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The relationship between emergence of mound builders in SE Uruguay and climate change inferred from opal phytolith records

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ABSTRACT

The strong correspondence between the spatial arrangement of archaeological sites and wetland environments is one of the main axes of the Merín Lagoon basin archaeology. Without implying a deterministic simplification from the epistemological point of view, the cultural and environmental history of the region hold evidence suggesting a more complex scenario, where cultural responses to climate change were not so mechanical or direct as previously argued. The relationship between paleoclimate and prehistoric mound builders development between 7.0 and 0.6 ka ^{14}C BP was studied in SE Uruguay. Paleoclimatic data were inferred from the phytolith record of three lagoon sediment cores. Four paleoclimatic periods were identified according to temperature/humidity changes. The first period, dated at 7.0–4.5 ka ^{14}C BP, was characterized by a warm/humid climate. Between 4.5 and 3.5 ka ^{14}C BP, the onset of a cool/dry climate was inferred. A hiatus between 3.5 and 2.6 ka ^{14}C BP was identified. In the third period, 2.5–1.2 ka ^{14}C BP, similar climate conditions to those of the present were inferred. Finally, the period 1.2 and 0.6 ka ^{14}C BP, was characterized by warmer and wetter conditions than those of the present. According to these data, it was determined that mounds were first observed during the transition from warm/humid to cool/dry conditions, but the complexity of the mounds increased after the full establishment of cool/dry conditions. With the inception of warm/humid conditions, an increased number of mounds was observed in the plains located close to the Merín Lagoon littoral. The mounds showed lower density and height than those recorded for the cool/dry period. This behavioral modification in mound construction was explained because of the paleoenvironmental change.

1. Introduction

The culture–environment relationship is one of the principal interpretative/explicative aspects of Merín Lagoon prehistory. The main reason is the spatial arrangement of the characteristic regional archaeological sites in relation with environmental units of the area. The Merín Lagoon basin was, from 5.5 to 0.2 ka ^{14}C BP, the site of the largest pre-Columbian anthropogenic landscape modification in the marginal Atlantic Ocean areas of the South American plains. Thousands of mounds were progressively built close to permanent or temporal wetlands (Bracco et al., 2000a; Bracco, 2006). The sites are composed of either isolated or clustered mounds, with relative height up to 7 m. Their bases were circular/elliptical, with a mean diameter of 30–40 m (Fig. 1). The geographical distribution of mounds extends further to the north, reaching the Los Patos Lagoon basin, and to the south, reaching the Castillos Lagoon (Copé, 1991; Bracco et al., 2000a, 2008a; Fig. 2). The mounds are located mainly on lowlands, following wetlands and water courses. They can also be found in the steep rocky hills ("*sierras*") and the gentler hills ("*lomadas*").

Based upon the first records from the Negra Lagoon, comprising a lapse in mound building development, the occurrence of two main climate periods was proposed: (a) prior to 2.0 ka ^{14}C BP (colder and drier conditions), and (b) after 2.0 ka ^{14}C BP, characterized by warmer and more humid conditions (Bracco et al., 2005a). The relationship between this climate sequence and the

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Fig. 1. Puntas de San Luis Mound site, Paso Barranca – India Muerta region.

cultural development indicated that mounds were built during periods of reduced humidity and spatially restricted to less inundated areas. In this sense, it was also observed that the age of mounds in the southern section of the Merín Lagoon corresponded with the two climate periods mentioned above. Thus, a colonization sequence was suggested in agreement with the inferred climate periods. The lowest plains closer to the Merín Lagoon became the location of mounds only after Holocene sea level became lower (Bracco and Ures, 1998) together with an increase in moisture levels that led to the onset of freshwater wetlands. However, the above interpretation on the relationship between culture and climate was inferred using a single sediment core. Bracco et al. (in press) took new sediment cores in Blanca, Negra and Rocha Lagoon, and presented preliminary Holocene climate data, which were related to the regional cultural changes. This paper presents new and more detailed evidence on the relationship between prehistoric mound builders and climate change from the Merín Lagoon basin, inferred from opal phytolith records of sediment cores which encompass a chronological record from 7.0 ka ^{14}C BP.

2. Materials and methods

2.1. Study area

The Merín Lagoon basin is located between 31°–34° S and 52°–54° W in the easternmost part of the South American plains (Fig. 2). The basin extends across 54,000 km^2, of which 24,000 km^2 belong to Brazil and 30,000 km^2 to Uruguay. In Uruguay, its western boundary is the Santa Lucía River basin, and the southern boundary is the Cuchilla de la Angostura, a narrow strand parallel to the Atlantic Ocean coast. A series of coastal lagoons is located along the ocean littoral fringe. The Rocha, Garzón and José Ignacio lagoons are directly connected with the ocean; the Castillos Lagoon is connected with the Atlantic Ocean through Valizas Creek; and the Negra Lagoon is currently separated from the Atlantic Ocean. Thus, the Negra Lagoon is the only water body located in the inner plains that drains towards the Merín Lagoon. From the western boundary of the basin to the Merín Lagoon, the region shows a smooth slope gradient composed of rocky hills and gentler valleys where the crystalline basement is located.

The wide Eastern Plain is situated to the east. It is composed of sedimentary deposits of the Merín Lagoon. In this plain, there are important flat extensions whose current elevation is slightly higher than the present mean sea level. Therefore, they exhibit low drainage rates, leading to extensive flooded areas where several wide streams, marshes, and wetlands are present.

The Merín Lagoon basin is located in a temperate/subtropical zone. The proximity to the ocean leads to moderate thermal amplitudes (daily, seasonally and annually) and high relative humidity levels (PROBIDES, 1999; IBERSIS, 2001). The mean annual temperature for the last 50 years at the Treinta y Tres Meteorological Station is 17 °C (Fig. 3), whereas mean total rainfall is about 1100 mm y^{-1} (Caffera and Berbery, 2006).

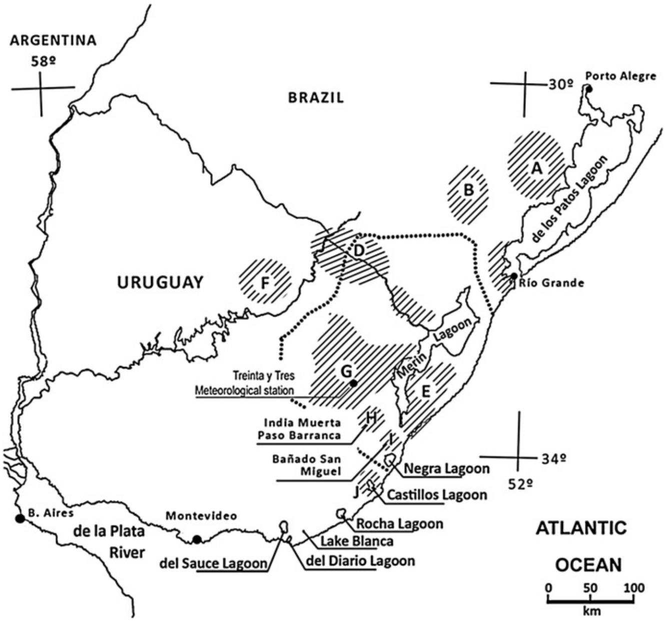

Fig. 2. Merín Lagoon Basin location (dashed line) and the littoral lagoons of Uruguay. A–J: areas of mound sites.

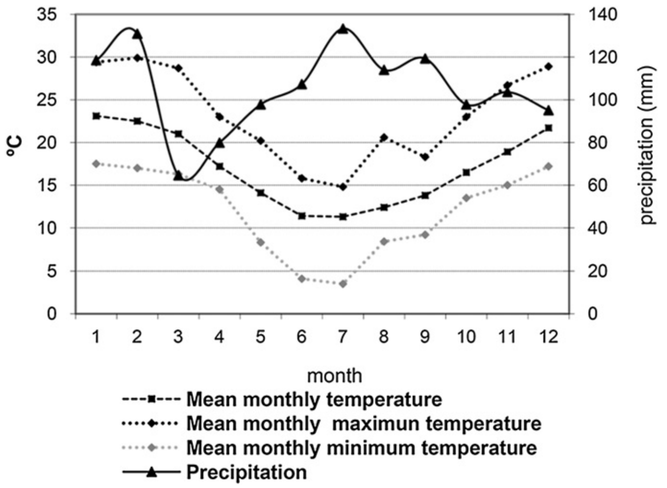

Fig. 3. Mean monthly precipitation and temperature. Data obtained from Treinta y Tres meteorological station.

The study area belongs, in phytogeographical terms, to the "Southern Campos" according to the regional classification proposed by Soriano (1991), or to the Pampa Province according to Cabrera and Willink (1973), Morrone (2001, 2006) for the "Río de la Plata Grasslands", or more specifically to the Uruguayense District (Cabrera, 1971, 1976; Cabrera and Willink, 1973) characterized by the dominance of wet grasslands. The high percentage of herbaceous species is reflected in the physiognomic configuration of the main vegetation type, referred as "campos", "prairies", "steppes", "sabana" or "grasslands" (Grela, 2004). It is composed by heterogeneous herbaceous communities where perennial short, middle and tall grasses are the most conspicuous traits. Some seasonal productivity is noted, caused mainly by temperature and rainfall regimens (Rosengurtt, 1944; del Puerto, 1969; Sganga, 1994; Panario and Bidegain, 1997). Coexistence of both winter and summer cycle species is explained by the location of Uruguay, with warmer climates below 30° S latitude and temperate/cold climates above 35° S latitude (Rosengurtt, 1979). Other herbaceous, shrub and tree dominated vegetation formations are also present in the Merín Lagoon basin. A detailed description of such units is presented in Table 1. Considering the southern part of the basin as a whole, several environmental units were defined according with geomorphologic, edaphic, biological and perceptual criteria (PROBIDES, 1999) (Fig. 4).

Steep rocky hills ("*Sierras*") comprise the highest terrains in the basin (200–500 m asl), and also the steepest slopes corresponding to the northwest, west and south boundaries between the Merín Lagoon basin and the Negro River basin, the Santa Lucia River basin and the Atlantic Ocean basin. Other elevations are also found inside the plains, i.e., the San Miguel and Los Ajos hill systems. The substrate is composed of crystalline, metamorphic and extrusive rocks to a lesser extent. The hydrology of the basin is controlled by this topography. The main rivers, such as Yaguarón, Cebollatí, Tacuarí, and Olimar, run eastward from hills. In the upper reaches, rivers exhibit gorges covered by riparian forest, which also extends to the surrounding hilly landscape. Summer grasslands and latifolian forestry ("*Monte Serrano*") communities are the most conspicuous vegetation units.

The Hills, Gentle Hills and Valleys ("*Colinas, lomadas y valles*") unit is a transition between steep rocky hills and high plains. It is characterized by a strongly to smoothly undulated landscape, with deep and moderately deep fertile soils. Dominant vegetation is grasslands with scattered shrubby patches. Valleys are linked to the steepest landscapes and related to hydrology in their genesis. Grasslands and forest patches develop over deep to moderately deep fertile soils.

The High plains ("*Planicies altas*") are flat terrains located above lowlands close to lagoons and water courses. Their topographic position prevents flooding, so they were originally characterized as grassland vegetation.

Palm groves ("*Palmares*") are present in the middle and high plains, as flat or gently undulated terrains, only exceptionally reached by floods. The matrix is composed by palm groves of *butia* (*Butia capitata* Cham. Becc.), with densities reaching 480 individuals/ha in some locations (surroundings of Castillos city). The current extent of this formation is probably relict. The age structure of palm populations indicates virtually no regeneration, with the

Table 1
Main vegetation forms in SE Uruguay. Sources: del Puerto (2009), PROBIDES (1999), Alonso (1997).

Community		Habitat	Typical species
Herbaceous	Summer prairies	Hills with well-drained superficial soils	*Axonopus compresus*, *Paspalum notatum*, *P. dilatatum*, *Setaria geniculata*
	Winter prairies	Valleys and hills with deep soils	*Bromus aulecticus*, Carex spp., *Medicago lupina*
	Psamophyllus prairies	Sandy soils in coastal zones	*Andropogon arenarius*, *Aristida pallens*, *Schyzachirium microstachyum*
	Wet prairies	Flat and poorly drained soils, waterlogged during the winter months	*Axonopus compresus*, *A. affinis*, *Chloris bahiensis*, *Cortaderia sellona*, *Distichlis spicata*, *Echinochloa helodes*, *Eragrostis lugens*, *Erianthus angustifolius*, *Eryngium pandanifolium*, *E. decaisneanum*, *Luziola peruviana*, *Panicum prionitis*, *Paspalidium paludivagum*, *Paspalum modestum*, *P. notatum*, *P. quadrifarium*, *P. vaginatum*, *Salicornia ambigua*, *Sporobolus poiretti*, *Stenotaphrum secundatum.*
	Wetlands	Low floodplains, which remain covered with shallow water most of the year.	*Canna glauca*, *Erythrina cristagalli*, *Juncus acutus*, *Phyllanthus sellowianus*, *Scirpus californicus*, *S. giganteus*, *Sebastiania schottiana*, *Spartina densiflora*, *Thalia geniculata*, *Thypha dominguensis*, *Zizaniopsis bonariensis*
	Hydrophytic	Permanently flooded areas (swamps and lacustrine littoral)	Floating: *Eichornia azurea*, *Pistia stratiotes*, *Pontederia cordata*, *P. rotundifolia*, *Salvinia auriculata*. Submerged: *Myriophyllum brasiliensis*. Emergent: *Scirpus giganteus*, *Typha dominguensis*
	Psamophyllus pioneers	Mobile dunes	*Panicum racemosum*, *Hydrocotyle bonariensis*, *Senecio crassiflorus*, *Androtrichum trigynum*, *Ischaemum urvilleanum*, *Calystegia soldanella*
Woody	Highland shrublands	Hills	*Colletia paradoxa*, *Dodonaea viscosa*, *Berberis laurina*, *Schinus longifolius*, *Celtis iguanaea*, *Maytenus ilicifolius*, *Iodina rhombifolia*, *Opuntia* arechavaletae, *Cereus* uruguayanus
	Psamophyllus shrublands	Coastal hills, in sandy incipient soils	*Cereus uruguayanus*, *Colletia paradoxa*, *Opuntia arechavaletae*, *Schinus engleri*
	Highland forest	Hills	*Celtis tala*, *Lithraea brasiliensis*, *Rapanea parvifolia*, *R. ferruginea*, *Scutia buxifolia,*
	Riparian forest	Margin of rivers and water streams	*Allophyllus edulis*, *Erythrina cristagalli*, *Pouteria salicifolia*, *Salix humboldtiana*, *Sapium montevidensis*, *Syagrus romanzoffiana*,
	Palm forest	Middle plains	*Butia capitata*
	Psamophyllus forest	Oceanic and lacustrine coast	*Cereus uruguayanus*, *Colletia paradoxa*, *Daphnosis racemosa*, *Lithraea brasiliensis*, *Opuntia arechavaletae*, *Rapanea laetevirens*, *Schinus engleri*, *Scutia buxifolia.*

Fig. 4. Main vegetation forms in SE Uruguay and mounds sites. The investigated sites are indicated: 1) Los Ajos, 2) Potrerillo, 3) Los Indios, 4) Isla Larga, 5) Puntas de San Luis (PSL), 6) Cráneo Marcado and 7) Estancia La Pedrera. Dashed lines indicate the Holocene transgression boundary.

entire population composed of older class individuals. Cattle/sheep grazing is thought to be the main cause of lack of regeneration, as cows feed on plantules (PROBIDES, 1999).

Wetlands ("*Bañados*") are characterized by a permanent to seasonal flooding regime. Within this unit it is possible to distinguish lower plains linked to the middle and lower section of rivers/streams and lagoon plains surrounding Merín, Negra and the coastal lagoon system. Characteristic swampy vegetation is present, with riparian forest developing as strands following the main rivers.

The Atlantic littoral ("*Litoral atlántico*") is dominated by beaches and dune fields whose continuity is interrupted by rocky outcrops that extend to the sea, creating points, capes and islands. The geologic substrates act as hard points that exert control over beach geometry (Panario and Gutiérrez, 2006). Besides the littoral, the inner lands are flat to gently undulated plains that were generated by marine transgressions during the late Pleistocene. Main vegetation types are sandy grasslands with shrubby patches.

2.2. Cultural record

The archaeological record of mound builders is mainly composed of lithic and bone artifacts, pottery, faunal remains, and human burials. Polished lithics are also found in mounds (i.e. millstones and manos, nut breakers) but their contribution to the total lithic material is not significant (Bracco, 2006; Bracco et al., 2008a).

The pottery is either simple or with coarse/fine sand as tempering material and less frequently with milled mollusc valves (Capdepont, 2001; Capdepont et al., 2002). The dominant form of pots is mainly globular, vertical straight walls or plain bowls. Decorated pottery is seldom observed and consists of simple geometrical dotted forms (Bracco et al., 2008a). Two Guarani funerary urns were also found in the Sierra de San Miguel mound (Cabrera, 2000). Brazilian researchers assigned the pottery recovered from the mound to the Vieira and Guarani Tradition (vide infra) (Brochado, 1969, 1974; Schmitz and Basile Becker, 1970; Schmitz, 1976). The most common bone artifacts are polls and hallmarks made of the metapodium of *Ozotocerus bezoarticus*. The human burials are very diverse. Primary burials of adult males are the most frequent (65%). The secondary and multiple burials are also dominated by male individuals. Females and children only account for 35% and 14% respectively. Elements interpreted as funeral offerings were only observed in 22% of the burials. These are mainly polished or picked stone artifacts, mollusc shells, and bone instruments such as seal fangs or fox jaws (Cabrera, 1999; Bracco, 2006; Bracco et al., 2008a).

The opal phytolith record indicates an early adoption of crops (corn, squash, beans) by ca. 3.0 ka ^{14}C BP. Variability in the frequencies of the opal phytolith indicators of domestic species have been used to infer changes in the intensity of crop practices (del Puerto and Inda, 2005, 2009). The lack of evidence related to containers, low frequency of mills and the isotopic data ($\delta\,^{13}$C of the organic and mineral fraction of the human bones) indicate a low incidence of corn in the diet (Bracco et al., 2000a, 2008a). The regional ethno-historical sources indicate the presence of hunter–gatherer groups (Cabrera, 2000). This evidence, together with the archaeofaunal and archaeobotanical record, indicate that mound builder groups focused their economy on the wild vegetation and animal sources from the wetlands of the Merín Lagoon basin (Bracco et al., 2000a, 2008a; Bracco, 2006).

2.3. Archaeological history of the Merín Lagoon basin mounds

In the archaeological history of the Merín Lagoon basin, the role of mounds has been controversial. It has been proposed that mounds were erected as platforms against floods, burial structures and/or rituals as territorial markers (see Bracco et al., 2008a,b) or multifunctional structures for agricultural purposes (Baeza and Panario, 1999).

The first scientific citation about mounds in Uruguay dates at the end of the 19th Century (Arechavaleta, 1892; Figueira, 1892). Other researchers also focused their work on the sites during the first half of the 20th Century and generated the main interpretations of mound builders archaeology. The main topics were the cultural complexity of mound builders, the link between this kind of site and the wetlands, and the relationship between archaeological sites and early ethnographic groups that inhabited the area (Bracco, 2006).

In the 1960s, Brazilian researchers began surveys and diggings at Rio Grande do Sul. Concomitant work also started in the east of Uruguay with participation of non-professional stakeholders (Santos, 1965; Prieto et al., 1970; Copé, 1991). The aim of this research was to reconstruct the cultural history of the area by means of seriation techniques (Schmitz, 1967, 1973, 1976; Schmitz and Basile Becker, 1967, 1970; Schmitz and Brochado, 1981). Conclusions derived from recovered material led to the proposition of two cultural components involved in mound building behavior. The first, or early component, was assigned to the Umbú tradition, with stone artifacts made from both percussion and polishing techniques, including triangular shaped and peduncle less spear like projectile points (Copé, 1991). The second or later component was defined by the presence of pottery, assigned to the Vieira tradition (Brochado, 1969, pp. 12). Within the Vieira tradition, several phases were distinguished. The older one is the Torotama phase (0–500 AD) characterized by rough finishing and incomplete burning ("primitive") small pots, with thick walls and sandy inclusions. In the basin of de los Patos Lagoon, the Torotama phase is followed by the early Vieira phase (500–800 AD), the middle Vieira phase (900–1200 AD), and the late Vieira phase (1200–1300 AD). Along the sequence, shallow and wider recipients with thin walls and coarse inclusions gradually evolved to taller, bigger and more uniformly made pots (Schmitz, 1976). The cultural sequence derived from pottery ends with Guarani pottery (Schmitz and Brochado, 1981; Schmitz et al., 1991).

Brazilian researchers interpreted mounds as domestic sites for hunter–fisher–gatherer groups. The location of such camps was linked to greater environmental resources, but the elevation from surrounding fields was interpreted as a need to avoid periodic floods. According with this reasoning, Schorr (1975) proposed that mound clusters were not only evidence of ancient villages, but also that size differences between sites could be interpreted in terms of social hierarchy. The Brazilian archaeologist also linked mound sites with historical native groups, particularly the Minuanes, also known as Guenoas (Basile Becker, 1984).

In the second half of the 1980s, systematic archaeological research began at the Uruguayan portion of the basin, in the San Miguel wetland area. Three mound sites (two mounds each) were excavated, one located on the hills, and two at the edges of wetlands (Curbelo et al., 1990; Femenías et al., 1991). Because artifacts were also recovered from surrounding areas, it was proposed that human occupation was spatially wider than the mound itself, the latter being a structure inside a site. Burial findings at the San Miguel diggings, together with those revealed by early references, were responsible for the functional interpretation of mounds as funeral structures (Femenías et al., 1991). Despite the fact that the archaeological records showed no conspicuous evidences of cultural complexity, such a social trait was implicit in the funeral interpretation of mounds (Bracco et al., 2008a). Wetland-rich environments with available resources, where an extractive subsistence strategy with horticulture was implemented, characterized the inferred framework through which socio-cultural development was achieved (López and Bracco, 1992, 1994). Opal phytolith analyses carried out at mound sites revealed the presence of domesticated plants, thus indicating the presence of horticulture (del Puerto and Campos, 1999). Nevertheless, isotopic analyses on human bones suggest that such resources were not important in terms of dietary contribution (Bracco et al., 2000b).

Since the 1990s, research has extended to India Muerta, Los Ajos (Bracco, 1993; Iriarte et al., 2004), Negra Lagoon, Potrerillo site and Los Indios (López, 2000; López and Pintos, 2001), San Miguel hills, Isla Larga site (Cabrera, 2000), Puntas de San Luis (Bracco et al., 2000c), Tacuarí, PR14D01 site (Cabrera Pérez and Marozzi, 2001), Castillos Lagoon, Cráneo Marcado site (Pintos, 1999; Pintos and Capdepont, 2001), and lately to the Atlantic littoral, Estancia La Pedrera site (López et al., 2009) (Fig. 4). At this time, morphologic similarities between Merín basin mounds and other areas of the Americas (Mississippi valley, Marajó island, coast of Perú, plains of Colombia and central Chili), supported the interpretation of some researchers that mounds in the Merín area implied an early formative social development (Andrade and López, 1998; Pintos, 1999; Bracco et al., 2000a, 2008b; Iriarte et al., 2004; Bracco, 2006).

Instead of observing a well defined pattern in the regional archaeological record, results from different areas strongly suggested a high regional variability in site chronology, and in site location/structure, including number, height, arrangement, presence/absence of human burials and even artifacts in surrounding areas. Recovered artifacts did not respond to any expected pattern or to "complexity". Although human burials were not present at all sites, and even domestic structures were not conclusively identified, the funeral function of mounds was nevertheless maintained until the end of the millennium. Mounds were depicted as sacred-ritual oriented spaces and differentiated from profane daily life spaces (López and Gianotti, 1997; Iriarte et al., 2004; cf. Bracco et al., 2008a,b). At the beginning of the millennia, the lack of evidence of elaborated technologies, exchange, storage and social hierarchies, together with a review of mound building techniques, led to a deep questioning of former interpretations (Bracco, 2006; Bracco et al., 2008a). Since the onset of systematic archaeology, inferred from stratigraphic analysis, it was proposed that mounds were built through different stages (Prieto et al., 1970; Bracco et al., 2000a; López, 2000). Radiocarbon age validation from samples of organic matter contained in the mound matrix, by comparison with dated materials from the same levels, together with mechanical sediment samplers, has allowed, since 1998, generation of a comprehensive systematic radiocarbon date database, including non-excavated mounds. Chronological data indicated that mounds were not built in a single event or in a reduced multistage cycle, but they were, instead, erected through centuries or millennia, as a consequence of a progressive process (Bracco and Ures, 1999; Bracco, 2006; Bracco et al., 2008a). According to these results, mounds could not be interpreted as the partial or final product of a process that was, in turn, designed and executed by one or a few generations. In contrast, evidence suggests that mounds should be rather interpreted as the result of trans-generational recurrent behavior.

Extended radiocarbon series for different areas not only provided evidence of the mechanisms and periods of construction, but also about the spatial and chronological range of each site, thus yielding a scale shift which is necessary to link environmental evolution and cultural history of mound builders. The cornerstone was a consequence of the increased number of radiocarbon ages obtained for several sites, extending the chronological frame from 2.5 to 0.2 ka ^{14}C BP to around 5.0 ka ^{14}C BP, and the spatial and chronological variability observed at each site and between sites. In addition, the generation of paleoclimatic models inferred from paleolimnological research (Bracco et al., 2005a; del Puerto et al., 2006; Inda et al., 2006) also contributed to better understanding of the cultural history of mound builders.

2.4. Sediment records of lagoons as indicators of humidity and temperature

Paleolimnological investigations on coastal lagoons were initiated in 2000 by a multidisciplinary group. Sediment cores were retrieved from the Negra, Blanca, Rocha, Castillos, Sauce and Diario Lagoon (Fig. 2), and multiproxy analyses (i.e. diatoms, opal phytoliths, pollen, molluscs, sediments, geochemistry, thin sections), together with radiocarbon dating, were performed (García Rodríguez et al., 2001, 2002, 2009; García Rodríguez, 2002; García Rodríguez and Witkowski, 2003; Blasi et al., 2005; Bracco et al., 2005a,b, 2008b; del Puerto et al., 2006; Inda et al., 2006). Only three stratigraphic units of the sediment cores retrieved from Blanca, Negra and Rocha Lagoon showed high enough resolution records, and therefore they are the basis of the paleoclinatic reconstruction presented here (Table 2). The record corresponds to lithological units dominated by fine sediments with enough chronological information to assume fairly continuous sedimentation within the resolution thresholds of the radiocarbon technique (core LBL1 unit VI, core LNB3 unit II, core LR012, Figs. 5 and 6). These three lithological units encompass a sediment record dated at 7.0–0.6 ^{14}C ka BP, with a hiatus between 3.5 and 2.6 ^{14}C ka BP.

Present paleoclimatic reconstructions were mainly based upon opal phytolith analysis, an approach successfully explored to reconstruct past environmental conditions of grassland ecosystems around the world (Fredlund and Tieszen, 1994, 1997; Fisher et al., 1995; Alexandre et al., 1997, 1999; Scott, 2002; Boyd, 2005; Zucol et al., 2005). Phytoliths are bio-mineral particles originated from the total or partial silicification of plant cells or inter-cellular spaces (Mulholland and Rapp, 1992). Because they are made of silica, their preservation is possible long after the decay of the parental plant. Such tremendous preservation potential, together with differential production from several plants, allows opal phytoliths as high resolution microfossils to be used to infer past vegetation changes.

Opal phytoliths are mainly produced in most monocotyledonous and tree and shrub dicotyledonous (Bozarth, 1992, 1993). Diagnostic capabilities of phytoliths are highly variable, allowing specific identification in some cases, but, in general, diagnosis is restricted to the family or genera level. Despite these limiting factors, in several cases opal phytoliths are better suited to solve plant taxonomy than other plant microfossils are. This is the case for grasses, highly relevant indicators in environmental reconstructions, because their high sensibility and rapid response to changes in surrounding environments. It is possible to determine the photosynthetic paths, C3 and C4, of parental grasses from silicified short cells produced in the epidermal tissue of such plants. The photosynthetic path is directly linked to atmospheric CO_2 and to climate in a broader sense (Twiss, 1992). This assertion has been tested against isotopic analyses on sedimentary profiles (Fredlund, 1993; Fredlund and Tieszen, 1997; Baker et al., 2000) but also against the occluded carbon that remains inside plant cells during mineralization process (Smith and Anderson, 2001; Smith and White, 2004).

Twiss (1992) proposed a classification of silicified short cells from grasses in three main groups, corresponding to three sub-families that are dominant in climatically different zones:

1. Pooid phytoliths are produced mainly in C3 species of the Pooideae (Festucoidae) sub-family which proliferate in temperate to cold regions at high latitudes or altitudes.
2. Panicoid phytoliths are produced mostly in C4 grasses of the Panicoideae sub-family, which proliferate in tropical or subtropical areas.
3. Chloridoid phytoliths are produced by C4 species that are abundant in arid to semi-arid or strongly seasonal rainfall regime climates.

From the relative abundance of each type of phytolith, Twiss (1992) proposed two indices for paleoclimatic reconstructions. The temperature index (TI) is defined as the amount of pooid phytoliths (C3) divided by the total amount of pooid, panicoid (C4) and chloridoid (C4) grasses. High index values suggest a cold climate, while low values indicate warm temperatures.

$$\mathrm{TI} = \frac{\mathrm{Pooid}}{\mathrm{Pooid} + \mathrm{Panicoid} + \mathrm{Chloridoid}} \times 100$$

The humidity index (HI) is defined as the percentage of chloridoid phytoliths to the total amount of C4 grass short cells (panicoids and chloridoids).

$$\mathrm{HI} = \frac{\mathrm{Chloridoid}}{\mathrm{Chloridoid} + \mathrm{Panicoid}} \times 100$$

High index values indicate either arid conditions or rainfall seasonality.

Table 2
Lithological and chronological characterization of sediment cores. The units used in the present reconstruction are highlighted with "◄" signs. Sources: Blasi et al. (2005), García-Rodríguez et al. (2004), Inda et al. (2006).

Water body	Core	Lithological unit	Texture	Dated interval (cm)		
					Chronology	Dating method
Negra	LNB3	I	Silty clay with roots (vegetal cover)			^{14}C
		II ◄	Silty clay, organic (peat)	75–78	930 ± 45 yBP	
				118–131	1600 ± 50 yBP	
				161–178	1980 ± 40 yBP	
		III	Alternance of bioclastic sandy silts and thin horizontally			
		IV	stratified compact muds. Pellitic and peat like interclasts.			
		V				
		VI				
		VII		242–245	4560 ± 70 yBP	
		VIII				
		IX				
		X		263–270	5220 ± 90 yBP	
		XI	Muds to compacted clays with laminated OM			
	LRO12	I ◄	Bioclastic sandy silt	66–81	4066 ± 126 yBP	^{14}C
				215–222	4410 ± 169 yBP	
				430–438	5269 ± 233 yBP	
				579–587	6209 ± 170 yBP	
				639–647	7207 ± 620 yBP	
Blanca	LBL1	I	Compact muds, dark to light grey			
		II				
		III				
		IV	Light Brown compact muds with thin stratified horizontal layers	30	1960 AD	210 Pb
				60	1890 AD	
		V	Stratified compact light grey muds			
		VI ◄	Dark grey compact muds	140–145	1020 ± 60 yBP	^{14}C
				250–255	2200 ± 60 yBP	
		VII	Sandy to silt-sandy, bioclastic.			
		VIII				
		IX		350–355	3710 ± 75 yBP	
		X	Alternance of silty sands with compact muds.			
		XI				
		XII				
		XIII				
		XIV	Sandy silt	536–545	7310 ± 230 yBP	

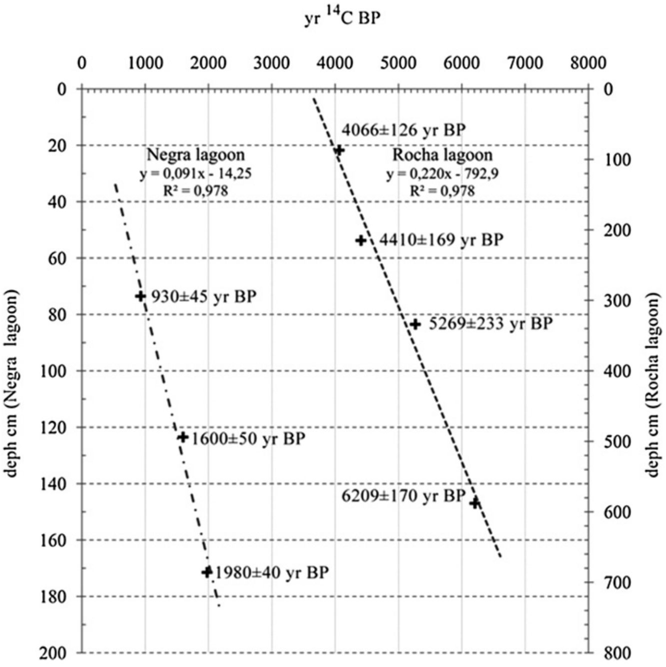

Fig. 5. Correlation between depth and ^{14}C chronology of different stratigraphic units for Rocha and Negra Lagoon. From the regression straight lines defined by the dated intervals, the chronology of the phytolith record was calculated for different depths.

Because of the negligible transport of phytoliths, lagoon bottom cores are excellent archives of information to reconstruct vegetation changes at local or micro-regional scales. Phytolith input to lakes and lagoons comes mostly from their own watersheds. Water courses and surface runoff after rains are responsible for phytolith transport to the water bodies. Nevertheless, the input from several sources could vary through time, depending primarily on climate conditions and plant cover changes (Piperno, 1988).

Opal phytoliths, because their silica nature and overwhelming production in several plants, means that they were preserved in large amounts and as such were incorporated to lacustrine sedimentary record. As well, they are resistant and abundant. Identification of parental plants is taxonomically and ecologically relevant and straightforward. As long as photosynthetic (C3 versus C4) growing habits (tall or short grasses) or even different habitats (swamps, prairies, forests) could be distinguished, information is available in terms of paleoclimatic and palaeoenvironmental trends on grasslands ecosystems such as occur in southeastern Uruguay.

The subfossil record interpretation from lacustrine cores is sustained in comparative analyses from both plant and surface sediment samples (del Puerto et al., 2006, 2008; del Puerto, 2009). Such studies focused on grass phytolith characterization, from a set of 70 native and introduced species (del Puerto, 2009). Climate sensitivity of grass phytoliths was tested with surface sediment samples from cattle exclusion distributed along a climate gradient (del Puerto, 2009).

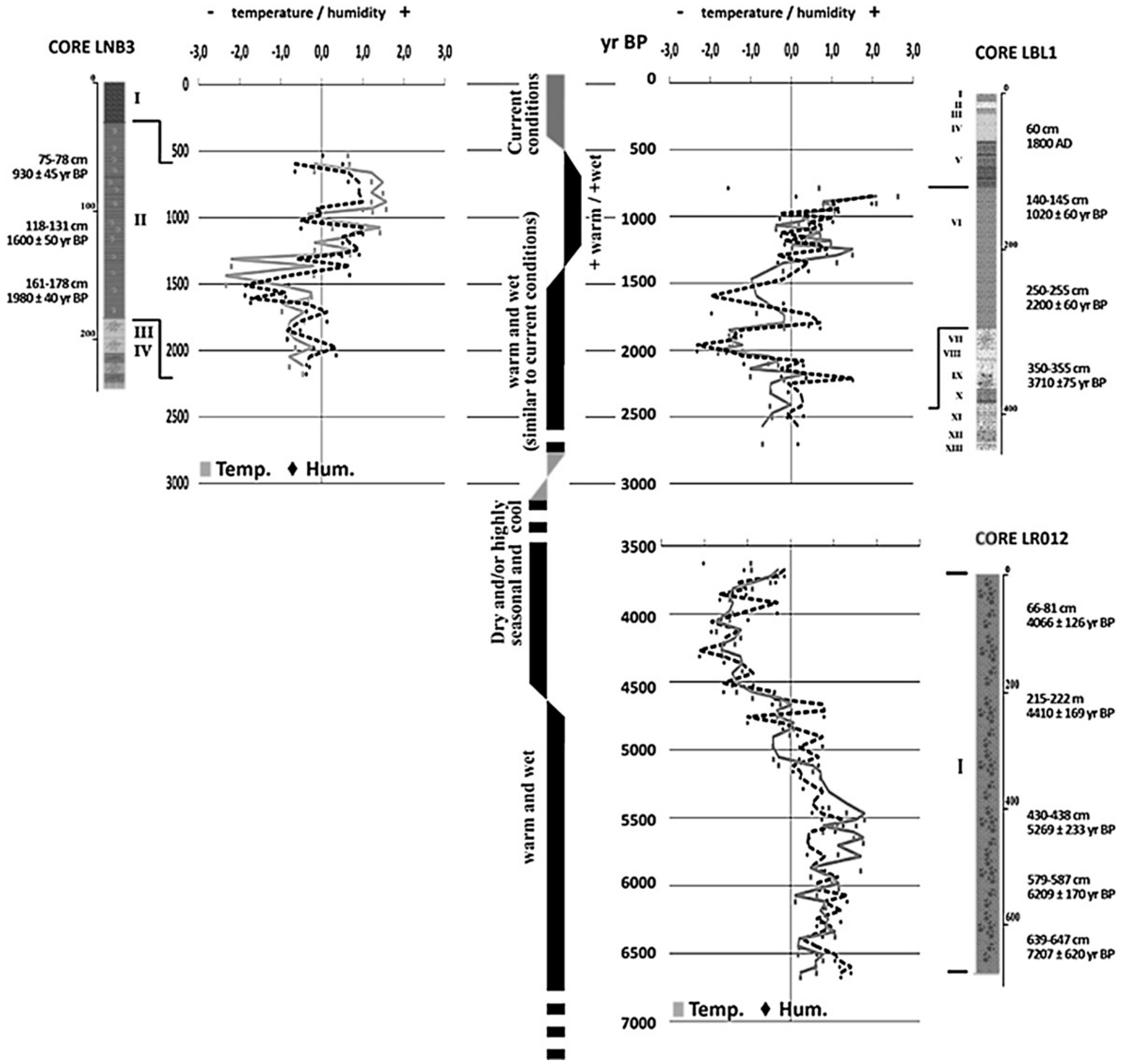

Fig. 6. Normalized ((X – X$_i$)/STD) humidity and temperature indices, core stratigraphy and ^{14}C chronology from Negra, Blanca and Rocha Lagoon.

3. Paleoclimatic results

The characteristics of the selected lithological units (core LBL1 unit VI, core LNB3 unit II, core LR012, Figs. 5 and 6) indicate a fairly uninterrupted sediment record. For the sediment cores of both Negra and Rocha lagoons, the age of each sediment interval was calculated based upon the ^{14}C dates, which show that deposition was fairly uninterrupted, as indicated by the equations listed below:

$$y = 0.091x - 14.25$$
$$r^2 = 0.9787, \quad n = 3$$

and

$$y = 0.220x - 792.9$$
$$r^2 = 0.9788, \quad n = 5$$

respectively (Fig. 5).

For the sediment core of Blanca Lagoon, where only two radiocarbon dates are presently available, the age of the sediments was calculated according to the linear function defined by two points:

$$y = 0.094x + 45.68$$

In order to minimize the expression of short term signals, the mobile mean every three consecutive values was plotted. Four climate zones were inferred (Fig. 6). In zone I, 7.0–4.5 ^{14}C ka BP, a warmer and wetter climate than the present was inferred from the sediment record of core LRO12. In zone II, 4.5–3.5 ^{14}C ka BP, the inference about moisture and climate was also made from the sediment record of core LRO12. Cooler and drier climate was inferred than in the former zone. The record shows a hiatus between 3.5 and 2.6 ^{14}C ka BP. The other climate zones were inferred from the sediment record of both Negra and Blanca lagoons. In zone III, 2.5–1.2 ^{14}C ka BP, climate conditions similar to the present were observed (i.e., warmer and wetter). In zone IV, 1.2–0.6 ^{14}C ka BP, climate was characterized by warmer and wetter conditions than those of zone III.

4. Discussion

4.1. Paleoclimate

The warmest and most humid period was inferred after 2.0 ^{14}C ka BP. This period had only been registered in the sediment record of Negra Lagoon (Bracco et al., 2005a). However, after further sampling (cores LNB3 and LBL1), a much better resolution was obtained (see Fig. 6). Between 1.2 and 0.6 ^{14}C ka BP, there are two peaks of extreme humid and warm events. The second peak fits chronologically into the "Warm Period" (Broecker, 2001; Roberts, 2009), whose occurrence has been already pointed out by Iriondo and García (1993) and Prevosti et al. (2004) in this region.

The record has a hiatus between 3.5 and 2.6 ^{14}C ka BP. This hiatus had already been observed in the first sediment core retrieved from the Negra Lagoon (Bracco et al., 2005a) as well as in other sediment cores of SE Uruguay (del Puerto, 2009). Even though this hiatus represents a loss of information, it might imply a change in sedimentary deposition conditions.

The trend of climate indices of the Rocha Lagoon between 4.5 and 3.5 ^{14}C ka BP indicates the onset of colder and drier conditions than those observed for 7.0–5.3 ^{14}C ka BP. Between 5.3 and 4.5 ^{14}C ka BP, there was a transition from warmer and wetter to colder and drier conditions. The overall results presented here are consistent with other paleoclimatic reconstructions (Bracco et al., 2005a; García-Rodríguez et al., 2009) and the synthesis presented by Mancini et al. (2005), and they are partially consistent with other regional studies (Iriondo and García, 1993; Prieto, 1996, 2000; Iriondo, 1999; Panario and Gutiérrez, 1999; Tonni et al., 1999; Zárate et al., 2000; Prieto et al., 2004; Quattrocchio et al., 2008; Piovano et al., 2009, in Argentina; Behling, 1995, 2002, 2007; Melo et al., 2003; Moro et al., 2004, in Brazil).

4.2. Relationships between culture and climate

The new paleoclimatic data are very consistent with those published by Bracco et al. (2005a,b) but they also encompass a wider temporal frame with a higher resolution. Therefore, it is possible to interpret with better detail the relationships between climate and prehistoric cultures. Taking into account that the oldest mounds are those of India Muerta-Paso Barranca, dated at 5.5 ^{14}C ka BP (Bracco, 2006), it is possible to confirm that this original cultural behavior was installed once warmer and wetter climate conditions ended. Furthermore, if the temporal extent of this period is inferred from the India Muerta-Paso Barranca mounds, for which three radiocarbon dates corroborate a constant growth (n = 19), the initial and final chronology of the mound building period can be assigned to this paleoclimatic record. It may also be observed that, in the transition to the onset of colder/drier conditions (ca 5.5–4.5/4.5–3.7 ^{14}C ka BP), there is an increase in the number of mounds (Fig. 7). After 3.0 ^{14}C ka BP, the series of India Muerta-Paso Barranca shows that the number of erected mounds dramatically decreased. However, the hiatus in the paleoclimatic record between 3.5 and 2.6 ^{14}C ka BP does not allow further relationship of cultural behavior to climate. After the onset of warmer and more humid conditions observed by 2.6 ^{14}C ka BP, a decrease in the number of mounds was recorded. Concurrently, as already pointed out for the archaeological chronologies of the southern section of the Merín Lagoon basin (see Figs. 7 and 8), an expansion of mound builders towards the littoral plains of the lagoon would have taken place. This behavioral change, totally or partially concomitant to climate change, seemed to be accompanied by a modification in the structure of archaeological sites. When comparing site density, mound height and chronology of mound erection in India Muerta-Paso Barranca to those of plains more closely located to the lagoon, it is possible to notice that the plains exhibit less density, less mounds per site, lower mound height and shorter erection time and a more recent chronology (see Bracco and López, 1987a,b; Cabrera, 2000; Bracco et al., 2008a). It has also been observed that radiocarbon ages of the Atlantic coastal sites without mounds indicate that, after 3.0

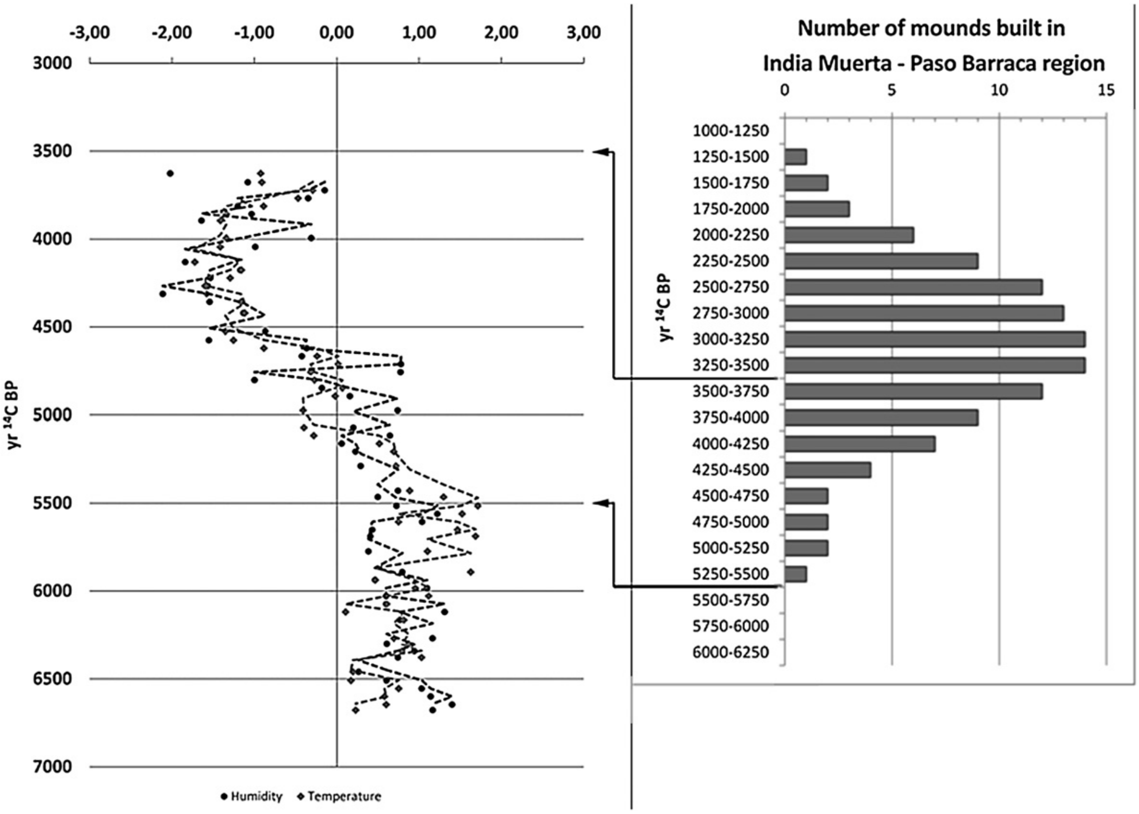

Fig. 7. Left: normalized humidity and temperature indices from Rocha Lagoon. Right: number of mounds built within the India Muerta-Paso Barranca region.

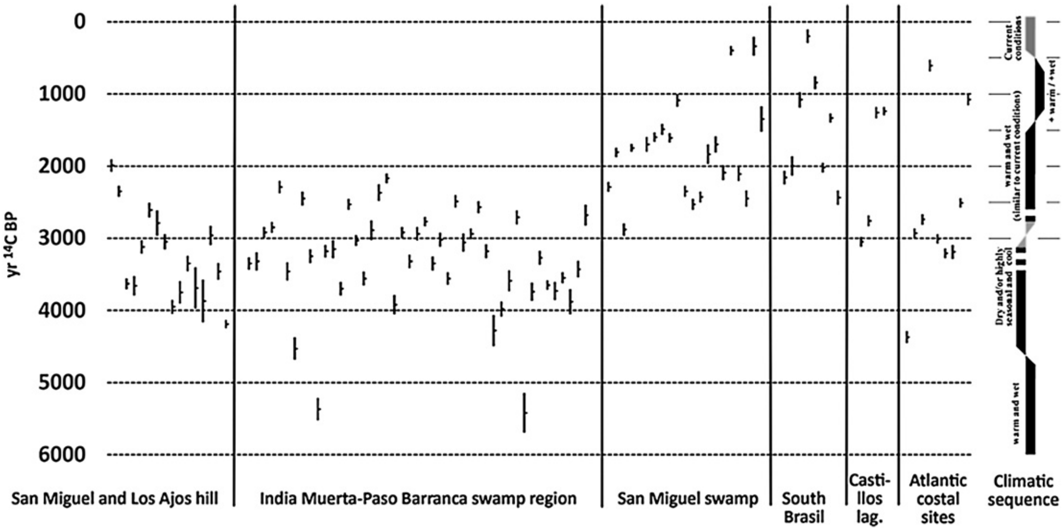

Fig. 8. ^{14}C dates from mound sites: India Muerta-Paso Barranca, San Miguel and Los Ajos Hill, San Miguel swamp, Castillos Lagoon, de los Patos Lagoon in SE Brasil and coastal sites (Schmitz and Basile Becker, 1967; Schmitz, 1973, 1976; Bracco et al., 2005a, 2008a; Iriarte, 2006; del Puerto, 2009; López et al., 2009). The inferred climate sequence is depicted to the right of the plot.

^{14}C ka BP, there was an increase in the number of occupations (Fig. 8).

5. Conclusions

The improvement in resolution of the regional paleoclimatic data supports the proposed paradox for environmental and cultural history of the mound builders (Bracco et al., 2005a). Mounds that are related to wetlands were erected under environmental conditions restricted, at least, to transitionally or permanently waterlogged areas. After an increase in humidity together with an associated increase in wetland area, the coercive pressure on the base of the mounds would have decreased (Bracco, 2006). The radiocarbon dates in different zones of the southern section of the Merín Lagoon basin indicate that the mound builders expanded towards the coast of the lagoon, when more humid and warmer conditions developed. The difference between the coast of the lagoons and the India Muerta-Paso Barranca zone, in terms of density of sites and mounds, would indicate that the expansion was accompanied by a higher dispersion following the model of permanent growth, and lower recurrence in behavior that had a negative effect on the elevation of the mounds. The absence of significant changes in the archaeological record indicates that redundancy was kept during the entire mound lifetime. However, the set of radiocarbon dates of mound burials ($n = 10$) during 2.0–0.2 ^{14}C ka BP would suggest a possible change in those practices that were linked to mounds for this late period.

From these data it may be suggested that dispersal towards the lagoon plains was accompanied by a decrease in coercive forces, at different scales, leading to a spatial widening, but also to lesser redundancy and span of occupations. Since this process took place during an increase in both temperature and humidity, cultural development was positively related to climate. The response seems to be equivalent to that inferred for the emergence of these sites, but with opposite signals. During periods of decreased temperature and moisture, an intensive colonization pattern of wetlands was inferred together with an increase in spatial redundancy and behavioral recurrence. Under non-restrictive conditions, the opposite pattern was observed. The chronology of coastal sites would indicate that both the expansion of mound builders and some changes in site structure, were almost parallel to the onset of warmer and more humid conditions.

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