Characteristics and Nature of Pans in the Semi-arid Temperate/Cold Steppe of Tierra del Fuego

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Abstract This work has the aim of presenting the geomorphological and morphometric characteristics of deflation hollows or pans which occur in northern Tierra del Fuego under temperate/cold climate. The shape, size, perimeter and density of each pan are analysed, as well as the landforms developed in their periphery. The study was conducted in the San Sebastián Bay and between the Chico and Grande rivers, grouped according to the geomorphological unit in which they were generated. Digital terrain models and optical images were used to digitalize the perimeter of the depressions and shallow lakes and to discriminate geomorphological features. The studied pans are deflation landforms generated in diverse geomorphological environments of fluvial and marine origin. The higher density of pans per square kilometre is found amongst the geomorphological units of marine origin, whereas those of larger size correspond to geomorphological units of fluvial environments, which are not functional in present times. All these closed depressions have aeolian accumulation landforms placed leeward.

Keywords Pans · Morphometry · Deflation · Aeolian landforms · Tierra del Fuego

1 Introduction

Argentine Patagonia and the Isla Grande of Tierra del Fuego are the continental and insular ends of South America, which extend under climatic conditions where the wind is the main geomorphological agent. The strong and constant winds from the NW, W and SW originated in the southern half of the South Pacific Anticyclone

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overpass the Patagonian and Fuegian Andes and blow leeward over the plains and low mountain chains. These winds take part in the relief modelling where they find soils with scarce vegetation fully devoid of them. The presence of snow, ice or water in soils and sediments prevents the aeolian action during southern winter months. Contrarily, during the remaining part of the year, and mainly in spring and autumn, when the maximum wind intensity takes place, wind generates strong deflation on soils and surficial sediments. The extensive cover of grasslands and shrublands that form the Patagonian and Fuegian steppes protects ample portions of the landscape from aeolian action, but the areas which have been affected by overgrazing and man-made action on the territory expose to erosion of the poorly developed soils or sandy/silty, unconsolidated surface sediments. These particles are removed by aeolian action and then accumulated in short distances, thus developing accumulation landforms. The finest materials are incorporated to the higher atmosphere dust (Gaiero et al. 2015; Gili et al. 2016).

The deflation hollows that are presented in this paper were defined under the term "pans" by Goudie and Wells (1995) as topographic lowlands or closed depressions which are formed in dry lands as a result of the combination of aeolian deflation and salt weathering, a product of a high rate of evapotranspiration. In the aforementioned paper, a world distribution of the dry lands is presented, including there the Argentine Pampas.

The modelling action of the wind in landscapes of temperate/cold climate in the southern hemisphere is still little known. However, a vast record of aeolian processes and landforms for the Canadian Arctic zone and the northernmost portion of Europe has been reported by Seppälä (2004). In the southernmost end of South America, the morphological types and the relationship between dune migration and vegetation cover in coastal desertic lands of NE Patagonia and Península Valdés (42°S) have been described, by means of remote sensing techniques and aeolian models (del Valle et al. 2008, 2010). The development of deflation hollows, named as "endorheic depressions" or "bajos sin salida", was described by Mazzoni (2001) for the southern portion of the province of Santa Cruz, (51°14′–52°S) in a variety of morphogenetic units such as Patagonian Gravels tablelands, basaltic mesetas and fluvial and glaciofluvial valleys. Likewise, in the aeolian plumes derived from them, several landforms as lunettes (clay dunes) and sandy dunes of various types were identified. Deflation hollows today occupied by water bodies in the Argentine Pampas were interpreted as sources for fine-grained materials forming clay dunes during dry climatic periods during the Late Holocene (Dangavs 1979). In Tierra del Fuego, Arche and Vilas (2001) suggested the development of lunettes in the Holocene supratidal deposits of San Sebastián Bay (Fig. 1), whereas Villarreal et al. (2014) described the formation of aeolian mantles as a result of deflation in shallow lakes with exposed dry beds.

In this chapter, the morphometric characteristics of aeolian landforms and their relationship with the geomorphological emplacement of deflation hollows generated in cold/subhumid environments and in different geomorphological units are

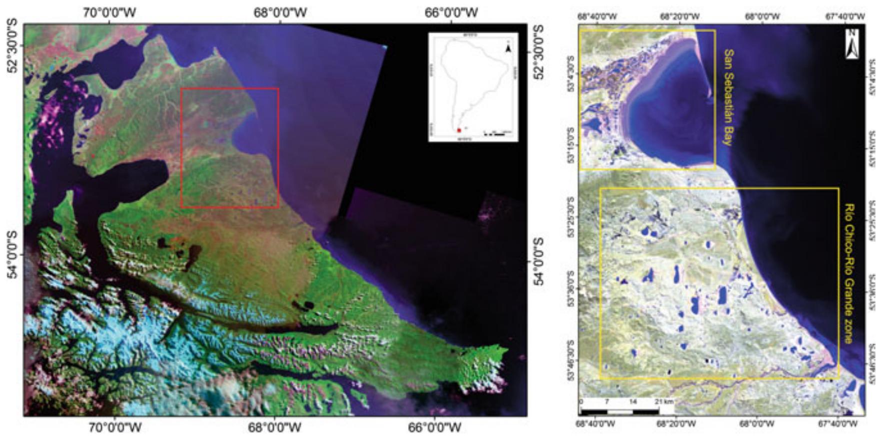

Fig. 1 *Left* Localization of the Isla Grande de Tierra del Fuego. *Right* Location of the study area, northern Tierra del Fuego. *Source* Satellite image Landsat ETM 227-97, year 2001, provided by the Comisión Nacional de Actividades Espaciales of Argentina (CONAE) and Image SID 19-50, obtained from the United States Geological Survey (USGS)

presented. Besides these, landforms are grouped into two geographical zones: the surroundings of San Sebastián Bay and the territory comprised between the Grande and Chico rivers.

2 Methods

A Geographical Information System (GIS) database was performed using ArcGis v.10 and the digital terrain model MDE-Ar as a topographic base of 30-m resolution, provided by the Instituto Geográfico Nacional of Argentina (IGN). Using the QuickBird satellite images available in Google Earth®, the pans were digitalized and the geomorphological units in which they are emplaced were mapped. A layer containing the perimeter outline of the pans was added, and a morphometric analysis was performed considering the variables proposed by Hutchinson (1957). They are: surface (A), perimeter (L), maximum length (Lm) as the distance in a rectilinear direction between the two farthest opposite points, maximum amplitude (Am) as the corresponding maximum distance between the margins of the hollow, and the perimeter development (DL) applying the formula:

$$\mathrm{DL} = L/(2\sqrt{(A \cdot \pi)}$$

Due to differences found amongst the results of the application of this methodology with the visual determination of the landforms, a classification based upon the Relationship of Axes Length (RAL) was presented. In this classification,

Table 1 Classification of pans according to their shape, based upon perimeter development (DL) and relationship of axes longitude (RAL)

Shape types			
After Hutchinson (1957)		RAL	
DL $\leq$ 1.4	Circular	RLE = 1	Circular
DL 1.5 $\geq$	Elliptic	RLE 1.1 $\geq$	Elliptic

the so-called circular shape is that one in which the two axes have identical length, and thus, the circular shapes correspond to values of RAL smaller than 1.1, whereas the elliptical shapes respond to values of RAL higher than 1.1 (Table 1), which means that one of the axes is longer than the other.

Pans density, considered as D = number per km^2, was calculated for each geomorphological unit

The climatic analysis was performed with weather records available from the Servicio Meteorológico Nacional (or SMN, the National Meteorological Survey of Argentina), at Río Grande meteorological station, corresponding to the 1959–2010 period. A hydrological balance analysis was done according to the Thornthwaite and Mather (1957) method, based upon precipitation (P) as the water input to the system and evapotranspiration (ETP) as water output.

3 Study Area

The San Sebastián Bay (SSB) is part of a very wide valley, which has been suggested of tectonic origin (Diraison et al. 2000), which had been modelled by glaciers in several glaciations during the Early to Middle Pleistocene. The zones of low elevation of the present SSB were reworked by the Middle Holocene marine transgression (Rabassa et al. 2009). These processes originated diverse landforms as marsh areas, littoral ridges, cheniers, and tidal plains and channels (Bujalesky 1997).

Likewise, the Río Chico–Río Grande zone (RCH-RG) is formed by low hill ranges composed of sedimentary rocks of marine and deltaic environments (the Carmen Sylva Formation, Early to Middle Miocene) changing to continental environment (the Castillo Formation, Middle Miocene) (Codignotto and Malumián 1981; Olivero et al. 2006). Three geomorphological units have been differentiated in this region: (1) a highly dissected hill range system, eroded by transitory or ephemeral stream channels that are draining to endorheic basins (Fig. 2) integrated in palaeo-drainage systems towards the Atlantic Ocean (Coronato 2014); (2) a glaciofluvial fan, of Middle Pleistocene age (Bujalesky et al. 2001) that forms a landscape of stepped plains of gentle slope (Coronato 2014) composed of sand and gravel deposits; and (3) a much reduced extent of palaeo-bays or ancient drainage lines which have been recurrently invaded by the marine transgressions that occurred during the Middle Pleistocene (Bujalesky et al. 2001).

Fig. 2 Laguna Carmen, in the range region between the Río Chico and the Río Grande. It is a typical deflation hollow or pan that bears a shallow lake which sometimes becomes dry during the summer. This photograph was taken at the beginning of the summer, after the period of snow melting

The climate of this region is subhumid, cold/temperate, with significant influence from the South Pacific Anticyclone, which provides wind coming from the NW, W and SW. Wind is constant during the entire year, with a predominant direction from the W, WNW and SW (Fig. 3). The mean velocity is 23.7 km h^{-1}, while maximum is of up to 152 km h^{-1}. The annual calm days are of only 6.6%, which clearly indicates the persistent action of the wind throughout the whole year. The mean annual precipitation is 324.6 mm, imposing semi-arid conditions. Snow precipitation takes usually place between May and August, although snow storms may occasionally occur before and after these dates. The mean annual temperature is 5.5 °C. The mean temperature of the coldest month (August) has been established in −2 °C and that of the warmest month (February) is 10 °C (Tuhkanen 1992). The hydrological balance of the 1974–2010 period shows a clear deficit during most of the year, concentrated during November and April, which corresponds to the months with higher mean monthly temperature (Fig. 4). Deficit increases in January and, between May and August, there is a recharge because the precipitation values exceed those of evapotranspiration. This reserve will be environmentally used between September and October (Fig. 4).

The region is part of the Fuegian Steppe, formed by grasslands and shrublands. The vegetation in the steppe is dominated by *Festuca gracillima* (locally named as "coirón") (Fig. 5). The soil characteristics between the SSB and RG-RCH zones determine the development of different species. In the first of them, such shrub species as *Lepidophyllum cupressiforme* (locally known as "Mata Verde") and herb species of the Sedum genus occur. In coastal areas, where there is an important

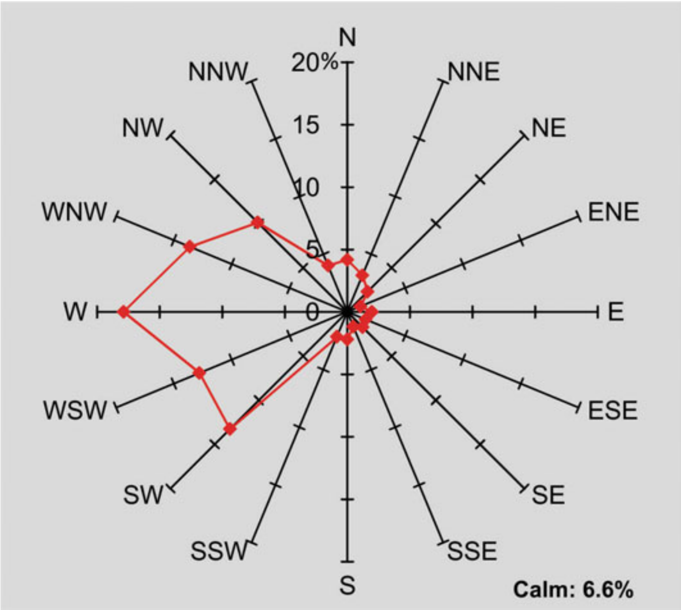

Fig. 3 Frequency of wind direction in northern Tierra del Fuego, according to climatological data from the Servicio Meteorológico Nacional of Argentina (SMN), Río Grande meteorological station, 1959–2010 period

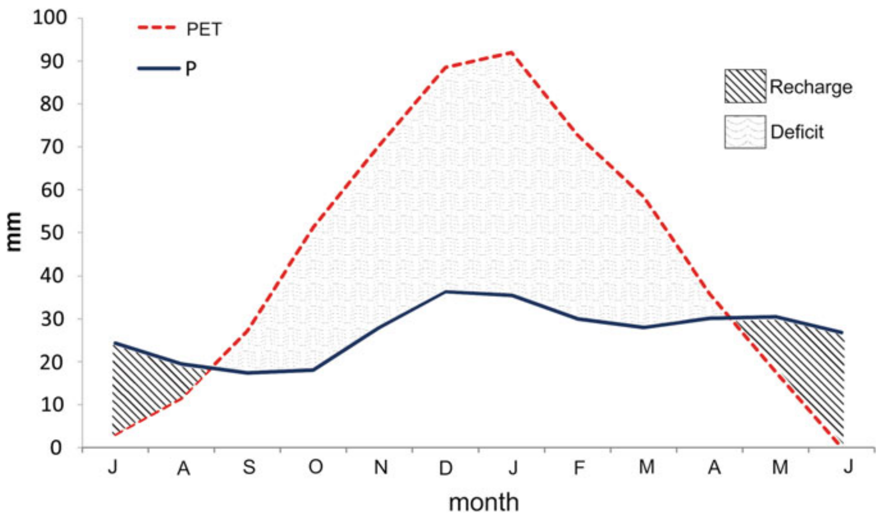

Fig. 4 Hydrological balance, 1974–2010 period, Río Grande station (SMN). *PET* potential evapotranspiration, *P* precipitation

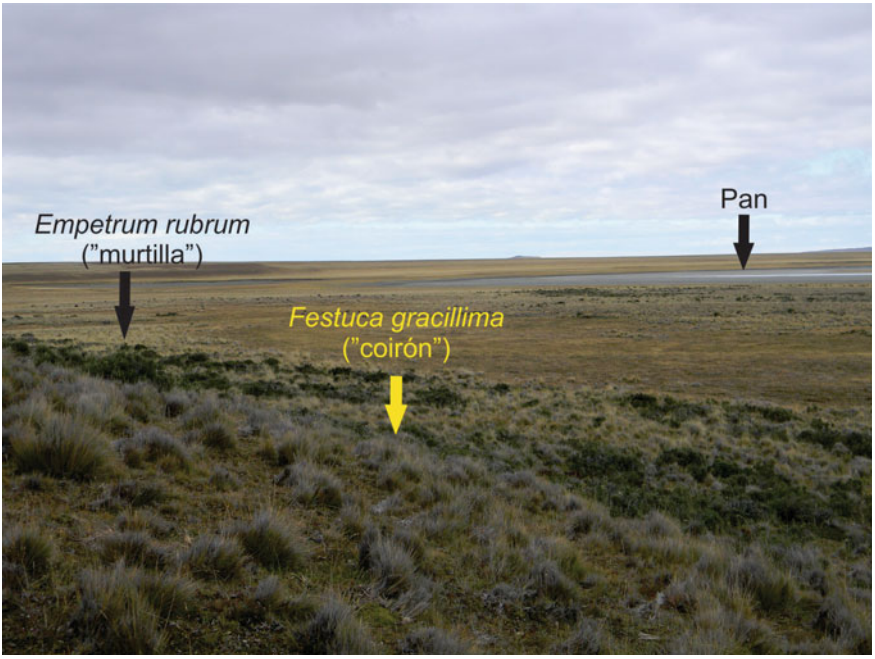

Fig. 5 Vegetation of degraded shrubby steppe due to overgrazing nearby Laguna Escondida, one of the pans that host shallow and temporary water body

saline content and large tidal influence, some characteristic species as *Salicornia ambigua* appear. Otherwise, *Empetrum rubrum* (known here as "murtilla"), *Chiliotrichium diffusum* ("mata negra"), *Hordeum cosmosum* and different Poa species are found in the RCH-RG zone. Cespitose species such as *Bolax gummifera* and *Azorella trifurcata* (Moore 1983; Collantes et al. 1989) may be recognized in this zone as well.

4 Morphometric Characteristics and Landforms

Based upon cartographic and morphometric analysis and the direct field observation, it may be stated that most of these pans are the depositional centres of endorheic basins which receive short and ephemeral streams, a product of superficial run-off. During the periods of hydrological excess, many of them sustain a small, shallow water body, locally affected by wave action as a consequence of permanent and intense action of the constant western winds. This generates significant erosion in the eastern coastal areas of these depressions and the development of 1- to 2-m scarp local relief. Contrarily, the western coasts do not show changes in slope. During the summer, water is evaporated from the shallow lakes and their dry

Fig. 6 Deflation produced in Laguna Grande by westerlies winds with bursts of up to 120 km h^{-1} over the Laguna Grande, in the Río Grande–Río Chico zone. It is a shallow lake that acts as a pan during the drought season. Note the linear character of the deflation plume and the separated, starting point of each of them, due to differential desiccation of the exposed bottom of the lake

bottoms become exposed, thus starting deflation (Fig. 6). The wind effect on the exposed depression bottoms causes overdeepening of the pans. According to Arche and Vilas (2001), in some places this process reaches up to approximately 2.5 m deep, reaching the phreatic level which acts as the base level for wind erosion, and a dynamic equilibrium is achieved between deflation energy and the interstitial moisture that generates the sediment resistance to be blown away. The migration of the eastern margin of the pan towards the east is caused by wave erosion on the leeward direction. Meanwhile, the water remnants at the windward margin of the basin disappear (Fig. 7).

5 San Sebastián Bay (SSB)

This bay is the most significant coastal feature along the Atlantic Ocean shore of the Isla Grande de Tierra del Fuego, extending between 53°–53°18′S and 68°11′–68°33′ W. It develops along 65 km, between Cabo Nombre and the gravel spit Península El Páramo which closes it in the N, and the moraines of the San Sebastián Drift (Meglioli 1992) that form a coast with cliffs in the S. It is affected by a very high tide amplitude, with up to 10 m. The coastline has the looks of a semicircular coastal plain, developed in a larger depression, probably of tectonic origin (Diraison et al. 2000) which has been deeply modified by Pleistocene glaciers (Coronato et al. 2004).

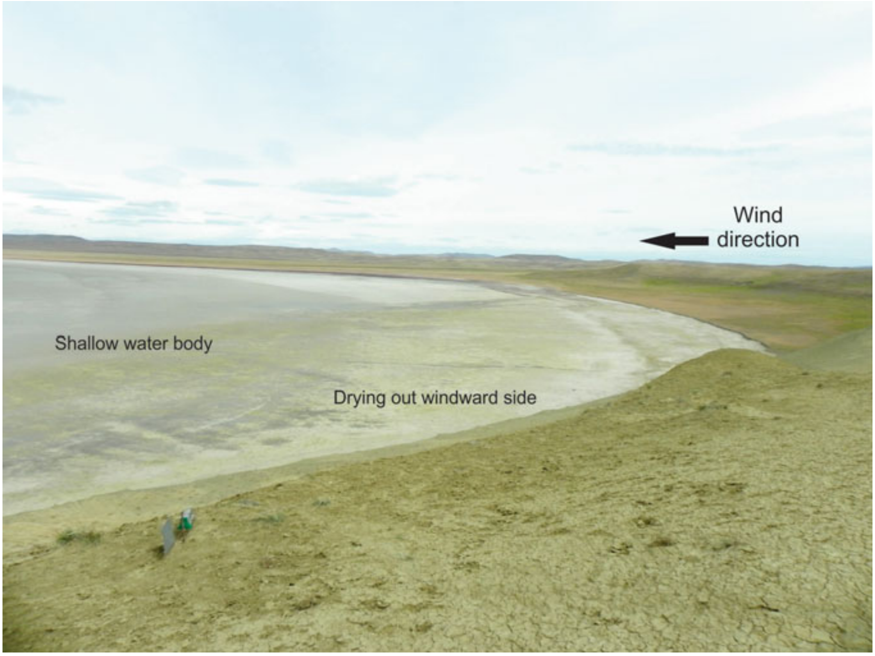

Fig. 7 Western sector of Laguna O’Connor, a pan containing a shallow water body, with progressive drying out eastwards

In the western end of this tectonic depression, Bahía Inútil is found, which opens to the Magellan Straits. In between both bays, morainic belts of Middle Pleistocene age were formed by Middle Pleistocene glaciations (Lagunas Secas Drift, Meglioli 1992). This tectonic depression of open ends affects marine and continental sedimentary rocks of Neogene age.

The pans develop in fossil marshes, formed by finer sediments of supra- and inter-tidal environments (Arche and Vilas 2001), in gravel ridges and cheniers. Besides, tidal plains and channels are also present in the littoral morphology of this area (Vilas et al. 2000). This fossil littoral environment is the result of the advance of the sea up to 7 km inland from the present coastline, between 5616 ± 282 and 509 ± 41.5 cal. yr BP (Vilas et al. 2000), that is, as a consequence of the post-glacial global sea level advance during the Middle Holocene marine transgression.

The pans developed in San Sebastián Bay are shallow depressions, generally 1 m deep, which in some cases present not very well-defined margins, either by the interconnection of several depressions or by the presence of drainage lines as fossil tide channels remnants. The dominant orientation of their longer axes is W–E or SW–NE. They have a highly variable size and type of grouping, depending upon the type of sediments and landforms on which they were formed. Three groups are distinguished: marsh pans, chenier pans and littoral ridges pans (Fig. 8).

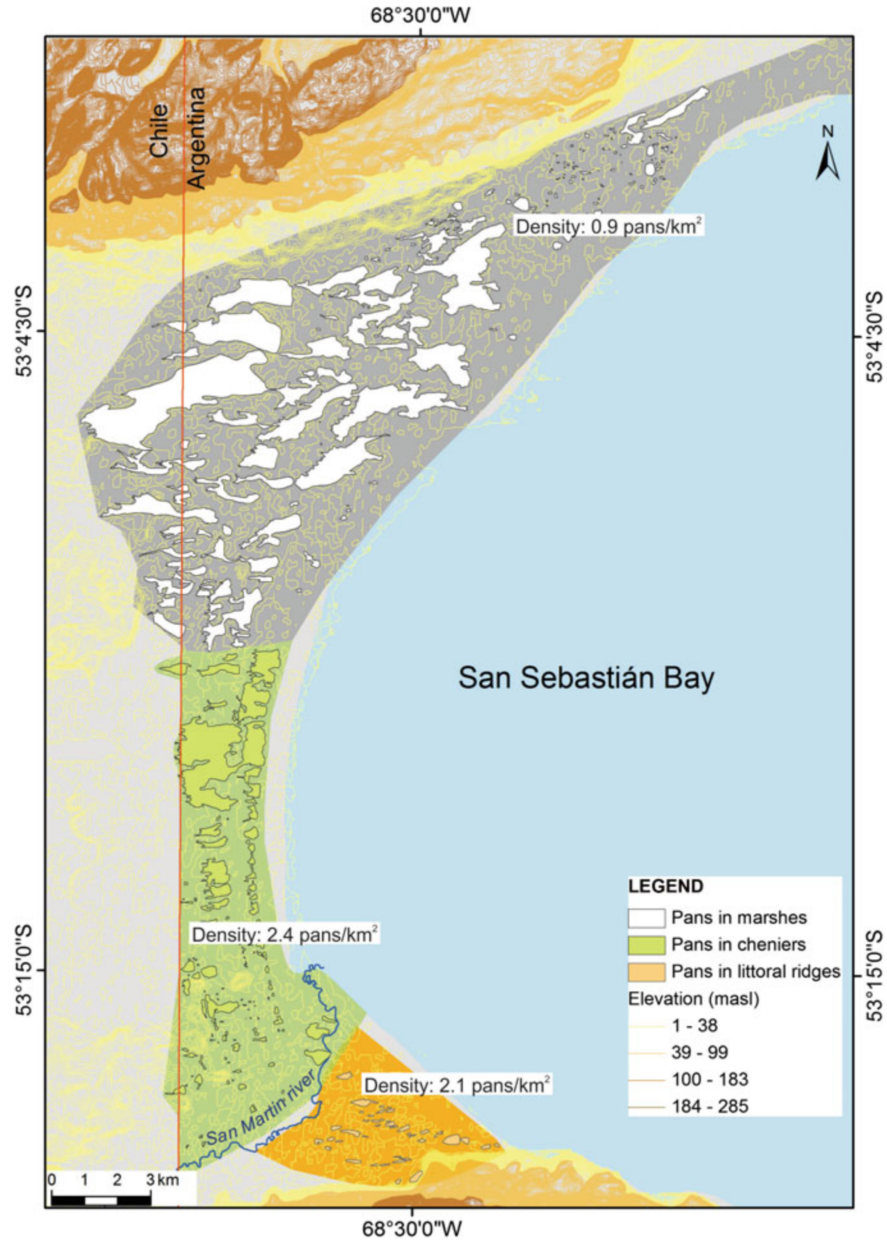

Fig. 8 Distribution and density of pans in the zone of San Sebastián Bay taking into consideration their geomorphological emplacement. The geomorphological units follow Vilas et al. (2000)

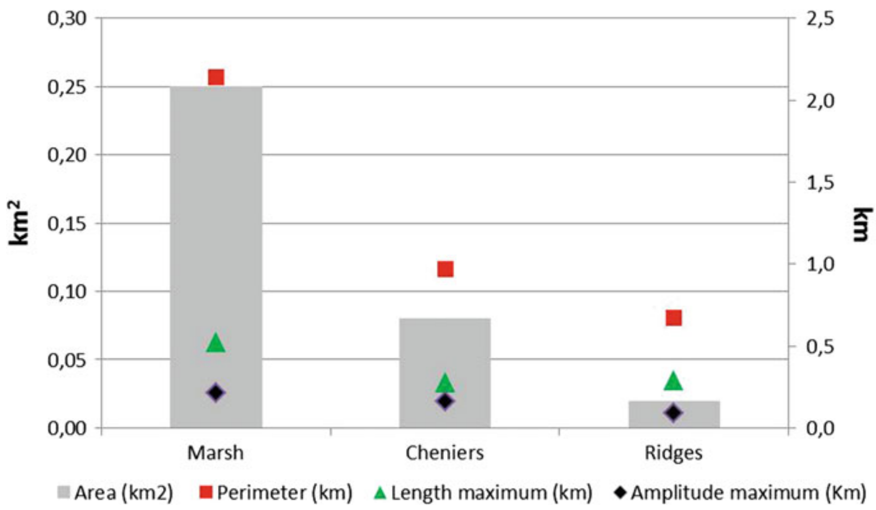

Fig. 9 Average morphometric characteristics of pans developed in San Sebastián Bay, according to the three groups of landforms

6 Marsh Pans

A large number of these hollows (N = 151) are developed in the northern portion of the bay, reaching a total surface of 162 km^2, the greater extent of all groups in this zone. In this sector, a basin density of 0.9 pans per km^2 is found. Many of them are interconnected by means of temporary drainage lines of the superficial run-off system. The mean surface of these basins is 0.25 km^2, with a range between 0.0002 and 7.3 km^2. This group represents the larger mean size of the pans that develop at SSB. Approximately 84% of the landforms of this group have an areal surface smaller than the mean value (Fig. 9). Towards the NE, the mean area diminishes, with depressions of more regular margins. DL oscillates between 1.0 and 4.3, being this the highest value with respect to the other groups of the bay, corresponding to several interconnected bays by means of channels and whose individual identification is difficult. In general, the margins of the basins are irregular in shape and the long axis has a SW–NE orientation. The dominant shape depends upon the method used; according to DL, the circular shapes predominate (64%); however, according to RAL, 94% of them present an elliptical shape.

7 Chenier Pans

These basins are developed in the central-south portion of SSB, and they reach a total number of 127. They form three aligned ridges in a N–S direction, projecting a semicircle in physical accordance with the coastal plain. They cover an area of

53 km^2 which gives a pans density of 2.4 pans per km^2. The mean surface is significantly smaller than in the previous group, reaching 0.08 km^2, within a range of 0.0001–4.2 km^2. The surface area is smaller than in those basins developed in the S and E of the chenier zone. Approximately 88% of the landforms of this group have a surface development smaller than the mean value of the group. The longest axis has an E–W direction.

According to DL, whose values vary between 1.0 and 2.6, most of these landforms have circular shape (73%); following the RAL criteria, 92% of the basins are elliptical.

8 Littoral Ridges Pans

These pans reach a total of 40 along the southern sector of the bay and they are located between two groups of littoral ranges, covering a smaller areal extent with respect to the previous groups at SSB. Density is 2.1 pans per km^2. These basins have a mean surface of 0.02 km^2, within a range of 0.03 and 0.12 km^2, which suggest that these are the smallest hollows of three groups. The whole group presents elliptical shapes, in which the long axis is oriented, mainly, in a W–E direction. At least 70% of the pans of this group present surface values lower than the mean. The DL index records that 56% of them are basins with circular shape, whereas RAL indicates that all the basins of this group have elliptical shape, in which the longest axis is oriented in a W–E sense. Note that the marsh basins have a larger surface development, L, Lm and Am than those described in cheniers and littoral ranges (Fig. 9).

9 The Río Chico–Río Grande (RCH-RG) Zone

The sector that comprised between the Chico and Grande rivers has a hilly range relief of low altitude (150–300 m a.s.l.) with strong fluvial dissection, in some cases with sub-horizontal summits. A set of endorheic basins, some of them totally closed, contain ephemeral shallow lakes which occur amongst the hilly ranges. In the N sector of this divide, glaciofluvial fans developed with their apexes in the upper valley of the Río Chico and formed terrains of gentle slope which extend up to the present coastal zone.

The development of deflation hollows is recognized in the three geomorphological units studied (Fig. 10).

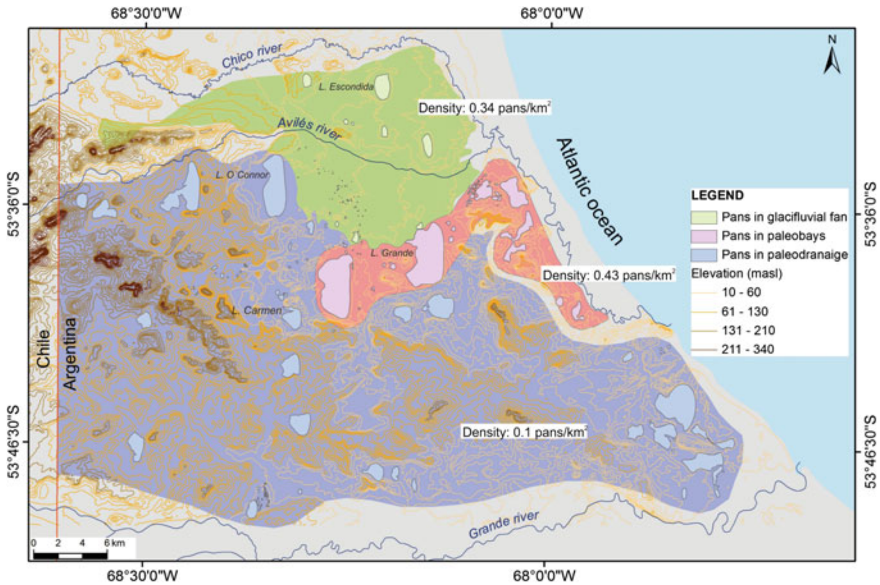

Fig. 10 Distribution and density pans in the zone comprised between the Chico and Grande rivers, according to the geomorphological units identified

10 Glaciofluvial Fan Pans

On the glaciofluvial fan, 81 pans have been carved developing 235 km^2 of depressed surface, limited towards the E by the Río Chico (or Carmen Sylva Creek). This group presents a pan density of 0.34 per km^2. The mean surface of these basins is 0.06 km^2, between a maximum value of 2.2 km^2 and a minimum one of 0.0001 km^2. The mean pan perimeter (*L*) of this group is 0.43 km, and the maximum length and width present values of 0.16 and 0.1 km, respectively, reaching the smaller morphometric values of the RCH-RG zone (Fig. 10). Approximately 90% of these basins have a surface smaller than the mean value. South of the Río Avilés, a greater hollow density is observed, although with smaller surface development (Fig. 10) related to channels oriented in a NW–SE direction. The values of the different measured parameters are markedly lower in this group with respect to the remaining ones which do not form the RCH-RG unit (Fig. 11). In the E and SW sectors of this group, hollows have not been developed, thus making for a very low density. According to DL, approximately 91% of the depressions are of circular shape; however, according to the RAL analysis, it is suggested that all basins in this area have an elliptical shape (RAE = 1.3–4.3). The axes of maximum length have a predominantly N–S orientation.

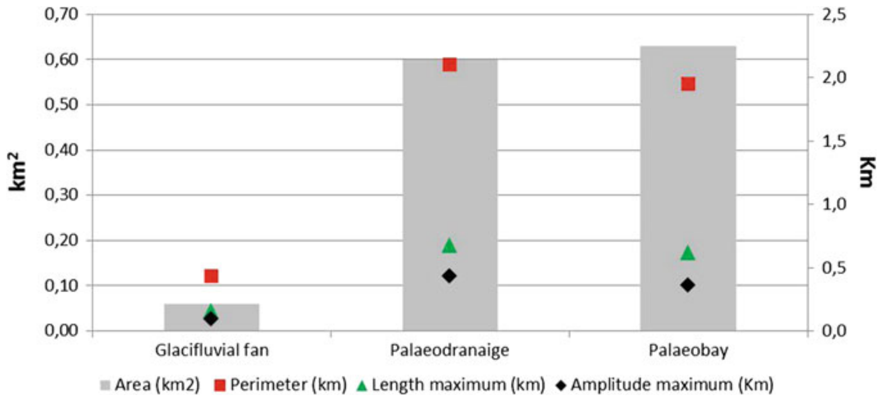

Fig. 11 Mean morphometric characteristics of pans developed between the Chico and Grande rivers, according to the geomorphological units observed

11 Palaeo-drainage Pans

The palaeo-drainage pans amount up to 90, located south of the previous group and west of the international boundary between Argentina and Chile. They occupy 1087 km^2, being the most extended area of the RCH-RG zone, and reach a very low density (0.1 pans per km^2). They present a mean surface of 0.6 km^2 (ranging between 0.0004 and 7.6 km^2), of which 81% is found below the mean value. The mean *P* value is 2.1 km, whereas Lm and Am reached values of 0.68 and 0.43 km, respectively (Fig. 11). The palaeo-drainage system in between the hilly ranges reflects surficial run-off conditions with greater yields than those of the creeks that flow along the present drainage basins. These water currents carved their valleys in a general direction SW–NE, and they are integrated within the Avilés and Grande rivers, or they discharge directly into the Atlantic Ocean palaeo-littoral environment. Based upon the DL analysis, the elliptical shape characterizes approximately 80% of the basins and 97% according to the RAL criteria.

12 Palaeo-bay Pans

The palaeo-bay basins include 51 depressions. They cover an area of 118.25 km^2, which is found in contact with the southernmost end of the glaciofluvial fan and part of the palaeo-drainage unit, limited towards the E by the Río Chico (Fig. 10). This group presents a density of 0.43 pans per km^2 and a mean surface of 0.63 km^2 in a range of values which oscillate between 0.002 and 12 km^2. The mean perimeter (*L*) is 1.95 km, and the variables maximum length and width have values of 0.62 and 0.36 km, respectively. Approximately 92% (47 pans) of them present a surface area lower than the mean value. Considering the DL index, the circular shapes predominate (84%), whereas according to RAL, 94% of them have an elliptical shape.

13 Landforms Developed from Pans

In the SSB zone, megaripples developed along the eastern margin of the pans have been identified, which generate later climbing dunes (Arche and Vilas 2001), composed of silty–clayey materials (Fig. 12). However, the most frequent landforms generated from the deflated basin materials are nebkhas, also known as "coppice dunes", as it has been mentioned by Cooke et al. (1993) and Gile (1975). These landforms are generated from the obstacles opposed by the dominant vegetation to the wind-transported particles, generally *Lepydophyllum* sp. Some dunes of the "lunette" type are also developed in this zone, and due to the shrubby vegetation effect, they develop asymmetrical shapes around branches and leaves. Pellet formation of particles 1–3 mm in diameter occur (Arche and Vilas 2001). Circular dunes are associated with other types of grassy vegetation, composed of *Sedum* sp., of smaller size than *Lepydophyllum* sp. Aeolian mantles are also developed in this zone, sometimes reaching up to 4 m in thickness.

In the RCH-RG zone, landforms generated leeward the pans are perched dunes on the cliffs, or phytogenetic dunes or nebkhas (Fig. 13) and the aeolian mantles (Fig. 14), (Coronato and Villarreal 2014; Villarreal and Coronato 2014; Villarreal et al. 2014). The perched dunes are found downwind of the depressions that occur on sedimentary rock cliffs, formed by wave erosion forced by the wind when blowing on the surface of a water body that may be transitorily occupying the pans.

The rocks exposed to the wind coming from the western quadrant receive the impact of the air on their weathered particles, and these are incorporated to ascending "twisters" that mobilize them towards the top of the cliff, thus forming a

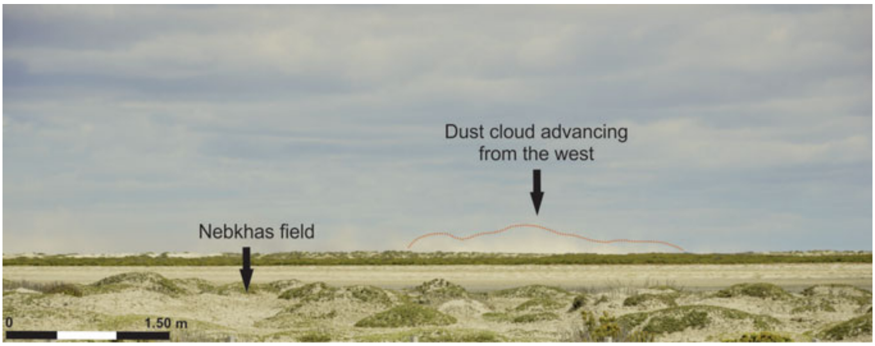

Fig. 12 Pan formed in marsh morphology of San Sebastián Bay zone with nebkhas development on halophyte vegetation in the leeward margin. At the background, a dust cloud formed by deflation advances from the west (photograph by Soledad Schwarz)

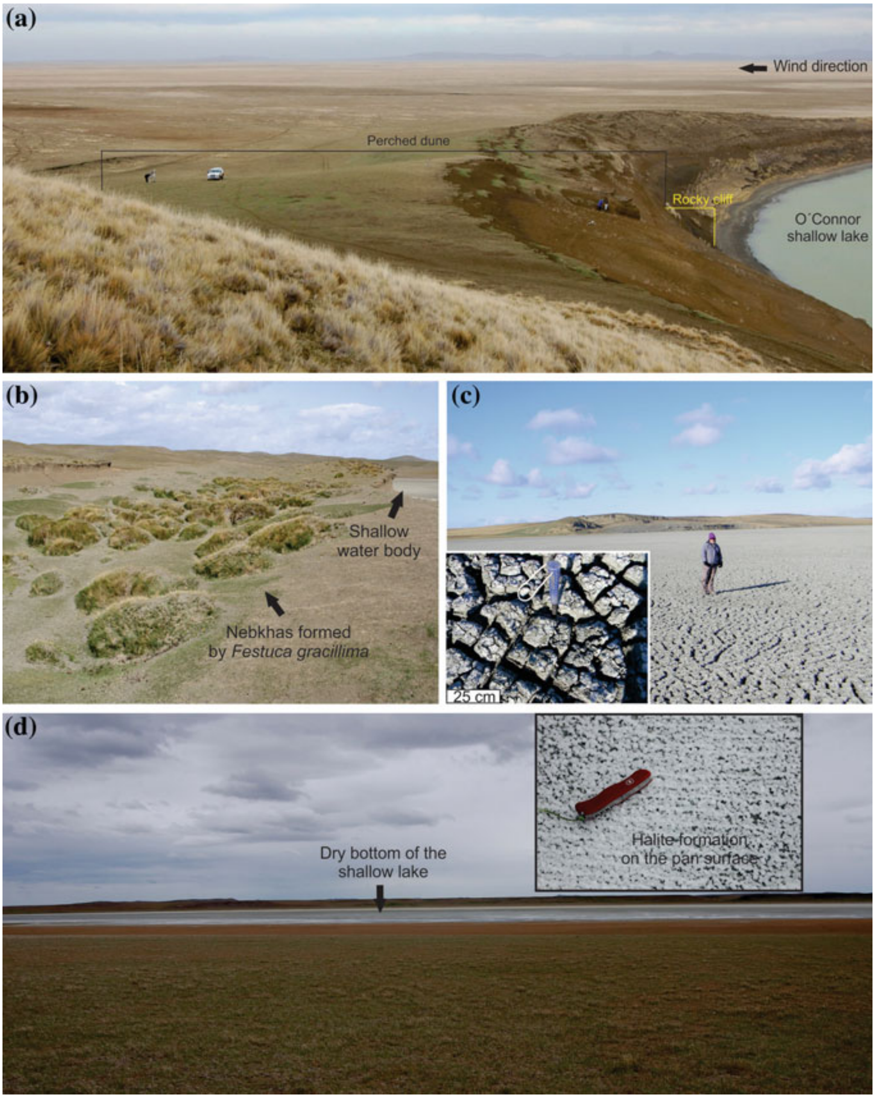

Fig. 13 Landforms originated from pans. **a** Perched dune on Lake O'Connor sedimentary rocky cliff. Note the asymmetric slopes of the dune and the erosion processes in the upward slope. **b** Nebkhas formed by sandy–silty particles and developed on *Festuca gracillima* bushes over a cliff at Laguna Amalia. **c** Lake Arturo shallow lake in dry conditions, playing the roll of a pan during the autumn. Desiccation cracks are 1–2 cm wide. **d** Escondida shallow lake in dessicating process. At the front, degraded vegetation covered by the aeolian dust mantle; in the small picture: halites formed by surface crystallization during desiccation cover the eastern side of the pan bottom

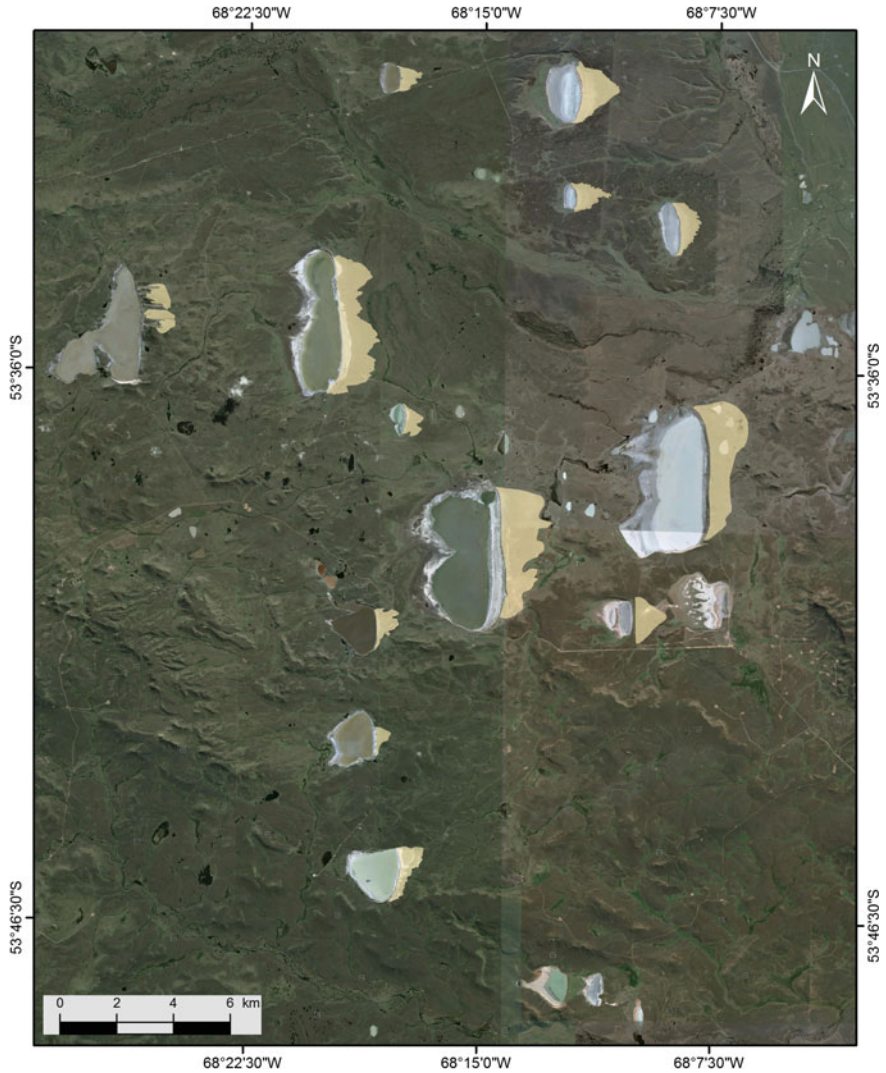

Fig. 14 Pan distribution in the RCh-RG zone, the bigger containing ephemeral, shallow water lakes. In all of the pans, aeolian mantles are developed leeward. They extend over cliffs and lacustrine terraces. Mantles are shown by polygons over the Google Earth® image

sedimentary pile. Besides, when the pans have lost the water body due to dessication or hydrological deficit, they supply sedimentary load to deflation which mobilizes leeward. Partly, these sediments are deposited at the top of the cliffs, forming part of the perched dunes. This type of dunes is found, mainly, within the palaeo-drainage group, where the pre-existing water currents would have intensified the erosion of certain cliffs, for instance, in the zone of Amalia and O´Connor shallow lakes (Fig. 1). The dune formed on the NW slope of this shallow lake is composed of silty deposits, whereas in Laguna Arturo, they are of the silty–clayey–sandy type (Coronato et al. 2011). The aeolian mantles are concentrated in the glaciofluvial fan pans group, in which they reached a larger development in relation to the other ones. These are sheet-like deposits developed leeward depressions, composed of deflation particles from the dry bottoms of the shallow lakes, mostly during the summer season (December–February). They are composed of sandy–silty–clayey or silty–clayey sediments and, according to their provenance, they provide an important salt content (Fig. 13) to the soil in which they are deposited (Crosta et al. 2014; Villarreal et al. 2014). The modification in the properties of the soils due to the salt supply modifies the vegetation cover, in which *F. gracillima*, a dominant species in the region, is replaced by *H. cosmosum*, *Poa alopecurus*, *Deschampsia flexuosa* and cespitose species, such as *B. gummifera* and *A. trifurcata* (Villarreal et al. 2014). The aeolian mantles become adapted very well to the micro-landscape on which they are deposited, without generating new relief. Nevertheless, they are recognized by means of satellite imagery as diffuse spots extending downwind of the depressions.

14 Pans in Tierra del Fuego and Other Regions of Argentina

Pans are erosion landforms that develop under semi-arid climate conditions. In Tierra del Fuego, these landforms occur in its northern portion of the island and they are concentrated in two geographical zones of different characteristics according to the origin of their geomorphological emplacement. The density of these landforms in the different geomorphological units varies between 0.1 and 2.4 pans per km^2. These values are higher to those proposed by Goudie and Wells (1995) for different sectors of Argentina, where a range of density was established between 0.05 and 0.9 pans per km^2 for basins generated in palaeo-lacustrine, palaeo-drainage, interdune and coastal surface environments. In Tierra del Fuego, the pans are carved on coastal environments such as cheniers, marshes, littoral ridges, and palaeo-bays or in the inner portion of glaciofluvial or palaeo-drainage fans. These are different geomorphological emplacements than those previously described by Goudie and Wells (1995), which expands the set of landforms subject to the possible formation of pans. At a regional scale, in southern Extra-Andean Patagonia, deflation basins are developed in terraced tablelands, volcanic mesetas and terminal and ground moraines (Mazzoni 2001), although they present a smaller mean density than in Tierra del Fuego. In the northern portion of the Isla Grande de Tierra del Fuego, the basins of the RCH-RG zone present defined perimeter and many of them are depressions which are not interconnected. Contrarily, the basins formed in marshes and cheniers have irregular margins and they appear interconnected, which suggests aeolian erosion affecting tidal palaeo-channels in the marsh plains and the occurrence of morphometric changes in the future. These pans should be considered as the most dynamic of the region.

According to Raedeke (1978) and Arche and Vilas (2001), one of the characteristics that identify the pans of Tierra del Fuego is their migration process towards the east, due to the effect of persistent westerlies on wave action, when these depressions hold transitory water bodies. In these periods, wind energy removes the surface of the water and generates waves that erode the leeward coast and progressively dessicate the water body, exposing the upward dry bottom. This process is produced both in the SSB pans and in those carved in the glaciofluvial fan and the palaeo-bays of the RCH-RG sector, all of them occur in geomorphological units in which the deflated material is of sedimentary origin. Contrarily, in some pans developed in the hill ranges zone, migration towards the east is impeded due to the occurrence of rocky outcrops of up to 20 m high, thus generating cliff recession erosion processes due to wave action. In those periods in which the basins are lacking water content, wind excavates the exposed bottoms, increasing depth and generating deflation and dust clouds.

The morphometric characteristics studied in each group of pans present clear differences, either between the two studied zones or even within them. The pan density is larger in the SSB zone, mainly in marsh and chenier areas. The mean surface area of pans is higher in the marsh and palaeo-bay geomorphological units. Concerning shape types and following the RAL index, most of the basins have elliptical shapes and extend their long axes perpendicularly to the dominant wind direction. In the SSB zone, the marsh and chenier basins are under intense dynamics. However, the pans found in the littoral ridge sector, where the availability of loose sediment is lower, resemble the shape of the basins of the adjacent RCH-RG zone. The aeolian mantles are present in both studied zones, although they have larger surface area in the SSB zone when compared to the RCH-RG one, which suggests that deflation is more effective here for short-distance accumulation dust, perhaps because winds speed is higher than in the hilly range area, promoting both desiccation and particle remotion. Nebkhas occur in both studied areas as well, and in SSB, they are the more abundant accumulation landforms, while they are blocked by halophilous vegetation in SSB; in the RCH-RG zone, nebkhas are formed by *F. gracillima* ("coirón") and they appear in slope terrains or in degraded soils away from the cliffs. Perched dunes are also some of the accumulation landforms associated with pans with cliff shores, but they are found only in the palaeo-drainage unit of the range portion of the RCH-RG zone.

15 Final Remarks

Pans in northern Tierra del Fuego are distributed in different geomorphological environments, which causes that they have diverse morphometric and morphological characteristics. In all cases, these features promote the genesis of various types of landforms along their leeward margins, such as phytogenetic dunes or nebkhas, with several species which act as obstacles to the wind, lunettes, perched dunes over cliffs and aeolian mantles. The highest density of pans occurs in the San Sebastián Bay (SSB) zone, where the marshy and chenier environments offer drier, fine-grained sediments, and where the wind has high intensity and persistency and there is a lack of topographic obstacles. Contrarily, the low hilly ranges of the RCH-RG zone generate obstacles to the air flow, generating interference to the wind influence as landscape modeller. Besides, during part of the year, these hollows retain a water body that occupies almost the entire depressions, thus diminishing the erosion potential by deflation. In the SSB zone, the higher density of pans is found here in the “palaeo-bay” unit, where sediments affected by deflation correspond to mixed deposits of marine and glaciofluvial origin, reworked by the sea during the various marine transgressions that took place in the region during the Middle Pleistocene.

Considering the morphometric parameters, the mean area of the pans in SSB is 0.12 km^2, which is the mean value lower than those of the RCH-RG zone (0.43 km^2), which brings up the analysis of the influence of the fluvial modelling previous to the erosion effect of the wind in this region. The hollows excavated on ancient glacial deposits of the SSB region found in the marsh and chenier zones would be a direct geomorphological response to the deflation effect over fine-grained sediments, whereas those of the RCH-RG zone would be a secondary morphological result upon non-functional valley bottoms, eroded on sedimentary rocks or sandy–gravelly, thin fluvial deposits.

Concerning the shape of the pans, there are some differences regarding the analytical method applied. The application of an alternative method to the classical methodology proposed by Hutchinson (1957) allowed us to determine that, of the six geomorphological units in which pans appear, only in the palaeo-drainage hollows, where the shapes are notably elliptical, there are coincident results amongst the applied methodologies (DL and RAL). This reveals that, for the intermediate shapes, those between the circular and the elliptical shapes, which are the ones with higher frequency in the region, the RAL or the relationship of axes length describes in a similar way as with the visual interpretation as it is done from remote sensing analysis or digital terrain models. This parameter is considered as more appropriate than the DL parameter (Hutchinson 1957) to characterize the shape of pans in this region.

The deflation hollows developed in northern Tierra del Fuego are a geomorphological feature characteristic of semi-arid zones, although in this case, conditions as cold temperatures with seasonal snowfall and soil freezing are added. The persistence of the wind during the ice and snow-free season favours the progressive excavation of pans with consequent genesis of short-distance, accumulation landforms and ample provision of atmospheric dust. The pans of larger size have a role as transitory water bodies, whose progressive desiccation depends upon the westerlies persistence and velocity.

The formation of these shallow lakes adds one more component to the steppe landscape, and it offers appropriate habitats for bird wildlife, although in many cases the turbidity and salinity of the water do not allow its use for drinking water or irrigation supply.

Pans—seasonally filled of water or dry—are remarkably active landforms in the subantarctic landscape of southern South America. Their activity is triggered by the interplay of the Southern Pacific Ocean high-pressure systems and the Polar Front which determines the intensity of winds and promotes dust supply to the southern hemisphere oceans and atmosphere.

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