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Glacial/interglacial changes of Southern Hemisphere wind circulation from the geochemistry of South American dust

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A B S T R A C T

The latitudinal displacement of the southern westerlies and associated climate systems is a key parameter for understanding the variations of Southern Hemisphere atmospheric circulation during the Late Quaternary Period. To increase understanding of past atmospheric circulation and of the paleoenvironmental conditions associated with continental dust sources, we dig deeper into dust provenance in paleo-archives of the Southern Hemisphere. We present here a Sr–Nd isotopic and rare earth element study of surface sediments collected along a ∼4000 km latitudinal band from arid and semi-arid terrains in southern South America. Findings from terrains that served as paleo-dust suppliers are compared with modern dust collected from monitoring stations along the same latitudinal band, which affords a test on how actual present-day aeolian compositions compare to those of the past potential source areas. Moreover, the comparison between past and present-day datasets is useful for understanding present-day atmospheric circulation.

Armed with a new comprehensive dataset, we revise previous interpretations of the provenance of dust trapped in the Antarctic ice and sediments deposited in the South Atlantic sector of the Southern Ocean. These comparisons support multiple source regions in southern South America that changed with climates. The findings reveal that, although Patagonia plays an important role in contributing dust to the higher latitudes, central Western Argentina and (to a lesser extent) the southern Puna region also emerge as potentially important dust sources during glacial times. The southern Altiplano appears to be a major contributor during interglacial periods as well. We rely in part on an understanding of modern wind–dust activities to conclude that the possible presence of southern South America source regions – other than Patagonia – in East Antarctic ice is consistent with an overall equatorward displacement during glacial times of both the mid-latitude westerlies and the subtropical jet stream.

1. Introduction

Southern South America (SSA) is of particular interest for paleoclimate studies because it is the only land-mass intersecting the zonal circulation of both the southern westerly winds (SWW, ∼50°S), and the high altitude subtropical jet stream (STJ, ∼30°S). The reconstruction of the position and strength of the SWW has particular importance given its interaction with the Southern Ocean is a major driver of regional and global climate (e.g. Toggweiler et al., 2006; Anderson et al., 2014). Also important are changes in location, intensity, or altitude of the STJ, which can promote variations in the frequency and intensity of storms (Archer and Caldeira, 2008), and thus can modulate the wetter–dry cycles of specific regions such as the Puna–Altiplano region. During glacial/interglacial cycles, these wind systems change their strength and latitudinal positions, affecting their capacity for erosion and transport of mineral dust from their sources to depositional areas in downwind marine and terrestrial environments, where dust is archived.

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The chemical/isotopic/mineralogical characterization of mineral dust in these paleo-climatic archives (e.g. the Southern Ocean, Antarctica) enables us to learn about its provenance. Such knowledge sheds light on strengthened wind erosion in the source areas and/or the weakening of the hydrological cycle in specific regions (e.g. Maher et al., 2010). Past studies of the provenance of dust deposited in the Southern Ocean (e.g. Walter et al., 2000; Lamy et al., 2014) and Antarctica (e.g. Vallelonga et al., 2010; Delmonte et al., 2010) have led to an increased understanding of past atmospheric circulation in the Southern Hemisphere.

Revisiting the literature on this topic, it became apparent that an important limitation, hampering increased understanding of the specific areas contributing past and present dust to the Southern Hemisphere atmosphere, is the lack of systematic studies at different potential source areas (PSAs) of the continents. Having this in mind, we carried out the first comprehensive north-to-south study of the rare earth element (REE) and Sr–Nd isotopic geochemistry of surface sediments and dusts from the Puna–Altiplano (PAP) to Patagonia, where we know the geomorphic context and age of the potential dust source deposits. Selected topsoil samples were collected from desert lands along a 4000 km long latitudinal band. This transect is more or less perpendicular to the main zonal atmospheric circulation (e.g. SWW and STJ), which ensures that we captured possible dust sources and transport to the easternmost settings such as the Pampas, the Southern Ocean (SO), and Antarctica. Furthermore, a series of dust monitoring sites located downwind from these desert areas were set up in order to capture the modern geochemical fingerprints of SSA potential source regions.

2. Settings of potential dust source areas

The rain shadow effects caused by the last Andean uplift (26–28 Ma) created the 'South American arid diagonal' (Blisniuk et al., 2005). This is a long and narrow region that extends from ∼2°S in the Gulf of Guayaquil to ∼53°S on the northern Tierra del Fuego island, following the coast in Ecuador to northern Chile, crossing into Argentina north and east of Santiago, and continuing southward through Patagonia. The region has an average annual precipitation of roughly 250 mm (Blisniuk et al., 2005). In central South America (∼15 to 30°S), along the west coast, the arid diagonal is dominated by desert areas, whereas towards the east it is characterized by the seasonally dry Chaco forest, and subtropical grasslands where the moisture mainly comes from the Atlantic. The major present-day dust source areas in SSA are located in a continuous N–S band of arid and semi-arid terrains coinciding with the arid diagonal (Prospero et al., 2002). We singled out three primary persistent source areas: Patagonia, central-western Argentina (CWA) and the Puna/Altiplano Plateau (PAP) (Fig. 1).

2.1. The Puna–Altiplano Plateau (PAP)

The main features of the PAP region are summarized in Gaiero et al. (2013 and references therein). Briefly, the PAP is a high elevation basin (∼4000 m a.s.l.) located in the central portion of the Andes and is over 1000 km long and ∼200 km wide. The area consists of extensive, internally drained depocenters flanked by N–S oriented mountain ranges, often between 5000 and 6000 m elevation (Strecker et al., 2007). The region consists of large areas covered by salt lake-beds, including the Salar of Uyuni (∼10,000 km^2) in Bolivia, as well as some smaller ones, for example, the Salinas Grandes (∼200 km^2), Salar del Hombre Muerto (500 km^2), Salar de Arizaro (1600 km^2), Salar de Antofalla (500 km^2) in Argentina.

The South American summer monsoon (SASM) promotes intense convective storms supplying about 80% of precipitation in the austral summer (November to March), while the STJ (westerly winds prevailing in middle and upper troposphere) causes extreme dry conditions from May to October (Garreaud et al., 2009). In addition, a subtropical high-pressure region (the Bolivian High) and atmospheric subsidence dominate the area, fostering extremely arid conditions between about 15°S and 27°S, comparable to the deserts at the same latitudes in western Africa and Australia (Strecker et al., 2007). During winter, the interannual seasonal change in the tropospheric temperature gradient between low and mid-latitudes supports a stronger STJ. This prevents regional moisture from reaching the eastern flank of the Andes, promoting a dry winter climate over the PAP (Prohaska, 1976). Also during this season, associated winds with gusts over 100 ms^{-1} have been recorded (Milana, 2009) leading to the development of extensive dust storms (Gaiero et al., 2013).

2.2. The central-western Argentina (CWA)

Central-western Argentina is located between ∼27° and ∼39°S, and extends from the eastern flank of the Andes to the western slope of the Sierras Pampeanas (Fig. 1). Covering ∼600,000 km^2, it contains varied and complex geological settings. Temperate climatic conditions characterize this part of South America. In the region, wind conditions are controlled by the subtropical high pressure cells (Pacific and Atlantic anticyclones), the intensity of the quasi-stationary low in the Gran Chaco, and the mid-latitudes westerlies. This sector consists mainly of long, wide longitudinal valleys and short, narrow valleys that cut Andean and extra-Andean geomorphologic features. The area is also crossed by several rivers and temporary streams that reach the Andean foothills to form extensive deposits of sand, marshes and saline lakes. The whole area is drained by the Bermejo–Desaguadero–Curacó hydrographic system that covers an extension of ∼250,000 km^2. At present, due to the dominant desert climate this hydrographic network is poorly integrated and almost inactive (Iriondo and Krohling, 1995).

The atmospheric circulation is dominated by northeasterly surface winds in summer and northwesterly winds in winter (Prohaska, 1976). From May to August (austral autumn–winter) katabatic winds (locally called Zonda) with a dominant west to east component are observed (Norte et al., 2008). These are hot and dry winds that occur over most central parts of western Argentina, being more prominent between 28°–37°S. These zonal winds are likely to occur farther south, in areas where strong westerlies cross the Andes, resulting in vigorous down slope flow, drying the lower troposphere to the east of the mountains (Garreaud et al., 2013), promoting deflation of northern Patagonia. On its way down in elevation the Zonda can break through the boundary layer and inject dust into the middle troposphere, which then is transported aloft by the jet streams (Norte, *personal communication*). As we make a case in this paper, CWA provides an unappreciated but persistent source of dust between 27°–36°S and 67°–70°W and along the eastern flank of the Andes.

2.3. Patagonia

The main features of the Patagonian region as a dust source are summarized by Gaiero et al. (2003, 2004, 2007 and references therein). Briefly, Patagonia is a large and diverse region in southern South America that covers an area of over 900,000 km^2, extending from ∼39°S down to the southern tip of the continent (∼55°S), including Tierra del Fuego in the southernmost part. The topography of the Argentinean side of Patagonia is dominated to the west and south by the Andes, and by dissected plateaus (often largely volcanic in nature) and low plains to the east. Throughout the year the area is situated in the core of the mid-latitudes and the climate is controlled by the dynamics of the strong SWW. This wind system blows from the Pacific Ocean, and given the presence of the Andes, most of its moisture is discharged on the west