Review article

Late Pleistocene and Holocene geomorphologic evolution of Laguna Las Vueltas area, Tierra del Fuego (Argentina)

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Recepción: 06 Agosto 2018
Aprobación: 25 Febrero 2019

Abstract

Laguna Las Vueltas (LLV) area retains the morphology of a late Pleistocene watershed that was flooded during a mid-Holocene marine transgression. Sediments associated with a paleosol dated at 22,582 cal yr BP reflect subaerial exposure of the area prior to the submergence during the marine transgression. This transgression produced an extensive tidal flat near the mouth of the former LLV watershed by 7,477 cal yr BP. Subsequent decoupling of the Las Vueltas valley from the sea occurred through the growth of a baymouth barrier and a beach-ridge plain to the east. This decoupling turned the lagoon into a pan environment in which subsequent lake-level fluctuations were controlled by climate. A lunette dune developed at the pans in the former lagoon, providing a narrow corridor where humans trapped, killed and processed guanacos as early as 3,402 cal yr BP. Changes in aeolian sedimentation hint at increased aridity during the past 500 years.

Keywords: Geomorphology, Incised valleys, Holocene marine transgression, Lunettes, Geoarchaeology, Pans..

1. Introduction

Shallow and salty lakes, termed "pans" (Shaw and Bryant, 2011; Villarreal and Coronato, 2017) are common coastal features on northeastern Tierra del Fuego. One of these pans, Laguna Las Vueltas (LLV, Fig. 1) is located within a steppe environment that extends from the Magellan Strait to the cape Viamonte area, south of the Río Grande, Argentina (Collado, 2007). Laguna Las Vueltas and other pans on Tierra del Fuego are the product of a marine transgression during the Holocene and subsequent isolation of former estuary mouths from the sea by the growth of barrier bars and dunes. Deflation of the bottom of the pans during dry periods produces clouds of dust that are carried eastward to the Atlantic Ocean (Goudie and Wells, 1995; Gaiero et al., 2007; Montes et al., 2017).

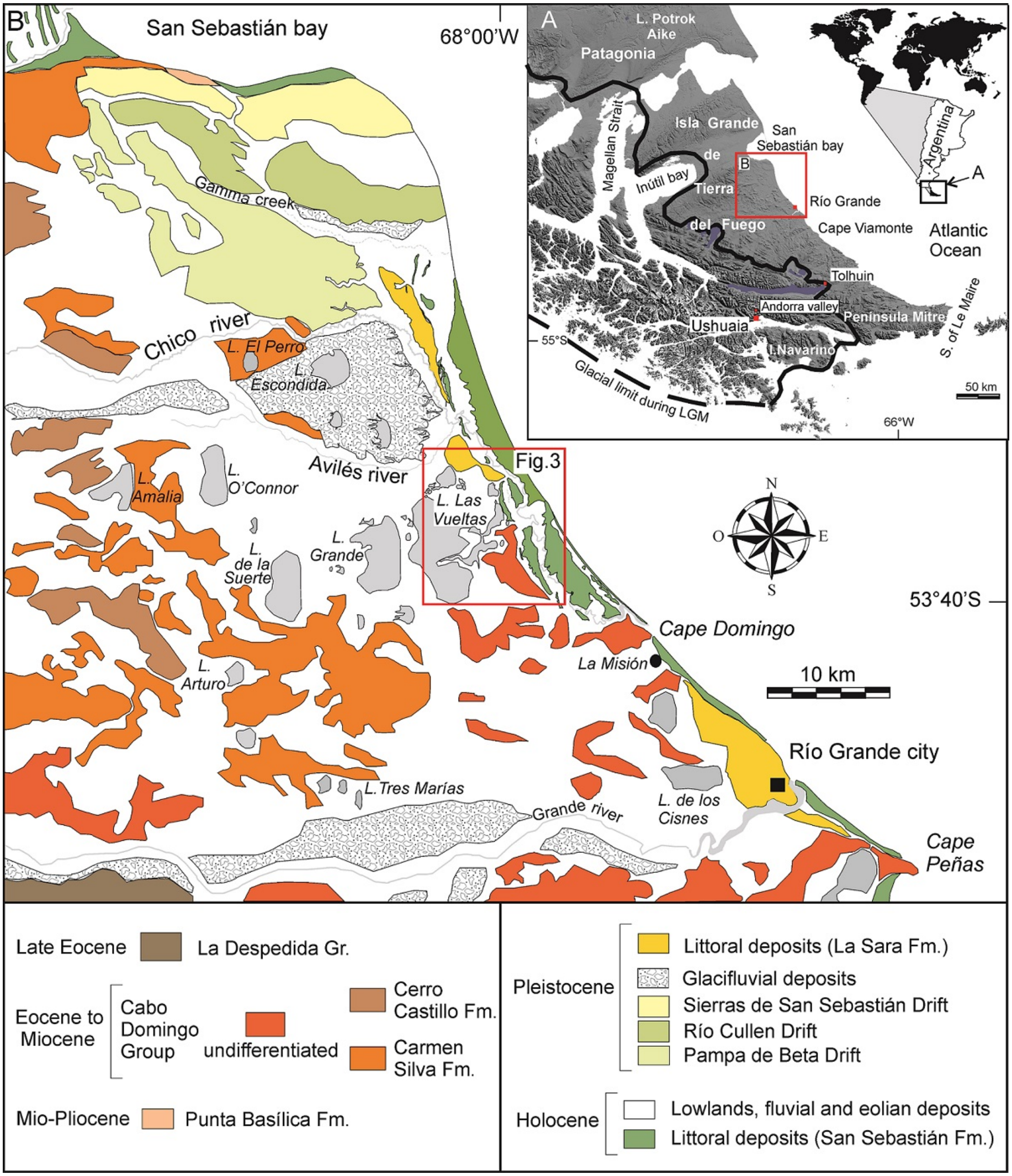

FiG. 1.

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FiG. 1. A. Location map of Tierra del Fuego showing the glacial limit during the Last Glacial Maximum (LGM), modified from Rabassa (2008). B. Distribution of geologic units, modified from Codignotto and Malumián (1981), Meglioli (1992) and Malumián and Olivero (2006).

In this paper, we document the geomorphologic evolution of the LLV area from the late Pleistocene to the Present based on its geomorphology and sedimentary records. We discuss the origin of the dune in which the

Las Vueltas 1 archaeological site (LV1) is situated, which was first occupied about 3,402 cal yr BP. Our specific objectives are to understand the morphology of these watersheds at northeastern Tierra del Fuego, reconstruct the Holocene landscapes in coastal areas and obtain information of climatic changes associated to the sedimentary and geomorphological processes of the area. These particular objectives lead to our main objective, which is to increase the understanding of the geomorphologic history of Tierra del Fuego during the period when hunters-gatherers first arrived to southernmost Argentina.

2. Climate

Tierra del Fuego lies within the circulation zone of the southern westerlies, which result from interaction of polar and subtropical air masses (Haltiner and Martin, 1957; Lambeck, 1980). The South Pacific anticyclone dries as it moves eastward over the Andes and generates strong and persistent föhen-type winds (Prohaska, 1976). This belt of low pressure, low precipitation, and turbulence lies between 40° and 60 °S, and moves northward in winter.

Climate at Río Grande, the closest meteorological station to LLV, is cold-temperate, with an average temperature of 10 °C in the warmest month (February) and -2 °C in the coldest month (August; Tukhanen, 1992). Westerly winds with an average speed of 29 km/h occur 63% along a year (Servicio Meteorológico Nacional, 1986; Tukhanen, 1992). Mean annual precipitation is 333 mm/year (Iturraspe and Urciolo, 2002). The coast has a macro-tidal range of about 8.4 m (Servicio de Hidrografía Naval, 2008).

3. Sea level change since the Last Glacial Maximum

Sea level off the coast of Patagonia rose rapidly during the Last Glacial Maximum from a low-stand of about -105 m (Fig. 2a; Guilderson et al., 2000). Schellmann and Radtke (2010) describe a rapid early Holocene rise in sea level in central and southern Patagonia (44° to 49 °S), which reached the current coastline about 8,600 cal yr BP. This transgression peaked between 7,400 and 6,600 cal yr BP, when the sea surface averaged 2-3 m above the present datum. On northeastern Tierra del Fuego, the maximum transgression was +1.55-2.69 m in the Chico river area (Fig. 2b) and +1.57 m in San Sebastián Bay (Bujalesky, 2007; Montes, 2015; Montes et al., 2018). Subsequently, sea level fell gradually until today (Violante et al., 2014a, b; Montes, 2015).

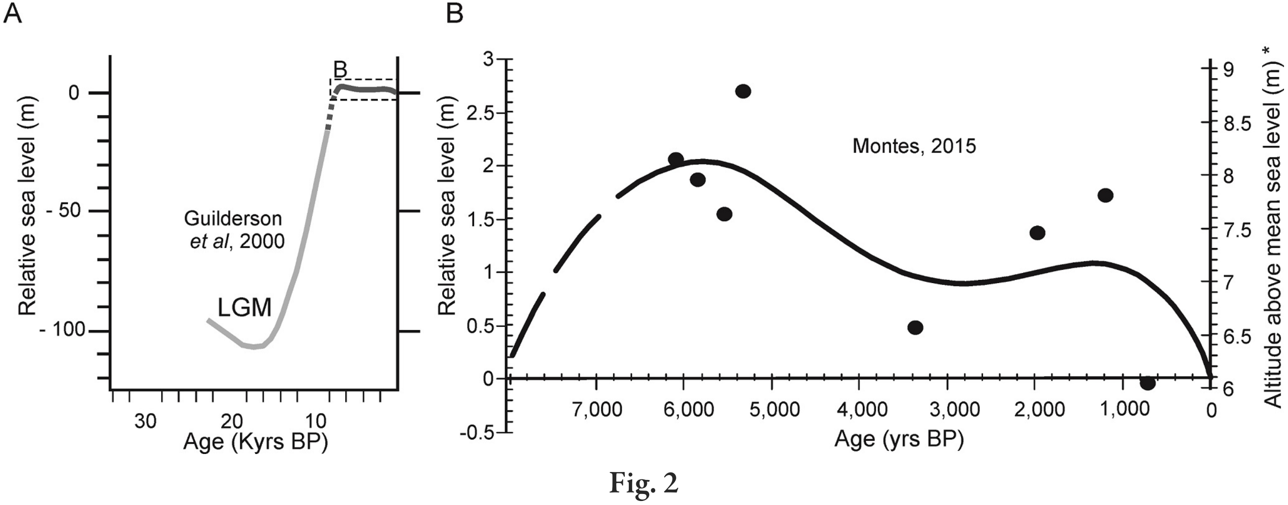

Fig. 2

Fig. 2.

Fig. 2. Relative sea-level change curve derived from A. Argentine Shelf bathymetric data (Guilderson et al., 2000) and B. The Chico river area (Montes, 2015). Relative sea-level change in the Chico river area was determined by comparing elevations of Holocene beach ridge with the elevation of the current storm berm. Points are the time-altitude plot of Holocene dated samples. *WGS 84 datum and 12,039 m ellipsoid undulation (sensu Perdomo and Hormaechea, 1999).

4. Geology and soils

The study area is underlain by Eocene-Miocene marine sedimentary rocks and Quaternary glacial, glacifluvial and littoral sediments (Meglioli, 1992; Malumian and Olivero, 2006). The LLV area was ice-free during the past four or five Pleistocene glaciations (Rabassa and Clapperton, 1990; Meglioli, 1992; Rabassa, 2008). Mid- and late Pleistocene coastal deposits have been recognized in northern Tierra del Fuego, associated to sand and gravel beaches (Bujalesky et al., 2001; Bujalesky, 2007). During Pleistocene transgressions, the area at the confluence of the Chico and Avilés rivers was a tidal inlet in which estuarine sediments accumulated up to 16 km landward of present-day lagunas Grande, de la Suerte and O'Connor (Bujalesky et al., 2001; Bujalesky, 2007). The Chico river mouth shifted southward during construction of a large Holocene beach ridge plain (Codignotto and Malumian, 1981; Bujalesky et al., 2001; Montes, 2015; Montes et al., 2018).

The soils in the study area are Mollisols and Inceptisols with relatively weak A and C horizons and loam to clay loam textures (Panigatti, 2010). They support a herbaceous and grassland vegetation cover with wet grasslands under a xeric soil moisture regime (Collado, 2007).

5. Human occupation

Human groups have inhabited Tierra del Fuego since the early Holocene (Morello, 2000; Massone, 2003). Archaeological sites are associated with hunter-gatherer populations living mainly of guanaco hunting (Lama guanicoe). Pans would have concentrated different resources for the hunter-gatherer lifeway, not only water but fauna and raw material useful for the groups living in the area during the Holocene (Massone et al., 1993; Santiago, 2013; Oría et al., 2016).

The LV1 archaeological site at LLV (Fig. 3) is associated to aeolian deposits (Santiago and Salemme, 2009, 2010, 2016; Colasurdo et al., 2012; Santiago, 2013). It is a multicomponent site located between two pans with evidence for at least four occupation events. The first occupation (3,402 cal yr BP) is recorded by lithic and bone flakes and a few guanaco bones with human-inflected fractures. The second occupation (569 cal yr BP) is recorded by one hearth and numerous remains of at least six guanacos. A thin layer of 4 cm separates this occupation from the third one (545 to 525 cal yr BP), which is marked by a bonebed (sensu Behrensmeyer, 2007), which includes skeletal remains of guanaco and rodents, mostly tuco-tuco (Ctenomys magellanicus), also lithic tools, flakes and many microflakes (Negre et al., 2017; Santiago and Salemme, 2016; Santiago et al., 2016).

LV1 is an appropriate location space to trap, kill and process guanaco (Santiago, 2013). A lunette between the pans enabled hunter-gatherers to drive animals to a central point, where they could be more easily to kill them with bows and arrows. Guanacos were also processed and partially consumed at the place (Santiago and Salemme, 2016).

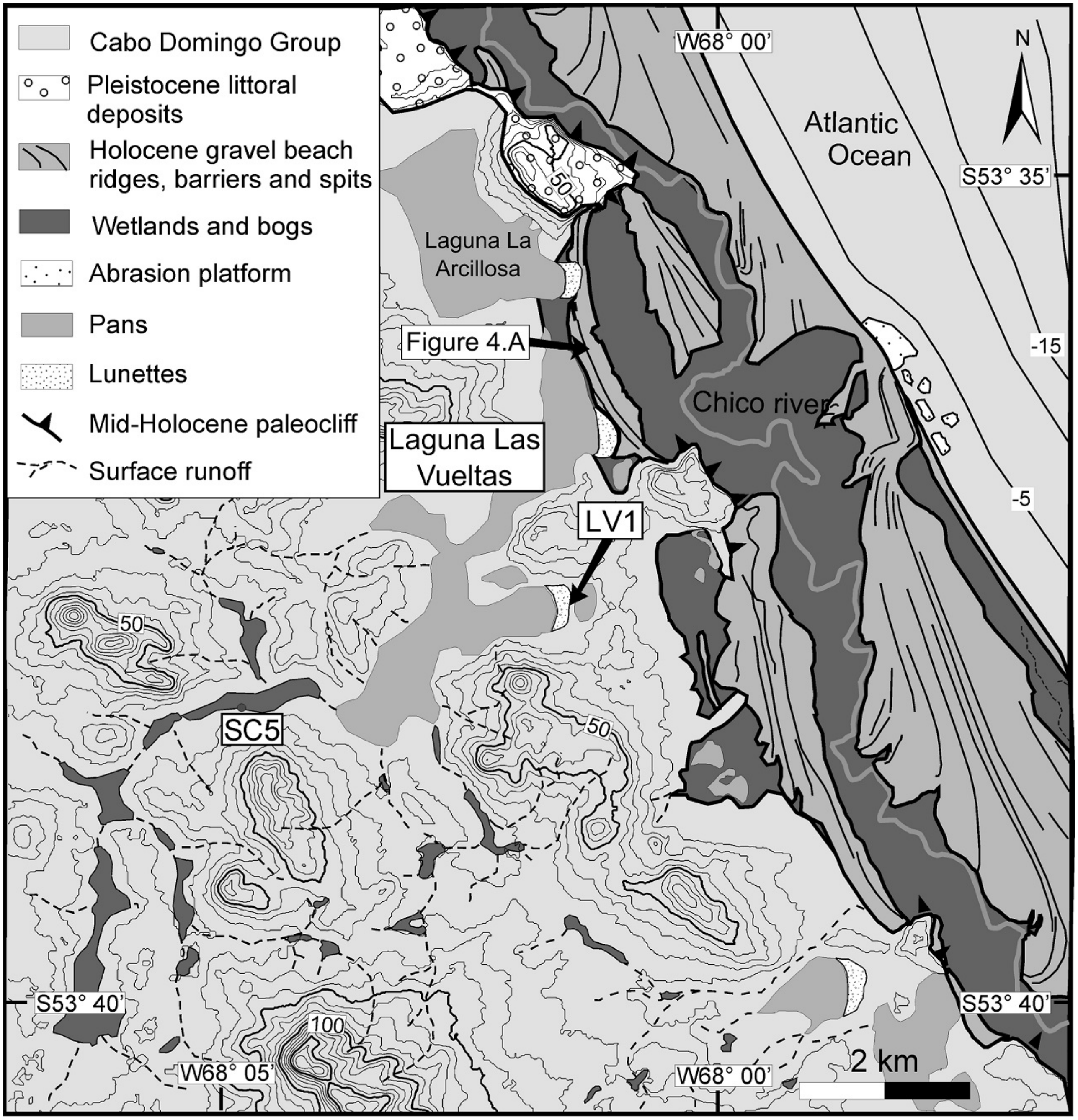

Fig. 3

Fig. 3

Fig. 3. Geomorphology of the study area; LV1: Las Vueltas 1 archaeological site; SC5: Stratigraphic column. LLV and other pans are bordered on the east by a mid-Holocene littoral barrier (Bujalesky et al., 2001).

6. Methods

Satellite imagery from Google Earth (2017) and digital elevation models (ALOS PALSAR, 2011; spatial resolution 12.5 m) were used to identify and map the main geomorphological units. The units were validated during the field survey. A topographic cross-section of the LV1 area was constructed with a differential GPS (ProMark 2), using the Stop and Go method with 30 seconds spent at each survey station. Data were processed in the field with Ashtech Solution 2.70 software. The vertical error in readings is estimated to be 2.2±0.7 cm.

Stratigraphic data were obtained from dug pits and percussion cores. Grain size was estimated in the field using the size scale of Friedman and Sanders (1978). Sedimentary environments were inferred from sediment lithology, geometry, structure and fossils (Boyd et al., 1992; Galloway and Hobday, 1996). Samples of soil organic matter, bone and charcoal were collected from the LV1 archaeological site and dated at the University of Arizona AMS laboratory. Radiocarbon ages from previous studies (Salemme and Bujalesky, 2000; Bujalesky et al., 2001; Salemme et al., 2007; Coronato et al., 2011; Santiago, 2013) were also used for paleoenvironmental reconstructions and interpretations. Ages were calibrated using SHCal04.14c and IntCal09.14c (McCormac et al., 2004; Heaton et al., 2009). Ages in the text are calibrated radiocarbon ages, but non-calibrated ages are also included in table 1.

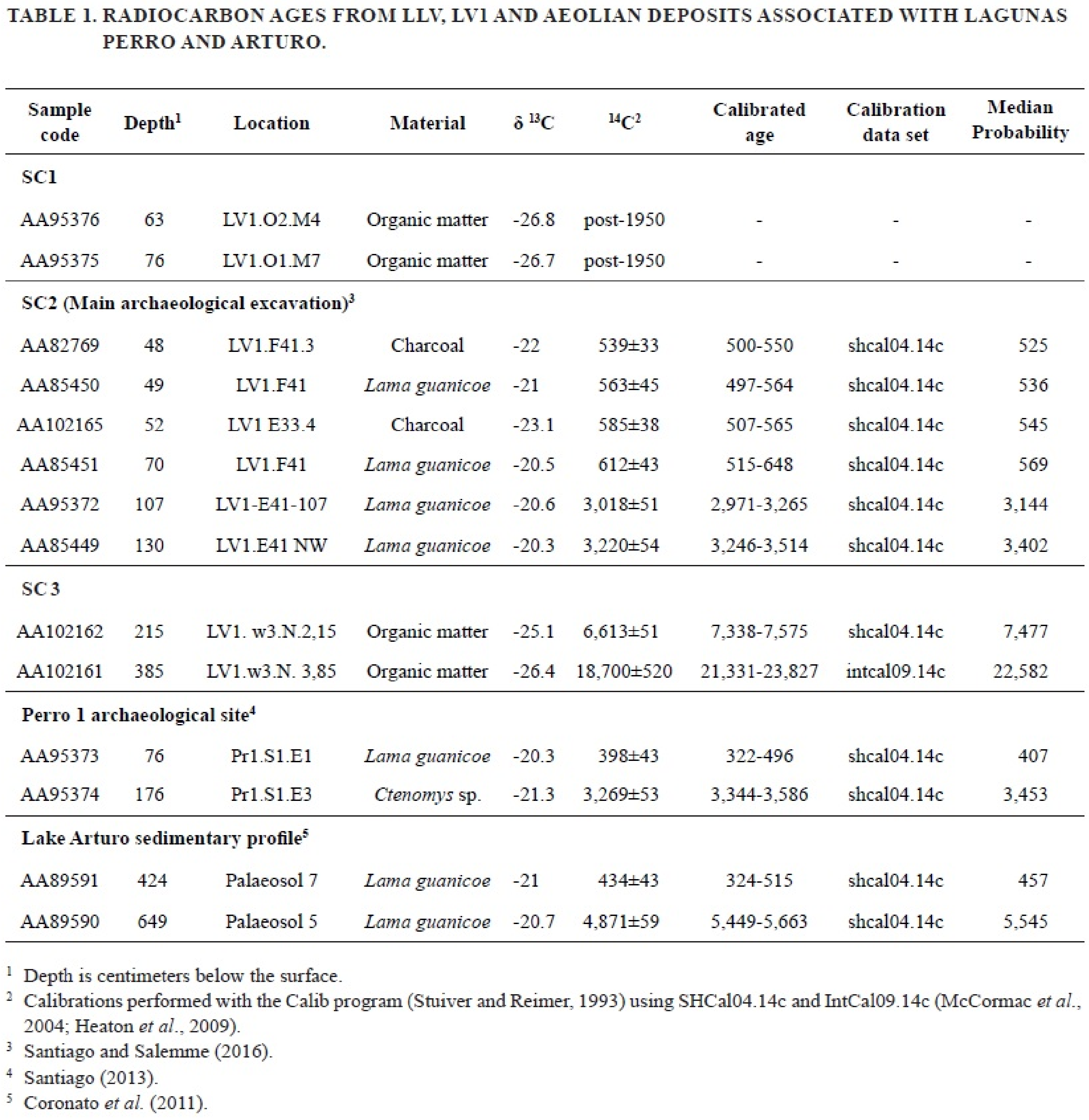

TABLE 1. RADIOCARBON AGES FROM LLV, LV1 AND AEOLIAN DEPOSITS ASSOCIATED WITH LAGUNAS PERRO AND ARTURO.

Sample code	Depth[1]	Location	Material	δ ^{13}C	^{14}C[2]	Calibrated age	Calibration data set	Median Probability
SC1								
AA95376	63	LV1.O2.M4	Organic matter	-26.8	post-1950	-	-	-
AA95375	76	LV1.O1.M7	Organic matter	-26.7	post-1950	-	-	-
SC2 (Main archaeological excavation)[3]								
AA82769	48	LV1.F41.3	Charcoal	-22	539±33	500-550	shcal04.14c	525
AA85450	49	LV1.F41	*Lama guanicoe*	-21	563±45	497-564	shcal04.14c	536
AA102165	52	LV1 E33.4	Charcoal	-23.1	585±38	507-565	shcal04.14c	545
AA85451	70	LV1.F41	*Lama guanicoe*	-20.5	612±43	515-648	shcal04.14c	569
AA95372	107	LV1-E41-107	*Lama guanicoe*	-20.6	3,018±51	2,971-3,265	shcal04.14c	3,144
AA85449	130	LV1.E41 NW	*Lama guanicoe*	-20.3	3,220±54	3,246-3,514	shcal04.14c	3,402
SC 3								
AA102162	215	LV1. w3.N.2,15	Organic matter	-25.1	6,613±51	7,338-7,575	shcal04.14c	7,477
AA102161	385	LV1.w3.N. 3,85	Organic matter	-26.4	18,700±520	21,331-23,827	intcal09.14c	22,582
Perro 1 archaeological site[4]								
AA95373	76	Pr1.S1.E1	*Lama guanicoe*	-20.3	398±43	322-496	shcal04.14c	407
AA95374	176	Pr1.S1.E3	*Ctenomys* sp.	-21.3	3,269±53	3,344-3,586	shcal04.14c	3,453
Lake Arturo sedimentary profile[5]								
AA89591	424	Palaeosol 7	*Lama guanicoe*	-21	434±43	324-515	shcal04.14c	457
AA89590	649	Palaeosol 5	*Lama guanicoe*	-20.7	4,871±59	5,449-5,663	shcal04.14c	5,545

[1] Depth is centimeters below the surface.

[2] Calibrations performed with the Calib program (Stuiver and Reimer, 1993) using SHCal04.14c and IntCal09.14c (McCormac *et al.*, 2004; Heaton *et al.*, 2009).

[3] Santiago and Salemme (2016).

[4] Santiago (2013).

[5] Coronato *et al.* (2011).

Table 1

Table 1

7. Results

7.1. Geomorphology of Laguna Las Vueltas area

The LLV area is dominated by rounded hills composed of marine sedimentary rocks of the Cabo Domingo Group (Eocene-Miocene; Malumián and Olivero, 2006). The Las Vueltas valley has been eroded into these sedimentary rocks, and pans have developed on the former valley floor near the coast (Fig. 1; Villarreal and Coronato, 2017).

LLV is a shallow temporary water body with a maximum surface area of 3 km2; it is recharged from precipitation, mainly during the winter season, and groundwater. It occupies the lower part of an endorheic basin that is fed by an intermittent stream from the southwest. The flat bottom of this and other pans in northern Tierra del Fuego and Patagonia is controlled by the near-surface groundwater table, which serves as base-level control for aeolian deflation (Jacobson et al., 1994; Rosen, 1994). LLV is bordered to the northeast by a mid-Holocene littoral barrier with a crest 2.68 m above present sea level (Figs. 3-4a; Montes, 2015). Neither the valley floor nor the headwater show evidence of active water erosion. The valley widens and constricts irregularly, and forms a poorly integrated and interrupted drainage network composed of small pans and wetlands (Fig. 3).

Waves formed by the dominant westerlies favor the development of sandy-gravel beaches and erosion scarps within pans. Beach scarps are present on the east side of the small pan at LV1 and show that water levels were higher in the past than today (Fig. 4c).

Aeolian deposits are common as lunettes, perched dunes and thin mantles on the east side of the pans (Coronato et al., 2011). The LV1 archaeological site is located within a lunette that is 570 m long and forms a corridor up to 150 m wide bordered by two pans: a small one on the east and a large one (LLV) on the west (Fig. 3b).

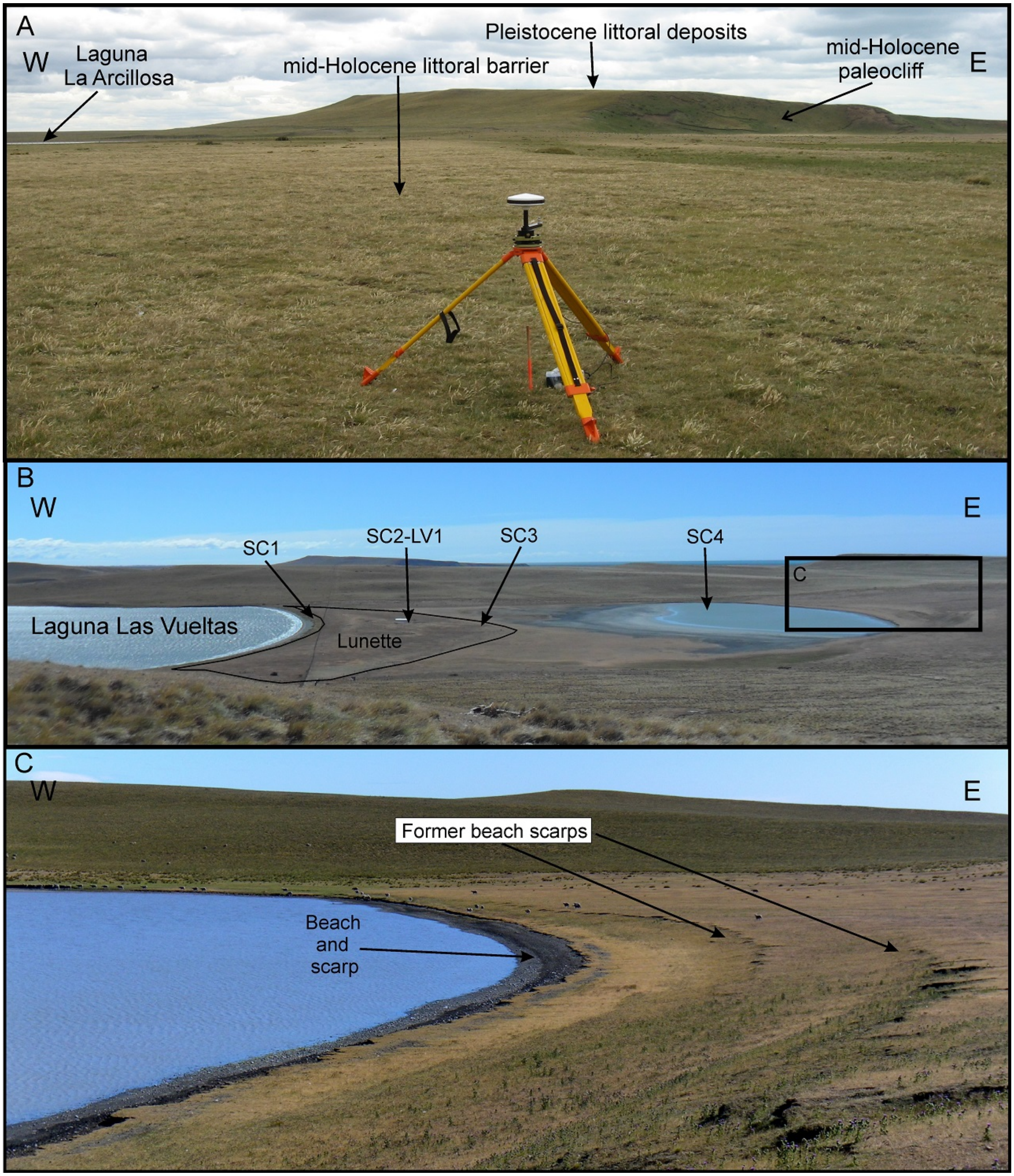

Fig. 4.

Fig. 4.

Fig. 4. A. Mid-Holocene littoral barrier located east of LLV and Laguna La Arcillosa (Fig. 3). B. Panoramic view of the LV1 archaeological site and its surroundings. C. View of the small pan located east of LV1, showing current and former beach scarps. Note the contrast in vegetation between the thin aeolian mantle and the surrounding hills. SC: Stratigraphic columns location.

7.2. Stratigraphy

The stratigraphy of five pits and core-samples (SC1 to SC5) from the study area was recorded. SC1, SC2, SC3, and SC4 lie along an east-west transect across the lunette and include the archaeological site LV1 (Figs. 3, 4b-5a). SC5 is a core taken at the west side of the LLV area in a frequently submerged wetland (Figs. 3-5b).

SC1 (Fig. 4b) is a pit on the upper beach scarp of LLV (53°37'49.9" S, 68°01'41.2" W; Fig. 5a). It shows alternating layers of well sorted, medium sand, sandy gravel with abundant plant matter; the beds are less than 13 cm thick. Post-1950 radiocarbon ages were obtained on plant remains of the deepest organic layers (O1 and O2; Table 1).

SC2 (Fig. 4b) is a pit near the crest of the lunette located east of SC1 (53°37'42.7" S, 68°01'39.0" W). Dark brown, sandy clayey is present at the base of the pit 1.97 m below the surface. Faunal remains (Lama guanicoe and Ctenomys sp.) with anthropic evidence were found 1.2-1.3 m below the surface, and dated to 3,402 and 3,144 cal yr BP (Fig. 5a). Above 80 cm depth, the sediments coarsen to dark brown silty sand with abundant archaeological and bone remains (mainly Lama guanicoe, but Mytilus sp. shells, charcoal associated with a hearth, and lithic artifacts are also present). Radiocarbon ages from this level are 569 and 525 cal yr BP (Figs. 5b-6a). A poorly developed soil with prismatic structure is present near the ground surface. It is covered by aeolian silty fine sand supporting roots and grasses.

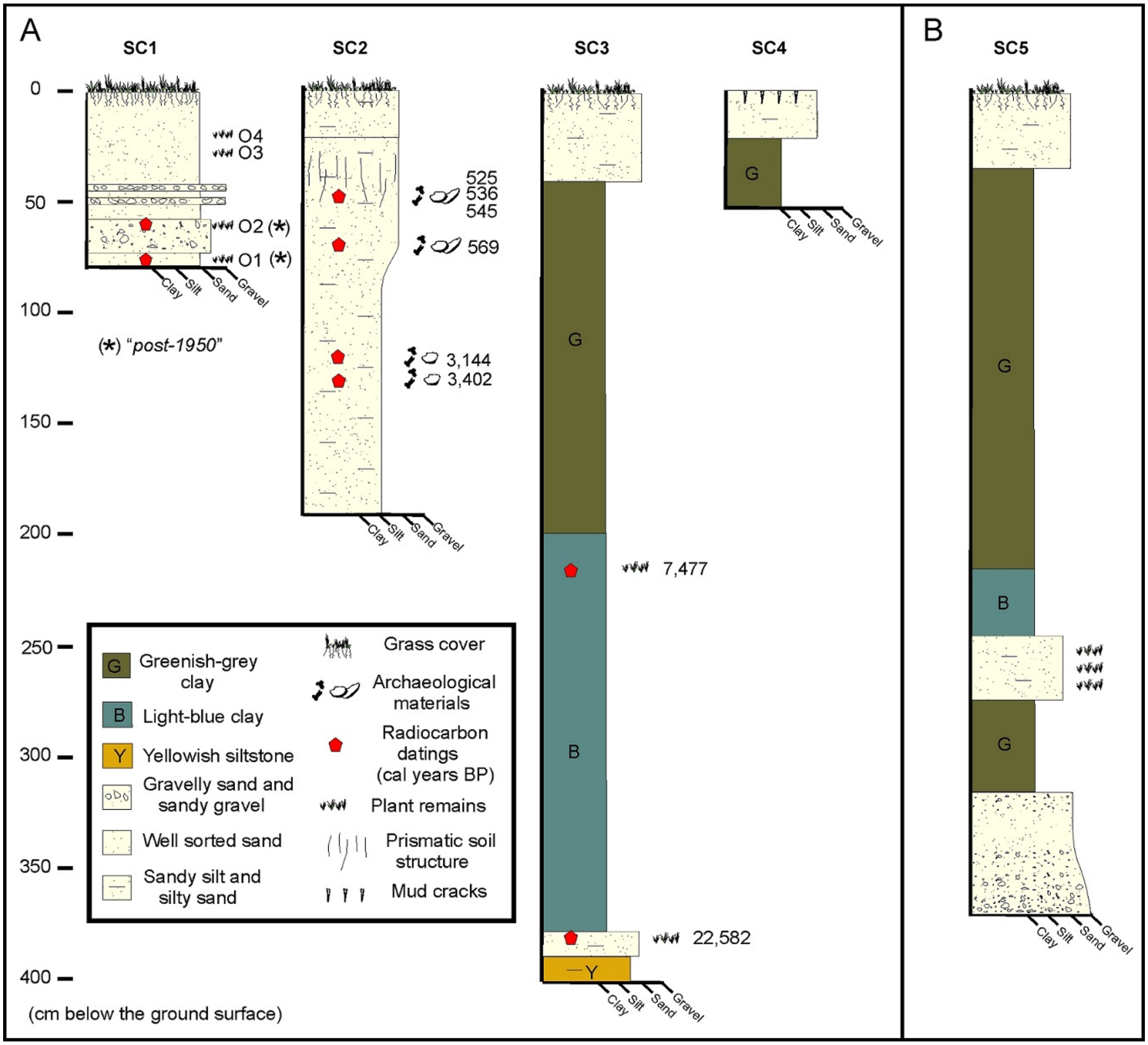

Fig. 5

Fig. 5

Fig. 5. Stratigraphic columns (SC) of (A) dug pits (SC1-SC4) and (B) a core (SC5) (see figures 3 and 4b for locations). Layers rich in plant remains at SC1 are numbered O1 to O4 for easy reference.

Fig. 6

Fig. 6.

Fig. 6. A. The bone bed at the LV1 archaeological site. B. Lower part of the core at SC3 showing a dark paleosol developed on sedimentary rocks of Cabo Domingo Group.

SC3 (Fig. 4b) is a 4 m long core and located east of LV1 (S53°37'42.7" W68°01'36.5") (Fig. 5a). Yellowish-brown, clayey siltstone of the Cabo Domingo Group is present at the base of the core (Fig. 6b). At 3.88 m, the siltstone is overlain by a dark, organic-rick silty sand with traces of fine roots, which yielded a radiocarbon age of 22,582 cal yr BP (Table 1). We interpret this unit to be a paleosol. Above 3.79 m are 1.8 m of light blue clay with plant fragments (possibly Salicornia sp.), which yielded a radiocarbon age of 7,477 cal yr BP (Table 1). The clay is overlain by 1.45 m of greenish-gray clay. The uppermost 45 cm of the core is sand with a capping weakly developed soil covered by grass.

The pit at SC4 is 0.53 m long and located east of SC3 (S53°37'42.8" W68°01'26.9") (Fig. 4b). Thirty-one centimetres of greenish-grey clay are overlain by 22 cm of clayey fine sand (Fig. 5a). The surface at this location exhibited mud cracks due to drying of the pan surface at the time the pit was dug.

SC5 is a 3.69 m long core located west of LLV (S53°38'17.1", W68°04'55.1") (Fig. 5b). Matrix-supported gravel is present at the base of the core. The gravel fines upward to coarse sand over a distance of 52 cm. Scattered fine gravel is present at the top of this unit. Above, it is 42 cm of gray-green clay. Dark, organic-rich sandy silt occurs at depths of 2.45-2.75 m and is covered by 30 cm of light-blue clay. The clay, in turn, is overlain by 1.83 m of gray-green clay. The uppermost 32 cm of the core is silty sand.

8. Discussion

The coastal area between San Sebastián Bay and Río Grande was not glaciated during most of the Pleistocene (Fig. 1a), but meltwater streams from glaciers to the west reached the coast, and the area was affected by marked sea-level changes accompanying the build-up and decay of the Patagonian ice sheet (Bujalesky et al., 2001; Bujalesky, 2007). The absence of Pleistocene marine and littoral deposits of La Sara Formation in the LLV basin suggests that the basin is younger than Marine Isotopic Stage (MIS) 5e, because the sandy-gravel coastal terrace associated to this interglacial period on Tierra del Fuego are typically higher in elevation than the floor of the basin (16-17 m above mean sea level; Codignotto and Malumián, 1981; Bujalesky, 2007). During the Last Glacial Maximum, sea level fell to about -105 m below its present position and the coastline was far to the east of its present location (Rabassa, 2008; Ponce et al., 2011; Violante et al., 2014a, b). Cutler et al. (2003) identified four periods of rapid sea-level fall between MIS 5e and MIS 2 with rates between 2.9 and 10.6 m/ka. Rapid lowering of sea level would lower base level and might cause an expansion of the drainage network and valley incision in the study area, as in other coastal areas of the world (Greene et al., 2007; Sloss et al., 2007). The friable sediments of the Cabo Domingo Group are susceptible to weathering and erosion and thus may have contributed to the development of a drainage network whose morphology is partially preserved today (Fig. 7a). The fining-upward gravel/sand unit at the bottom of the core at SC5 is interpreted to be fluvial sediment deposited in the LLV paleovalley before MIS 2. Sediments in the core at SC3 dated at 22,582 cal yr BP reflect subaerial conditions after the end of the incision of the paleovalley.

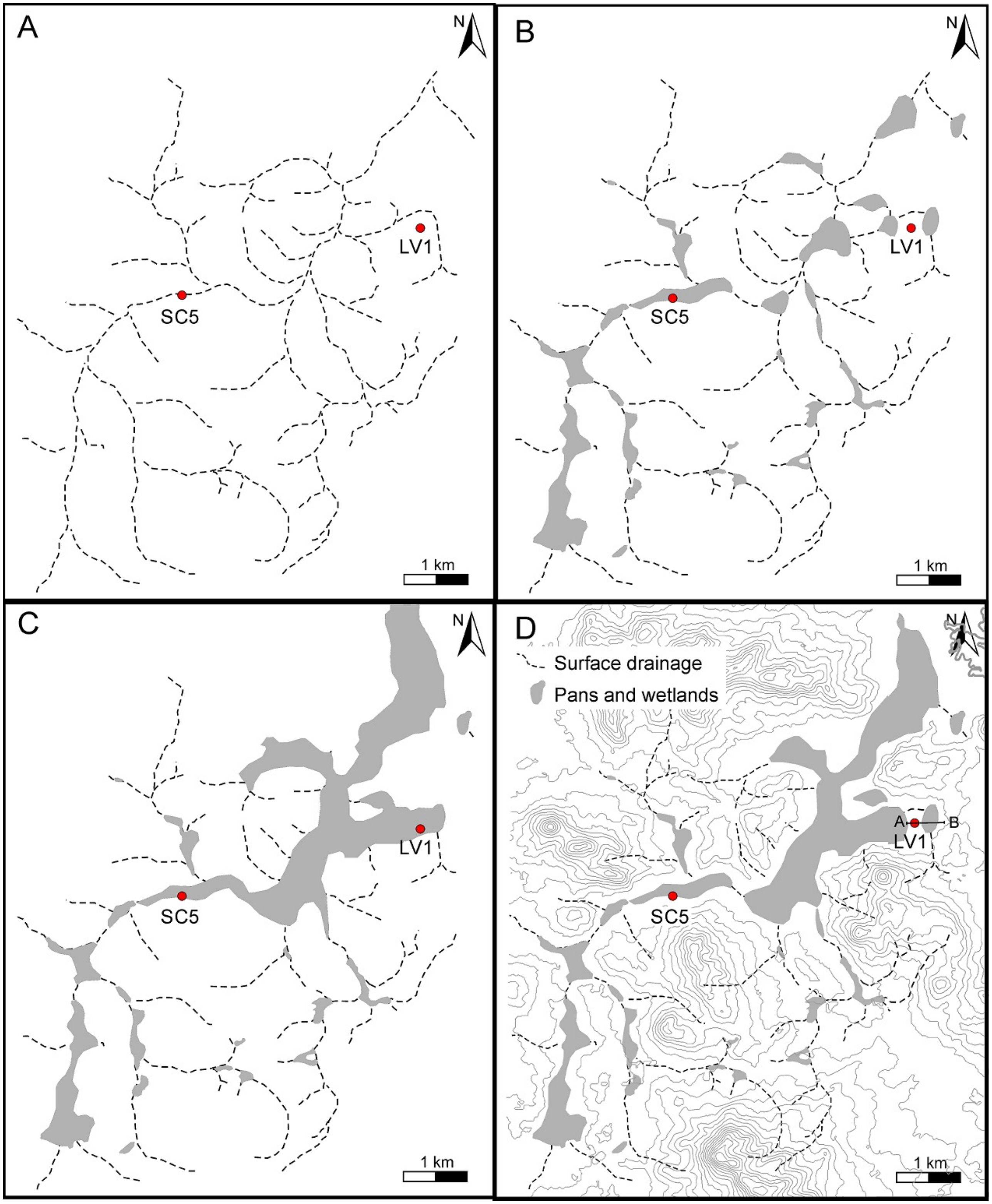

Fig. 7

Fig. 7

Fig. 7. Evolution of the drainage network in the LLV area: A. Late Pleistocene, B. Early Holocene, C. Mid-Holocene, D. Present (A-B: topographic cross-section; see figure 8). LV1: Las Vueltas 1 archaeological site; SC5: stratigraphic column 5.

Sea level rose at a rate of 11-12 mm a-1 early after the Last Glacial Maximum, and even faster later (Guilderson et al., 2000; Cavallotto et al., 2004; Violante and Parker, 2004; Schnack et al., 2005). With the rise in base level and increased aridity, the studied drainage network may have disintegrated. Winds eroded the bottoms and sidewalls of the valleys. These processes generated the present landscape, with wetlands and small deflation basins blocking the drainage system (Fig. 7b). The regional decrease in precipitation during the Late Glacial and alternating wetter and drier periods during the Holocene (Coronato et al., 2011; Massaferro et al., 2012; Schäbitz et al., 2013; Oehlerich et al., 2015; Borromei et al., 2018) may have promoted these environmental changes.

During the mid-Holocene, the lower area of the Las Vueltas valley was flooded and became a lagoon in which the clay dated at 7,477 cal yr BP was deposited. These sediments are associated with the maximum Holocene marine transgression (Fig. 7c). The lagoon was situated behind a gravel bay-mouth barrier that developed between the ancient headlands of the Cabo Domingo sedimentary rocks (Fig. 3). Similar sedimentary sequences to those recognized in LLV area have been described by Auer (1974), Markgraf (1980) and Mörner (1991) at the La Misión site, a few kilometers south of the study area. Those authors identified a lake deposit, dated about 9,000 14C yr BP, and younger tidal-flat sediments capping peat deposits. In this sense, they recognized the postglacial transgression levels between continental deposits. Similar ideas on the evolution of coastal incised valleys and blocking Holocene baymouth barriers have been presented by Roy (1984) and Sloss et al. (2007) at coastlines in southeastern Australia that are tectonically stable and were subject to similar sea-level changes as those on eastern Tierra del Fuego (Baker and Haworth, 2000; Belperio et al., 2002).

The growth of the baymouth barrier and subsequent development of the beach-ridge plain to the east closed the marine entrance to LLV (Bujalesky, 2007; Montes, 2015), decoupling the Las Vueltas valley from any tidal influence. This decoupling turned the lagoon into a pan environment (Iturraspe and Urciuolo, 2002; Villarreal and Coronato, 2017; Borromei et al., 2018). The fall in relative sea level since the mid-Holocene maximum (0.352 mm yr-1; Montes, 2015) contributed to a ca. 2 m reduction in water levels and a coincident increase in deflation activity (Coronato et al., 2011; Massaferro et al., 2012). Low water levels disconnected several small pans and wetlands and led to the development of the lunette bedforms that were occupied by humans at 3,402 cal yr BP (Fig. 8).

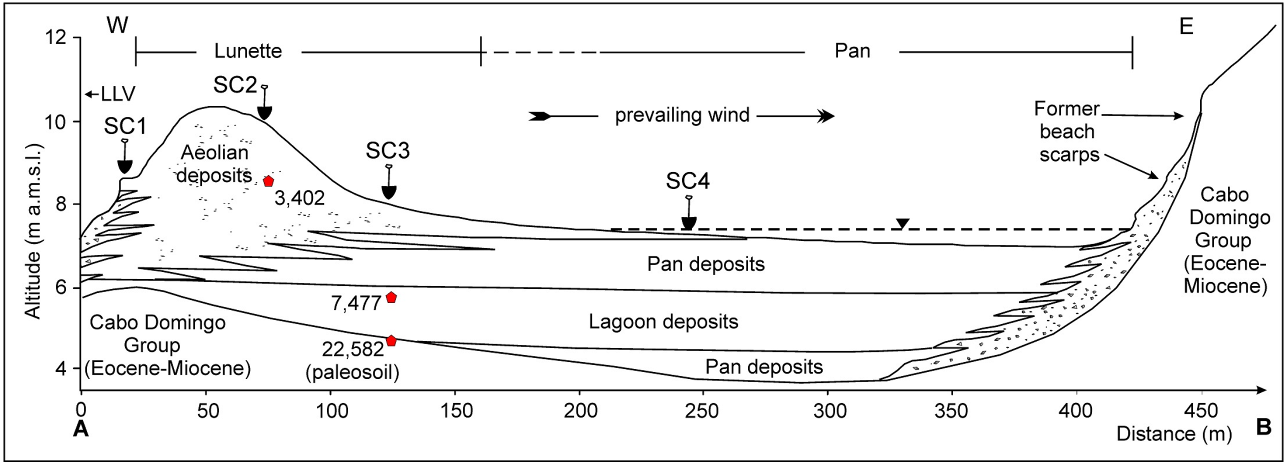

Fig. 8

Fig. 8

Topographic cross-section showing depositional environments, calibrated radiocarbon ages (red polygons, cal yr BP), and the Eocene-Miocene substrate. See figure 7 for location of cross-section. SC stratigraphic columns (see figure 4b for location); dashed line present water level.

Lancaster (1978) proposed that pan-margin lunette dunes are derived from sediment deflated from pan floors at times of dry climate. Small fluctuations of water level in LLV leave the pan-floor sediments partially or totally unprotected and available for entrainment and wind transport. The lunette east of LLV is the product of strong westerlies that dominate wind circulation in Tierra del Fuego (Mazzoni and Vazquez, 2009; Villarreal and Coronato, 2017; Montes et al., 2016, 2017). The aeolian sediments forming the lunette comprise fine sand, silt and clay. Muddy particles are lifted from the lake bottom by wind and carried to the lunette where they are deposited. After deposition, these particles lose cohesion when exposed to rainwater (Tricart, 1969; Arche and Vilas, 1986-1987). Silt and clay are mobilized and transported to depth, where they become concentrated (SC2). This process destroys any sedimentary structures that may have been present, giving the sediment and generates a post-depositional reverse gradation (Arche and Vilas, 1986-1987; Oría et al., 2010).

Dune development in Fuegian steppe pans buried archaeological materials, favoring their preservation (Favier Dubois and Borrero, 2005; Oría et al., 2010; Coronato et al., 2011; Santiago, 2013; Montes et al., 2016). The studied lunette provided a corridor up to 150 m wide and 570 m long that was an appropriate place to trap, kill and process guanacos. It thus supported the hunting activities of human groups inhabiting the northern portion of Tierra del Fuego (Santiago and Salemme, 2016). Zooarchaeological analysis and identification of a hearth and bonebed suggest that the second and third human occupation layers of the LV1 site were rapidly buried, likely during periods of lower lake levels.

Radiocarbon ages and stratigraphical provenance of archaeological remains at LV1 were used to calculate aeolian sedimentation rates (Table 2). Data from other sites on eastern Tierra del Fuego (Perro 1 and Arturo 1; Fig. 1, Table 1) were included to estimate aeolian deposition more regionally. Laguna Perro is located 22 km northwest of LV1. The archaeological site there is buried by aeolian sediments (Santiago, 2013). Two archaeological sites have been studied at Laguna Arturo, located approximately 20 km southwest of LLV (Oría and Salemme, 2016). Aeolian sedimentation rates there exceed those at the LV1 and Perro sites over similar periods. Sedimentation rates at all three sites were higher over the past 500 years than before. This increase may be due to drier climatic conditions during the Little Ice Age, which caused a lowering and drying of lakes in the Fuegian steppe. This hypothesis is consistent with the observations of Favier Dubois (2003), who concluded that Mollisols formed in northern Tierra del Fuego and southern Patagonia are a result of a regional moisture increase during the Medieval Warm Period (MWP), followed by drier conditions and burial of soils by aeolian deposits.

The pit at SC1 (Figs. 5a-6a) displays an alternation of sand beds, organic-rich horizons, and sandy gravel beds. Well sorted sand beds are interpreted to be aeolian sediment transported from the nearby LLV beach to the west. The gravelly sand and sandy gravel beds are similar to modern pan beach deposits a few metres away, they have the same grain size distributions, similar clast shape (generally discoidal), and slope (5-7%). These beds thus record periods of high lake level relatively wetter climate. The organic-rich horizons record times when vegetation colonized aeolian or beach sediments (Jenkinson, 1988); the plant remains are the same grasses that presently grow around the lake. They would be associated with periods of intermediate lake levels, during which the areas east of LLV also support grasses.

The LLV water-level fluctuations have a maximum amplitude of less than 2 m, measured from the bottom of the lake to the top of the upper beach scarp. These fluctuations seem to be recent because the organic horizons at SC1 (Fig. 5a) yielded “post-1950” radiocarbon ages. These ages indicate that three times of higher lake levels occurred during the recent decades and might be related to the fluctuations in Laguna de los Cisnes measured by Iturraspe and Urciuolo (2002) over the period 1974-2001.

9. Conclusions

This study is one in a series of paleoenvironment reconstructions of coastal landforms and sedimentary sequences on Tierra del Fuego made over the past four decades (Auer, 1974; Markgraf, 1980; Mörner, 1991; Bujalesky et al., 2001; Montes et al., 2016; Montes and Martinioni, 2017; Montes et al., 2018). It contributes to understanding landscape evolution in areas affected by sea-level change. The landscape and sediment interpretations are consistent with: 1) a rise in sea level after the LGM as described by Guilderson et al. (2000), Ponce et al. (2011) and Violante et al. (2014 a, b); 2) the high-stand in sea level during the middle Holocene (around +2); and 3) the following fall in sea level described by Bujalesky et al. (2001) and Montes (2015) in the Chico river area. The evolution of the Las Vueltas valley has similarities with that of the La Misión valley where lake sediments were transgressed during the post-LGM rise in sea level, and a tidal flat was replaced by a lake during the mid-Holocene (Auer, 1974; Markgraf, 1980; Mörner, 1991).

Key conclusions from our study are the following:

1. The irregular morphology of the Las Vueltas area is related to an ancient drainage network dated about Late Pleistocene. Valley incision accompanied the falls in sea level after MIS 5e. Deflation basins formed under an arid climate, creating the irregular morphology of the valleys. A paleosol dated at 22,582 cal yr BP records subaerial exposure of the area that was subsequently submerged. The darker colour and abundant organic matter observed in SC3 and SC5 stratigraphic sections suggest humid conditions, at least locally.
2. A marine transgression generated an extensive tidal flat during the mid-Holocene. This tidal flat covered the LLV area and its surrounding pans. Decoupling of the Las Vueltas valley from the sea occurred when a baymouth barrier and beach-ridge plain blocked the mouth of the valley. The lagoon was transformed into a pan environment with water-level changes controlled by climate and the fall in sea level from the mid-Holocene high stand.
3. Lunette development between pans at LLV area generated a narrow corridor that favored trapping, killing and processing of guanacos as early as 3402 cal yr BP. Aeolian sedimentation during dry periods buried the archaeological remains. Estimates of aeolian sedimentation rates from LLV and two other sites on the Fuegian steppe suggest that aridity has increased over the past 500 years.

Acknowledgments

We thank J. Rabassa, J. Federico Ponce (CADIC-CONICET) and J. Clague (Simon Fraser University) for reviews that improved the preliminary manuscript. Cristina San Martín (CADIC-CONICET) helped us with GIS. We thank the creation of Ministerio de Ciencia, Tecnología e Innovación Productiva in December 2007, which allows the growth of Scientific System of Argentina. Funding for the research was provided by CONICET (Grants PIP 0302 to FS and PIP 0422-10 to MS) and the Agencia Nacional de Promoción de la Ciencia y la Tecnología (Grant PICT 2012-1944 to MS). We also thank F. Isla, E. Fucks, G. Bujalesky and W. Vivallo for their comments and suggestions that improved the manuscript.

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Late Pleistocene and Holocene geomorphologic evolution of Laguna Las Vueltas area, Tierra del Fuego (Argentina)

Andean Geology
vol. 47, núm. 1, p. 61 - 76, 2020
Servicio Nacional de Geología y Minería, Chile
andeangeology@sernageomin.cl

ISSN: 0718-7092 **/ ISSN-E:** 0718-7106

DOI: https://doi.org/10.5027/andgeoV47n1-3219