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A soil chronosequence in the semi-arid environment of Patagonia (Argentina)

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Abstract

Soil development with time was investigated on beach ridges with ages ranging from about 1380 to 6240 ^{14}C-years BP at the eastern coast of central Patagonia. The main pedogenic processes are accumulation of organic matter and carbonate leaching and accumulation within the upper part of the soils. Soil formation is strongly influenced by incorporation of eolian sediments into the interstitial spaces between the gravel of which the beach ridges are composed. Different amounts of eolian material in the soils lead to differentiation into Leptosols (containing ≤10% fine earth in the upper 75 cm) and Regosols (containing >10% fine earth). Soil depth functions and chronofunctions of organic carbon, calcium carbonate, pH, Ca:Zr, Mg:Zr, K:Zr, Na:Zr, Fe:Zr, Mn:Zr, and Si:Al (obtained from X-ray fluorescence analysis) were evaluated. To establish soil chronofunctions mean values of the horizon data of 0–10 cm below the desert pavement were used, which were weighted according to the horizon thicknesses. The depth function of pH shows a decrease towards the surface, indicating leaching of bases from the upper centimeters. Chronofunctions of pH show that within 6000 radiocarbon years of soil development pH drops from 7.0 to 6.6 in the Leptosols and from 8.1 to 7.5 in the Regosols. The higher pH of the Regosols is due to input of additional bases from the eolian sediments. Chronofunctions of Ca:Zr and K:Zr indicate progressive leaching of Ca and K in the Regosols, showing close relationships to time (R^2=0.972 and 0.995). Na leaching as indicated by decreasing Na:Zr ratios shows a strong correlation to time only in the Leptosols (R^2=0.999). Both, Leptosols and Regosols show close relationships to time for Fe:Zr (R^2=0.817 and 0.824), Mn:Zr (R^2=0.940 and 0.803), and Si:Al (0.971 and 0.977), indicating enrichment of Fe and Mn and leaching of Si. Leaching of mobile elements takes place on a higher level in the Regosols than in the Leptosols from the beginning of soil formation. Hence, a significant part of the eolian sediments must have been incorporated into the beach ridges very soon after their formation.

Keywords: Soil chronosequence; Beach ridges; Patagonia; Eolian sediments; Calcium carbonate accumulation; Soil chronofunctions

1. Introduction

1.1. Soil chronosequences

Since soil formation can hardly be observed directly over more than a few decades, the study of soil chronosequences is the most suitable way to assess quantitative knowledge on soil development with time. Therefore, the number of soil chronosequence investigations has considerably increased in the last decades. Numerous studies were carried out especially on marine terraces along the Californian coast (Harden, 1982; Muhs, 1982; Aniku and Singer, 1990; Merritts et al., 1991), on river terraces in California (Busacca, 1987; Harden, 1988; Busacca and Singer, 1989; White et al., 1996, 2005), Spain (Torrent et al., 1980; Alonso et al., 1994; Dorronsoro, 1994; Alonso et al., 2004), Italy (Arduino et al., 1984, 1986; Scalenghe et al., 2000) and Slovenia (Vidic and Lobnik, 1997; Vidic, 1998), on volcanic rock on the island of Lanzarote, Spain (Jahn et al., 1985, 1987; Jahn and Stahr, 1996), on beach ridges and sand dunes of Lake Michigan (Barrett and Schaetzl, 1992; Lichter, 1998; Barrett, 2001) and Lake Huron (Vanden-Bygaart and Protz, 1995), and on moraine sequences in Norway (Mellor, 1986, 1987) and in the Swiss Alps (Egli et al., 2001, 2003). Several soil development indices were developed (*e.g.* Harden, 1982; Busacca, 1987; Langley-Turnbaugh and Evans, 1994; Magaldi and Tallini, 2000). In many studies ratios of mobile elements and Ti or Zr were used to identify enrichment or depletion of elements with time (Egli and Fitze, 2000). Since Ti can also be mobilized, Zr is considered more suitable for this purpose (Sudom and Arnaud, 1971; Langley-Turnbaugh and Bockheim, 1998).

Most of the soil chronosequence studies suggest exponential, linear, power or logarithmic changes of soil properties with time

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(Bockheim, 1980; Birkeland, 1984; Huggett, 1998). After a chronofunction has been obtained from a data set the *y*-intercept may also be used to reconstruct the situation at time zero (Schaetzl et al., 1994).

1.2. Soils of the dry areas of Patagonia

Knowledge about soils in the arid and semi-arid environments of Patagonia is rare. The only area-wide soil information is the soil atlas of Argentina at a scale of 1:500 000/1:1 000 000 (SAG y P, INTA and CIRN, 1990). For the province Chubut, which includes central Patagonia, it describes the following soil orders: Aridisols: 55.0%, Entisols: 18.6%, Mollisols: 17.9%, Andisols: 3.3%, Inceptisols: 0.2%, Alfisols: 0.04% (Salazar Lea Plaza et al., 1990; del Valle, 1998).

Soils showing carbonate accumulations cover 10.6% of Patagonia, including soils with calcretes, which account for 2.6% of the area (del Valle, 1998). Hence, several studies on calcrete formation were carried out (*e.g.* Buschiazzo, 1985, 1986, 1988). Salomon and Pomel (1997) assumed eolian-volcanic material originating from the Andean volcanic chain as a major calcium carbonate source, as they identified considerable amounts of volcanic tracer minerals in the calcretes. In contrast, Vogt (1992) assumed that the carbonates were blown out from the shelf regions during marine regressions in the Quaternary cold periods, because she found that calcium carbonate accumulations contained Ba, Br, and S, while the underlying sediment did not contain any of these elements. This would also explain the close relationship of some carbonate accumulations and cryogenic features described by several authors (*e.g.* del Valle and Beltramone, 1987; Vogt, 1992; Vogt and del Valle, 1994). Douglass et al. (2001) investigated a soil chronosequence on moraines with ages ranging from 13 ka to 1 Ma at Lago Buenos Aires. Also, in this area the dominant process was carbonatization, which in soils on the last glacial moraines led to 5%, in those on older moraines to 15% carbonate in the calcic horizons.

Recapitulating the existing studies, it must be stated that very little information about the soils of Patagonia is available. This lack of knowledge is a severe deficit especially with regard to analyzing and combating desertification, which is the main socioecological problem in Patagonia (del Valle et al., 1998). Moreover, while numerous soil chronosequence studies have been reported from Mediterranean and humid-temperate climates, soil chronosequence studies in semi-arid environments in general are rare (Muhs, 1982). One reason for this is that such studies necessitate certain requirements. The most prominent pedogenic changes in semi-arid environments take place within the first millennia of soil development, and soil chronosequences providing the time resolution required to assess these changes are extremely rare. Holocene beach ridge sequences offer the opportunity to study soil development in accordingly small time steps. The aim of this study was therefore to characterize recent soil forming processes in dated Holocene beach ridges of Patagonia and to establish soil chronofunctions in order to improve the understanding of soil formation with time in semi-arid environments.

2. Materials and methods

2.1. Study area

Soil development with time can most precisely be assessed by studying soil chronosequences. Therefore, an area was chosen, in which a series of beach ridges occur, which after being dated, provided suitable conditions for studying soil formation. It is located at the northern edge of the Golfo de San Jorge in the province Chubut in central Patagonia, Argentina (Fig. 1). Within this area two locations were chosen for establishing soil

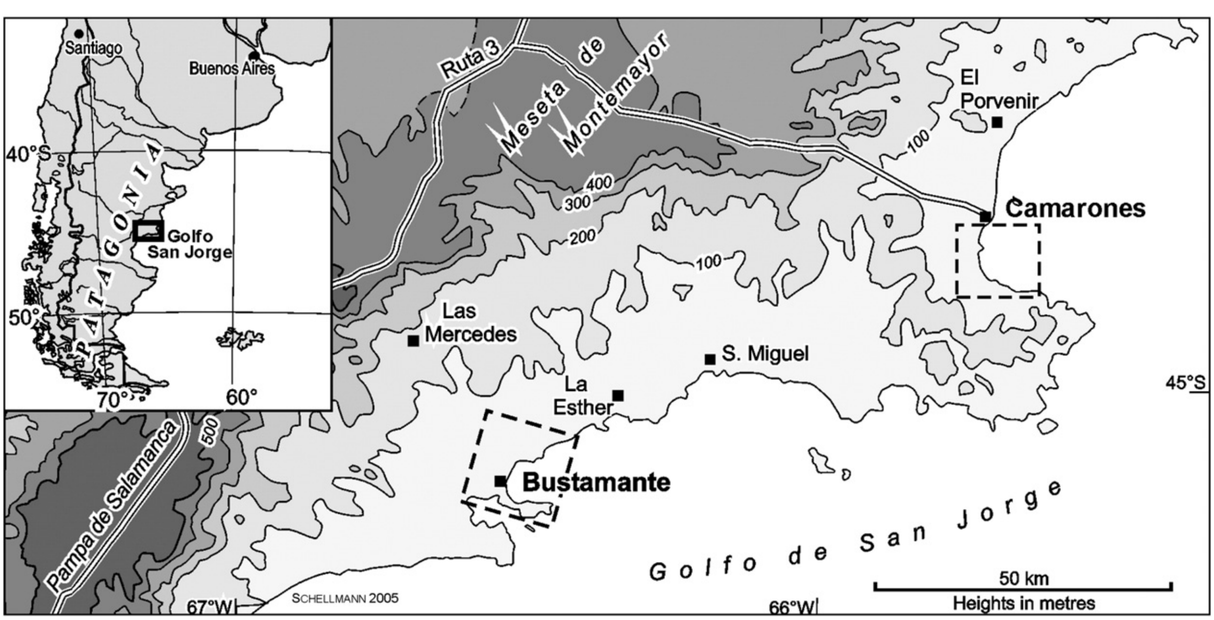

Fig. 1. Locations of the soil chronosequence within the study area at the Golfo de San Jorge, Argentina.