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Genesis, mineralogy and ecological significance of ornithogenic soils from a semi-desert polar landscape at Hope Bay, Antarctic Peninsula

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ABSTRACT

Large amounts of organic matter of marine origin are seasonally deposited on ice-free soils by birds and mammals, especially penguins, in some restricted Antarctic terrestrial ecosystems. The incorporation of this material into the mineral soil matrix becomes the main pathway for the widespread formation of phosphate minerals and ornithogenic soils, enhancing local biodiversity and complexity. These soils have been well-studied in Maritime Antarctica, and comparatively neglected in the cold, dry polar Antarctica. Hence, we studied the influence of penguins on soil and landscape formation at Hope Bay, a transition climatic zone in Antarctic Peninsula, where no previous pedological study has been undertaken with regards to soil phosphatization. Ten pedons, nine of which are ornithogenic, were described, sampled, and analyzed for physical, chemical and mineralogical properties. Results indicate that the slow mineralization of bird guano, coupled with high levels of organic matter and reduced leaching, notably Ca, contribute to reduced soil acidification and low exchangeable Al^{3+} content, unlike ornithogenic soils from Maritime Antarctica. Phosphate minerals typical of the phosphatization process, such as taranakite, minyulite, leucophosphite, struvite, and fluorapatite, were detected. In Hope Bay, they are subjected to very slow rates of dissolution, neoformation of secondary phosphatic minerals, and mineralogical transformation and leaching processes. Ornithogenesis is viewed as a mechanism of sea-land nutrient transfer, enriching the latter, since the parent rocks are chemically poor sedimentary materials. On the other hand, the presence of kaolinite indicates wetter climate conditions in the past, with periods with greater moisture and weathering, compared with the current semi-polar desert environment. We conclude that the phosphatization process overprints previously weathered sedimentary materials.

1. Introduction

In the short summer season, the ice-free terrestrial environments of Antarctica experience a direct influence on the trophic relationships and transfer pathways of mass and energy between the ocean and coastal areas (Rakusa-Suszczewski, 1993). Large amounts of organic matter are deposited by birds and mammals, especially penguins. The incorporation of organic matter into the mineral soil strongly influences the formation of clay minerals and secondary phosphate, forming the characteristic “ornithogenic soil” (Schaefer et al., 2004; Simas et al., 2007; Tatur, 2002; Tatur and Myrcha, 1989), a term originally proposed by Syroechkovsky (1959).

The annual deposition of penguin guano reaches 10 kg m^{-2} of excreta, representing the most abundant source of organic matter and P in Antarctic terrestrial ecosystems (Rakusa-Suszczewski, 1980). However, unlike dry areas from elsewhere, where guano has accumulated, most nutrients carried onshore by penguins soon return to the sea as partially mineralized guano in suspension. However, under favorable conditions, more than 10% of the P can be incorporated into the soil (Myrcha and Tatur, 1991), indicating that the nutrient concentration and high turnover may be important for the productivity, structure and distribution of naturally nutrient-poor coastal ecosystems, such as those of Hope Bay, located in the northern end of the Antarctic Peninsula.

In cold polar desert or semi-desert areas of Antarctica, the deposition of guano apparently has little influence on alteration of silicate minerals in underlying rock (Ugolini, 1972). However, under a moderately humid climates of Maritime Antarctica, the intense cryoturbation and water percolation leaches guano in subsurface. These N and P-rich

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leachates react with the mineral substrate in a complex process of soil phosphatization, first described by Tatur and Barczuk (1985), and recently detailed by Michel et al. (2006), Simas et al. (2006), and Simas et al. (2007). High amounts of P are found in areas of phosphatized rock, e.g., Ca-phosphate and Fe/Al-phosphate, formed by the action of chemically reactive solutions released by the weathering of mineral compounds on rocky substrates and guano.

Secondary phosphate minerals such as taranakite, minyulite and leucophosphite are newly formed by the intense P mobilization, in a distinctive process of phosphatization in a cryogenic environment (Schaefer et al., 2008; Tatur, 2002; Tatur and Myrcha, 1989). In addition, other rare phosphate clay minerals can be observed on Brazilian oceanic islands, similarly developed from bird guano (Oliveira et al., 2010; Schaefer et al., 2010).

Ornithogenic soils are clearly distinguished from non-ornithogenic soils by several properties, e.g., low pH and base saturation, and very high P (Mehlich-1), exchangeable Al and total organic carbon (TOC) levels (Simas et al., 2007). On some of these soils, oases with extensive and continuous vegetation cover are formed, where the microbial activity is higher than usual for Antarctic standards (Michel et al., 2006; Tatur et al., 1997).

The purpose of this study was to assess the influence of birds (penguins) on the process of soil formation at Hope Bay, as well as to evaluate physical, chemical and mineralogical changes in soil properties after phosphatization in a semi-arid transitional climate of Antarctic Peninsula.

We hypothesized a contrast between the phosphatization process in cold, dry semi-polar climates (Hope Bay), with those wetter ones (South Shetlands). The rationale is the proposition that combined mineralogical and chemical soil studies can help elucidate past climate changes in this sector of Antarctica, where oasis of nutrients only occurs when associated with ornithogenesis.

2. Material and methods

2.1. Study area

The study was conducted in Hope Bay, in the northern tip of the Antarctic Peninsula (Fig. 1). The study area is bordered in the south by Mount Flora (520 m asl) and in the east by the Buenos Aires glacier, whose snout reaches over 100 m in terms of elevation. SCAR (2002) defined the area of Mount Flora and surroundings as an Antarctic Specially Protected Area (ASPA 148). Excluding Mount Flora, the ice-free area between the sea and the glaciers covers a region of approximately 3 km^2, with average elevations close to 100 m (Birkenmajer, 1993a; Martín-Serrano et al., 2005).

The region was an EF (polar) climate according to Köppen's classification. Between 1952 and 2010 the average temperature at the nearby Esperanza Station was −5.1 °C, with an annual precipitation of approximately 250 mm. These conditions characterize a semi-desert climate.

Hope Bay is composed of a metasedimentary (Trinity Peninsula Group-Hope Bay Formation: marine siliciclastic turbidites and sandstones), sedimentary (Botany Bay Group-Mount Flora Formation: sandstones, conglomerates and schists) and volcanic rock sequences (Antarctic Peninsula Volcanic Group-Kenney Glacier Formation: rhyolite–dacites, ignimbrites, conglomerates and cemented tuff) (Birkenmajer, 1993b; del Valle et al., 2001; SCAR, 2002).

The geomorphology is related to both paraglacial and periglacial processes and landforms, reflecting the widespread late Quaternary retreat of glaciers (Martín-Serrano et al., 2005), with shorter intervals of minor glacial advances. Most geomorphic processes are related to the coastal environmental, with persistent winds, summer melting, and increasing periglacial erosion, and local thermokarst features.

In Hope Bay area, permafrost was observed at 30 cm depth in most area, with extensive occurrence of Gelisols (Cryosols). Soils are, in

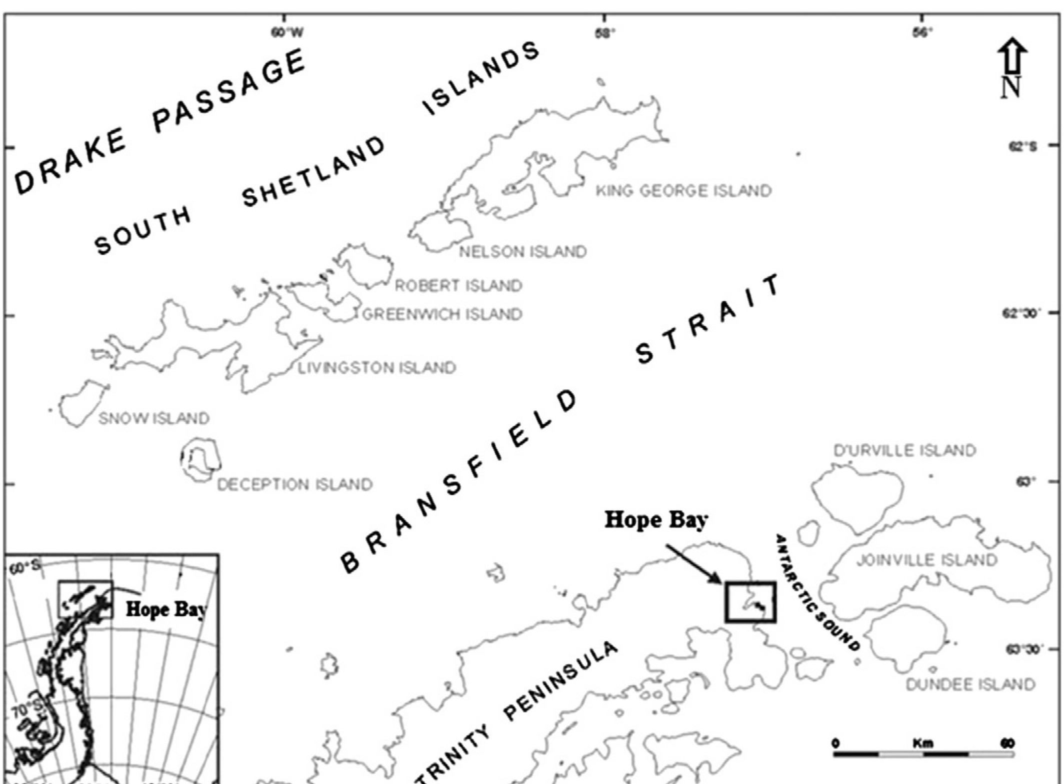

Fig. 1. Hope Bay, Antarctic Peninsula.
Adapted from SCAR (2002).