impact markers identified in the YDB provide an empirical basis for hypothesizing that the massive North American animal extinctions may have resulted from the direct effects of a cosmic impact (shockwave, heat, flooding, and wildfires) and subsequent cascading ecological changes associated with rapid climate change. This viable and testable hypothesis seems consis-tent with the evidence for wildfire, ecosystem disruption, animal extinction, and human population reduction on the Channel Islands and possibly more broadly in California. It is hypothesized that wildfires were ignited broadly across the continent and resulted from multiple aerial impacts that produced a severe radiation flux represented by intense fireballs distributed widely (Firestone et al., 2007). The evidence for biomass burning at the YDB in the Santa Barbara channel region is consistent with the hypothesis of broad continental biomass burning at this time. Furthermore the evidence for such a conflagration on Santarosae Island, a relatively small and isolated landmass supports the possibility that such an airburst barrage included the southern California region.

7. Conclusions

A dark black, deeply buried organic carbon-rich layer in Arlington Canyon (AC-003), dating to the Ållerød–YD boundary (13–12.9 ka), has produced high concentrations of charcoal, "elongate" carbon particles, and carbon spherules indicative of intense biomass burning on Santarosae at this time. This was fol-lowed by landscape mass sediment wasting that continued into the early YD. Near consistency of radiocarbon ages throughout much of the ∼5 m sediment sequence indicates that these sediments accumulated rapidly during the early YD. Later fires during this interval are recorded by thin charcoal-rich layers also containing charcoal, glass-like carbon, and "elongate" carbon particles, although these materials could have been redeposited following

the erosion of original YDB sediments located upslope or upstream. It seems unlikely that a very small population of hunter–gather–fisher peoples triggered these wildfires. The absence of a range of other archaeological site types contemporary with the Arlington human skeleton suggests this early human presence was small and is inconsistent with extensive use of fire to transform landscapes for subsistence purposes. The possible absence of humans on the islands for 600–800 years following these wildfires is also inconsistent with anthropogenic burning. Finally, although there were clearly episodic wildfires on the Northern Channel Islands throughout the LGM and the Holocene, the intensity of the conflagration at 12.9 ka suggests that a fundamentally different process may have occurred at the YDB.

The last known occurrence of *M. exilis* on Santarosae is 13–12.9 ka (Agenbroad et al., 2005). *M. exilis* populations were small and almost certainly would have contracted with coastal plain habitat loss associated with sea-level rise between 19.5 and 13 ka (Agenbroad, 2002b). However, the fragmentation of Santarosae into its four modern islands did not occur until after the YD (∼10.8–9 ka) and there were no abrupt losses of habitat at 13–12.9 ka to trigger final extinction. Abrupt cooling at the onset of the YD in the SBB ODP Site 893 record is similar in magnitude to earlier abrupt climatic episodes during the Late Quaternary and thus does not help explain final extinction. The co-occurrence of the first evidence for human exploration of Santarosae and/or the terminal age of *M. exilis* is tantalizing. Human predation pressure or anthropogenic ecosystem disruption is a plausible hypothesis in this insular environment (Agenbroad et al., 2005; Kennett, 2005; Pinter and Anderson, 2006). However, there currently is no evidence for significant human presence on the island before 13.1–12.9 ka. This near lack of evidence cannot simply be explained as resulting from sea-level inundation of coastal plains. Humans were clearly present on the Channel Islands and throughout California between 13.1 and 12.9 ka. There is negligible evidence for human populations on the islands or elsewhere in California during most of the YD. This provides an empirical foundation for hypothesizing that there were major reductions in human populations during the YD. This hiatus is not easily explained by abrupt cooling given that the average temperature drop was only a few degrees Celsius in coastal California and particularly because marine conditions remained relatively productive through this interval.

Wildfire and mass sediment wasting of the landscape in Arlington Canyon are synchronous with evidence for wildfires at Daisy Cave on San Miguel Island (Firestone et al., 2007) and "megafires" elsewhere on Santarosae at ∼13 ka (Pinter and Anderson, 2006). They also appear to be synchronous with a peak in the charcoal/pollen ratio in the SBB ODP Site 893 interpreted independently as a regional biomass burning event including the adjacent mainland (Heusser and Sirocko, 1997). The distinctive dark layer at AC-003 in Arlington Canyon also correlates in time with other dark sedimentary layers distributed widely in North America marking the Allerød–YD boundary (Haynes, 2008). Wildfire indicators (e.g., soot, glass-like carbon, and carbon spherules) occur in this layer with other exotic materials (e.g., magnetic spheres; Firestone et al., 2007; Haynes, 2008). This is consistent with the hypothesis that wildfires in southern California and elsewhere on the continent were ignited by an intense radiation flux associated with multiple airbursts resulting from a cosmic impact (Firestone et al., 2007). Hemispheric wildfires also increase abruptly at the beginning of the YD (Mayewski et al., 1993, 1997). The synchrony and geographic extent for wildfire in North America at 13–12.9 ka is inconsistent with human-induced fire, the growing evidence for Pre-Clovis occupations of the continent (Gilbert et al., 2008; Goebel et al., 2008), and the abrupt extinction of *Mammuthus* and additional Pleistocene animals. Based on current evidence, we argue that the synchronous and abrupt nature of wildfire and Pleistocene

animal extinction on Santarosae and more broadly in North America are more consistent with the YDB cosmic impact hypothesis (Firestone et al., 2007) than any other hypotheses explaining Late Pleistocene megafauna extinctions.

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