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ORIGINAL ARTICLE

The relationship between hydrodynamic properties and weathering of soils derived from volcanic rocks, Galapagos Islands (Ecuador)

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Abstract The aim of this interdisciplinary study is to examine a component of the hydrological cycle in Galapagos by characterizing soil properties. Nine soil profiles were sampled on two islands. Their physical and hydrodynamic properties were analyzed, along with their mineralogical composition. Two groups of soils were identified, with major differences between them. The first group consists of soils located in the highlands (>350 m a.s.l.), characterized by low hydraulic conductivity ($<10^{-5}$ m s^{-1}) and low porosity (<25%). These soils are thick (several meters) and homogeneous without coarse components. Their clay fraction is considerable and dominated by gibbsite. The second group includes soils located in the low parts of the islands (<300 m a.s.l.). These soils are characterized by high hydraulic conductivity ($>10^{-3}$ m s^{-1}) and high porosity (>35%). The structure of these soils is heterogeneous and includes coarse materials. The physical properties of the soils are in good agreement with the variations of the rainfall according to the elevation, which appears as the main factor controlling the soil development. The clayey alteration products constrain soils physical and hydrodynamic properties by reducing the porosity and consequently the permeability and also by increasing water retention.

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Introduction

During the last decades, the Galapagos Islands have experienced a constant increase of human population and consequently a growing demand for water. Understanding that the hydrological cycle is fundamental for water resource management, soil porosity, permeability, mineral composition and particle size are important elements within this cycle. Spatial variations of hydraulic properties can influence the amount and distribution of infiltration in the recharge areas.

Soil development from volcanic material depends largely on the weathering conditions. These conditions can be considered a result of geomorphological, climatic and biological factors (Quantin 1974). The effects of climate have been studied in different parts of the world by characterizing mineral composition, e.g., in Asia (Watanabe et al. 2006), America (Dubroeucq et al. 1998) and Europe (Lulli et al. 1988). Soil profile description, mineral composition inventory and physical property investigations are common ways of studying volcanic island soils (Quantin et al. 1991; Malucelli et al. 1999; Tegedor Salguero et al. 1986).

Weathering of volcanic parent material produces different minerals of phyllosilicates and oxyhydric oxides. The nature of these minerals depends on the environment in which they are formed. On the basis of their structures and chemical compositions, phyllosilicate clay minerals can be divided into three main classes: kaolinitic, smectitic and illitic. Oxyhydric oxides (Zebrowski 1975) and organometallic complexes (Buytaert et al. 2005) are the final products and appear under intense weathering conditions. Vertical drainage of water also affects mineral alteration. Oxides (gibbsite, hematite, etc.) are characteristic of very well drained soils, whereas illite and smectite minerals appear preferentially in poorly drained ones (Gense 1970). First stage weathering products are commonly 2:1 type clays (smectite and illite), while second stage products consist of oxide minerals (Ndayiragije and Delvaux 2003). In a volcanic parent material, primary minerals (pyroxene, olivine, feldspar) can weather to clay, but the volcanic glass preferentially leads to the formation of oxides due to Si depletion in relation to Al (Certini et al. 2006).

Besides the mineralogical composition, measurements of the physical properties and hydraulic conductivities of volcanic soils make it possible to understand their water retention and buffering capacity. Several authors have investigated the hydraulic properties of soils and related them to land-use (Giertz and Diekkrüge 2003; Dorel et al. 2000; Leroux and Janeau 1996; Spaans et al. 1989). On an African soil, Giertz et al. (2005) showed that the infiltration capacity was significantly lower in cultivated soils than in natural soils (savannah and forest environments). In a similar approach, Spaans et al. (1989) highlighted the impact of clearing tropical rain forest (Costa Rica) on the degradation of the structure and physical properties of volcanic surface soils. Few studies have focused on the hydrodynamic behavior of volcanic soil. Fontes et al. (2004) investigated the behavior of Andosol (a type of volcanic soil) in Tercera (Azores) and showed unusual physical properties such as high total porosity, >60%, but low hydraulic conductivity, $<10^{-5}$ m s^{-1}. At a larger scale, Tanaka and Sunarta (1994) showed, on Bali Island, a relationship between the regional changes in physical soil properties and the volcanic stratigraphy. These data enabled the authors to identify the hydrogeological recharge areas on Bali.

This paper focuses on the hydraulic and physical properties of the Galapagos soils and their relationship with the mineralogical composition, particularly the identification of the clay fraction. The purpose of this study is to understand the role of the soils in the hydrological cycle of volcanic islands by relating soil hydraulic properties with the weathering processes at the interface between the atmosphere and the subsurface.

Material and methods

Study area

The Galapagos archipelago is located on the Equator in the Eastern Pacific Ocean. Santa Cruz and San Cristobal Islands are located in the central and eastern part of the archipelago (Fig. 1). Geologically they belong to the “Central Sub-province” (Mc Birney and Williams 1969). These volcanic islands have not been active in historical time. They are shaped smooth shields without summital calderas in contrast to the active western volcanoes of the archipelago. Major geological characteristics of the two islands are summarized in Table 1. The emergence of Santa Cruz Island is dated to about 2 million years (m.a.) and the youngest lava flow is dated to about 0.6 m.a. Lavas younger than several thousand years, characterized by lack of colonizing vegetation, cannot be dated, but are found on the northern part of the island. The emergence of San Cristobal island is dated to around 2.4 m.a. The last lava flows on the southern part of the island are dated to around 0.65 m.a. (Geist et al. 1985). The northern part of the island consists of low-lying recent lava flows and was not included in the study. The Galapagos Islands are formed by mixed basaltic rocks. The lavas are generally alkaline in nature with some tholeiithic MORB at certain stages (White et al. 1993, Geist et al. 1998). Unlike Santa Cruz Island, the highlands of San Cristobal are covered by thick pyroclastic deposits dated from the end of its volcanic activity to a depth of 10–20 cm (Geist et al. 1985).

The climate of the Galapagos Islands is unusually dry and cold for their equatorial position. This is due to the prevailing south–east (SE) 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 rates. From January to June (the hot season, “invierno”), the climate is warm with occasional heavy rain showers. From June to December (the cool season, “garua”), the air is cooler and an inversion layer is created. 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 1,500–2,000 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. As a consequence, the soils on the two sides of the islands are different in their thickness, structure and composition. This study focused on the soils developed on the windward side of the islands as the soil cover on the northern side is poorly developed.

The vegetation distribution shows direct dependence on altitude, slope, exposition to trade winds and level of air moisture (Ingala et al. 1989). Three main climatic units are distinguishable: a dry zone, a humid zone and a summit zone. The vegetation distributions on Santa Cruz and San Cristobal are similar while their geomorphologies are very distinct. The low parts of Santa Cruz, near the coast, are relatively flat; the morphology becomes more abrupt in the

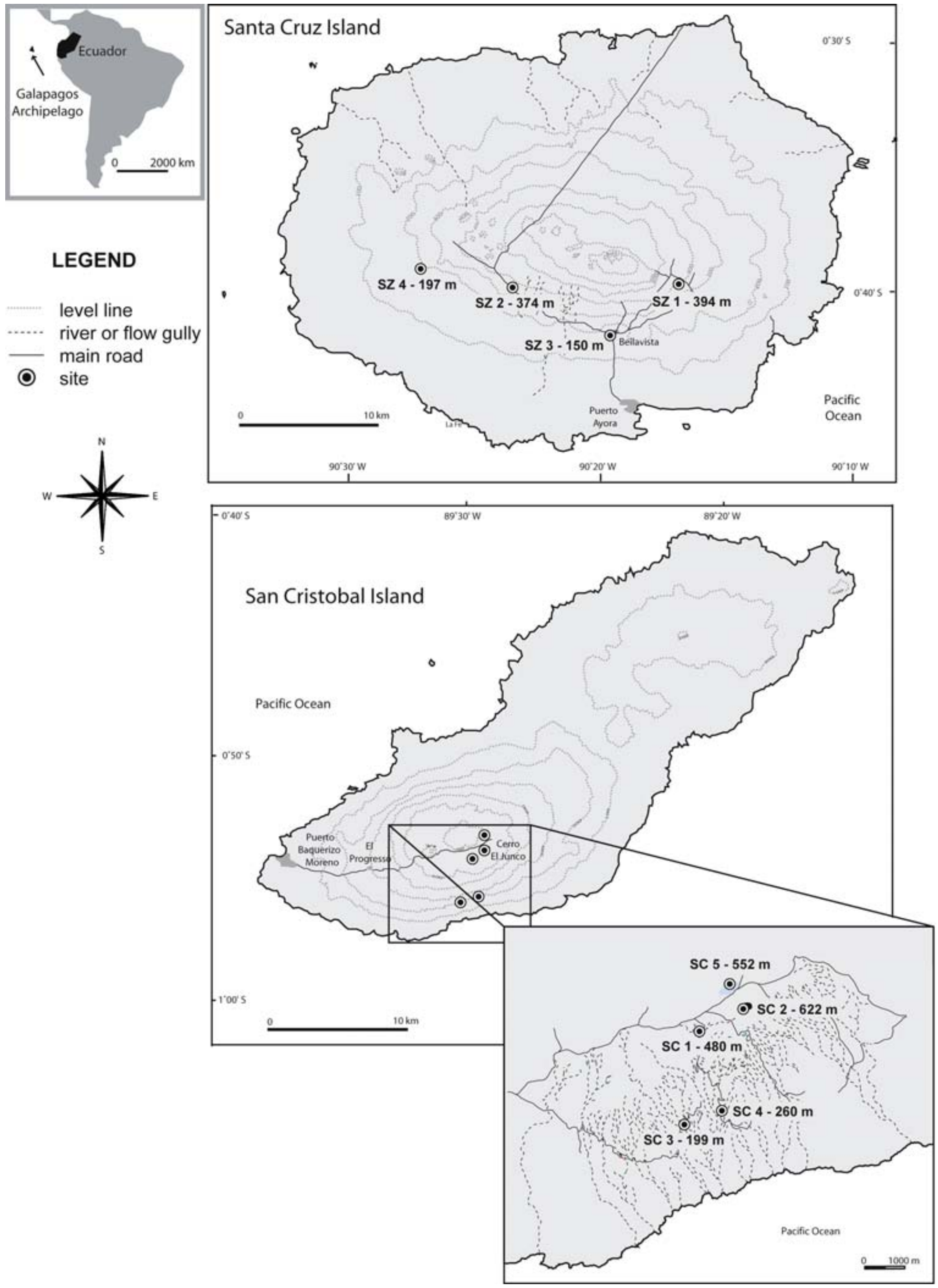


Fig. 1 Location of studied sites on Santa Cruz and San Cristobal Islands, Galapagos archipelago, Ecuador (modified from Ingala et al. (1989) and Adelinet (2005)). Rivers or flow gullies are represented by *thick dotted lines*. Sites for in-situ measurements and samples collecting were selected at different altitudes on the slopes of Santa Cruz and San Cristobal Islands. Different parent material was another criterion for choosing sites

highlands with steep slopes. On San Cristobal, the slopes are consistent from coast to highland. In its summit area, Santa Cruz is marked by an east–west cone alignment, whereas San Cristobal has a gentler landscape with rows of hills and plateaus.

Despite apparently similar climatic conditions and vegetation distribution, Santa Cruz and San Cristobal islands differ greatly in their hydrological characteristics. On Santa Cruz, surface flow exists only during heavy rainfall and intense “garua” seasons. A single spring exists at an altitude of 400 m a.s.l. at the foot of a cinder cone. On the southern part of San Cristobal, about 30 permanent streams are known; all recharged by permanent springs located at different altitudes (Fig. 1).

Laruelle (1966) studied soils of Santa Cruz and described several pedological units based on differences in structure and composition. The Santa Cruz and San Cristobal morphopedological maps from Ingala et al. (1989) focus on agricultural areas. The study showed that the islands have the same general structure, successive underlying lavas, but a different evolution leading to different soil units. The main factor identified as a cause of

Table 1 Geological and morphological characteristics of studied islands

Island	Area (km^2)	High point (m)	Emergence age (m.a.)	Last lava flow age (m.a.)
Santa Cruz (SZ)	1,000	870	2	0.6
San Cristobal (SC) southern side	550	730	2.4	0.65

soil differentiation is the quantity of rainfall and not the age of the geological formations. In an agricultural area on San Cristobal, a study was made to characterize the cultivated soils. Measurements of hydraulic conductivity using a double-ring infiltrometer were carried out on sites located at different altitudes but always on ploughed fields (Ipade and Fundar 2003).

Study site

Based on differences between climate zones and parent material, respectively four and five soil profiles were selected on Santa Cruz and San Cristobal Islands (Table 2). Figure 1 shows the sampling sites and their elevation. The sites were selected on preserved areas, which had not been ploughed and were representative of a natural Galapagos area, with limited human disturbance. Soil sampling was carried out in April 2006, in the middle of the hot season.

Table 3 Volume fraction of particles with size lower than 10 μm from three samples from San Cristobal

Site	Altitude (m)	Clay-silt fraction <10 μm (%)
SC 1	480	14
SC 2	622	36
SC 4	260	5

These fractions are not exactly the clay volume contents but the volume content of clay and part of silt

Determination of the clay fraction

In order to evaluate the clay volume fraction, three samples from San Cristobal (SC-1, SC-2, SC-4) were air dried and sieved. The volume fraction of particles with size less than 10 μm was deduced. These data are summarized in Table 3. This fraction is not exactly the clay volume fraction, but the "clay and a part of silt" volume fraction.

The X-ray diffraction (XRD) method was chosen to characterize the mineral composition of the studied soils. On each site, disturbed soil samples were taken in 20 cm^3 plastic bottles. Two types of soil sampling were carried out: deep extraction for SZ-1A and SC-3A and surface extraction for all others. In the laboratory, clay fractions (<2 mm) were separated by sedimentation and flocculation with $SrCl_2$. Well-oriented clay fractions were obtained through sedimentation on glass tiles for X-ray diffractograms. A Philips diffractometer equipped with an X-celerator fast counter was used to record the diffraction patterns in the range of 2θ = 2–35°(Cu radiation).

Table 2 Major morphological characteristics of studied profiles

	Horizon	Altitude (m)	Depth (cm)	Parent material	Soil division	Vegetation
Santa Cruz	SZ 1 A	394	50	Ash	Argiudolls	Bush
	SZ 1 B	394	10	Ash	Lithic Argiudolls	Bush
	SZ 2	374	3	Basalt	Lithic Dystrandepts	Green meadow
	SZ 3	150	0	Basalt	Lithic Argiudolls	–
	SZ 4	197	0	Basalt	Lithic Argiudolls	Dry meadow
San CristobalOBAL	SC 1	485	30	Basalt blocks	Oxic Dystropepts	Arborescent shrub
	SC 2	622	5	Ash	Rhodudalfs	Bush
	SC 3 A	199	60	Basalt	Vertic Haplustalfs	Bush and tree
	SC 3 B	199	20	Basalt	Vertic Haplustalfs	Bush and tree
	SC 3 C	199	10	Basalt	Vertic Haplustalfs	Bush and tree
	SC 4	260	10	Basalt	Vertic Tropudalfs	Tree
	SC 5	552	2	Sour lime	–	Dry herbs

Soil divisions come from Ingala et al. (1989)

Hydraulic conductivity in situ measurements

Two methods were used to measure the saturated hydraulic conductivity. The first was the double-ring infiltrometer, a common method to study spatial variability (Boivin et al. 1987; Touma and Boivin 1988). Two metal rings with diameters of, respectively, 28 and 53 cm were inserted into the soil. The rings were filled with water several times to ensure soil saturation before the measurements. Then, the decrease of the water level in the central ring was measured as a function of time. The hydraulic conductivity was deduced from Darcy's law, using a unit hydraulic gradient. Errors due to the procedure of the double-ring method are estimated to be in the order of 50%. Sources of errors include reading of the water level, time measurements and unit hydraulic gradient hypothesis.

The second method is based on the protocol used by Humbel (1975) and was adapted and improved for this study. A plastic ring with a 16 cm diameter and 10 cm length was inserted into the saturated soil and then removed. The sample was placed under a Mariotte bottle, which maintains a constant pressure head on the soil. The volume in the Mariotte bottle was measured as a function of time. The saturated hydraulic conductivity was deduced from Darcy's law, using a constant pressure head. Errors due to this method are estimated to be ion the order of 30%. Main sources of errors are the reading of the water level in the Mariotte bottle and the time measurement. There are two disadvantages to this method: first, the sample can be damaged during extraction and second, the soil hydraulic conductivity is measured on a smaller scale than with the double ring. The advantage of this method is that it does not need the unit hydraulic gradient hypothesis to be made.

Porosity measurements

The protocol for measuring surface porosity was developed by Bruce Velde from the *Laboratoire de Géologie* at the *Ecole Normale Supérieure* in Paris and is based on image analysis in relation to surface structure and pore observations (Velde 1999; Li et al. 2004). Undisturbed soil samples were taken in 10-cm diameter plastic tubes. Samples were sealed and transported to the laboratory. There, they were impregnated with Epoxy resin (Ciba-Giegy DY0397 resin) mixed with a yellow fluorescent dye (fluorescein). The different tubes containing the soil samples were cut into horizontal segments of 2 cm thickness from the top of the tubes. These sections are photographed under ultraviolet light of high intensity in the 365-nm region. The pictures are treated by the Adobe Photoshop© software. Using a threshold maximum intensity, the yellow color appears as white revealing the pores. The solid soil material is not affected by the ultraviolet light and appears black (Fig. 2). This method allows measurements of surface porosity by calculating the distribution of the white and the black portions of the sample. As the resin used for filling the pores is forced to flow through the porosity network, the actual porosity calculated *P* is the connected porosity, Errors due to the porosity measurement protocol are estimated to be in the order of 10% (Li et al. 2004).

The influence of air humidity on the porosity was investigated on samples from two sites, SC2 and SC4. Each soil sample was placed in a controlled atmosphere with a prescribed air humidity rate (HR = 0; 76; 96%), as described in Table 4. After 20 days in a controlled atmosphere, the samples were treated by the same procedure as mentioned above.

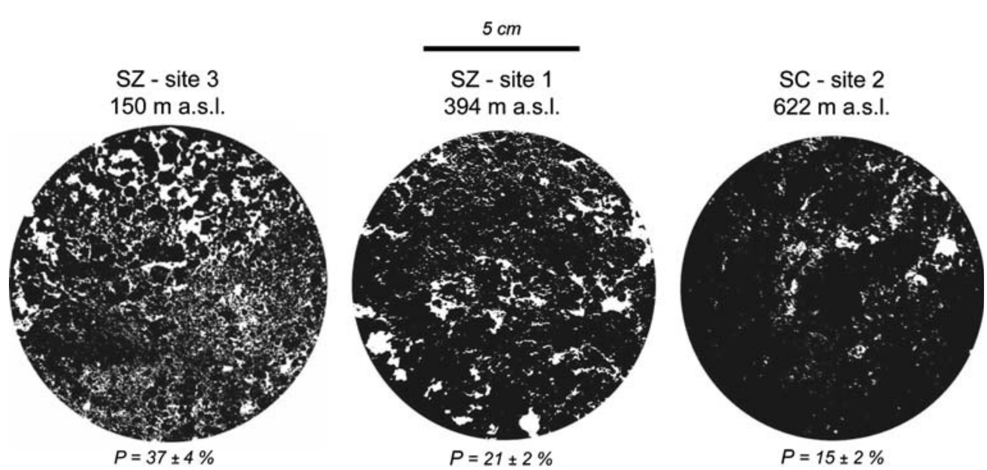


Fig. 2 Selected binary images after a threshold treatment. For example, porosity of sample collected at 150 m a.s.l. (SZ3) is about 37%. These images show that the porosity decreases when the altitude increase. This is partially explained by the clay fraction contained in soils: more present and diversified in samples from high altitude than in samples from the low parts

Table 4 San Cristobal samples were conditioned under controlled atmosphere with prescribed relative humidity (RH)

Site [altitude (m)]	Sample no.	RH rate (%)
SC2 (622)	1	0
SC2 (622)	2	76
SC2 (622)	3	96
SC4 (260)	1	0
SC4 (260)	2	96

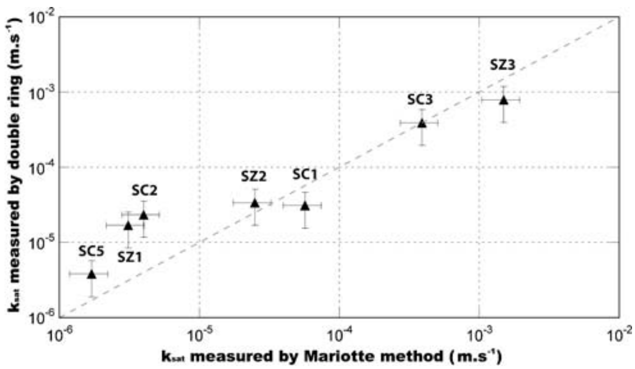


Fig. 3 Hydraulic conductivities obtained by double ring plotted against hydraulic conductivities obtained by Mariotte method. *Error bars* are estimated to be in the order of 30% for double ring method and 50% for the Mariotte method. This figure shows a very good agreement between the values obtained with these two methods

Results

In situ and laboratory results

Hydraulic conductivity measurements

Figure 3 shows hydraulic conductivities determined by both methods. There is a good agreement between the measurements obtained by the double ring and Mariotte method. For example, on SC3, the hydraulic conductivities determined by both the methods are identical and $k_{sat} = 3.9 \times 10^{-4}$ m s^{-1}. More generally, values obtained by both the methods are similar and always are of the same order of magnitude.

The measured hydraulic conductivities of Galapagos soils are in the range of 1.5×10^{-3} to 1.7×10^{-6} m s^{-1}. Figure 4 shows hydraulic conductivities plotted against altitude. The hydraulic conductivities measured in the high altitude parts of the islands are much lower than the ones measured in the low elevation parts. Moreover, the decrease of the log-hydraulic conductivity measurements versus altitude is linear (Fig. 4). This trend is observed in both Santa Cruz and San Cristobal. For instance, SZ4 and SC3 are located at around the same altitude (197 and

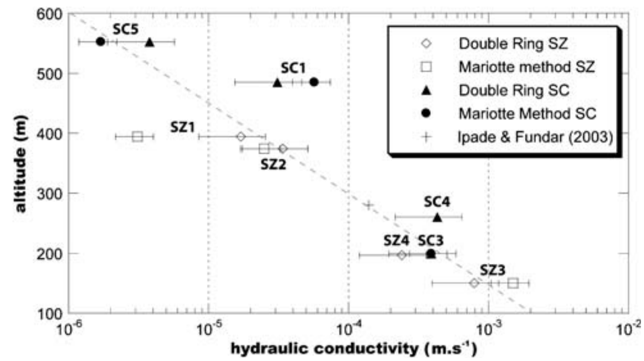


Fig. 4 Sites altitude plotted against hydraulic conductivity. *Error bars* are estimated to be in the order of 30% for double ring method and 50% for the Mariotte method. The value denoted *K IPADE* comes from Ipade and Fundar (2003). This figure highlights a relationship between altitude and hydraulic conductivities of soils: log-hydraulic conductivities are lower in high altitude than in low altitude and the trend seems to be linear

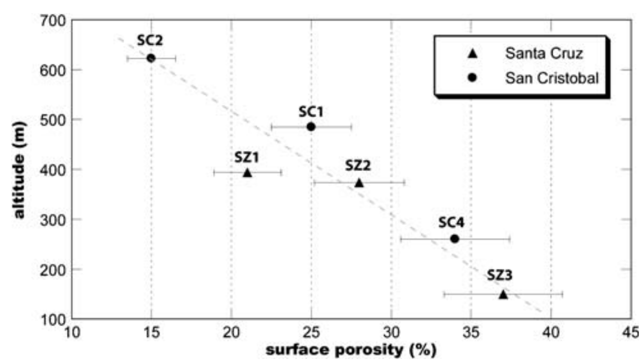


Fig. 5 Sites altitude plotted against surface porosity. *Error bars* are estimated to be in the order of 10% due to the porosity measurement procedure. This figure shows a relationship between altitude and porosity measurements: soils are less porous in high altitude than in low elevation parts and the trend seem to be linear

199 m, respectively) and both their measured hydraulic conductivities are close to 3×10^{-4} m s^{-1}.

Porosity measurements

The different porosity measurements obtained from the six study sites versus altitude are plotted in Fig. 5. Porosity is in the range of 15–37%. A strong correlation between porosity and altitude is again noticeable. Indeed, at an altitude of 622 m, the porosity is 15% whereas at an altitude of 150 m, near the coast, the porosity is 37%. The shape of porosity evolution as a function of altitude (Fig. 5) is similar to the shape of the evolution of log-hydraulic conductivity versus altitude shown in Fig. 4.

Samples from sites SC2 and SC4 were placed under controlled atmospheric conditions (see "Hydraulic

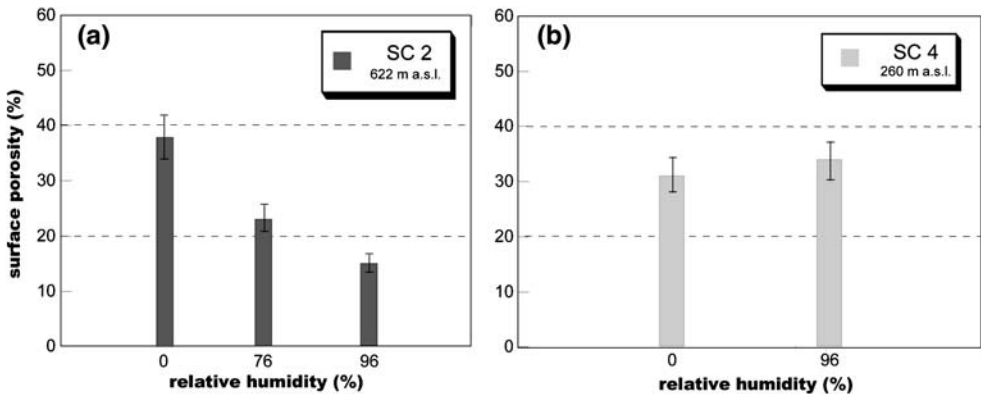


Fig. 6 Surface porosity plotted against relative humidity rate with *error bars* of 10%; SC2 (**a**) and SC4 (**b**) was respectively extracted at 622 and 260 m of altitude. This figure shows that the highland soil is sensitive to variation in humidity rate, which is not observed for soil from low-lying areas. This observation can be related to the structure of soils. At altitude, clay fraction is more important, thus soil is sensitive to humidity variation. The clay swells which result in a decrease of the porosity. On the contrary in the low-altitude zones, soils are more granulous (without clay cement). Thus the humidity rate variation has a weak impact on the hydrodynamic behavior

conductivity in situ measurements" and Table 4). Results are presented in Fig. 6. In the case of SC2, samples were extracted at 622 m. Figure 6a shows that porosity is sensitive to air humidity and decreases when the humidity rate is raised. In the case of SC4, samples were extracted at 260 m. Contrary to the behavior of SC2 samples, any variation in porosity with a fluctuating relative humidity rate is observed (Fig. 6b). This difference of behavior was discussed in "Porosity versus prescribed air humidity".

X-Ray diffraction results

X-Ray diffractograms of Santa Cruz and San Cristobal samples are presented in Fig. 7I–VI, respectively. Semi quantitative composition is shown in Table 5.

Results from samples extracted on the surface

Samples collected at low altitude (SZ3 and SZ4) from Santa Cruz Island, show very poor diffraction patterns although weak kaolinite peaks appear (Fig. 7I-bc; Table 5). Samples from the highlands (SZ2 and SZ1 B) show several characteristic peaks of gibbsite, kaolinite and hematite (Fig. 7I-a, II-d; Table 5). These results prove that the clay crystallogeny is more pronounced at high altitude than in the lower parts of the island.

Samples from San Cristobal Island show different XRD signatures. Samples extracted from the lowlands (SC3 and SC4) present a pattern with recognizable peaks of kaolinite and gibbsite (Fig. 7V-ij; Table 5). Moreover, SC4 shows a sharp peak, characteristic of hematite (Fig. 7V-i). For SC1 sample collected at high altitude, the XRD signature is characterized by a very sharp peak typical of gibbsite and peaks of kaolinite (Fig. 7III). A broad peak at 4.16 Å may be due to the presence of cristobalite probably of high-temperature origin (Fig. 7III). The SC2 sample diffractogram is very noisy and only characterized by a peak of gibbsite (Fig. 7IV-h). Finally, the SC5 sample presents a pattern with sharp peaks of gibbsite and kaolinite (Fig.7IV-g). Contrary to Santa Cruz, clay crystallogeny from low parts of San Cristobal seems to be already diversified.

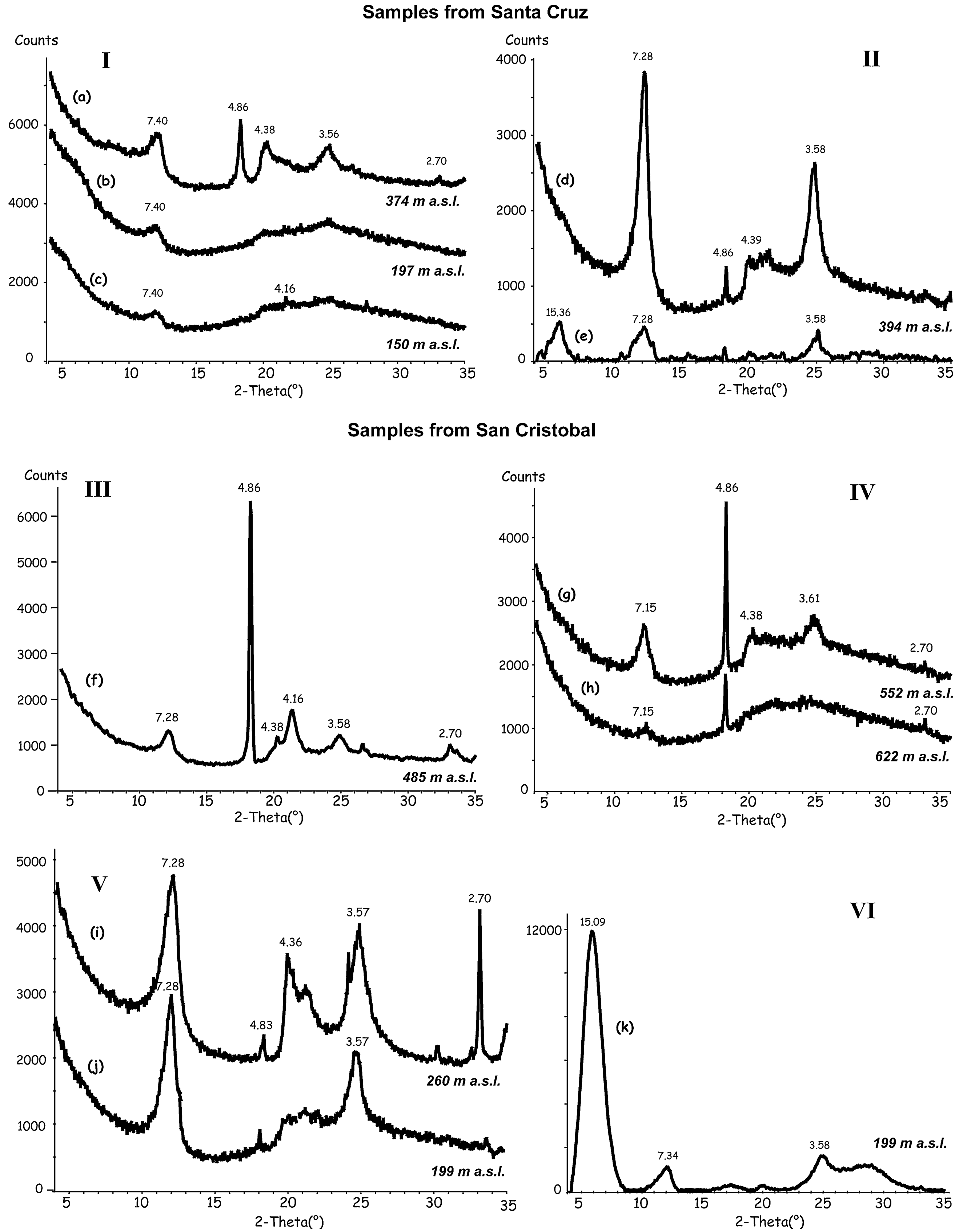
Results from samples extracted at depth (more than 20 cm)

The XRD diffraction diagrams of samples from deep soils, SZ1 A (Santa Cruz) and SC3 A (San Cristobal), are shown in Fig. 7II-e and VI-k, respectively. Both show the presence of a sharp reflection ~15.36 Å, characteristic of a new clay family smectite. To summarize, the material extracted at depth shows the trace of a 2:1 clay mineral (smectite), whereas on the surface, all the identified clay minerals are 1:1 or oxide minerals (gibbsite and hematite).

Discussion

Soil physical properties versus altitude

Figure 4 shows that the hydraulic conductivity of soils is controlled by altitude. This observation can be related to the variation in rainfall with altitude. The linear decrease of log-k_{sat} versus altitude (Fig. 4) could be related to the orographic gradient of rainfall. However, there are not enough weather stations on the islands to obtain a good trend of the rainfall evolution versus altitude. This relationship between rainfall and hydraulic conductivities has been studied on other volcanic complexes. For example, on


Samples from Santa Cruz
I
II
Counts
2-Theta(°)
(a)
(b)
(c)
374 m a.s.l.
197 m a.s.l.
150 m a.s.l.
7.40
4.86
4.38
3.56
2.70
4.16
(d)
(e)
394 m a.s.l.
7.28
4.39
3.58
15.36
Samples from San Cristobal
III
IV
(f)
485 m a.s.l.
(g)
(h)
552 m a.s.l.
622 m a.s.l.
7.15
3.61
V
(i)
(j)
260 m a.s.l.
199 m a.s.l.
4.36
3.57
4.83
VI
(k)
15.09
7.34

◀ **Fig. 7** Diffractograms of Santa Cruz samples: **I** Results from (*a*) SZ2 sample, (*b*) SZ4 sample and (*c*) SZ3 sample. **II** Comparison between samples collected at the same altitude (394 m a.s.l.) but (*d*) extracted on the surface (SZ1 B), (*e*) extracted at depth ~50 cm (SZ1 A). Diffractograms of San Cristobal samples: **III**, **IV** Results from samples collected at high altitude (*f*) sample SC1, (*g*) sample SC5, (*h*) sample SC2. **V** Results from samples collected at low altitude (*i*) sample SC4, (*j*) 199 m a.s.l., sample SC3. **VI** (*k*) Results from sample extracted at depth (~60 cm) at 199 m a.s.l. (SC3 A). For highland soils prevailing mineral is gibbsite (4.86 peak), whereas at lower altitude crystallogeny is less diversified with only presence of kaolinite clay (~7.40 peak), especially on Santa Cruz. For samples extracted at depth, we observe the presence of smectite family clay minerals (~15–15.5 peak). This implies that the degree of alteration is less important at depth than in surface

Bali Island, Tanaka and Sunarta (1994) showed that the soil hydraulic conductivity trend is inversely correlated to rainfall and altitude.

As for hydraulic conductivity, porosity is also a function of altitude (Fig. 5). Soils at high altitudes are characterized by a lower porosity than that measured on samples from low elevation zones. Trends of porosity evolution and hydraulic conductivity evolution are similar.

On Galapagos Islands, the main part of the precipitation is brought by the trade winds, thus the geographical position of islands play a key role (see "Differences between Santa Cruz and San Cristobal" and Fig. 1). The highland soils of both theislands receive moisture throughout the year, by rain showers during the hot season and permanent mist during the cold season. As a consequence, soils in the highlands are wet, mostly during the whole year, due to the permanent supply of atmospheric water. Furthermore, it has been proved on volcanic islands that meteoric water is one of the main weathering agents (Quantin 1974). The quantity of rainfall, via the alteration processes, seems to be the main factor controlling hydraulic conductivity of the Galapagos soils.

Vegetation can affect the soil physical properties via the root system. A soil is more cohesive if covered by dense vegetation, even if it is only bushes or shrubs (Sarah and Rodeh 2003). On Santa Cruz and San Cristobal Islands, vegetation is much more developed in the highlands than near the coast and consists of endemic or introduced shrubs and trees (Ingala et al. 1989; Adelinet 2005). Thus, at high altitudes, the root systems can play a key role in the soil structure and hydrodynamic behavior by reducing the hydraulic conductivity and porosity. Note that these two factors (rainfall variation and vegetation) are not independent.

Effect of the clay fraction on the physical properties of soil

Clay minerals composition

The mineralogical data reveals three results of interest.

(1) In the surface samples extracted at high altitude, gibbsite is always present and associated with a 1:1 clay mineral (kaolinite family) and sometimes with another oxide (hematite). The presence of these three minerals is the result of intense chemical weathering and indicates that these soils are well drained (Gense 1970; Zebrowski 1975).

(2) The mineralogical data show a difference in mineral composition between the soils from high and low altitudes. This difference is clearly observed in Santa Cruz Island. Samples from low

Table 5 Semi-quantitative composition of the clay fraction

	Cristobalite SiO_2	Smectites	Kaolinite $Si_2O_5Al_2(OH)_3$	Gibbsite $Al(OH)_3$	Hematite Fe_2O_3
Main peaks	4.2	15/16	7.4–3.5	4.8–4.4	2.7
Santa Cruz					
SZ 1, 394 m, D	–	++	+	–	–
SZ 2, 374 m	–	–	++	++	+
SZ 3, 150 m	tr	–	+	–	–
SZ 4, 197 m	–	–	+	–	–
San Cristobal					
SC 1, 485 m	+	–	+	++	+
SC 2, 622 m	–	–	tr	+	tr
SC 3A, 199 m, D	–	++	+	–	–
SC 3B	–	–	++	+	–
SC 3C	–	–	++	+	–
SC 4, 260 m	–	–	++	+	++
SC 5, 552 m	-	–	++	++	+

D depth sampling, *tr* traces, +clearly present, ++abundantly present, –absent altitudes (Fig. 7I-b, I-c) produce very noisy diffractograms with poor patterns. This can be explained not only by a lack of extracted clay material but also by the fact that clays are not well crystallized. On the contrary, at higher altitudes clay crystallogeny is more diversified. In San Cristobal Island, the difference in clay composition between low and high elevation soils is not so clear. The diffractograms from all the samples (from high and low altitudes) show distinct clay crystallogeny. To understand this mineralogical difference between the two islands, we need to take into account the age of the islands (Table 1). Quantin (1972) showed on Andosols that clay crystallogeny becomes more diversified with time, and the lavas from San Cristobal are older than those from Santa Cruz. Moreover San Cristobal is located further east than Santa Cruz. Consequently, the San Cristobal climate is more influenced by the trade winds, which bring most of the rainfall. Thus, the difference between the islands can be explained not only by time but also by climate differences.

(3) Our XRD results show mineralogical differences between the samples extracted at depth (>20 cm) and taken from the surface. The deep samples are characterized by the presence of smectite, a mineral of the 2:1 clay family. This implies that the weathering is less effective at depth than on the surface. Ndayiragije and Delvaux (2003) report similar results on a perudic Andosol. As a consequence, the soil drainage is weaker at depth than on the surface, which suggests that the water flow is mostly sub-horizontal in the studied soils.

Porosity versus prescribed air humidity

As shown on Fig. 6, samples placed under controlled atmospheric conditions highlight two different soil structures. The porosity of the soil sample from high altitude is sensitive to humidity rate variations, a result, which is not observed in the sample collected from low-lying area. Such difference can only be explained by a different content in buffer clays. The clays recognized as buffer clay are predominantly the 2:1 phyllosilicate clays. Some clays of this family, such as smectites and vermiculites, possess a greater fraction of tetrahedral charge substitution, which confers them a swelling capacity (Pusch and Weston 2003; Skipper et al. 2006).

Assuming that soils from Galapagos Islands are a mixture of clay and aggregates, the total porosity Pt is given by Marion et al. (1992):

$$Pt = P_a - c(1 - P_c) \tag{1}$$

Where P_a is a pure aggregates porosity, P_c the porosity of pure clay, and c the clay fraction volume. Note that this last equation holds until clay entirely fills aggregates pore space. However in our porosity measurement protocol (see "Porosity measurements"), macropores are more easily taking into account than porosity of clay. Indeed the resin fills the macropores, but not the porosity clay, which is characterized by thin pores. Due to this artifact, the measured porosity can be approximate to:

$$P \approx Pa - c \tag{2}$$

Note that the measured porosity is close to the effective porosity, as the clay porosity contributes for a small amount to the global hydraulic conductivity.

Equation (2) can explain the observations reported in Fig. 6. Soil sample collected at high altitude areas (Fig. 6a) is characterized by an important clay fraction volume (36% of the volume fraction is made of particles with size lower than 10 μm, Table 3). When humidity rate increases, clays swell. This process not only induces an increase of the clay porosity Pc, but also of the clay fraction volume c (Fig. 8). As a consequence, an increase in c implies a decrease in the measured porosity (Eq. 2), which is in agreement with our experimental observation (Fig. 6a). On the contrary, sample collected from low-lying area is characterized by a small fraction of clay (5% of the volume fraction is made of the particles with size lower than 10 μm, Table 3). The swelling process also induces an increase of the clay volume content c, but in the proportion of the clay fraction, i.e. <5%. In this last case, the effect of swelling on the measured porosity can be negligible in agreement with our experimental data (Fig. 6b).

Relationship between porosity and permeability

As noted by several authors (e.g. Walsh and Brace 1984, de Marsily 1986; Guéguen and Palciaukas 1994; Revil and Cathles 1999), the relationship between porosity and permeability is not straightforward, as permeability is controlled by the porosity microstructure as well as the macroporosity. The different theoretical and empirical laws usually relate the "effective porosity" P to the "intrinsic permeability" k' (m^2). k′can be expressed as a function of hydraulic conductivity k:

$$k' = k\frac{\eta}{g.\rho} \tag{3}$$

where g is the acceleration due to gravity and $\frac{\eta}{\rho}$ the water cinematic viscosity and are assumed to be 0.804×10^{-6} m s^{-1} at 30°C.

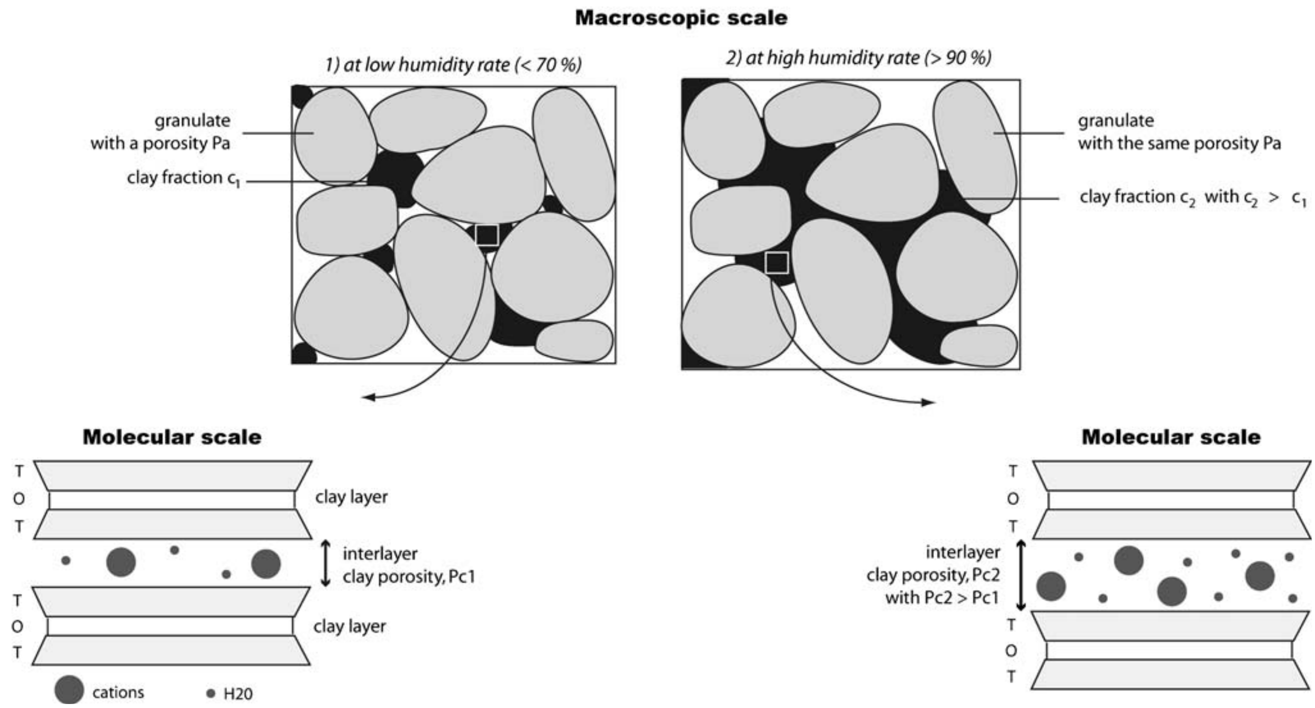


Fig. 8 Diagram showing the evolution of soil structure from high altitude areas. When humidity rate increases, clays swell. This process induces an increase of the clay porosity Pc, but also of the clay fraction volume c. As a consequence, an increase in c implies a decrease in the measured porosity, which is in agreement with our experimental observations

Intrinsic permeability of Galapagos soils was directly deduced from the experimental hydraulic conductivity measurements.

Experimental data are summarized in Fig. 9. This figure shows a rapid reduction in permeability of more than two orders of magnitude as the porosity decreases from 37 to 25%. Then the permeability is almost constant ($k \approx 3 \times 10^{-13}$ m^2) in the porosity range of 21–15%.

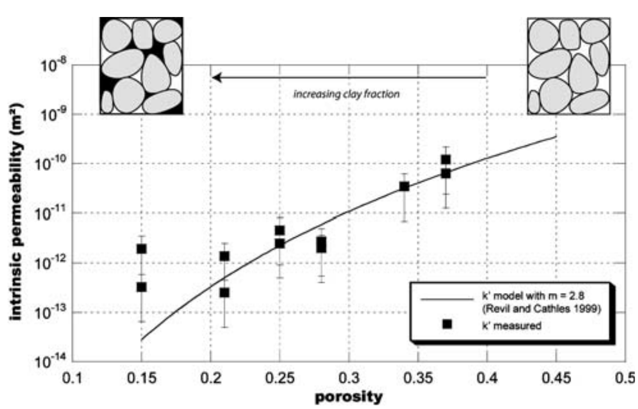


Fig. 9 Evolution on intrinsic permeability versus porosity (*Black squares* are experimental data). This figure shows a rapid reduction in permeability with decreasing porosity. An existing model had been employed (Revil and Cathles 1999) to supplement the experimentally observed trends between permeability, porosity and composition (predicted permeability trends is given by the *black curve*)

To supplement these experimentally observed trends between permeability, porosity and composition, an existing model (Revil and Cathles 1999) can be used to predict permeability as a function of porosity and clay content. Soils from low-lying areas (<300 m a.s.l) are assumed to be the result of a mechanical process and are mostly composed of aggregates. Then with increasing altitude, clay minerals are present due to alteration processes and fill the pore space. The total porosity of a mixture of aggregates and clays is given by the relation (1). Porosity can be related to intrinsic permeability following the methodology developed by Revil and Cathles (1999), where the permeability of a clayed aggregate is related to the permeability of a clean aggregate (k_a, P_a):

$$k' = k_a \left(\frac{Pt}{P_a}\right)^{3m} \tag{5}$$

m: cementation exponent.

Approximations are (1) sample SC4 from low-lying area is characterized by a measured porosity $P = 34\%$ and a low clay content $c < 5\%$, this leads from Eq. (2) to a pure aggregates porosity, $Pa \sim 40\%$; (2) in the same way the permeability of a clean aggregate is fixed to $k_a = 1.3 \times 10^{-10}\ m^2$, a value extrapolated from the permeability of soil at low altitude; (3) the measured porosity is assumed to be equal to the total porosity. This last assumption will introduce errors as clay content increases; (4) as mentioned

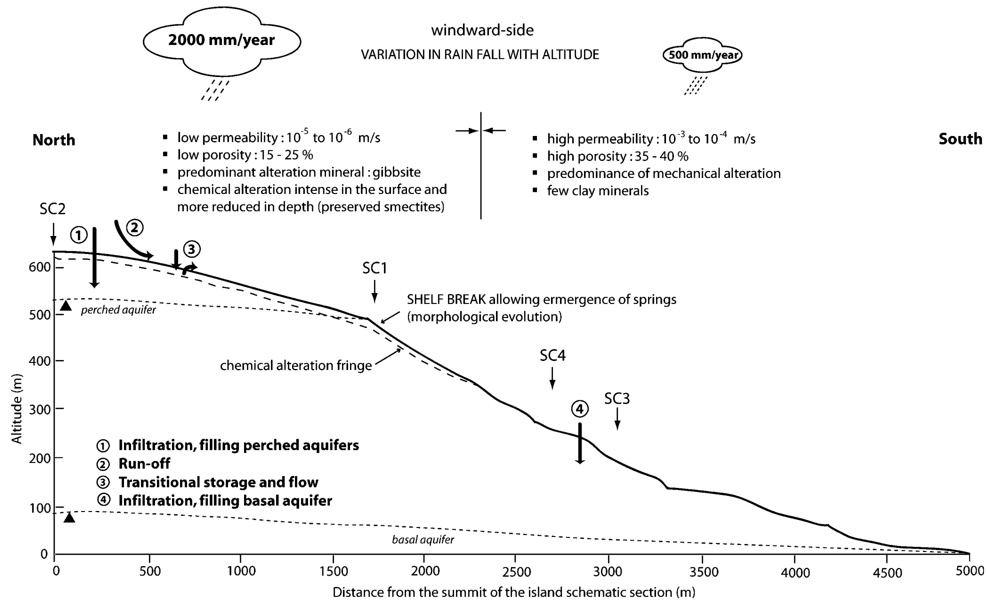


Fig. 10 Schematic cross section of San Cristobal. Soil sampling locations and spatial variation of rainfall with altitude are represented on the figure. This diagram summarizes the role of soils in the hydrological cycle on San Cristobal Island. At altitude, precipitation can: (*1*) seep through the soil and recharge perched aquifers (*2*) run off if the infiltration capacity of the soil is exceeded and (*3*) be temporarily stored in the soil structure and fill streams for several days or even continuously. On the contrary, in the lowlands only infiltration process (*4*) takes place

in Revil and Cathles (1999), the cementation exponent m varies with pore geometry between $m = 1.5$ (interconnected open fractures) and 3 (large pores connected by narrow throats), here m is fixed to 2.8.

Intrinsic permeabilities estimated by the model are shown on Fig. 9. The model conforms correctly with the general trend observed in our measured permeability. In particular the rapid decrease in permeability, where the effective porosity decreases from 37 to 21%, is well reproduced and is explained with this model by the increasing clay content in the soil. For the high porous soils (range: 21–37%), according to the analyses of Revil and Cathles (1999), greater dependency of k' on the porosity of these soils suggests there are many more large pores interconnected with narrow throats and the interconnections increase with increasing porosity. In contrast, for the soil from high-lying areas (>300 m a.s.l), characterized by porosity in the range of 15–21%, there is a discrepancy between the predicted values and our measurements. This last observation points out the limit of the assumptions, especially the third one. At this stage, the model might underestimate the effect of the clay content and clay permeability on the global permeability.

Hydrological implications

Differences between Santa Cruz and San Cristobal

Ingala et al. (1989) and other authors showed that Santa Cruz and San Cristobal do not have the same soil parent material. Moreover, soils developed on San Cristobal are usually thicker than those on Santa Cruz. However, our results demonstrate that the soils on both islands are characterized by a similar hydrodynamic behavior. This implies that climatic factors are more important than lithological ones. The same climatic impact was partially reported by Lulli et al. (1988) on the slopes of the volcanic complex of Vico in Italy.

As seen in "Study area", the hydrological behaviors of Santa Cruz and San Cristobal Islands are very different. About 30thirty permanent streams exist on San Cristobal and none on Santa Cruz. However, our results prove that this difference cannot be explained by a distinct hydrodynamic behavior of the soils. The trends of physical soil properties (hydraulic conductivity and porosity) as functions of altitude are the same for both the islands. Soils from Santa Cruz and San Cristobal do not present the same clay minerals at a given altitude (see "Clay minerals composition"). However, the hydraulic properties seem to be primarily controlled by the clay volume content (see "Relationship between porosity and permeability"), which is broadly the same for both islands at the given altitude. As a consequence, the hydraulic conductivity trend is the same on both the islands: high conductivity at low altitude, and then a decrease in permeability with altitude as clay volume content increases.

The two distinct hydrological behaviors can be explained by differences in island morphology. Erosion is more advanced on San Cristobal than on Santa Cruz. The landscape on San Cristobal is gentler than on Santa Cruz and is characterized by rows of hills. This morphology allows springs to emerge at different altitudes (Adelinet 2005). On the contrary, the Santa Cruz landscape is steep which prevents springs from occurring. Two processes can explain these morphological differences: (1) a longer erosion time (San Cristobal is older than Santa Cruz) (2) wetter climatic conditions (San Cristobal is more influenced by trade winds because of its eastern position. See Fig. 1).

Implications for surface runoff and infiltration areas

Our results have implications for the understanding of the hydrological cycle on the Galapagos Islands. Tanaka and Sunarta (1994) suggest that Bali areas of high permeability (more than 10^{-5} m s^{-1}) are groundwater recharge zones and areas of low permeability (less than 10^{-9} m s^{-1}) are discharge zones. On the basis of our measurements, we can also identify distinct hydrological processes (Fig. 10).

In the low-altitude zones (<300 m a.s.l.), soil hydraulic conductivity is high ($\sim 10^{-3}$ m s^{-1}) which gives the soils a high infiltration capacity. The infiltration recharges the basal aquifer. Note that, rainwater as well as water from the streams can be infiltrated into this layer of soil. A previous study has shown that the flow in the streams is much weaker at 200 m a.s.l. than at 500 m a.s.l. (Adelinet 2005).

The hydraulic conductivity is lower in the high-altitude areas (>350 m a.s.l.), than in the low-altitude areas but large when compared with other data (Tanaka and Sunarta 1994; Fontes et al. 2004). The minimum values (10^{-6} m s^{-1}) are, in fact, higher by three orders of magnitude in the Galapagos Islands than in Bali (Tanaka and Sunarta 1994). Thus, we think that these soils play a key role in the hydrological cycle. As they are located at altitude, they are always under the influence of water (rainfall or mist). As a consequence, their infiltration capacity is often close to its maximum value. Precipitation in these areas can (1) seep through the soil and recharge perched aquifers, (2) run off if the infiltration capacity of the soil is exceeded and (3) be temporarily stored in the soil structure and fill streams for several days or even continuously.

Conclusion

Figure 10 presents a schematic cross-section of San Cristobal Island. The figure summarizes all the information collected during this work. The Galapagos soil data show marked differences in soil distribution derived from variations in rainfall with altitude. It is obvious that soil and aquifer hydrodynamics are partially controlled by soil weathering.

Regarding our results, a difference can be made between the weathered soils in the areas at high altitude and those in low-elevation parts of the islands. At altitude >350 m a.s.l., all the main weathering factors are brought together to chemically alter the soils: rainfall, local landform and time. The resulting soils are characterized by many clay minerals involved in water retention. The hydraulic conductivity and porosity of these soils are around 10^{-6} m s^{-1} and 20%, respectively. These relatively low values can be explained by a process of pore space filling by the clayey alteration products. On the contrary, in the low-lying areas (<300 m a.s.l.) soils are less chemically weathered and the alteration processes are more mechanical; local landform and weather conditions can explain such difference. The hydraulic conductivity and porosity of the soils are around 10^{-4} m s^{-1} and 35%, respectively. These values in the low-lying soils suggest the presence of interconnected large pores.

While the aim of this paper was to characterize soil properties on the Galapagos Islands and their influence on soil hydrodynamic behavior, the next step is to simulate the hydrological processes in order to understand all of the hydrological cycle on the islands with the prospect of a better water management.

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