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Chemical weathering of the volcanic soils of Isla Santa Cruz (Galápagos Islands, Ecuador)

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Abstract
We present a study on weathering of volcanic soils using 43 profiles (131 horizons) sampled in Santa Cruz Island (Galapagos Islands). Several weathering indices, based on chemical composition, are used. Since the geological material is highly homogeneous the intensity of weathering is mostly related to climatic conditions controlled by topography. There is a gradient of increasing weathering from the arid conditions predominant in the coast to elevations of 400-500 m a.s.l. where much more humid conditions prevail.

Introduction

Accessible information on soils from Galápagos Islands is very limited. Up to now it was only the Belgian geo-pedological mission of 1962 that made a systematic soil survey of Isla Santa Cruz. An evaluation of the existing knowledge on Galápagos soils and a global interpretation from a micromorphological point of view was recently published by Stoops (2013 a and b). However, information on the chemical composition (Rodríguez Flores et al., 2006) and especially on the weathering processes is very scarce and the properties of soils developed from volcanic material largely depend on weathering conditions.
The objective of this work was to study the chemical weathering of volcanic soils in Isla Santa Cruz using the soils collected by the Belgian scientists' (J. Laruelle, P. De Paepe and G. Stoops) mission. The aim is to help to increase the knowledge on the formation and evolution of the soils in Galápagos Islands.

Materials and methods

Galápagos is an archipelago of oceanic islands formed by the interaction between the Galápagos hotspot and the Cocos-Nazca ridge. Isla Santa Cruz belongs to middle aged islands and consists of a core of marine sediments, the Platform Series, covered by basaltic lava flows, known as the Shield Series. In the more elevated parts of the island, many ash cones are present. The age of the Shield Series ranges between 590 ± 27 ka and 24 ± 11 ka (White et al., 1993, Geist et al. 2011). These volcanic islands have not been active in historical time (White el al., 1993, Adelinet et al., 2008, Sallarés et al., 2009). The petrology and geochemistry have been studied by White et al. (1993), who concluded that the volcanic materials are alkaline and tholeiitic basalts.
The climate of Galápagos Islands is unusually dry and cold for their equatorial position. This is due to the prevailing south–east trade winds and cold oceanic currents that converge in the archipelago. There are two main seasons on the islands with major differences in temperature and rainfall. From January to June, the climate is warm with occasional heavy rain showers. From June to December, the air is cooler and an inversion layer is formed. It brings a moisture-laden mist to the highlands whereas the lowland areas remain dry. Average annual rainfall ranges from 500 mm on the coast to 1500–2000 mm in the highlands (above 500 m a.s.l.) on the southern windward side. The northern leeward side of the island only receives

rainfall during heavy storms in the hot season. Rainfall can quadruple during El Nino years (Trueman and d'Ozouville, 2010; Pryet et al., 2012).

Isla Santa Cruz is characterized by a broad low elevation coastal apron surrounding a main central shield, which culminates at Cerro Crocker 855 m a.s.l. Due to the orographic effect, contrasts are more acute during the rainy season, when the fog layer is observed along the windward slope from 300 to 400 m a.s.l. up to the summit (Trueman and d'Ozouville, 2010; Pryet et al., 2012).

Forty-three soils sampled from the coast and along the windward slopes of Isla Santa Cruz (Galápagos Islands) were analyzed: six in the coastal area near Puerto Ayora (PAy); nine in the surroundings of Bella Vista (BV); six along a catena to Crocker Mountain (CrM) to the north and six along a catena to the Camote volcano (CMt) NE of Bella Vista; four in the vicinity of El Occidente (OC); seven along a catena to Santa Rosa (SR) NW of Bella Vista; and four in the Table and Rambeck Mountain (TRM) in the NE of the island.

Most PAy, BV, OC and TRM soils are developed on basalts; CrM soils develop on basaltic tephras and slope deposits; and CMt soils on basaltic tephras. The sampling was also representative of four of the bioclimatic belts of the area: the arid coastal zone, the transition zone (situated between the arid coastal area and the more humid higher areas) (TZ, 100-240m a.s.l.); the *Scalesia* zone (SZ, 240-400 m a.s.l.); and the brown zone (BZ, 400-500 m a.s.l.). TRM soils include a group of azonal profiles, located at 370 m a.s.l. in flat depressions with a gilgai-like microtopography.

The major elements composition of the fine-earth fraction was determined: Si, Al, Fe, Mg, Mn, Ca, Na, K, Ti and P were measured by X-ray fluorescence (XRF) at the CACTI laboratories of the University of Vigo. These data were used to calculate weathering chemical indices, which convert bulk major element contents into a single value for each sample. In this study we use: Weathering index of Parker (WIP) (Parker, 1970) based on the proportions of alkaline and alkaline earth metals (Na, K, Ca, and Mg), which are the most mobile of major elements; Chemical index of alteration (CIA) (Nesbitt and Young, 1982) and Chemical index of weathering (CIW) (Harnois, 1988), both based on the ratio between a group of mobile to immobile elements (these indices assume that Al is immobile), and the Silica-Titania index (STI) based on the ratio of a group of the immobile elements (Al, Ti and Si) (Jayawardena and Izawa, 1994). As a result of their formulation CIA and CIW values increase as weathering progresses while WIP and STI values decrease.

Results and discussion

In most of soils of Isla Santa Cruz changes in the values of the weathering indices (WIP, CIA, CIW and STI) with depth are not gradual and systematic. This may indicate the presence of additions of recent materials, due to volcanic activity and colluviation. These continuous rejuvenation processes are common in soils of volcanic areas (Taboada et al., 2007).

WIP, CIA and CIW are positively correlated, but no correlation was found to STI. The highest correlation was found for CIA and CIW ($r > 0.99$), while WIP presents correlation coefficients greater than 0.86 with CIA and CIW. The highest WIP and STI values (greater than 20 and 70 respectively) were found for PAy soils developed on basalt flows near the coast. Slightly lower values were shown by BV and OC soils (WIP 16.8±5 and STI 61±3.4), which are brown soils developed from basaltic flows at elevations between 140 and 225 m a.s.l. (in some epipedons of these soils Stoops (2013b) identified pyroclastic material). The lowest values, representing the more weathered materials, were found in the CMt (WIP 13.2±4.3 and STI 52.4±4.5), SR (WIP 9.9±3.4 and STI 50.8±6.3) and CrM soils (WIP 8.2±6.3 and STI 46.5±8.4), which are found at higher elevations (230 to 500 m a.sl.) and mostly develop on pyroclastic materials (tufa and tephra), although some of them appear mixed with basaltic colluvium (as in SR and CrM). In these three areas (CMt, SR y CrM), soils at the

highest elevations (400-500 m a.s.l.) have lower WIP and STI values, and thus a higher degree of weathering, than those located at altitudes between 325-400 m a.s.l.
CIA and CIW show a similar trend to WIP, some samples (as in CrM soils) with values close to the theoretical weathering maximum of the geological materials.
For the TRM soils, the indices which account for the cation mobility (WIP, CIA, CIW) suggest that they present a much higher degree of weathering when compared to that indicated by the STI, which only considers the behaviour of the less mobile elements (Al, Ti and Si). This may be related to deficient drainage, leading to a higher depletion on base cations than on Si, and to the large abundance of phytoliths found on them (Stoops, 2013b).
The values of the weathering indices were normalized for the sake of representation in the same graph and comparison with published data. Figure 1 presents WIP and STI values, normalized with respect to their value in the parent material (basalts of Isla Santa Cruz, White et al., 1993); for each studied area the soils are ordered from lower to higher elevations (left to right).

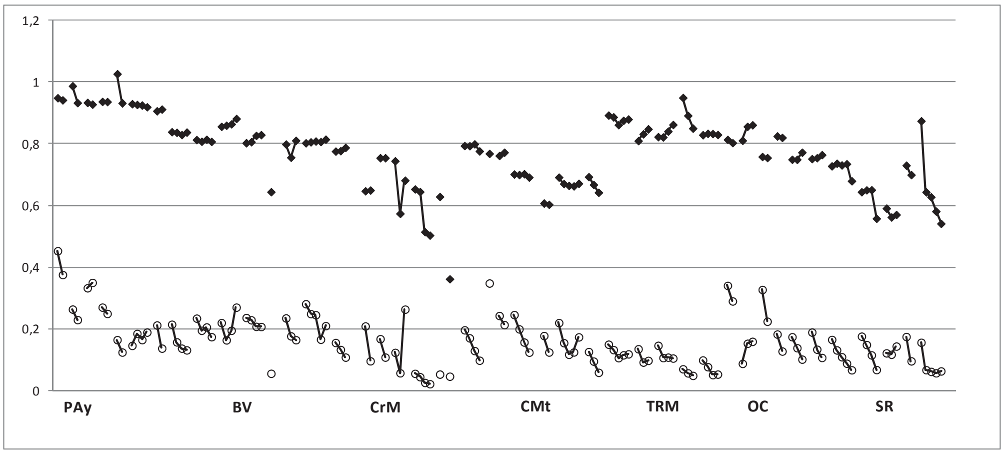

Figure 1. Normalized WIP (open circles) and STI (filled squares) values for soils from Isla Santa Cruz

The composition of the geological materials of the island is quite homogeneous, although small variations in texture have been noted. The differences in the degree of weathering are related to altitude through the control exerted in local climatic conditions. This is particularly the case for precipitation, which is maximum in the windward slopes at altitudes between 400 and 800 m a.s.l. (Pryet et al., 2012). At the same time, the degree of weathering is related to the bioclimatic zones described by Stoops (2013 a and b): soils with the lowest degree of weathering, PAy, are located in the arid coastal zone; in the transition zone (ST), BV y OC soils located at 140-240 m a.s.l. show slightly higher values; soils from CMt, SR and CrM develop in the *Scalesia* zone (SZ) at altitudes between 240-400 m a.s.l.; while the soils from CMt, Sr and CrM with the largest degree of weathering appear in the brown zone, at elevations higher than 400 m a.s.l. The small differences within each of these groups may be related to age and soil use.
Compared to the results obtained for soils of volcanic regions of Europe studied in the framework of COST-622 action (Taboada et al., 2007), soils from Isla Santa Cruz show a much higher degree of weathering than most of them, only comparable to soils from Azores and Tenerife developed on basalts. These are quite consistent results since Isla Santa Cruz soils develop on materials (basalts) and under oceanic conditions which promote intense weathering.
This degree of weathering may be responsible for the evolution of the non-crystalline phases, which may have formed in the early stages of weathering, to more crystalline forms

(halloysite, gibbsite, 2:1 phyllosilicated), as it was described for soils from Azores and Tenerife (Taboada et al., 2007). Eswaran et al. (1973) found that the mineralogy of the clays of soils from the arid and transition zones is dominated by esmectites and halloysite while soils at higher elevations contain halloysite and gibbsite.

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