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Physical properties of "sorriba"-cultivated volcanic soils from Tenerife in relation to andic diagnostic parameters

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Abstract

In volcanic regions, soils containing both noncrystalline materials and layer silicates are widespread. Although the respective contribution of these components to soil physical behaviours is difficult to quantify, it is an important issue in the Canary Islands, where Andisols and andic soils are transported to the low lands for cultivation ("sorriba"). In this new soil environment, salinisation and sodification processes, induced by irrigation and heavy fertilisation, are potential threats to soil degradation. The purpose of this work was to evaluate some relevant physical properties of the sorriba-cultivated volcanic soils from Tenerife in order to relate them to salinity and sodicity soil conditions, amounts of layer silicates and remaining andic properties, characterised by: bulk density (ρ_b), Al and Fe extracted with ammonium oxalate (Al_o, Fe_o) and P retention. An Andisol under forest was included in the study as a representative natural reference. Clay dispersion, water release curves and saturated hydraulic conductivity, K_s, were the selected physical properties.

Four distinctive types of water release curves were identified, showing sandy behaviour at low suctions while retaining large water holding capacity at large suctions. The van Genuchten parameters helped to differentiate these curves and identify the main pore-size ranges.

Under certain combinations of exchangeable cations distribution, salinity and clay mineralogy, very low K_s values were observed for Al_o contents lower than 3%. The results suggest that the aggregating effect of Al_o (allophanes) could not counterbalance soil structure deterioration. Furthermore, only a multivariable analysis carried out on chemistry, mineralogy and physical data had the merit to classify the studied sorriba-cultivated volcanic soils in terms of soil quality and soil functioning.

Keywords: Andic properties; Transported cultivated volcanic soils; Soil quality; Saturated hydraulic conductivity; Soil water retention; Clay dispersion; Canary Islands

1. Introduction

In volcanic regions, soils containing both andic materials and layer silicates are widespread. The contribution of layer silicates and amorphous materials to the soil physical behaviour is difficult to quantify and depends on management soil conditions that determine the soil physical and chemical environment.

Physical properties of volcanic clayey soils are strongly affected by allophanes and Fe and Al oxy-hydroxides. These components induce strong aggre-

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gation that imparts favourable structural properties such as reduced swelling and increased aggregate stability of clay minerals (El-Swaify, 1975). Currently, the amounts of acid ammonium oxalate extractable aluminium, iron and silicon (Al_o, Fe_o and Si_o) are widely used for the quantification of allophane, imogolite and ferrihydrite, which are the main contributors to "amorphous" materials in soils. Soil andic properties are defined by $(Al_o + 1/2Fe_o) \geq 2\%$, phosphate retention $(\Delta P) \geq 85\%$ and bulk density ≤ 0.9 g cm^{-3} (Soil Survey Staff, 1998). Similar criteria define the andic horizon in WRBSR (FAO, 1998).

Although the andic diagnostic parameters are widely used in the Canary Islands for pedological studies, these are seldom considered in cultivated soils in spite of the special behaviour displayed by these soil types in which ad hoc methodologies are needed for their characterisation. Thus, the use of inadequate, conventional particle-size analysis can explain the abnormally high water retention and hydraulic conductivity values frequently observed in relation to soil texture. Furthermore, high hydraulic conductivity values have been reported in clayey soils with no apparent dispersion problems (Muñoz-Carpena, 1998). The peculiar behaviour of Andisols can greatly change when these soils are brought into cultivation. Desiccation and compaction appear to be two main processes affecting the structure of these soils (Dorel et al., 2000).

In the Canary Islands, the export crops (mainly bananas and tomatoes) are located at low altitudes where soils have been generally eroded or degraded. This explains the common practice to transport soil materials from the high–mid altitudes to the low lands for cultivation, locally named "sorribas". The soil types generally transported are Andisols and soils with more or less andic properties (Inceptisols and Ultisols). No horizon selection is made; thus, topsoils are mixed with B horizons and weathered tephra. As already mentioned, the sorriba preparation itself is a first stage of degradation by soil desiccation in an arid or semiarid environments (Dorel et al., 2000). Therefore, it is difficult to classify the resulting artificial soils except perhaps in the case of Andisols if they show andic properties to the required depth. In the Canary Islands, soil structure degradation can also be induced by salinisation and sodification processes, especially in soils under intensive agriculture, irrigated with low quality waters. However, a high structural stability in sodic Andisols has been frequently observed. This phenomenon has been studied in Hawaiian Andisols (El-Swaify et al., 1969), but the references on the subject are scarce. The purpose of this work was to evaluate the influence of remaining andic properties on selected physical properties of a set of sorriba-cultivated, irrigated volcanic soils from Tenerife (Canary Islands) with a range of andic diagnostic parameters in different situations of salinity and sodicity. Water release curves, grain-size distribution (hexametaphosphate (HMP) and cation exchange resin dispersion treatments) and saturated hydraulic conductivity were the studied physical properties and behaviours as relevant soil physical quality indicators.

2. Materials and methods

2.1. Soils

2.1.1. Soil selection

The agricultural fields were situated in the South (field plots B, F and X) and in the North (fields Pajalillos and Cuevas) of Tenerife. The northern plots were located in the Valle Guerra valley, both cultivated with bananas. The mean annual temperature for the area is 20 °C, and annual precipitation and crop evapotranspiration measured at the plot are around 380 and 1000 mm, respectively. The southern plots, also cultivated with bananas, were located in the Valle de San Lorenzo valley with an annual precipitation lower than 200 mm/year and evapotranspiration rates over 2000 mm. The mean annual temperature is 24 °C.

"Sorriba"-cultivated volcanic soils from field plots Pajalillos and Cuevas were described by Departamento de Suelos y Riegos, Instituto Canario de Investigaciones Agrarias (ICIA) and the final report INIA project SC95-059 (Muñoz-Carpena, 1998), respectively. Those from field plots B, F and X were described by Departamento de Edafología y Geología de La Universidad de La Laguna (1999). An Andisol from Tenerife was also studied as a reference and was denoted "0" or Andisol within the text.

The Andisol was located in northern Tenerife and was developed from basaltic ash and lapilli, at 1100 m a.s.l. under pine forest. The mean annual temperature is 15 °C and the moisture regime is udic. This representative Andisol profile (La Esperanza), classified as a Typic Hapludand, was described in the field guide of the International Congress on Volcanic Soils (Departamento de Edafología y Geología de La Universidad de La Laguna, 1984) and by Fernandez-Caldas et al. (1982), Horizons A and Bw were both studied.

2.1.2. Sampling

A total of 49 vertical undisturbed soil samples were collected using cylindrical steel cores of 96.6 cm^3 at two soil depth ranges (0–15 cm and 15–30 cm). A total of 65 samples were additionally taken for chemical analysis and determination of diagnostic andic parameters. Samples for chemical and particle-size analyses were air-dried and sieved to 2 mm. Soils were numbered by decreasing andic properties according to the analysis reported in Section 3.1: 0 (Reference Andisol)>1 (Field Pajalillos)>2 (Field B)$\cong$3 (Field F)$\cong$4 (Field X)>5 (Field Cuevas).

2.2. Clay dispersion

Sodium hexametaphosphate (HMP) dispersion treatment (Gee and Bauder, 1986) was carried out on 44 air-dried (<2 mm) samples. Additionally, Na-Amberlite IR-120 (500 μm mesh) cation exchange resins (Bartoli et al., 1991) were also applied in 26 air-dried samples. Particle-size distribution was determined by the Bouyoucos densimeter method (Gee and Bauder, 1986).

2.3. Water retention characteristics

The soil water retention curves (drainage) were determined on 49 undisturbed saturated soil cores employing two types of apparatus: pressure cells on 10 steps of pressure up to 0.9 bar suction and Richard's pressure plates (Klute, 1986) for these additional pressure steps: 1, 3 and 15 bar.

The van Genuchten equation

$$S_e = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} = (1 + (\alpha\psi)^n)^{-m}, \qquad (1)$$

was used to describe the moisture retention curve of the 100 measured water release data sets. In Eq. (1), ψ [L] is the matric potential; S_e is the effective saturation; θ [−] is the volumetric water content; θ_r [−] and θ_s [−] are the residual and saturated water content, respectively; α [L^{-1}], n [−] and m [−] are fitting parameters that describe the shape and slope of the curve. The fitting parameters in Eq. (1) were estimated with the Soil Hydraulic Properties Fitting (SHIPFIT) program (Durner, 1994). A linear combination of van Genuchten retention functions was fitted to those samples which exhibited clear multimodal behaviour

$$S_e = \sum_{i=1}^{\mu} w_i(1 + (\alpha_i\psi)^{n_i})^{-m_i}, \qquad (2)$$

where w_i are weighting factors for each subcurve, with $\Sigma w_i = 1$, $n_i > 1$, $m_i > 0$, and μ is the mode of the pore-size distribution (Durner, 1992).

The goodness of fit was estimated both visually and by the root-mean-square error, $RMSE = \sqrt{\frac{1}{k}\sum(\theta_i - \hat{\theta}_i)^2}$, where $(\theta_i - \hat{\theta}_i)^2$ is the difference between fitted and measured water contents at the matric potential i. The relation $C = d\theta/d\psi$ is defined as the "specific moisture capacity".

The relative gravimetric water release, w_r, was calculated as follows: $w_r = w_i/w_{0.01} \times 100$, where w_i and $w_{0.01}$ are the gravimetric water content for a given moisture suction i and 0.01 bar, respectively (Dorel et al., 2000).

2.4. Andic diagnostic parameters

Bulk density (ρ_b) was measured on an oven-dried weight basis of a 96.6 cm^3 core sample taken at field-moist conditions. Oxalate-extractable Al, Fe and Si and phosphate retention were determined according to Blakemore et al. (1981).

2.5. Saturated hydraulic conductivity, K_s

Undisturbed soil samples were slowly saturated in the laboratory using a deaerated 0.005 M $CaSO_4$ solution with thymol, from bottom to top to prevent air entrapment.

Laboratory hydraulic conductivity measurements (K_s) were made on a recirculating constant head permeameter following the procedure described by Klute and Dirksen (1986).

2.6. Statistics

We performed the statistical analysis with the SPSS package (SPSS, 1988).

3. Results and discussion

3.1. Main soil characteristics

Andic diagnostic parameters and clay mineralogy are listed in Table 1. The sorriba-cultivated volcanic soils derived from basaltic materials cannot be strictly classified as Andisols. However, their andic diagnostic parameter (ρ_b, $Al_o + 1/2Fe_o$, ΔP) values were very near to the required thresholds (0.9 g cm^{-3}, 2% and 85%, respectively) (Table 1). The exception was the sorriba-cultivated volcanic soil from Las Cuevas, poor both in Al_o, Fe_o and proportion of P retention. Furthermore, a factorial analysis of the diagnostic variables (ρ_b, Al_o, Fe_o, ΔP) classified the soils into four groups of decreasing andic properties: Reference Andisol>Pajalillos>B ≅ F ≅ X>Cuevas. Soils were therefore numbered in this sequence (Section 2.1). No significant differences were obtained between field plots B, F and X. Bulk density showed a monotonic decreasing shape with Al_o content (results not shown). No apparent relation of ρ_b with Fe_o was observed, except that soil 5, with the highest ρ_b values, also showed the lowest contents of Fe_o. On the other hand, extraction of Fe by ammonium oxalate often lack of selectivity for dissolving poorly crystalline Fe phases (Reyes and Torrent, 1997). In the reference Andisol of this study (La Esperanza), these authors found an important part of Fe_o could correspond to allophane Fe or poorly crystalline oxides occluded in allophane aggregates.

Halloysite was the dominant phyllosilicate in all the studied soils, as it has been widely reported in volcanic soils (Quantin, 1990). Soil 2 showed an unusual mineralogical composition because both gibbsite and smectite were present. This was attributed to the mixing of top- and subsoils.

Relevant soil chemical characteristics are listed in Table 2. Amounts of organic matter (20 to 36.3 g kg^{-1} O.M.) were low compared to the reference Andisol topsoil (77 g kg^{-1} O.M.). This was attributed to the mixing of top- and subsoils and to the large biological activity occurring in these warmer climatic conditions. Soil reaction ranged from slightly acid to slightly alkaline. Conversely, saline conditions were observed in the sorriba-cultivated volcanic soils 1 and 3 and large exchangeable sodium percentage (ESP) values were recorded in soils 3 and 4. Large available phosphorus levels also characterised these sorriba-cultivated volcanic soils. All these chemical properties were attributed to irrigation and heavy fertilisation. Soil 1 can even be described as an Andisol, except for the relatively low ΔP values, caused probably by the high P Olsen levels (Table 2) and consequent saturation of the retention capacity.

3.2. Clay dispersion

The role of poorly ordered Al and Fe hydrous oxyhydroxides and aluminosilicates on clay dispersion has been previously discussed by Bartoli et al. (1991, 1998), showing the advantages of Na resins over other routine techniques to reach a complete dispersion.

Table 1
Clay mineralogy and Andic parameters (mean values ± standard error)

Field plot	Soil	Halloysite	Illite	Smectite	Gibbsite	ρ_b (g cm^{-3})	Al_o (%)	Fe_o (%)	$Al_o + 1/2Fe_o$ (%)	ΔP (%)
Andisol	0	−	−	−	−	0.58 ± 0.07	6.9 ± 0.2	3.4 ± 0.1	8.6 ± 0.2	96.4 ± 0.2
Pajalillos	1	+	+/−	−	−	0.82 ± 0.02	2.4 ± 0.2	3.4 ± 0.5	4.1 ± 0.3	80.9 ± 2.4
B	2	++	+	+	+	0.96 ± 0.02	1.3 ± 0.1	1.6 ± 0.1	2.1 ± 0.1	74.2 ± 1.0
F	3	++	+	−	−	0.99 ± 0.03	1.4 ± 0.3	2.2 ± 0.3	2.4 ± 0.2	62.5 ± 1.2
X	4	++	+	−	−	1.07 ± 0.04	1.0 ± 0.2	2.4 ± 0.3	2.2 ± 0.2	68.9 ± 5.4
Cuevas	5	+++	++	−	−	1.11 ± 0.03	0.4 ± 0.02	0.8 ± 0.07	0.8 ± 0.04	20.0 ± 2.0

Soils (0 = reference Andisol, 1 to 5 = sorriba-cultivated volcanic soils) numbered according to their decreasing andic character: 0>1>2 ≅ 3 ≅ 4>5.
++++ = Very much; +++ = Much; ++ = Moderate; + = Little; +/− = Very little; − = Non-detected.

Table 2
Exchangeable cations and basic chemical soil properties (mean values ± standard error)

Soil	N	pH^{a}_{ext}	EC^{a} (dS m^{-1})	Ca (cmol$_c$ kg^{-1})	Mg (cmol$_c$ kg^{-1})	K (cmol$_c$ kg^{-1})	Na (cmol$_c$ kg^{-1})	ESP (%)	O.M.(g kg^{-1})	P Olsen (mg kg^{-1})
1	19	7.1 ± 0.1	3.5 ± 1.0	16.1 ± 0.9	5.6 ± 0.3	2.5 ± 0.3	3.3 ± 0.5	11.7 ± 1.4	23.9 ± 0.9	57.3 ± 18.8
2	16	7.8 ± 0.1	2.2 ± 0.1	27.8 ± 2.7	18.7 ± 1.2	7.9 ± 0.8	3.4 ± 0.2	6.2 ± 0.5	31.2 ± 1.8	102.8 ± 12.5
3	7	7.7 ± 0.2	12.4 ± 2.0	21.0 ± 2.8	16.0 ± 1.1	10.5 ± 1.0	15.2 ± 2.0	24.2 ± 1.7	36.3 ± 1.5	70.4 ± 7.9
4	12	7.9 ± 0.1	2.5 ± 0.3	9.7 ± 0.6	10.9 ± 1.0	1.0 ± 0.1	7.6 ± 0.7	26.1 ± 1.6	26.1 ± 2.8	51.1 ± 5.7
5	8	6.5 ± 0.3	1.5 ± 0.1	11.8 ± 1.2	5.2 ± 0.4	2.5 ± 0.2	2.2 ± 0.1	10.6 ± 1.0	20.0 ± 3.6	158.3 ± 29.9

“Sorriba” cultivated volcanic soils numbered according to their decreasing andic character: $0 > 1 > 2 \cong 3 \cong 4 > 5$.

N = number of replicates.

[a] pH and Electrical Conductivity of the saturation extract.

Table 3
Clay (HMP, resin) contents, gravimetric water content (*w*) at 1/3 and 15 bar and $w_{15\ \mathrm{bar}}$/percent clay (mean values ± standard error)

Soil	Percent clay				*N*	$w_{1/3\ \mathrm{bar}}$ (%)	$w_{15\ \mathrm{bar}}$ (%)	w_{15}/clay	
	N	HMP	*N*	Resin				HMP	Resin
0	2	11.3	2	51.5	3	71.1 ± 9.0	47.0 ± 5.9	4.24	1.02
1	19	13.6 ± 1.6	7	35.9 ± 1.4	19	48.7 ± 1.1	35.9 ± 1.1	3.03 ± 0.22	1.02 ± 0.05
2	6	35.4 ± 1.4	6	42.7 ± 1.5	9	51.8 ± 1.2	36.0 ± 1.4	1.23 ± 0.05	0.98 ± 0.04
3	3	44.9 ± 1.7	3	45.6 ± 2.2	4	42.2 ± 1.5	30.1 ± 1.0	0.67 ± 0.06	0.71 ± 0.03
4	6	45.4 ± 1.3	6	43.9 ± 1.7	6	42.5 ± 1.8	28.6 ± 1.1	0.67 ± 0.04	0.70 ± 0.02
5	8	43.8 ± 1.1	2	46.0	8	34.5 ± 1.3	23.7 ± 0.9	0.49 ± 0.02	0.48 ± 0.02

Soils (0 = reference Andisol, 1 to 5 = sorriba-cultivated volcanic soils) numbered according to their decreasing andic character: 0>1>2 ≅ 3 ≅ 4>5.
N = number of replicates, except for the Andisol reference (soil 0), where *N* represents the number of studied A and Bw horizons.

Dispersion with resins was so much more efficient than that with Na hexametaphosphate (HMP) in the more andic soils, reference Andisol and soil 1 (Table 3). In contrast, no significant differences in clay dispersion were observed in soils with $Al_o < 0.64\%$ (soil 5 and some samples from soils 3 and 4). In Fig. 1, the decrease of the ratio HMP/resin clay with the Al_o content is shown. A clear clay dispersion threshold occurred at $Al_o = 2\%$, with very low HMP clay dispersion for large Al_o values (soil 1 and reference Andisol). A similar trend was found by Bartoli et al. (1998). In this work, no apparent influence of Fe_o on HMP/resin clay ratio was also found. This is consistent with the results of El-Swaify (1975) who found that Al hydroxide was more effective than Fe hydroxide in increasing the resistance of clay to dispersion. However, the Fe_o values were large in all soils, except soil 5, with lower variability than that of Al_o value counterparts. Therefore, no conclusions can be drawn on the influence of Fe_o.

The water content at 15 bar to clay (w_{15}/clay) ratio or dispersion index was also used to verify the goodness of clay dispersion, a value of 0.6 representing the upper limit for an adequate clay dispersion (Soil Survey Staff, 1975). Therefore, it is not surprising that the dispersion index (HMP dispersion) was larger

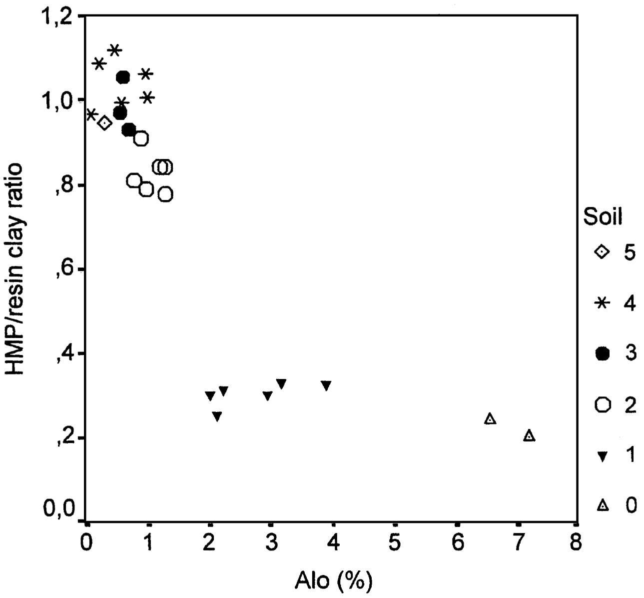

Fig. 1. Relationship between HMP/Resin clay ratio and Al_o content as a function of soil types. Soils (0 = reference Andisol, 1 to 5 = sorriba-cultivated volcanic soils) numbered according to their decreasing andic character: 0>1>2 ≅ 3 ≅ 4>5.

than 0.6, especially in the more andic soils, reference Andisol and soil 1 (Table 3). It was still higher than 0.6 in the resin-dispersed samples, except for soil 5 (Table 3). Values greater than 1.0 for w_{15}/clay ratios are attributed to the aggregative effect of allophanes (Soil Survey Staff, 1975). These large w_{15}/clay ratios were attributed to both the high retention capacity of the microporous systems induced by the short-ordered materials and their high aggregate stability. An average ratio of 2.3 was so reported by Nanzyo et al. (1993) in Andisols dispersed by ultrasonication and pH adjustment. Similarly, in Caribbean Islands, Dorel et al. (2000) found values between 0.55 and 1.5 for allophanic Andisols. In this study, w_{15}/clay values

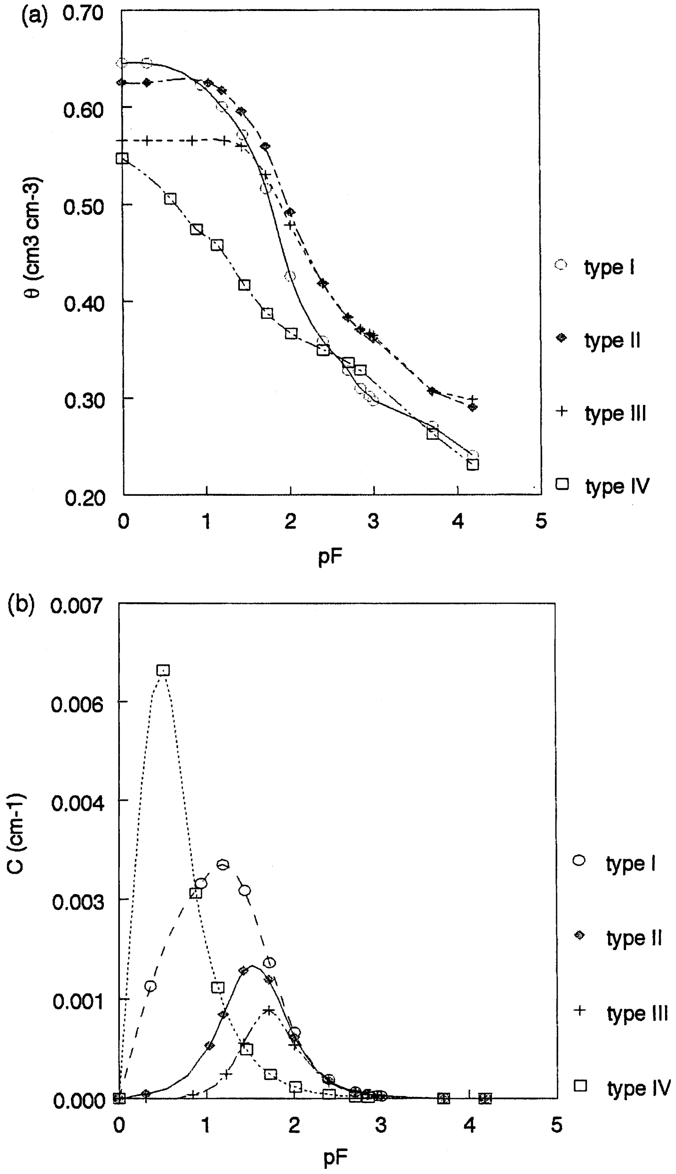

Fig. 2. Examples of (a) volumetric water retention curves and (b) specific moisture capacity, C ($d\theta/d\psi$), for the four identified types of water retention curves.

increased with the sequence of andic character previously described (Table 3).

3.3. Water retention curves

3.3.1. Description

The water retention data were analysed using Eqs. (1) and (2). The results were as follows. We have obtained a good agreement between the measured and predicted water retention data ($R^2 = 0.98$, $P < 0.05$). The curves were predominantly unimodal. Six cases of bimodal curves were obtained in soils 2, 3 and 4. In contrast, multimodal water retention curves were always obtained for the reference Andisol (results not shown), with sandy behaviour at large matrix potential values but large water holding capacity at low matrix potential values (Fig. 2a). This specific hydric behaviour has been previously described in Hawaiian soils (Sharma and Uehara, 1968; Tsuji et al., 1975; El-Swaify, 1980). The important release of water at low suction values and the large water content at larger suction values was attributed to inter- and intraaggregate voids, respectively.

The unimodal water retention curves of the sorriba-cultivated volcanic soils were grouped into four types on the basis of their shape and maximum water capacity value, *C* (Fig. 2b). These four curves may be seen as representative of certain water retention characteristics within a wider class of curve shape possibilities, and not as unique curve types. In type I curve, *C* was located at potentials lower than *p*F 1.5. Type II curve represented an intermediate case between type I and type III curves in which water release began at *p*F 1. In type IV curve, most of the water release took place near saturation. Soils 2, 3 and 4 presented examples of types I, II and III curves, while types I and III curves dominated in soil 1. Soil 5 only showed type IV curves.

The van Genuchten parameters for these curves were useful "shape factors" in characterising the four types of curves a priori observed (Table 4 and Fig. 3). The dimensionless parameter, *n*, reflected the steepness of the S-shaped curve towards high *p*F values (Wösten and van Genuchten, 1988) and discriminated type III curve from the rest. After the same authors, α (cm^{-1}) equalled approximately the inverse of the pressure head at the inflexion point where $d\theta/d\psi$ has its maximum value. Factor α^{-1} distinguished significantly type IV curve, with the lowest value, and type I curve from type III curve (Fig. 3a). The ratio *m/n* is related to the pore distribution width towards the large pores (Durner, 1994). This ratio separated type III curve, with the lowest value, from the rest, and type II from type I curve (Fig. 3b and Table 4). With respect to the bimodal curves, in the six cases observed, α_2^{-1} values ranged between *p*F 3.3 and 3.4.

In this study, the actual pore-size distribution cannot be assessed because allophanic soils show considerable shrinking with drying (Maeda et al., 1977) and the influence of *p*F on soil volume was not measured. However, the water released between two *p*F values can be related to a pore-size interval (Dorel et al., 2000). In Fig. 4a, gravimetric water contents (*w*) at relevant soil *p*F values were compared as an inverse function of expression of andic properties. As a complement, their relative changes (w_r) were plotted in Fig. 4b. The decrease of w_r with *p*F showed two extreme behaviours. In the more andic soils (reference Andisol 0 and soil 1) there was a regular decrease down to *p*F 4.2. The reference Andisol 0 attained w_r values larger than 40, which represents more than 60% water loss. The behaviour of the reference Andisol and of the soil 1 could be interpreted in terms of an evenly distributed pore size, according to Dorel et al. (2000) who compared relative water and void ratios in allophanic soils. In

Table 4
The van Genuchten parameters for the different types (see Fig. 2) of unimodal water retention curves (mean values ± standard error)

Curve type	N	θ_s (%)	θ_r (%)	α (cm^{-1})	n	m
I	11	63.1 ± 0.4	24.2 ± 1.4	0.0493 ± 0.008^{a}	1.44 ± 0.05^{a}	0.30 ± 0.02^{c}
II	4	62.8 ± 2.2	20.2 ± 6.9	0.0347 ± 0.009^{a}	2.63 ± 0.51^{ab}	0.20 ± 0.08^{b}
III	14	61.1 ± 1.1	16.4 ± 3.2	0.0260 ± 0.003^{a}	3.57 ± 0.53^{b}	0.08 ± 0.02^{a}
IV	9	56.0 ± 1.8	30.3 ± 1.0	0.2200 ± 0.049^{b}	1.46 ± 0.05^{a}	0.31 ± 0.02^{c}

N = number of replicates.
Different letters indicate significant differences from Duncan's test ($P < 0.05$).

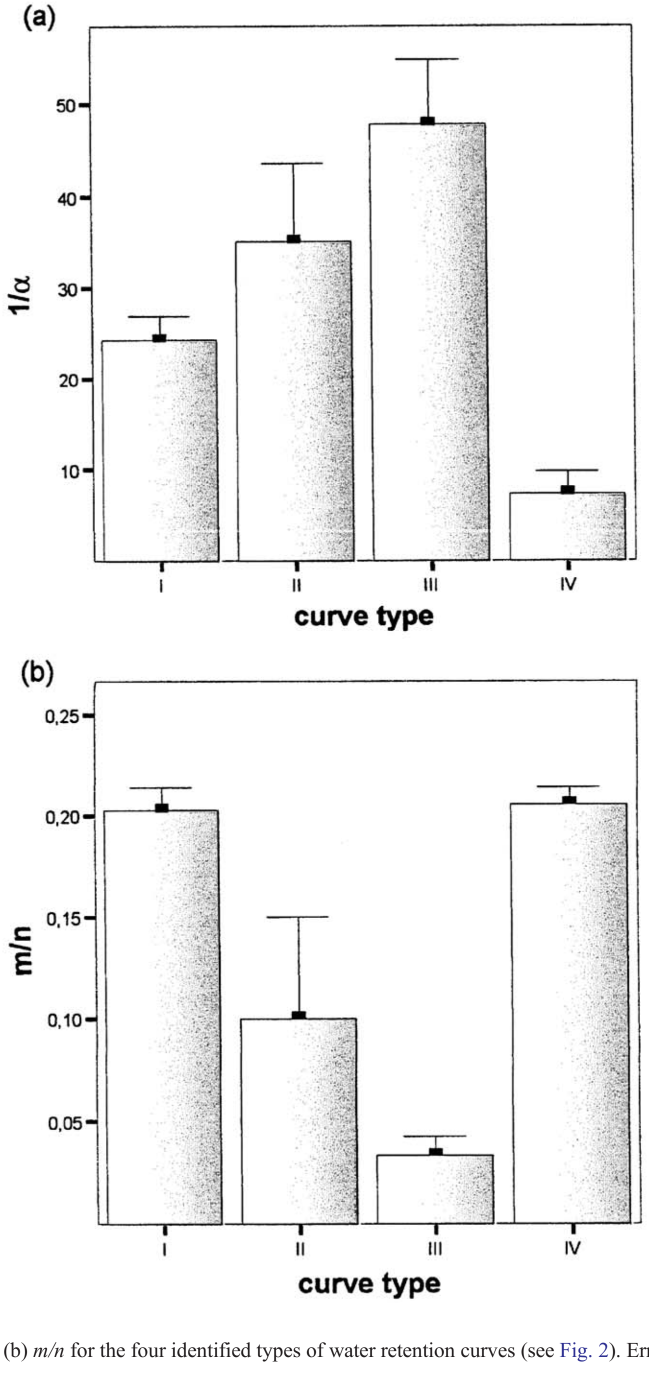

Fig. 3. (a) Shape factors α^{-1} and (b) *m/n* for the four identified types of water retention curves (see Fig. 2). Error bars denote one standard error on either side of the mean.

contrast, soil 5, the least andic sorriba-cultivated volcanic soil, presented a plateau between *p*F 2 and 3. Soil 5 behaved like a Nitisol as also previously described by Dorel et al. (2000). The Nitisol studied by these authors had a similar mineralogy than that of soil 5 and its porosity was mainly distributed in macro

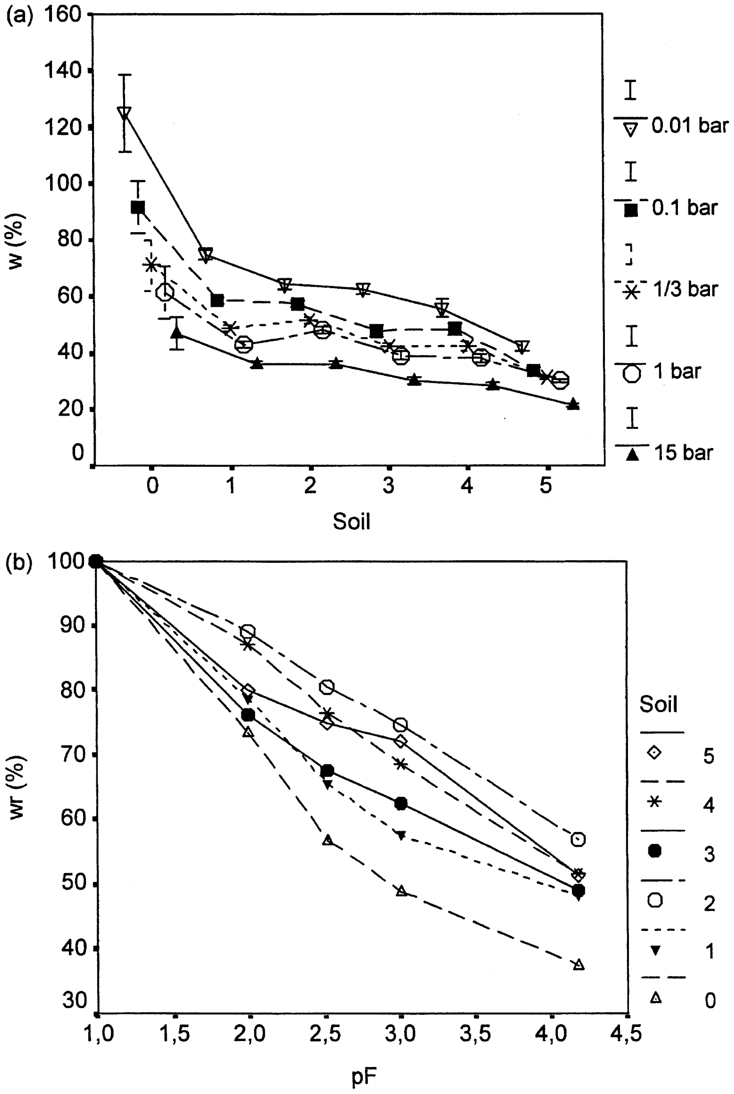

Fig. 4. Mean gravimetric water content, within the 0.01–15 bar soil water suction range, as a function of (a) decreasing soil andic character (increasing soil number) and (b) of mean relative gravimetric water content as a function of soil water suction head ψ in cm, $pF=\log\psi$, for each soil type (soils, 0 = reference Andisol, 1 to 5 = sorriba-cultivated volcanic soils, numbered according to their decreasing andic character: $0>1>2\cong3\cong4>5$). Error bars denote one standard error on either side of the mean.

and micropores. Soils 2, 3 and 4 showed intermediate water retention behaviours between those described.

In order to have indirect information on pore-size distributions, the lower limit of macroporosity was taken at 0.1 bar suction value (Quirk and Murray, 1991) and of mesoporosity at 0.3 bar suction value (Luxmoore, 1981). Table 5 lists the water-filled pore volumes of the main selected pore-size ranges. Type IV water retention curve was significantly different from the others by its very large water-filled macroporosity ($MP_{0.01}$) that was attributed to the well-developed blocky structure displayed by soil 5. "Textural microporosity" (w_{15}) was also significantly lower in type IV curve. Both the sum of macro- and mesoporosity $MP_{0.3}$ or "effective porosity" (Ahuja et al., 1989) and MP_f ($w_{0.01\ \mathrm{bar}} - w_{0.1\ \mathrm{bar}}$) separated type

Table 5
Gravimetric water content (%) at or between characteristic pF values and plant available water (PAW) for the different types (see Fig. 2) of water retention curves (mean values ± standard error)

Curve type	N	$MP_{0.01}$ (%)	MP_f (%)	$MP_{0.3}$ (%)	w_{15} (%)	PAW (%)	
						$w_{1/3\ bar} - w_{15\ bar}$	$w_{0.1\ bar} - w_{15\ bar}$
I	14	3.3 ± 0.4^{b}	18.3 ± 1.3^{c}	30.1 ± 2.1^{c}	33.8 ± 0.5^{b}	12.5 ± 0.7^{ab}	20.2 ± 0.9^{b}
II	6	0.5 ± 0.1^{a}	12.6 ± 2.2^{b}	21.6 ± 3.4^{b}	34.1 ± 1.5^{b}	15.1 ± 2.0^{b}	23.5 ± 1.4^{b}
III	17	0.1 ± 0.03^{a}	7.6 ± 0.8^{a}	14.5 ± 1.3^{a}	34.6 ± 1.6^{b}	14.0 ± 0.8^{b}	20.3 ± 0.8^{b}
IV	9	6.7 ± 0.6^{c}	9.7 ± 1.4^{ab}	19.5 ± 2.0^{ab}	22.7 ± 1.2^{a}	10.8 ± 0.8^{a}	13.6 ± 1.7^{a}

N = number of replicates.
Different letters indicate significant differences from Duncan's test ($P < 0.05$).
$MP_{0.01} = w_s - w_{0.01\ bar}$; $MP_f = w_{0.01\ bar} - w_{0.1\ bar}$; $MP_{0.3} = w_s - w_{1/3\ bar}$.

II from type III curve and discriminated type I curve, with the largest value.

Considering these results, the plant available water for these soils should be defined as PAW = $w_{0.1\ bar} - w_{15\ bar}$ (El-Swaify, 1980) instead of the more conventional definition with the lower limit at 1/3 bar. With this criterion, the available water increased significantly in all soils, the difference being lower in type IV curve (Table 5).

3.3.2. Water release characteristics and andic properties

Fig. 4a shows that the gravimetric water content values (w) at a given pF diminished with decreasing soil andic character over the whole pF range studied. These values were larger than those predicted by the pedotransfer methods derived from soil texture (Saxton et al., 1986), which can be explained by the andic character of the studied soils. However, w values were lower than those predicted by their Al_o values (Nanzyo et al., 1993; Dorel et al., 2000), especially in the cultivated soils. As already mentioned, this can be attributed to the desiccation the soils have been subjected to during transportation and land preparation, and the semiarid conditions of the soil environments, all these circumstances leading to an irreversible loss of water retention capacity (Warkentin and Maeda, 1980). In our study, w was signifi-

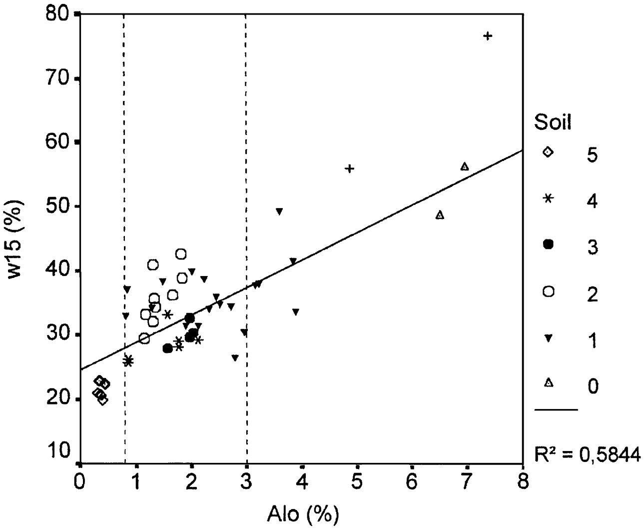

Fig. 5. Relationship between gravimetric water content at 15 bar and Al_o content as a function of soil types. Soils (0 = reference Andisol, 1 to 5 = sorriba-cultivated volcanic soils) numbered according to their decreasing andic character: 0>1>2≅3≅4>5. Symbols + correspond to data from Dorel et al. (2000) that are not included in the regression analysis.

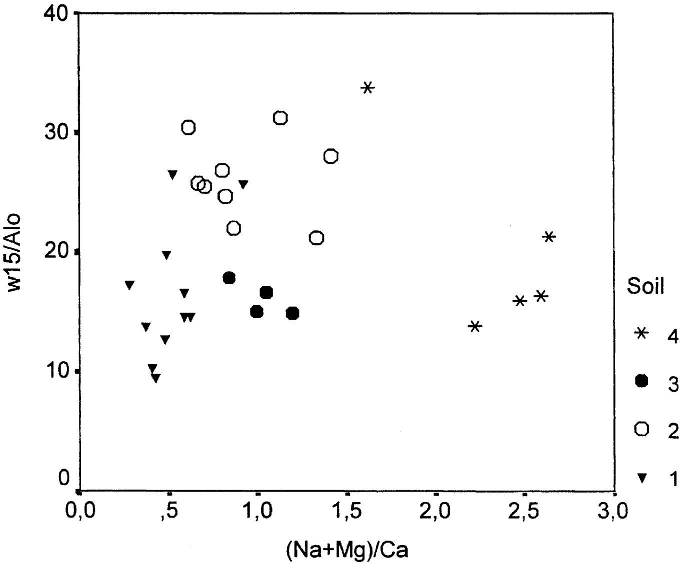

Fig. 6. Relationship between $w_{15\ \mathrm{bar}}/\mathrm{Al_o}$ ratio and exchangeable (Na + Mg)/Ca for the $\mathrm{Al_o}$ range 1–3% as a function of sorriba-cultivated volcanic soil types (soils numbered according to their decreasing andic character: 0>1>2≅3≅4>5).

cantly and linearly correlated with $\mathrm{Al_o}$ at low and intermediate *p*F ranges (at *p*F 2.0, $R^2 = 0.76$, $P < 0.05$). The significance was lower at *p*F 4.2 (Fig. 5). No improvement was obtained by including the organic carbon in the model, as it was the case of Dorel et al. (2000) for *p*F values lower than 2.5, which they attributed to the role of organic matter in the formation of macropores. In the sorriba-cultivated volcanic soils, the organic carbon content (OC) were specifically low and no significant OC differences were observed at the two sampling depths (15 and 30 cm) for the majority of analysis. Furthermore, we can observe that in Fig. 5 no apparent relation between w_{15} and $\mathrm{Al_o}$ was identified within the range 1–3% $\mathrm{Al_o}$ (dashed lines). The same behaviour, albeit less pronounced, was also observed at lower *p*F values. Moreover, *w*

Table 6

Frequency of hydraulic conductivity classes for the studied soils (0 = reference Andisol, 1 to 5 = sorriba-cultivated volcanic soils; these are numbered according to their decreasing andic character: 0>1>2≅3≅4>5) and water retention curve types (see Fig. 2)

	Very low	Low	Moderate	Moderately rapid	Rapid	Very rapid	*N*
Soil							
0	–	–	–	–	–	3	3
1	1	1	5	2	2	8	19
2	4	–	2	1	2	–	9
3	–	–	–	–	–	4	4
4	–	1	–	–	–	5	6
5	–	1	1	–	1	5	8
Curve type							
I	–	–	3	–	1	10	14
II	1	1	1	2	1	–	6
III	4	1	4	–	2	7	18
IV	–	1	1	1	1	4	8

Very low (< 8 mm/h), low (8–20 mm/h), moderate (20–60 mm/h), moderately rapid (60–80 mm/h), rapid (80–125 mm/h), very rapid (>125 mm/h) (FAO, 1963).

values were frequently larger than those expected from the clay contents and the relationship obtained for the whole Al_o range, especially in soil 2, where smectite was detected. A moisture retention mechanism due to swelling pressures is not improbable. Swelling pressures increase with increasing ESP and decreasing soil solution EC (Emerson, 1977). Therefore, the relation of these properties with water retention was studied. Among the different expressions of the exchangeable cation distribution, the exchangeable (Na + Mg)/Ca ratios were the most significant to discriminate the "atypical" high retentive samples. Magnesium can increase swelling at a given ESP (Emerson, 1977). In Fig. 6, the (Na + Mg)/Ca ratios were plotted against the normalised w_{15} values with respect to Al_o (w_{15}/Al_o ratio), in the 1–3%Al_o range. Although scattered, a positive relation trend was observed, except for soil 4 samples, which seemed insensitive to high exchangeable Na and Mg values.

3.4. Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_s) values were classified according to the K_s ranges recommended by FAO (1963). The frequency of K_s classes for soils and water retention curves types were listed in Table 6. Despite its large variability, measured K_s values were generally larger than those expected from their texture pedotransfer functions (Saxton et al., 1986). Generally, K_s values were larger than the "low" K_s range except for soil 2 in which 4 cases out of 9 were "very low". This class was absent in types I and IV curves, which presented the larger values of water-filled macroporosity $MP_{0,01}$. Hydraulic conductivity was positively related to the logarithm of $MP_{0.3}$ for soils 2, 3 and 4.

The influence of the andic and other soil properties on K_s was investigated by means of a principal components analysis (PCA). The main trends can be observed in the PCA scatter diagram of the first two components (accounting 68% of the variance) including the variables EC, Al_o, exchangeable (Mg + Na)/Ca, w_{15}, wr_{15} and $MP_{0.3}$ (Fig. 7). Soils 0 (reference Andisol) and 5 (the least andic sorriba-cultivated volcanic soil) were not considered in the analysis because their relatively homogeneous K_s values and extreme limits of the characterised andic properties would have biased the results. In Fig. 7, soil samples

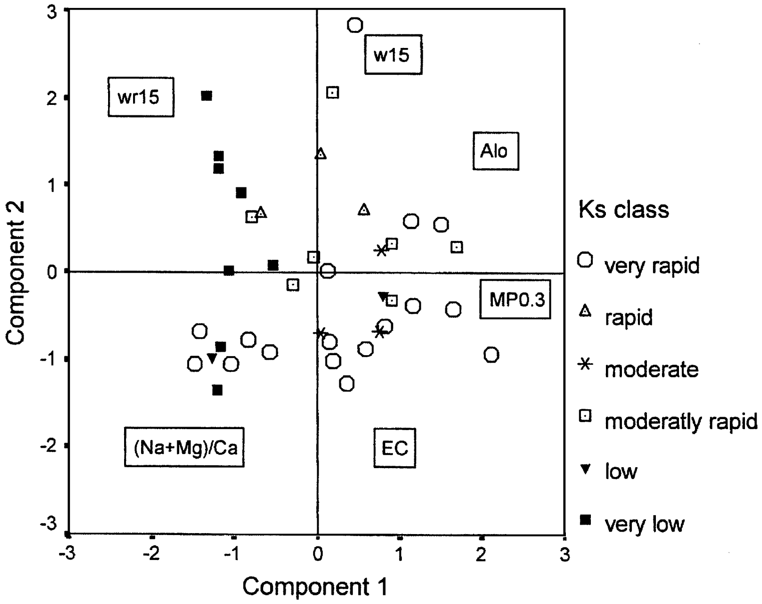

Fig. 7. Scatter plot of the two first principal components (see Section 3.4), soil sample plots were labelled according to their hydraulic conductivity classes, from very rapid (>125 mm h^{-1}) to very low (<8 mm h^{-1}) K_s values.

were labelled with the K_s class. Component one shows the effect of Al_o on aggregation (water-filled mesoporosity, $MP_{0.3}$) and its partial influence on w_{15}. Samples with "very low" K_s values were associated with large values of both wr_{15} and (Na + Mg)/Ca and low values of both Al_o and EC. This can be probably attributed to the increase of swelling pressure in conditions of low EC and high exchangeable (Na + Mg) for the less andic soil samples (Emerson, 1977), leading to a decrease in K_s. Soil 2 showed high frequency of "very low" K_s values. This soil contained small amounts of smectites, which can be very effective in promoting structural instability in halloysitic soils (El-Swaify, personal communication). Additionally, very large values of exchangeable potassium were found in soil 2 (Table 1), which could have also contributed to soil structural deterioration (Ahmed et al., 1969). No conclusive results were found with other soil properties although Van Essen (1999) reported a negative effect of sulphate and phosphate on aggregate stability in soils 2 and 3.

4. Conclusion

The results obtained in this study contribute to explain the special physical behaviour of the sorriba-cultivated volcanic soils of the Canary Islands. Complex interactions exist between allophanes and clay minerals. In the former, the nature of exchangeable cations has small influence on the physical properties (Warkentin and Maeda, 1980). By contrast, physical properties in layer silicates are very sensitive to exchangeable cations distribution and electrolyte concentration.

The influence of Al_o values on soil physical properties, greater than that of Fe_o, was strongly correlated with bulk density, HMP/resin clay ratio and water retention. The lower variability of Fe_o values and the possible lack of selectivity of ammonium oxalate for Fe phases could account for this result.

Water release curves showed sandy behaviour at low suction values, corresponding to large α values while retaining high water holding capacity at high suctions. The amounts of water released at low suctions, associated with macro- and mesopores, were positively related with Al_o contents. No direct relationships were found between the van Genuchten and the andic parameters, which reflects the influence of other factors on the relative macro- and mesopore volume distribution.

A combination of exchangeable cations distribution and salinity with clay mineralogy could lead to very low values of K_s. This was observed for Al_o values lower than 3%, suggesting that the aggregating effect of Al_o (allophanes) could not counterbalance the structure deterioration due to clay minerals. The rate at which these degradation processes occur needs further investigation. The study of soil shrinkage characteristics and the refinement of the determination of Fe phases should be very valuable to understand the interaction between amorphous and layer silicates components.

Finally, this study shows the merit to combine chemical, mineralogical and physical approaches to the soil quality description of the sorriba-cultivated volcanic soils of the Canary Islands. Physical soil quality was controlled on a complex way by both pedogenetic (remaining andic properties) and anthropic parameters (soil transport, irrigation and heavy fertilisation).

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