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An examination of possible relationships between paleoenvironmental conditions during the Pleistocene–Holocene transition and human occupation of southern Patagonia (Argentina) east of the Andes, between 46° and 52° S

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ABSTRACT

Spatial and temporal variations in evidence for human occupation of Argentinian south Patagonia closely resemble changes in past vegetation reconstructed from pollen records. The Antarctic Cold Reversal was cold and dry in the Deseado Massif and there is little evidence of humans at this time. In contrast, the Younger Dryas interval was warmer and slightly wetter and this was when humans moved into the Deseado area. Increasing temperatures during the early Holocene brought higher precipitation to much of Patagonia east of the Andes except the northern Deseado Massif, explaining the increase in evidence of human occupation in western areas and the decrease in evidence in the massif. Spatial and temporal variations in the frequency of radiocarbon dates indicating human presence, show that in southern Patagonia humans were not only influenced by the major climate shifts of the Pleistocene–Holocene transition but possibly also by distinct short-term changes lasting only a few to several centuries that are apparent in the high-resolution Antarctic Byrd ice core. Water availability may have had the greatest influence on human use of the landscape rather than temperature. However, as temperature is crucial in controlling the latitude of the core of the Southern Westerly Winds, associated with reduced precipitation over most of eastern Patagonia, it is difficult to separate water from temperature in examining impacts on the first humans in southernmost South America.

1. Introduction

The Patagonian region has been one of the most relevant areas for studies of the peopling of South America and the interpretation of human–environmental interactions during the Late Pleistocene and the Early Holocene (e.g. Borrero, 1999; Coronato et al., 1999; Miotti and Salemme, 2004; Paunero et al., 2007; Salemme and Miotti, 2008; Paunero, 2009; Ariztegui et al., 2010). The Deseado Massif and the Magellan basin have been especially important as these areas have produced the oldest dates for human occupation of south Patagonia (e.g. Miotti and Salemme, 2004; Paunero et al., 2007; Salemme and Miotti, 2008; Paunero, 2009). The first occupants would have needed time to learn about and adjust to the new environment, including its physical features – i.e. water availability and seasonal variations, as well as the location and availability of raw materials (e.g. Kelly, 2003; Meltzer, 2003; Steele and Rockman, 2003). The length of time needed for this to happen would vary and depend on the homogeneous/heterogeneous nature of the landscape and its similarity/difference with the landscape/s from which the new inhabitants had come.

According to Salemme and Miotti (2008, p. 456) the human colonization of Patagonia was both continuous and discontinuous with periods of rapid movement of people and widespread occupation followed by periods of stasis. They suggest that there were probably two reasons for this pattern: environmental conditions and choices made by humans from the options available to them. This paper focuses on the possible effects of variations in environmental conditions on hunter-gatherer strategies. In order to do this we examine in detail the evidence for human occupation, and

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using the frequency of radiocarbon ages as a proxy, the intensity of human occupation in Argentinian southern Patagonia using archaeological data from the area between 46° and 52° S. Our objective is to assess the degree to which variations in archaeological visibility in particular areas can be linked to climate conditions. If we find a correlation this might suggest that environmental conditions influenced the decisions that humans made (e.g. to move to an area with more reliable water or to change how different spaces were used) and thus played a role in how humans spread through this area.

Using pollen data, we have recently summarized some of the environmental changes that occurred and the probable effect these might have had on human populations in the Deseado Massif (Mancini et al., 2013). In this paper we will focus on comparing temporal and spatial variations in radiocarbon ages that document human occupation east of the Andes, between ~46° and 52°S, with paleoenvironmental data from the Antarctic Byrd and Greenland GISP2 ice cores, and pollen data from peat bogs and archaeological sites. We will examine the extent to which climate changes at the Pleistocene–Holocene transition may have affected human choices during the earliest occupation of this area. Specifically, we examine the possible impacts on humans of major climate intervals such as the Antarctic Cold Reversal (ACR) and Younger Dryas (YD) but also "minor" climate intervals such as the cold intervals in the Byrd ice core centered at ~10.4 and 10.9 cal ka BP (Blunier et al., 1997; Blunier and Brook, 2001). By doing this we hope to determine if there is any evidence that the major, relatively long lasting climate intervals impacted human activities. We will also try to assess whether shorter and less-pronounced periods of climate change affected humans and what their impact was.

Borrero (1989–90) defines exploration as the initial radiation of humans into uninhabited areas and has described the possible locations of the first occupation sites and the likelihood that they will be discovered. At this stage we have limited our interest only to the presence of humans and how intensively the sites were used. We use radiocarbon ages to indicate presence and the frequency of radiocarbon ages as a proxy measure of intensity of use.

2. Climate changes during the Late Glacial–Holocene transition

There has been considerable debate as to whether the rapid and profound climate changes that affected southern South America during the Late Glacial–Early Holocene are equivalent to those that occurred in the Northern Hemisphere (Heusser and Rabassa, 1987; Heusser, 1989, 1993; Markgraf, 1989, 1991, 1993; Bennett et al., 2000; Moreno et al., 2001; Ackert et al., 2008). There is also no clear consensus on whether climate changes affected humans as they colonized the region and if they did what impact they had (e.g. Borrero, 2012; Dillehay, 2012). Several distinct periods of climate are usually recognized including the ACR in the Southern Hemisphere, and the Bølling-Allerød (BA), and YD in the Northern Hemisphere. Pollen records confirm that vegetation and fire regimes in southern Patagonia varied on millennial timescales during these events (e.g. Lamy et al., 2010; Fletcher and Moreno, 2011).

Blunier et al. (1997) synchronised the Greenland GRIP and Antarctic Vostok and Byrd ice core records using methane content to show that the ACR of the Southern Hemisphere preceded the YD of the Northern Hemisphere by at least 1800 years lasting from ca. 14.5–12.7 cal ka BP, while the YD lasted from ca. 12.7–11.5 cal ka BP. Analysis of ocean and land proxy climate records for the period 15 to 11 cal ka BP indicates that northern and southern modes of climate variability characterized the YD – BA interval (Shakun and Carlson, 2010). These modes dominate at higher latitudes in each hemisphere so the magnitude of the YD climate anomaly increases with latitude in the Northern Hemisphere (cooler/drier), with an opposite YD pattern (warmer/wetter) in the Southern Hemisphere.

It has been suggested that the ACR was triggered by warming at southern high latitudes that produced an Antarctic meltwater event. This increased Atlantic Ocean thermohaline circulation producing Northern Hemisphere warming during the B–A from ~14.5 to 13 cal ka BP (Bianchi and Gersonde, 2004). Subsequent YD cooling in the Northern Hemisphere shut down the Atlantic thermohaline circulation resulting in warmer conditions in the Southern Hemisphere that reached a postglacial maximum temperature around 11.5 cal ka BP (Bianchi and Gersonde, 2004). Thus, although the YD was a period of marked global climate change, it was not a global cooling event and in fact at high-latitudes in the Southern Hemisphere, including Argentinian Patagonia, temperatures increased (Shakun and Carlson, 2010). In the following sections we will refer to the YD with the understanding that in the Northern Hemisphere this was a cold event while in Patagonia it was a period of increasing temperatures.

3. Study area

Patagonia is underlain mostly by sedimentary and volcanic rocks of Mesozoic and Cenozoic age that form a series of progressively lower plateaus eastward from the Andes (Soriano, 1983). From north to south these plateaus are crossed by rivers such as the Deseado, Chico, Santa Cruz and Coyle that flow from the Andes to the Atlantic. South of the Deseado Massif there are several low plateaus formed by inter-bedded lava flows and till deposits (Coronato et al., 2008). Proximity to the Antarctic continent means that Patagonia's climate is arid to semi-arid, and cool to cold, with mean annual temperatures decreasing from 12 °C in the north to 3 °C in the south (Soriano, 1983; Paruelo et al., 1998). Climate is influenced mostly by Pacific Ocean air masses forced inland by the Southern Westerly Winds (SWW). The Andes Cordillera between the moist air to the west and the Patagonian steppes to the east creates an extensive rain-shadow that controls climatic patterns (Paruelo et al., 1998). There is a very steep gradient of mean annual precipitation, decreasing towards the east, from 1000 mm in the Andes eastern foothills to less than 200 mm in the central plateau (Soriano, 1983).

Along the wetter eastern slopes of the Andes between 800 and 400 mm mean annual precipitation supports deciduous forest of *Nothofagus antarctica* and *N. pumilio*. East of the 400 mm isohyet, grass, shrub and dwarf shrub steppes have developed in areas with glacial terminal and lateral moraines and a highly variable precipitation (Movia et al., 1987). Extra-Andean Patagonia is an area of semi-arid grass and shrub steppes with dwarf-shrub communities in the drier areas of the central plateau (León et al., 1998; Roig, 1998). The dwarf-shrub steppe is characterized by woody elements of low height and cover which have evolved remarkable adaptations to cope with severe water deficits (León et al., 1998).

Within the study area there are marked spatial variations in the distributions of caves, rock shelters and lithic raw materials of excellent flint knapping quality. The Deseado Massif has the oldest human occupation sites in our study area. The massif is dominated by closed depressions in volcanic rocks that may contain seasonal lagoons and occasionally permanent bodies of water. In the north, the Deseado River drains eastwards into the Atlantic Ocean, while to the south of the massif there are seasonal streams. In the southern Deseado Massif caves are abundant while the availability of water is highly dependent on annual rainfall amount and seasonality (Paruelo et al., 1998). In contrast, south of the Deseado Massif, caves are less common in the extensive areas underlain by basalt but springs and small streams in canyons cut in the basalt are a reliable source of water (e.g. Russo and Flores, 1972; Russo et al., 1980; Panza and Franchi, 2002; Cobos et al., 2004).

The Deseado Massif has abundant raw materials including silicified ignimbrites, silicified wood, tuffs and epithermal quartz veins of the Chon Aike and La Matilde Formations (e.g. Panza and Marin, 1998; Panza and Haller, 2002; Echeveste, 2005). Chalcedonies, jasper and opal are also available in some areas. Overall, the region has numerous caves as well as excellent raw materials for high-quality flint knapping (e.g. Cattáneo, 2000; Paunero et al., 2007; Paunero, 2009; Skarbun, 2009) that have been transported over distances of more than 150 km (Franco and Cirigliano, 2009; Franco et al., in press-a). Pampa del Asador, west of the massif, is the only recognized source of black obsidian (Stern, 2000) and this raw material has been transported over longer distances than other raw materials (e.g. Civalero and Franco, 2003). Early humans in south Patagonia are known to have used high quality rocks (e.g. Skarbun, 2009), and it has been suggested that high-quality raw materials were extremely important during the exploration of environments, especially for the manufacture of bifacial tools (Steele and Rockman, 2003).

4. The archaeological record

In this study we consider radiocarbon ages associated with human artifacts to be evidence of when humans were using a site and region, and we assume that the frequency of ages is an indication of the intensity of human presence. We have used variations in the frequency of ages to assess both temporal and spatial variations in human presence in our study area by comparing patterns and frequencies during four time periods: a) prior to 13 cal ka BP, b) between 13 and 11 cal ka BP, c) between 11 and 10 cal ka BP, and d) between 10 and 8 cal ka BP (Fig. 1). These time periods were selected for study because there are distinct differences between them in terms of the total number and/or the spatial distribution of the radiocarbon ages. The two oldest periods correlate approximately with the ACR and YD, the two youngest with maximum warming, and the following period of cooling during the early Holocene. Radiocarbon ages in radiocarbon years BP (^{14}C yr BP) were calibrated using CALIB 6.0

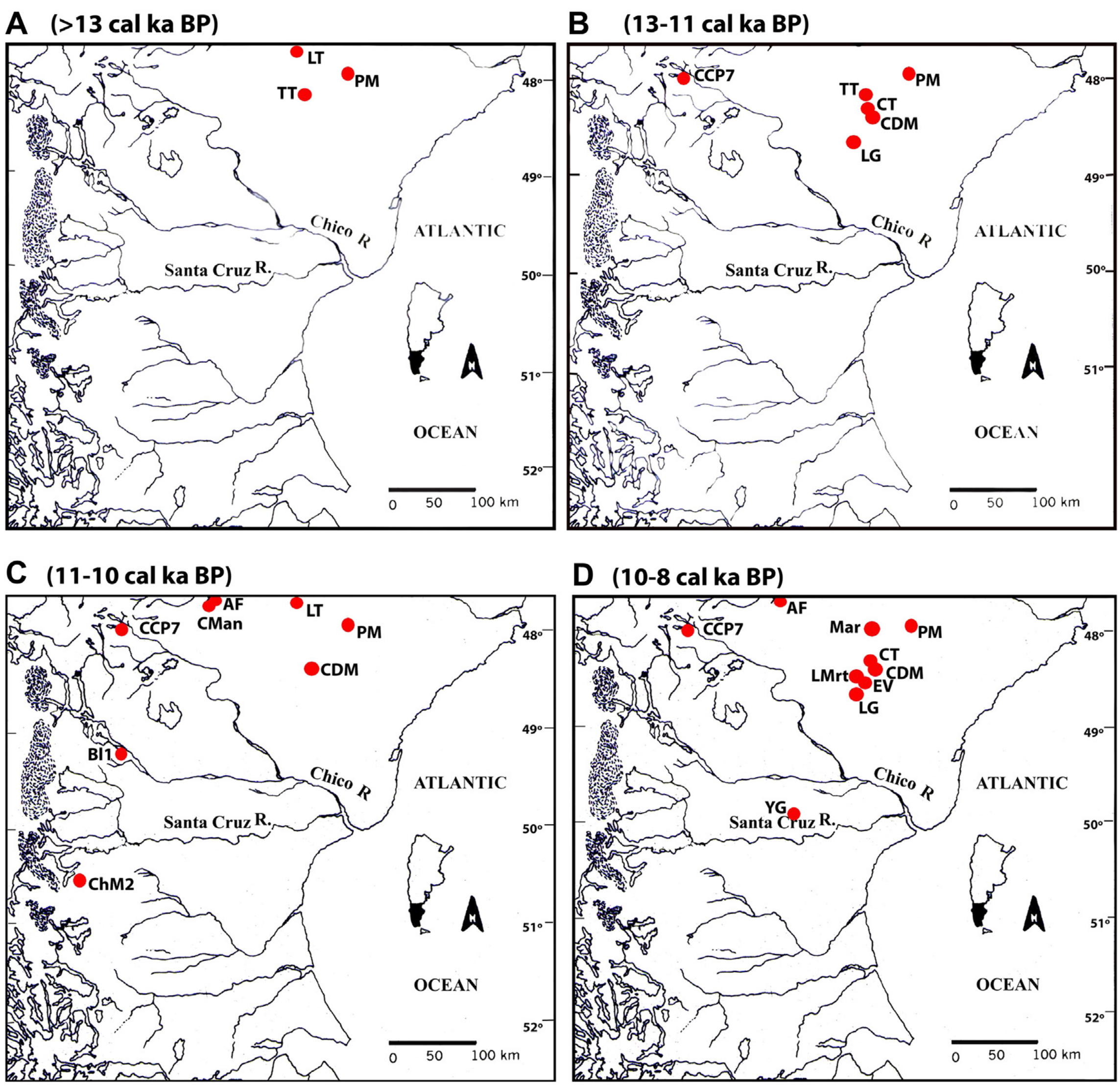

Fig. 1. Archaeological sites with radiocarbon ages indicating human occupation during different periods of the Pleistocene–Holocene transition. (A) > 13 cal ka BP, (B) 13–11 cal ka BP, (C) 11–10 cal ka BP, (D) 10–8 cal ka BP. Sites are: LT: Los Toldos, PM: Piedra Museo, TT: Cerro Tres Tetas; CMan: Cueva de las Manos, AF: Cueva Grande del Arroyo Feo; CDM: Casa del Minero, La Mesada and Cueva de la Ventana (La María locality); CCP7: Cerro Casa de Piedra 7; CT: Cueva Túnel; Mar: Cueva Maripe; Bl1: Bloque 1 Oquedad; LMrt: La Martita; EV: El Verano; LG: La Gruta 1; YG: Yaten Guajen; ChM2: Chorrillo Malo 2.

(Stuiver and Reimer, 1993). The SHCal04 Southern Hemisphere calibration curve of McCormac et al. (2004) was used to calibrate samples younger than 11 cal ka BP and the IntCal09 calibration curve based on Northern Hemisphere data was used for samples older than this (Reimer et al., 2009). Calibrated ages, including previously published ages that were re-calibrated for consistency, are in calendar years BP (cal BP) or calendar 10^3 ka BP (cal ka BP).

There are very few sites in the Deseado Massif with ages earlier than 13 cal ka BP (Fig. 1A). Ages have been obtained from sites in the north, central and south Deseado Massif, although there are problems with the ages from Los Toldos in the north and Piedra Museo in the central region as neither has been replicated by other dated samples. There is more reliable evidence of human occupation from the central and south Deseado Massif at least by 13 cal ka BP (Fig. 1B). In the west, the evidence of human presence ~13–11 cal ka BP is scanty, being limited to Cerro Casa de Piedra 7.

Between 11 and 10 cal ka BP there is evidence of human occupation in the Deseado Massif and in the west, at or near the forest-steppe ecotone, where evidence of human presence is more abundant that during earlier times (Fig. 1C). To the south, at Bloque 1 Oquedad (south of Lago San Martín) and Chorrillo Malo 2 (south of Lago Roca and Lago Argentino) there is clear evidence of human presence but we don't know for certain where the people in the area south of Lago Argentino came from. The presence of black obsidian beneath the oldest dated deposits at Chorrillo Malo 2, which according to geochemical analysis by Stern (2000) came from the Pampa del Asador area, suggests contacts to the north (Franco, 2004). By this time, there is also evidence of early occupation of the Magellan basin (e.g. Borrero, 1999; Miotti and Salemme, 2004).

From 10 to 8 cal ka BP the number of sites showing evidence of occupation increased (Fig. 1D), particularly in the Deseado Massif (e.g. La Gruta 1, El Verano, La Martita, Cueva Maripe, Casa del Minero, La Mesada, and Cueva de la Ventura) but also in the basalt canyons south of the Chico River (e.g. Yaten Guajen 12), close to small hills that could be seen from some distance. Much of this increase in occupied sites may have been due to a natural increase in the population but some could be due to movements of humans into these areas from outside. Human occupation was discontinuous at some sites (e.g. Chorrillo Malo 2, cf. Mehl and Franco, 2009; Franco and Borrero, 2003).

Spatial variations in the evidence for human occupation shown in Fig. 1, and described briefly above, will now be examined in light of the latest information on environmental changes, principally climate and vegetation, during the Pleistocene–Holocene transition. In particular, we will examine the possible impact of changing climate on human use of space.

5. The paleoenvironmental record from pollen data

Vegetation responses to climate changes around the time of the Pleistocene–Holocene transition have been reconstructed by compiling pollen records from sites located between 46° and 50°S in the Andean region and Deseado Massif in Santa Cruz Province (Table 2, Fig. 2). Some of the pollen data are from the peat bogs at La Tercera near Lago San Martín (Bamonte and Mancini, 2011), and Cerro Frías, south of Lago Argentino (Mancini, 2009). Other data are from archaeological sites in the Deseado Massif (e.g. Mancini, 1998; Borromei, 2003; de Porras, 2010) and the Andean area (Mancini, 2002, 2007; Mancini et al., 2012a, c). The interpretations of the fossil sequences are based on comparison with present-day pollen assemblages from different vegetation communities (Bamonte and Mancini, 2011; Mancini et al., 2012b).

Representative variables of the main vegetation units at each site, obtained through pollen analysis, are plotted in Fig. 3. Based on these data and on the interpretation of the sequences (Mancini,

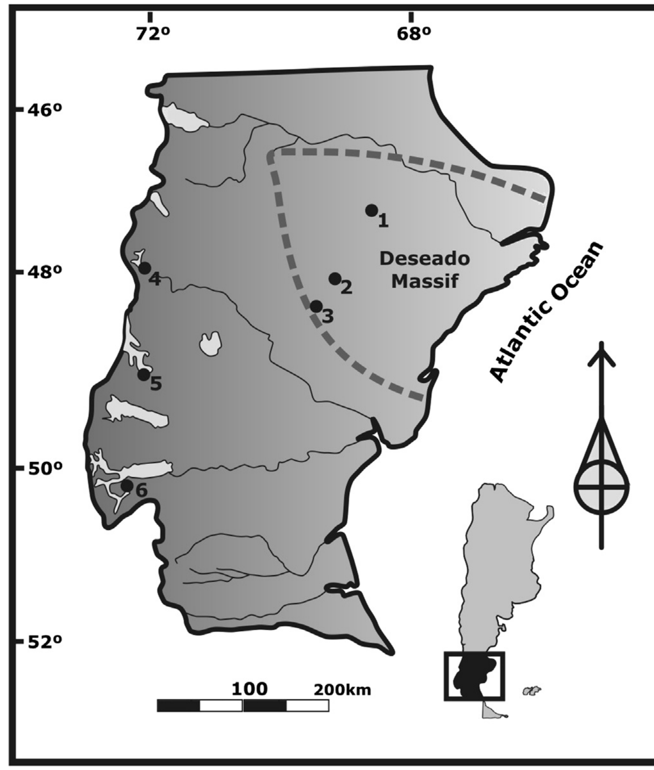

Fig. 2. Location of wetland (mallines) and archaeological sites between 46° and 50°S in the Andean region and Deseado Massif that were used in determining spatial and temporal variations in vegetation during the Pleistocene–Holocene transition. 1 – Los Toldos; 2 – La Martita Cave 2; 3 – La Gruta 1; 4 – CCP7; 5 – La Tercera; 6 – Cerro Frías.

1998, 2007, 2009; Paez et al., 1999; de Porras, 2010; Bamonte and Mancini, 2011; Mancini et al., 2013), vegetation was reconstructed for the periods 13–11 cal ka BP, 11–10 cal ka BP, and 10–8 cal ka BP (Figs. 3 and 4). However, the spatial variability of vegetation prior to 13 cal ka BP could not be reconstructed effectively because there are very few sites with data for this period. These time periods conform to major climate intervals during the Pleistocene–Holocene transition (>13 cal ka BP – ACR; 13 – 11 cal ka BP – YD; 11–10 cal ka BP – reduced sea ice and maximum temperatures in Antarctic ice; 10–8 cal ka BP – increase in sea ice and declining temperatures in Antarctic ice – e.g. Byrd – Blunier and Brook, 2001 and Dome C – Jouzel et al., 2001; Bianchi and Gersonde, 2004) and it is important to evaluate how these may have influenced the initial entry of humans into the study area and their subsequent use of it.

Before 13 cal ka BP pollen sequences from the Los Toldos (northern Deseado Massif, Fig. 3) and La María archaeological localities (Casa del Minero, southern Deseado Massif – Paunero, 2003; de Porras, 2010) show a dwarf-shrub steppe with high values of *Ephedra* suggesting arid conditions with annual precipitation less than 200 mm. These vegetation communities have no present-day analogs. The Piedra Museo sequence, from the central Deseado Massif, suggests shrub steppe with Asteraceae subf. Asteroideae and dry conditions (Borromei, 2003).

Between 13 and 11 cal ka BP, at Los Toldos, Piedra Museo, La Gruta 1 (formerly La Gruta Lagoon 2 Cave 1, see Mancini et al., 2013) and in the Lago San Martín area (La Tercera site, close to the Andes from 11.3 cal ka BP), there was steppe vegetation dominated by grass with low shrubs (Figs. 3 and 4), mainly *Nassauvia* and *Ephedra* (Fig. 4A). The vegetation at these localities probably resembled grassy areas in the present-day dwarf-shrub vegetation of the Deseado Massif above 700 m asl. The same plant communities are indicated by pollen spectra from the La María locality (Casa del

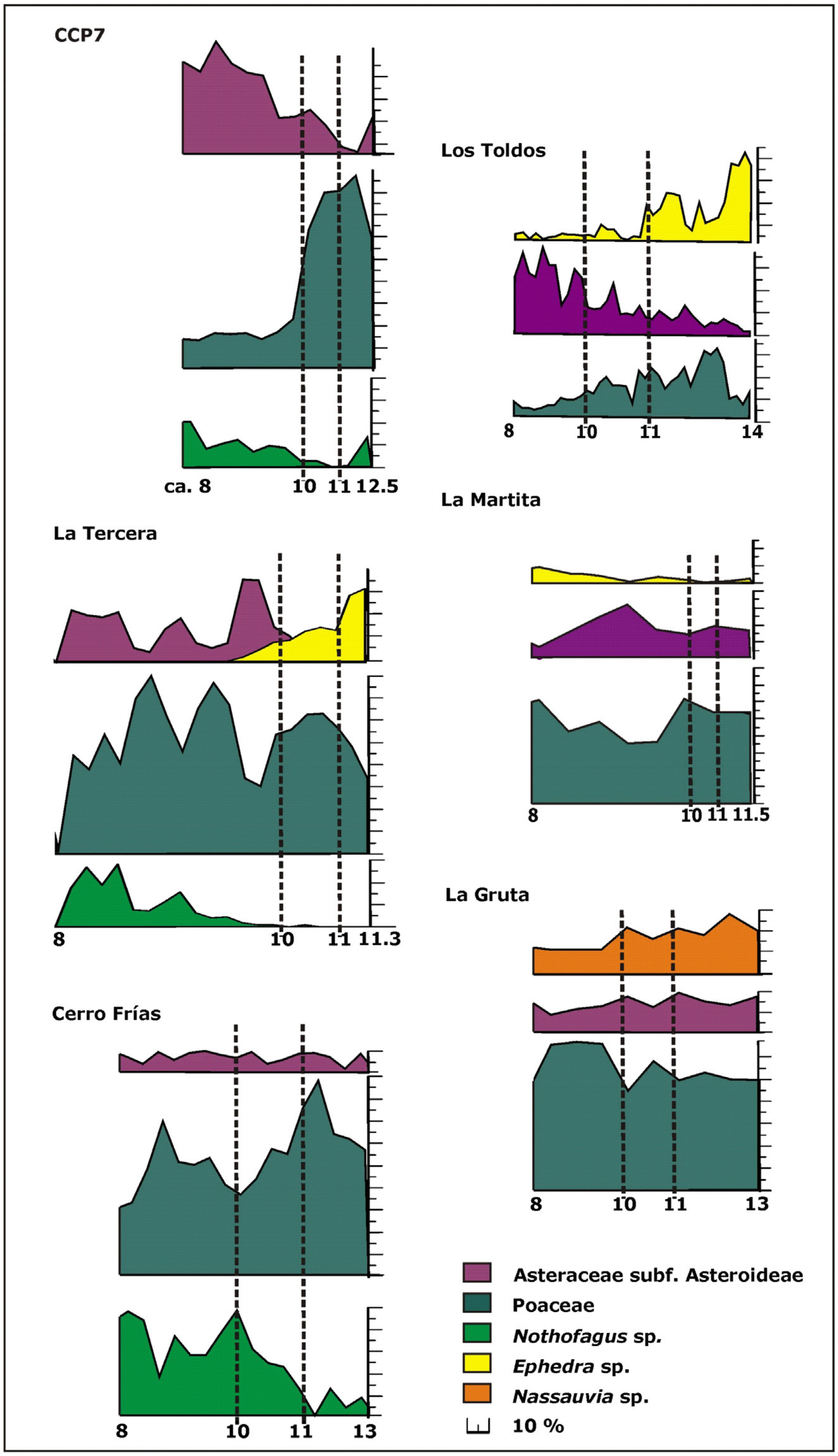

Fig. 3. Main pollen variables in sequences from sites shown in Fig. 2 showing differences during the periods before 11, 11–10, and 10–8 cal ka BP. Information from: Paez et al., 1999; de Porras, 2010 (Los Toldos); Mancini, 1998 (La Martita Cave 2); Mancini et al., 2013 (La Gruta 1); Mancini, 2007 (CCP7); Bamonte and Mancini, 2011 (La Tercera); Mancini, 2009 (Cerro Frías).

Minero) suggesting an increase in effective moisture on the plateau compared to the previous period, probably due to higher precipitation under cold and semiarid conditions (de Porras, 2010).

Soon after humans first explored the Deseado Massif it appears that the climate and environment changed (Fig. 4). Grass steppe with low shrubs was replaced by shrub steppe at the more northerly sites of Los Toldos and Piedra Museo around 11.5 cal ka BP, and 10.8 cal ka BP, respectively, signalling the onset of more arid conditions in these areas. However, in the southern part of the Deseado Massif, at La Martita, grass steppe with low shrubs persisted until at least 8.9 cal ka BP when it was replaced by shrub steppe suggesting arid conditions (Fig. 4B). At La Gruta 1 there was grass steppe with low shrubs until ∼11 cal ka BP when it was replaced by grass steppe. Therefore, during the early Holocene, the

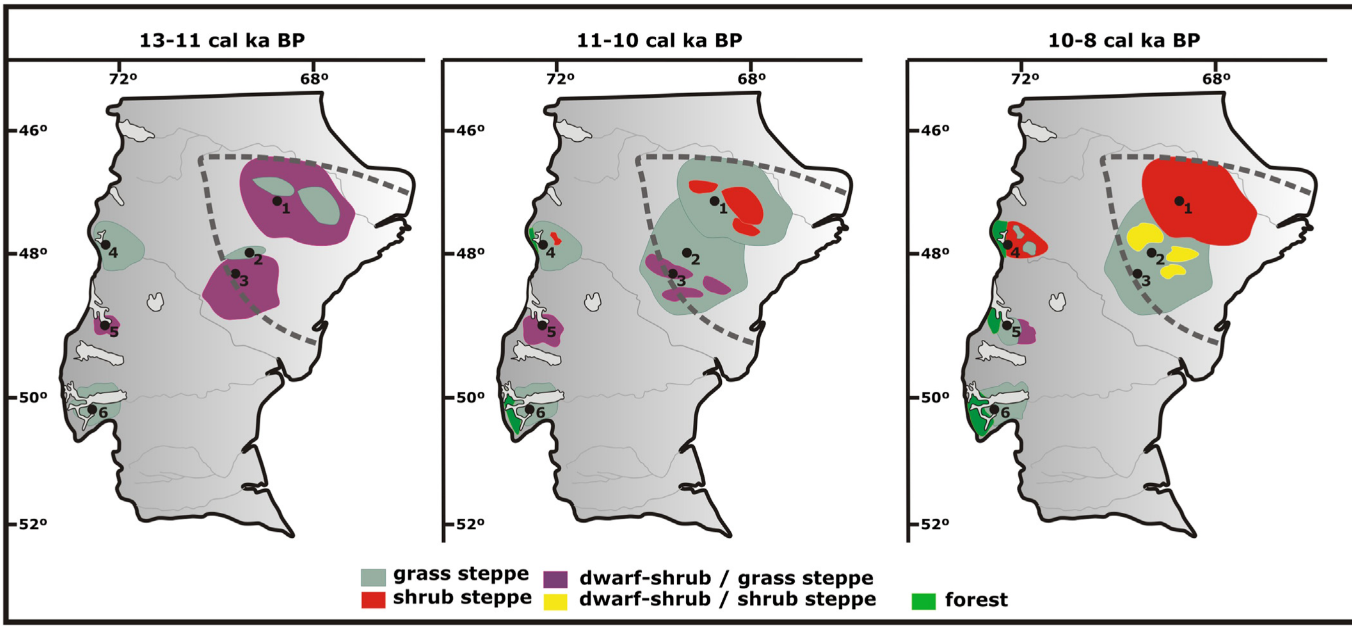

Fig. 4. Vegetation reconstructions for the periods 13–11, 11–10, and 10–8 cal ka BP based on the main vegetation units indicated by site pollen records.

vegetation on the plateau east of the Andes was a mosaic of dwarf shrub, shrub and grass steppes very similar to the present pattern.

The Cerro Casa de Piedra 7 (CCP7) archaeological site is located in the west at ~900 m asl in a transition zone between *Nothofagus* forest and shrub steppe. Before ~10 cal ka BP high values of Poaceae (60–80%) in pollen assemblages indicate grass steppe (Mancini, 2007) typically associated with a precipitation higher than today. After ~10 cal ka BP, grass pollen declines and there is an increase in shrub and cushion plants (*Empetrum, Azorella*) suggesting greater heterogeneity in vegetation with a composition similar to the present forest-shrub steppe ecotone (Figs. 3 and 4).

In the Lago San Martín area, close to the Andes (La Tercera), dwarf-shrub steppe or grass steppe with low shrubs, implying arid conditions, persisted until 10 cal ka BP, but was replaced after this by steppe communities similar to those in the area today. There was *Nothofagus* forest expansion in the Andean zone, while grass steppe dominated till 8 cal ka BP suggesting higher moisture availability than before (Bamonte and Mancini, 2011). This vegetation change and a higher fire frequency from 10 to 9 cal ka BP, suggest western precipitation reaching the area. In a steppe environment, grass abundance due to more precipitation favors horizontal fuel continuity allowing surface fires to the take place (Bamonte and Mancini, 2011; Sottile et al., 2012) (Fig. 4C).

In the southern part of the upper Santa Cruz basin, at Cerro Frías, the dominance of Poaceae, and high charcoal deposition rates between 13 and 12 cal ka BP, imply dry conditions in this area or frequent shifts from humid to dry conditions providing fuel to support fires (Sottile et al., 2012). Temperatures must have been high enough to allow grass-type fuels to reach ignition temperatures.

Pollen spectra from the Cerro Frías peat bog dating between ~12 and 10 cal ka BP indicate a decrease of grass steppe and forest expansion (Figs. 3 and 4) suggesting colder and humid conditions (Sottile et al., 2012). A decline in *Nothofagus* and an increase in Poaceae at 10–9 cal ka BP are coincident with a change from grass to shrub steppe a short distance to the east at Chorrillo Malo 2 indicating drier conditions (Fig. 4C; Mancini, 2002; Mancini et al., 2012a). Precipitation modeling estimates also show drier conditions at this time (Tonello et al., 2009, Fig. 5E).

The available data show that fire was important in driving vegetation change in both Andean and extra-Andean areas in southern Argentina. Early Holocene paleoclimate models (Renssen et al., 2005) describe higher than present mean annual insolation poleward of 45°S due to changes in Earth obliquity. This large-scale phenomenon is a possible mechanism for generating weaker SWW in the early Holocene and shifting them poleward. During periods with weaker SWW, west–east precipitation gradients would be gentler than during periods with stronger SWW (Whitlock et al., 2007; Garreaud et al., 2009; Moy et al., 2009). High charcoal levels at Cerro Frías during the early Holocene (9–7 cal ka BP), and also other southern Patagonia forest-steppe ecotone records, support this hypothesis (Sottile et al., 2012).

The progressive migration of *Nothofagus* forest from glacial refugia under conditions of favorable climate was initiated by large and rapid, possibly step-like climatic changes at the onset of the Holocene. Early Holocene climate was different from today in seasonality, combinations and extremes of temperature, precipitation and circulation patterns, and temperature and precipitation means (Birks, 1986).

6. The archaeological and paleoenvironmental records compared

Early inhabitants of southern Patagonia, east of the Andes, had to face an unstable climate that led to discontinuous use of most areas (Borrero, 2012). Fig. 5 shows the Greenland GISP2 and Antarctic Byrd ice core isotope records with the chronologies synchronized using the methane content of the two cores (Blunier and Brook, 2001). These are compared with age data (2σ significance) for archaeological sites in Argentinian southern Patagonia between 46° and 52°S and with pollen, lake level, glacial moraine, and precipitation evidence from the same region.

The present climate of Patagonia is dominated by the SWW. The uplift of moist air masses over the cordillera induces significant amounts of orographic precipitation on the western slopes of the Andes Mountains, while subsidence farther to the east produces an overall drying effect in Argentinian Patagonia towards the Atlantic. On the western side of the Andes there is a positive correlation

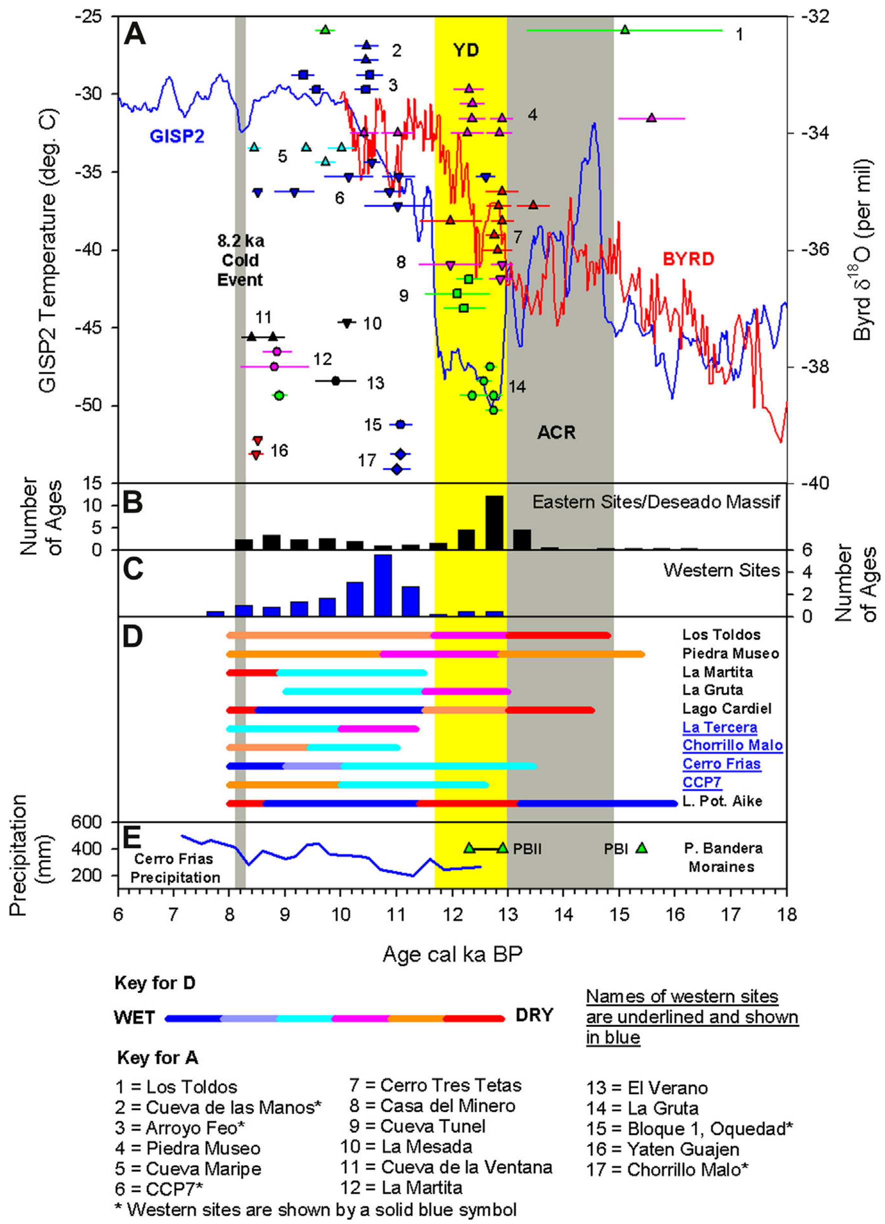

Fig. 5. Comparison between evidence of human occupation in southern Patagonia, climate estimated from pollen and lake level records, and high-resolution proxy temperatures for the Northern and Southern Hemisphere based on variations in GISP2 and Byrd ice core oxygen isotope data. Calibrated radiocarbon ages (2σ) in (A) are from Table 1. The calibrated age range is shown as a line and the age at the center of the range is shown as a symbol. In (A) and (D) sites are arranged from north (top) to south (bottom). In the histograms (B and C) the age class intervals are 7.50–7.99, 8.0–8.49, 8.50–8.99 cal ka BP and so on. If a calibrated age was entirely in one age class it was weighted 1.0, if it fell in two age classes it was weighted 0.5 in each class, in three classes 0.33, in four classes 0.25 and so on. In (A) the boundaries for the 8.2 ka cold period and Younger Dryas (YD) were drawn to conform to evidence in the GISP2 ice core record while those for the Antarctic cold Reversal (ACR) conform to evidence in the Byrd ice core. Modeled precipitation data for Cerro Frías in (E) are from Tonello et al. (2009) and ages of the Puerto Bandera moraines are from Strelin and Malagnino (2000).

between precipitation and SWW wind strength while the eastern slopes of the Andes exhibit a weaker positive correlation. Further east in the steppe region SWW strength is slightly negatively correlated with precipitation due to an increase in moisture from the Atlantic, in particular when the SWW are weak (Garreaud, 2007; Kilian and Lamy, 2012). This trend implies that precipitation sources different from the SWW affect the steppe regions of Patagonia and the Atlantic seaboard (Moreno et al., 2012). In fact, occasionally atmospheric blocking of the SWW over Patagonia enables moisture-rich easterly winds from the South Atlantic to migrate over the Patagonian steppe as far as the eastern range of the Andes. Furthermore, northward advection of cold Antarctic air masses can reach southern parts of the continent and sometimes can reach as far north as the subtropics particularly during winter (Kilian and Lamy, 2012). In the lee of the Andes and in the Patagonian steppe the dry foehn winds produce high evaporation and a negative water balance, in particular during summer so that many lagoons dry out during the warm season.

At present, the SWW extend northward during austral winters providing rainfall to western areas between ~33° and 40°S but at the same time zonal winds are reduced particularly in the SWW core zone at ~50°S (Garreaud et al., 2009). Seasonal forcing of the SWW results in a dominance of winter rainfall north of the core and summer rain south of it (Fletcher and Moreno, 2011). During austral summer, the SWW in the core zone are more confined latitudinally and are intensified (Lamy et al., 2010). Because precipitation on the western and eastern slopes of the Andes in Patagonia is positively correlated with the strength of the SWW, in the following

discussion we interpret increases in western precipitation as reflecting enhanced westerly flow and increases in easterly precipitation as indicating weaker westerly flow.

6.1. Before 13 cal ka BP including the ACR

The only ages from archaeological sites that pre-date the onset of the ACR around 14.8 cal ka BP (Fig. 1A) are from Los Toldos on charcoal scattered over an area 1.5×1.5 m and not firmly tied to human activities, and from Piedra Museo (Miotti, 1996; Borrero and Franco, 1997; Salemme and Miotti, 2008). There is still no consensus among researchers that the earliest date from Piedra Museo is reliable because only one age has been obtained for this time period (for opposing arguments see Politis et al., 2009 and Salemme and Miotti, 2008).

Only one age from an archaeological site, Cerro Tres Tetas (Paunero, 2000), falls within the ACR and given its 2σ range (13,732–13,161 cal BP) it could be a record of human occupation near the very end of the ACR around 13 cal ka BP (Fig. 1A). The almost total absence of ages during the ACR suggests that there were few people in the area, or that people were only just arriving. It is likely that western spaces were colder than today and the Deseado Massif colder and drier than today due to the more northerly position of the core of the SWW, making these areas less attractive for human settlement (see also Mancini et al., 2013). In fact, pollen records from Los Toldos and Piedra Museo, as well as lake levels at Lago Cardiel (Stine and Stine, 1990; Markgraf et al., 2003) confirm dry conditions at these sites during the ACR (Figs. 4 and 5D). Before 13 cal ka BP the level of Lago Cardiel was very low, and the lake probably even dried out for short time periods (Gilli et al., 2005). Lago Cardiel, at ~49°S, is in the rain-shadow east of the Andes Cordillera close to the present-day zone of maximum SWW speeds (~50°S) and precipitation is negatively correlated to zonal wind strength (Fletcher and Moreno, 2011). Lago Condorito at 41°S, on the west side of the Andes in Chile, received above average moisture between ~14 and 12.5 cal ka BP implying strong westerly flow that is consistent with dry conditions and low lake-levels east of the Andes (Moreno, 2004; Fletcher and Moreno, 2011).

The lake level record from Laguna Potrok Aike (~52°S), in southeastern Patagonia (Haberzettl et al., 2007), contrasts with records from the Deseado Massif during the ACR and YD. Laguna Potrok Aike experienced wetter conditions from 16 to 13 cal ka BP (ACR) when the Deseado Massif was dry, and drier conditions from 13.2 to 11.4 cal ka BP (YD) when it was somewhat wetter (Fig. 5D). Laguna Potrok Aike lies just south of the modern core of the SWW and precipitation does not appear to be influenced by SWW speed, possibly because proximity to the Andes and Atlantic Ocean means that it can receive precipitation from the west when the SWW are strong as well as moisture from the South Atlantic at times of weak SWW (Fletcher and Moreno, 2011).

The difference between the ACR and YD climates in these two areas suggests that in the past climatic conditions varied with latitude in response to north-to-south movements of the core of the SWW. It is possible that during the ACR, when Antarctic sea ice expanded and the Polar Front shifted northward (Bianchi and Gersonde, 2004), that the core of the SWW moved north and intensified bringing more precipitation to the western and eastern slopes of the Andes. However, this change would have brought less precipitation to the steppe areas further east as precipitation in these areas is negatively correlated with SWW wind speed (see also Moreno et al., 2012). If the core of the SWW was north of ~50°S during the ACR, the Deseado Massif would have been relatively dry. In contrast, in winter the Laguna Potrok Aike area may have been well south of the SWW core and may have been influenced by easterly winds that would have brought moisture from the Atlantic, explaining high lake levels at this time. Glacier expansion at higher latitudes in parts of western Patagonia and on the South Island of New Zealand ~13 cal ka BP (Putnam et al. (2010) also indicate a more northerly position of the SWW during the ACR. Glacial moraines at Lago Argentino at 50°S document a glacier advance on the lee-side of the Andes during the ACR (Kaplan et al., 2011). Paleoenvironmental data from peat on the Isla de los Estados, located at ~56°S to the east of Tierra del Fuego in the core of the SWW, indicate that the intensity of the SWW was at a maximum 13.6–13.3 cal ka BP, in the middle of the ACR. This was followed by a steady decline in wind strength possibly because of a gradual southerly shift of the SWW in summer when the ACR weakened (Björck et al., 2012).

6.2. The YD (13–11 cal ka BP)

The end of the ACR and the beginning of the YD brought about a remarkable change in our study area, with abundant evidence of human occupation at several sites in the Deseado Massif (Figs. 1B and 5B). Evidence for occupation begins around 13 cal ka BP and continues through the YD time interval, with multiple ages in this time period from Piedra Museo, Cerro Tres Tetas, Casa del Minero, Cueva Túnel, and La Gruta in the central and southern Massif (Fig. 5). The oldest ages are from Cerro Tres Tetas (12,520–11,411 cal BP) and Casa del Minero (12,512–11,408 cal BP). One age from Cerro Casa de Piedra 7, close to the Andes, raises the possibility of limited occupation of western spaces at this time (Aschero et al., 2007) although the evidence for this is scarce.

Although the histogram in Fig. 5B suggests a single peak in the number of radiocarbon ages from sites in the Deseado Massif during the YD, on closer inspection the distribution appears to be bimodal with peaks centered at ~12.8 and 12.3 cal ka BP. These peaks correspond with prominent warm peaks in the Byrd ice core that are separated by a marked cold interval at ~12.5 cal ka BP (Fig. 5A). This is the only evidence in the Byrd core of a significant cold period around the time of the Northern Hemisphere YD that is so prominent in the GISP2 ice core. This cold period corresponds with glacial advances west of Lago Argentino evidenced by the Puerto Bandera II moraines (Fig. 5E), which date in the range 12.9 and 12.3 cal ka BP (Strelin and Malagnino, 2000; Rodbell et al., 2009).

The bimodality of ages in the YD is also indicated by the age ranges at individual sites. For example there are two groups of ages for Piedra Museo, Cerro Tres Tetas, and Casa del Minero spanning periods that do not overlap: Piedra Museo, 13,086–12,622 cal BP (2 ages) and 11981–12576 cal BP (4 ages); Cerro Tres Tetas, 13,174–12,566 cal BP (5 ages) and 12,520–11,411 cal BP (1 age); Casa del Minero 13,080–12,660 cal BP (2 ages) and 12,512–11,408 cal BP (1 age). In each case the older group corresponds with the earlier of the two Byrd warm periods mentioned above and the younger group with the younger warm period. In addition, ages from La Gruta (5 ages 12,894–12,140 cal BP; 4 ages 12,894–12,437 cal BP) appear to center on the first Byrd warm period while 3 ages from Cueva Túnel (12,668–11,508 cal BP) center on the second Byrd warm period.

The apparent increase in the archaeological visibility of humans in the Deseado Massif around 13 cal ka BP may correspond to the beginning of a period with higher temperatures and slightly increased rainfall making the area more suitable for human occupation, especially taking into account the abundance of caves and suitable flint-knapping rocks (Figs. 1B and 4A). Certainly, the evidence from the Byrd ice core indicates a trend towards higher temperatures at high latitudes in the Southern Hemisphere throughout the YD.

During the YD, Southern Hemisphere temperatures rose quickly as recorded by isotopes in the Byrd ice core (Fig. 5A), sea surface temperatures (SSTs) were higher than today, and Antarctic sea ice was less extensive (Bianchi and Gersonde, 2004). We believe that together these changes pushed the core of the SWW further south

than it is today bringing dry conditions to Laguna Potrok Aike (Fig. 5D) and slightly wetter conditions to western sites like Cerro Frías and CCP7 (see also Moreno et al., 2012). The southward displacement of the westerlies may have begun at ~12.5 ka (Moreno et al., 2010; Fletcher and Moreno, 2011). Because the SWW were somewhat weaker during the YD, particularly in winter, Lago Cardiel (~49°S) and the Deseado Massif (~48°–50°S) received slightly more precipitation from the Atlantic. In fact, on the western slopes of the Andes, a decrease in SWW-derived moisture and an increase in fire in northwest Patagonia after ~12.5 cal ka BP, coupled with increased moisture in southwest Patagonia between ~52° and 55°S, confirms that there was a southward shift of the SWW at this time (Moreno, 2004; Fletcher and Moreno, 2011). Palynological data do record an increase in effective moisture between 13 and 11 cal ka BP at sites located in the central and southern Deseado Massif (Los Toldos and Piedra Museo) (Fig. 4). We assume that the cold interval at ~12.5 cal ka BP, lasting around 400 years, was colder and drier as the SWW intensified and extended slightly northwards.

There is some evidence for a period of reduced archaeological visibility (a relative absence of ages from archaeological sites) from ~12 to 11 cal ka BP at the end of the YD around 11.6 cal ka BP (Fig. 5A–C). For example, there are no ages in this time interval from La Gruta 1 where the closest age to it is 12,578–12,140 cal BP, and there is a gap in ages from Piedra Museo between 12,555–12,029 and 11,303–10,726 cal BP. One age from Cerro Tres Tetas, 12,520–11,411 cal BP (10,260 ± 110 ^{14}C yr BP), and two ages from Cueva Túnel, 12,668–11,508 cal BP (10,420 ± 180 ^{14}C yr BP) and 12,580–11,847 cal BP (10,400 ± 100 ^{14}C yr BP), extend into the 12–11 cal ka BP time interval, but all three uncalibrated radiocarbon ages have high uncertainties of 100–180 ^{14}C years compared to most other ages shown in Table 1, resulting in broader calibrated age ranges. There are also few ages from western archaeological sites in this time period. The oldest age from Bloque 1 Oquedad is 11,273 cal BP and the two oldest ages from Chorrillo Malo (11,246–10,883 and 11,236–10,775 cal BP) date to this period. There is also a gap in ages from CCP7 from 12,757–12,431 to 11,607–10,419 cal BP. However this last age is calibrated from a radiocarbon age with a large uncertainty (9640 ± 190 ^{14}C yr BP) making the age range quite broad. Two other ages from CCP7 of 11,320–10,745 and 11,131–10,600 cal BP are calibrated from radiocarbon ages with uncertainties of ±100 and ±70, respectively, and these ages may be a better indication of the timing of Holocene occupation at CCP7.

Table 1
Calibrated (1σ and 2σ) radiocarbon ages for archaeological sites in southern Patagonia between 46° and 52°S. Ages beyond the range (11,000 cal BP) of the SHCal04 Southern Hemisphere calibration curve (McCormac et al., 2004) were calibrated using the IntCal09 calibration curve based on Northern Hemisphere data (Reimer et al., 2009).

Site	Age ^{14}C yr BP	Calibrated age in cal BP (1σ)	Calibrated age in cal BP (2σ)	Reference
Older than 13 cal ka BP				
Los Toldos	12,600 ± 650	13,893–16,038	13,340–16,844	Cardich et al., 1973[a]
Cerro Tres Tetas	11,560 ± 140	13,280–13,578	13,161–13,732	Paunero et al., 2007
Piedra Museo	12,890 ± 90	15,085–15,637	14,976–16,162	Miotti and Salemme, 2004
13–11 cal ka BP				
Cerro Tres Tetas	11,100 ± 150	12,732–13,071	12,609–13,174	Paunero et al., 2007
Cerro Tres Tetas	11,015 ± 66	12,763–13,060	12,694–13,093	Paunero et al., 2007
Cerro Tres Tetas	10,915 ± 65	12,685–12,873	12,611–13,045	Paunero et al., 2007
Cerro Tres Tetas	10,853 ± 70	12,628–12,806	12,594–12,911	Paunero, 2003
Cerro Tres Tetas	10,850 ± 110	12,621–12,849	12,566–13,061	Paunero et al., 2007
Cerro Tres Tetas	10,260 ± 110	11,766–12,374	11,411–12,520	Paunero et al., 2007
Piedra Museo	11,000 ± 65	12,966–13,035	12,686–13,086	Miotti and Salemme, 2004
Piedra Museo	10,925 ± 65	12,691–12,882	12,622–13,056	Miotti and Salemme, 2004
Piedra Museo	10,390 ± 70	12,096–12,410	11,981–12,561	Miotti and Salemme, 2004
Piedra Museo	10,470 ± 60	12,221–12,548	12,134–12,573	Miotti and Salemme, 2004
Piedra Museo	10,470 ± 65	12,221–12,549	12,127–12,576	Miotti and Salemme, 2004
Piedra Museo	10,400 ± 80	12,121–12,412	12,029–12,555	Miotti and Salemme, 2004
CCP7	10,690 ± 72	12,560–12,663	12,431–12,757	Aschero et al., 2007
Casa del Minero	10,999 ± 55	12,735–12,960	12,691–13,080	Paunero, 2009
Casa del Minero	10,967 ± 55	12,720–12,917	12,660–13,067	Paunero et al., 2007
Casa del Minero	10,250 ± 110	11,757–12,373	11,408–12,512	Skarbun, 2009
Cueva Túnel	10,420 ± 180	12,043–12,558	11,508–12,668	Paunero, 2009
Cueva Túnel	10,408 ± 59	12,146–12,405	12,070–12,529	Skarbun, 2009
Cueva Túnel	10,400 ± 100	12,092–12,512	11,847–12,580	Skarbun, 2009
La Gruta 1	10,845 ± 61	12,624–12,786	12,596–12,894	Franco et al., 2010
La Gruta 1	10840 ± 62	12,620–12,780	12,593–12,892	Franco et al., 2010
La Gruta 1	10,790 ± 30	12,609–12,708	12,576–12,791	Franco et al., in press-b
La Gruta 1	10,656 ± 54	12,555–12,636	12,437–12,705	Franco et al., 2010
La Gruta 1	10,477 ± 56	12,224–12,553	12,140–12,578	Franco et al., 2010
11–10 cal ka BP				
Los Toldos	8750 ± 480	9557–9683	9541–9885	Cardich et al., 1973
Piedra Museo	9710 ± 105	10,808–11,237	10,726–11,303	Miotti and Salemme, 2004
Piedra Museo	9230 ± 105	10,236–10,488	10,168–10,656	Miotti and Salemme, 2004
La Mesada	9090 ± 40	10,190–10,235	9952–10,267	Paunero, 2000, 2003
C. de Las Manos	9320 ± 90	10,297–10,560	10,241–10,667	Gradin and Aguerre, 1994
C. de Las Manos	9300 ± 90	10,278–10,513	10,233–10,655	Gradin and Aguerre, 1994
Arroyo Feo	9410 ± 70	10,442–10,684	10,297–10,748	Gradin and Aguerre, 1994
Arroyo Feo	9330 ± 80	10,298–10,570	10,247–10,660	Gradin and Aguerre, 1994
CCP7	9730 ± 100	10,829–11,248	10,745–11,320	Aschero, 1996[b]
CCP7	9100 ± 150	9918–10,406	9696–10,571	Aschero, 1996
CCP7	9640 ± 190	10,718–11,220	10,419–11,607	Civalero, 2009[b]
CCP7	9390 ± 40	10,441–10,649	10,409–10,690	Civalero, 2009

Table 1 (*continued*)

Site	Age ^{14}C yr BP	Calibrated age in cal BP (1σ)	Calibrated age in cal BP (2σ)	Reference
CCP7	9530 ± 70	10,711–11,071	10,600–11,131	Civalero, 2009,[b]
Bloque 1 Oquedad	9760 ± 60	11,155–11,241	10,872–11,273	Belardi et al., 2010,[b]
Chorrillo Malo 2	9690 ± 80	10,830–11,217	10,775–11,236	Franco and Borrero, 2003,[b]
Chorrillo Malo 2	9740 ± 50	11,146–11,226	10,883–11,246	Franco and Borrero, 2003,[b]
10–8 cal ka BP				
Piedra Museo	7670 ± 110	8332–8544	8181–8626	Miotti, 1996
C. de la Ventana	7665 ± 75	8348–8514	8212–8581	Paunero, 2000
C. de la Ventana	7970 ± 40	8598–8761	8564–8977	Paunero, 2003
C. de Las Manos	7280 ± 60	7969–8155	7945–8173	Civalero, 2009
CCP7	8300 ± 115	9034–9401	8814–9520	Aschero, 1996
CCP7	7766 ± 52	8430–8542	8407–8591	Civalero, 2009
Arroyo Feo	8610 ± 70	9471–9583	9431–9694	Gradin and Aguerre, 1994
Arroyo Feo	8410 ± 70	9292–9467	9135–9515	Civalero, 2009
La Martita	8050 ± 90	8724–9002	8594–9114	Aguerre, 2003
La Martita	7940 ± 260	8416–9025	8202–9415	Aguerre, 2003
El Verano	8960 ± 140	9781–10,200	9550–10,267	Durán et al., 2003
La Gruta 1	8090 ± 30	8785–9013	8769–9025	Mancini et al., 2013
Cueva Maripe	8992 ± 65	9925–10,196	9785–10,232	Hermo, 2008
Cueva Maripe	8762 ± 50	9554–9732	9545–9888	Hermo, 2008
Cueva Maripe	8333 ± 63	9135–9403	9033–9447	Hermo, 2008
Cueva Maripe	7703 ± 47	8390–8512	8374–8545	Hermo, 2008
Y. Guajen 12-1	7775 ± 44	8434–8545	8416–8589	This paper
Y. Guajen 12-2	7717 ± 77	8399–8538	8338–8600	Franco, 2008

[a] Age for dispersed charcoal at the site.
[b] IntCal09 calibration curve used.

Table 2
Pollen records used in the analysis of vegetation changes in southern Patagonia shown in Fig. 4.

Site	Elevation (m asl)	Type of Site	Period with data (cal ka BP)	References
Los Toldos	300	Archaeological	14–8	Paez et al., 1999; de Porras 2010
La Martita Cave 2	400	Archaeological	11.5–8	Mancini, 1998
La Gruta 1	400	Archaeological	13–9	Mancini et al., 2013
La Tercera	<300	Peat	11.3–8	Bamonte and Mancini, 2011
Casa de Piedra 7	900	Archaeological	12.5–8	Mancini 2007
Cerro Frías	200	Peat	13–8	Mancini, 2009; Sottile et al., 2012

The relative absence of ages from archaeological sites in the range 12–11 cal ka BP could be due to incomplete sampling and/or selective dating but we can't rule out that it is an indication of reduced human presence. Some pollen records do indicate drier conditions at this time. For example, at Los Toldos in the northern Deseado Massif this interval has increased *Ephedra* and lower Poaceae indicating drier conditions beginning around 11.5 cal ka BP (Figs. 3 and 5D). At western sites such as CCP7 there was a significant reduction in *Nothofagus* around 11 cal ka BP while *Nothofagus* did not increase at La Tercera until after 10 cal ka BP. In the extreme south at Cerro Frías *Nothofagus* pollen percentages and modeled precipitation were low from 12 to 11 cal ka BP reaching a minimum around 11 cal ka BP (Figs. 3 and 5E).

This possible period of reduced human visibility corresponds with distinct warm periods in both the Byrd and GISP2 ice core isotope records (Fig. 5A) and with marked shifts in climate at several sites such as La Gruta and Lago Cardiel at ~48°–49°S, Cerro Frías at 50°S, and Laguna Potrok Aike at ~52°S, generally towards wetter conditions (Fig. 5). These changes correlate with resumption of North Atlantic Deep Water (NADW) circulation that led to the gradual cooling of the southern Oceans, a change that could have impacted climate and thus human activities in Patagonia.

6.3. Early Holocene maximum warming (11–10 cal ka BP)

During the period of maximum warming at the beginning of the Holocene (~11–10 cal ka BP) the SWW were situated at ~55°S but during the subsequent cooling that marked the end of the Antarctic temperature maximum they moved north to ~52°S and intensified (McGlone et al., 2010; Björck et al., 2012). The more southerly position of the SWW from ~11 to 10 cal ka BP and their reduced intensity may have facilitated the incursion of air masses from the Atlantic Ocean and thus increased precipitation in eastern Patagonia between 41° and 52°S. In addition, less intense foehn winds would have reduced evaporation making the precipitation more effective (e.g. Fletcher and Moreno, 2011, Fig. 5D).

Between 11.5 and 10 cal ka BP conditions appear to have been wetter throughout much of Patagonia east of the Andes except in the northern part of the Deseado Massif, which remained relatively dry (e.g. Los Toldos and Piedra Museo; Fig. 5D). There is a significant increase in the number of ages from western sites (e.g. Cueva de las Manos, Arroyo Feo, and CCP7 in the north, and in the south Bloque 1 Oquedad in the Lago San Martín area and Chorrillo Malo 2 south of Lago Argentino), suggesting wetter, milder climatic conditions that are confirmed by pollen data from Cerro Frías and Chorrillo Malo. Wetter conditions are also indicated for central and east Patagonia by pollen data from La Gruta 1 and La Martita, and by lake level data from Lago Cardiel and Laguna Potrok Aike (Figs. 1C and 5C, D). The level of Lago Cardiel increased significantly from −80 m (compared to present day) after 11.5 cal ka BP and reached a maximum of +60 m around 10 cal ka BP (Stine and Stine, 1990; Gilli et al., 2005; Ariztegui et al., 2010; Cusminski et al., 2011). High lake conditions at Laguna Potrok Aike before 9.2 cal ka BP indicate a weakened SWW that allowed moisture from the Atlantic to reach the lake (Mayr et al., 2007). Furthermore, high winter solar insolation would have limited the northward expansion of the SWW in winter. Lamy et al. (2010) suggest that during the peak warmth in Antarctica 12–8.5 cal ka BP, the latitudinal extent of the SWW belt was relatively narrow, possibly similar to the present-day summer configuration (~50°–55°S).

If wetness in Patagonia is related to the position and strength of the SWW, as we and other researchers have argued, why does the

pollen and lake level evidence suggest that both western and eastern areas east of the Andes were wetter during the early Holocene? What appears clear is that weakened SWW, south of their position today, allowed more moist air masses to enter Patagonia from the Atlantic, some possibly reaching as far as the eastern slopes of the Andes as can happen today (Garreaud et al., 2009). Coupled with significantly reduced evaporation in the rain shadow of the Andes due to weaker foehn winds, this would have made any precipitation in western spaces (and indeed eastern spaces) much more effective.

The increase in the number of ages from western sites in the interval 11.5–10 cal ka BP may reflect increases in temperature and effective moisture (less effective foehn winds) during the early Holocene. However, the age distribution raises another possibility. Although the histogram in Fig. 5C depicts a single mode for western ages, the distribution may be bimodal with 6 ages between 10,748 and 9696 cal BP and 6 ages between 11,607–10,419 cal BP. These age groups are centered on cool intervals in the Byrd ice core at ~11 and ~10.4 cal ka BP (Fig. 5A), respectively that may have triggered short-term northward displacements of intensified SWW bringing slightly increased precipitation to western sites east of the Andes at these times.

The large number of early Holocene ages from western sites is in contrast to the few ages from sites in the Deseado Massif between 10.5 and 11.5 cal ka BP (Fig. 5B, C). One possible explanation for this is that the winter position of the SWW, which brought above-average moisture to Lago Condorito (41°S on the west side of the Andes in Chile) between ~14 and 12.5 cal ka BP, was at ~48°–49°S during the early Holocene. This would have brought drier conditions to the Deseado Massif in eastern Patagonia and slightly wetter conditions to western spaces at these latitudes. In fact, pollen data from Los Toldos and Piedra Museo show dry conditions in the northern Deseado Massif throughout the early Holocene, while moisture levels at Lago Condorito declined from ~10.5 to 7.8 cal ka BP with a strong trend from ~9.5 to 8.5 cal ka BP (Moreno, 2004; Fletcher and Moreno, 2011).

6.4. *Early Holocene cooling (10–8 cal ka BP)*

Cooling during the early Holocene from ~10 to 8 cal ka BP was accompanied by an increase in Antarctic sea ice, which pushed the SWW to the north after ~9 cal ka BP (Bianchi and Gersonde, 2004) producing extremely dry conditions at Laguna Potrok Aike from 8.7 to 7.4 cal ka BP (Mayr et al., 2007), and the lowest Holocene lake level (Haberzettl et al., 2007). Relatively high, but declining, temperatures and low SWW intensities maintained moist conditions over much of Patagonia from ~10 to 9 cal ka BP perhaps explaining the increased number of ages from archaeological sites in eastern Patagonia and the decrease in ages from western sites at this time (Fig. 5B–D). However, lower temperatures after this increased precipitation on the western and eastern sides of the Andes and reduced precipitation over much of eastern Patagonia north of ~52°S (Fig. 5D). Pollen data from Lago San Martín (La Tercera) and Cerro Frías indicate more moisture between ~10 and 8 cal ka BP (Mancini, 2009; Bamonte and Mancini, 2011). After ~8 cal ka BP, the Lago Cardiel record shows dry conditions indicating stronger SWW (Gilli et al., 2005).

There is an apparent north–south pattern to the ages from archaeological sites in the Deseado Massif with more ages in the range ~9–8 cal ka BP from the southern part of the massif than from the northern part and very few ages from the central region (Figs. 1D and 5A, B). This pattern appears to reflect the vegetation reconstructions in Figs. 4 and 5D, which show dry conditions in the northern Deseado, very dry conditions in the central section and moister conditions in the south (see also Mancini et al., 2013) but we are aware that it could also be an artifact of bias by researchers who prioritized the oldest evidence of human occupation. Pollen records show that the northern Deseado Massif experienced drier conditions as early as 10 cal ka BP (e.g. Los Toldos and Piedra Museo) and that these drier conditions had spread to the southern Deseado Massif (e.g. La Martita) by ~8.6 cal ka BP.

The earliest dates so far obtained for occupation of canyons in the basalt plateau to the south of the Deseado Massif, between the Chico and Santa Cruz rivers, were obtained in recent excavations at the Yaten Guajen 12 site where evidence of human occupation dates to at least 8.6–8.4 cal ka BP (YG 12-1 and YG 12-2 in Table 1) (Franco, 2008). If further excavations confirm these ages as the oldest evidence of human occupation, this will mean that humans occupied the basalts almost 4000 years after the first occupation of the Deseado Massif at a time when our pollen data suggest wetter conditions in the basalt area (Figs. 4 and 5D). This might mean that as the southern Deseado Massif became more arid during the early Holocene (e.g. La Martita; Aguerre, 2003), people moved southwards into the basaltic areas where water and animal and plant resources were relatively more abundant. Additional, reliably-dated archaeological data will be needed to confirm this hypothesis. However, at the very least the evidence shows that the human population in the basalts increased during a wetter climatic period.

If the northern Deseado Massif was in the winter core of the SWW from 9 to 8 cal ka BP this area would have been very dry in winter while areas slightly to the south may have received moisture from the Atlantic. This could explain the observed increased visibility of humans in the basalt canyons during the early Holocene, which would have been due to natural population growth or because humans moved into the area because of the dry conditions further north.

7. Discussion and conclusions

Borrero and others have argued that the ACR and YD had no limiting effect on the peopling of southernmost South America. However, there can be no doubt that the humans who first occupied and then spread through southern Patagonia east of the Andes, had to adapt to the constantly changing climate conditions (see also Borrero, 1994–95; Salemme and Miotti, 2008). Temperature was probably less important than the availability of water for human populations; however the impact of each variable on its own is difficult to determine because temperature plays a major role in determining the latitude of the core of the SWW. The data we have presented suggest that the ACR may have been too cold and dry to attract large numbers of hunter-gatherers to southern Patagonia. However, temperatures rose throughout the YD except for a four-century-long cold interval centered on 12.5 cal ka BP. In fact, at a number of sites in the Deseado Massif the first clear evidence of human occupation dates to the very beginning of the YD. There is some evidence (bimodal age frequencies), although not yet conclusive, that human use of the area increased during two time periods, first around 12.8 cal ka BP and later at 12.3 cal ka BP; alternatively the second peak in ages may simply be an indication of a larger human population in the area. Each of these periods corresponds with evidence of significantly increased warmth in the Antarctic Byrd ice core.

Antarctic ice sheet and ocean temperatures were higher and sea ice less extensive immediately following the YD but temperatures appear to have fluctuated significantly during the period 11–10 cal ka BP (Fig. 5D; Blunier and Brook, 2001; Bianchi and Gersonde, 2004). Many eastern and western sites experienced wetter conditions at this time, except perhaps in the northern Deseado Massif where conditions may have been more arid (Figs. 4 and 5D). It is possible that the widespread increase in moisture was at least

partly a response to weaker SWW, as this would have allowed more moisture to enter Patagonia from the Atlantic, possibly even bringing moisture as far as the eastern slopes of the Andes. If the core of the SWW was at ∼46°–48°S this would have prevented Atlantic moisture from reaching the northern sections of the Deseado Massif bringing about more arid conditions and possibly limiting human activities. Complicating this interpretation is that the ages from western sites suggest human occupation during two periods centered at 11 and 10.2 cal ka BP, which correspond with marked cold episodes in the Byrd ice core at ca. 11 and 10.4 cal ka BP. We can't rule out that during these cold periods the core of the SWW pushed further north and strengthened bringing more moisture to western spaces over a considerable latitudinal range and thus encouraging human occupation of these areas at these times.

The predominant mode of vegetation response to climatic change depends on the space and time frame and resolution of the data set in which the response is observed (Prentice, 1986). Although there are few high-resolution records from southernmost Patagonia, the pollen information presented in this paper shows a clear vegetation response to the climate variability documented at higher chronological resolution in the GISP2 and Byrd ice cores. In particular, vegetation changed significantly paralleling changes in the isotopic characteristics (a temperature proxy) of the Byrd ice core. Thus, vegetation was different during the ACR compared to the YD, and compared to the much warmer conditions of the early Holocene. The variations in vegetation characteristics and shifts in vegetation boundaries that we have discussed above may have influenced guanaco populations (i.e. winter stress, see for example Belardi and Rindel, 2008) and human use of space. They may also have impacted human behavior by making humans choose from a limited number of possible options as they constantly selected strategies in relation to rapidly changing conditions with the technological and environmental knowledge they had at their disposal.

Our vegetation reconstructions from pollen data have helped us to define broad relationships between vegetation, climate and the human use of space. However, the chronologic resolution of our vegetation reconstructions has not allowed us to assess the impact of significant but shorter climate changes on human populations. As a result, we have attempted to do this by comparing one measure of human presence on the landscape, namely radiocarbon ages from archaeological sites, with the high-resolution, proxy climate data in the GISP2 and Byrd ice cores. This comparison has revealed a possible relationship between climate signals in the ice cores, particularly the Antarctic Byrd core, and human presence in southern Patagonia. We admit that our data set is incomplete and we are trying to rectify this by our continued study of the southern Deseado Massif and the basalt plateaus to the south of it. However, the data we have examined seem to suggest that humans in Patagonia did respond to major, relatively long-term climate changes such as the ACR and YD. It also suggests that humans were impacted by shorter-term climate changes apparent in the Byrd ice core isotope record. Prime examples of this are: 1) the two periods of increased occupation of the Deseado Massif at the beginning of the YD, which correspond with evidence in the Byrd ice core of warmer conditions, and 2) the two pulses of settlement of western spaces at 11 and 10.3 cal ka BP, which correspond with evidence for colder conditions in the Byrd core. The cold and warm events that seem to have triggered human movements were relatively short in duration but apparently significant in impact.

The research outlined here suggests that during the Late Pleistocene–Holocene transition humans were affected positively or negatively by longer-term and shorter-term changes in climate. In times of water scarcity, they probably moved to rivers north and south of the Deseado Massif or to western spaces with more reliable sources of water. It is also clear that the differential availability of lithic resources was not a problem for early inhabitants, who continued to obtain raw materials from the Deseado Massif until the late Holocene (Franco et al., in press-b). Likewise, the lack of caves and rock shelters in certain areas did not impact the human use of space. In general such shelters were widely available in the Deseado Massif and in adjacent basaltic areas but where they were not common human groups could easily have assembled open air shelters.

The one environmental commodity that seems to have impacted human populations the most was water as previously suggested for the late Holocene by other researchers working west and south of the Deseado Massif (e.g. Borrero, 1994–95; Borrero and Franco, 2000; Goñi et al., 2000–2002). Human populations have daily water requirements and during periods when water is scarce they must find alternate supplies. Water availability is not as important for the main human prey, *Lama guanicoe*, as this animal is not highly dependent on water and can when needed drink salty water (Borrero, 1994–95). Like other members of the camelid family, guanacos can survive on small amounts of water for extended periods, as they obtain and store water from the plants that they eat and can go for days without drinking. Guanaco herds are known to move seasonally to areas with better grass and we believe that during severe droughts in the past, which would have affected their water supplies and the quality of their grazing, they probably moved to the main water courses. Winter stress, however, may be a major cause of death among South American camelids (e.g. Belardi and Rindel, 2008).

As we have seen, during the Pleistocene–Holocene transition the availability of water varied spatially throughout the region changing with every climate fluctuation that impacted the high latitudes of the Southern Hemisphere, and affecting the Deseado Massif and western spaces in different ways. The ACR is a good example of the importance of water as this period was particularly dry in the northern Deseado Massif which might explain why there is so little evidence of human presence at this time, although the lack of evidence could also be due to a very small human population. The YD appears to have been wetter than the ACR and this may have facilitated occupation of the area by human groups.

The first evidence of human presence beyond the Deseado Massif is often found along water courses confirming how important these were to the first human explorers (see Borrero, 1994–95; Miotti and Salemme, 2004). Even within the Deseado Massif, water availability was crucial so that when the winter core of the SWW was pushed south and located over the northern part of the massif, reducing rainfall, archaeological visibility increased in areas to the south where there was more water. Movement of the winter core of the SWW even further south would have reduced water throughout the Deseado Massif and it was possibly then that humans first occupied the basalts to the south (or the existing population increased in number) where they utilized springs in the basalt canyons fed by groundwater from the extensive basalt aquifer.

In conclusion, it can be said that early human hunter-gatherer groups in southernmost South America used different strategies to cope with long-term changes in climate and the availability of water. Changes in behavior probably included the abandonment of some spaces and the utilization of other nearby spaces with a more abundant and reliable water supply. In this sense, they may have "followed the rains." However, areas with less water were probably still exploited by small numbers of hunter-gatherers from the main group if they contained desirable resources. We believe that future, intensive archaeological and paleoenvironmental research in smaller areas will provide more information about the strategies used by humans faced with less reliable water supplies. Hopefully,

these studies will also prove or disprove the possible links between past climate and human activities that we have proposed here.

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