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A micromorphological evaluation of pedogenesis on Isla Santa Cruz (Galápagos)

Estudio micromorfológico de la edafogénesis en la Isla Santa Cruz (Galápagos)
Avaliação micromorfológica da génese de solos da Ilha de Santa Cruz (Galápagos)

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ABSTRACT

Thin sections of about 200 horizons or layers, representing 60 soil profiles in the coastal area and on the windward slopes of Isla Santa Cruz (Galápagos Islands) were analysed. Based on the fabric and the composition of the groundmass and the presence of pedofeatures in individual layers or horizons, clusters of similar material are made and 7 units and 3 subunits distinguished. Plotting these units on a survey map gives a good insight in the spatial distribution of soil materials, expressing different combinations of parent material and precipitation.
In the coastal area and the lowest slopes, with a summer dry climate, respectively reddish and greyish and brown materials with a porphyric c/f related distribution pattern and striated b-fabrics, and often with fragmented illuvial clay coatings are observed. The coarse material contains mainly holocrystalline basalt fragments, unweathered in the coastal area, or basalt derived individual minerals. The micromass has a halloysitic-smectitic composition. On the higher slopes, with a permanent moist climate, materials have also a porphyric or fine monic c/f related distribution pattern, but the b-fabric is undifferentiated and no illuvial features are present, gibbsitic features sometimes occur and the micromass consists mainly of halloysite and gibbsite. Subunits are distinguished here according to the microstructure, and the quantity and type of coarse material. Mesocrystalline basalt, often vesicular, dominates over holocrystalline, pointing to the influence of scoria. Soils on the higher slopes are more strongly weathered than those on the drier lower slopes and the coastal area. In depressions in the higher areas, materials with a yellowish or brownish grey micromass with a striated b-fabric, and well developed limpid illuvial clay coatings and impregnative iron oxide nodules occur. The micromass has a halloysite-smectite composition.
Contrary to existing hypotheses the reddish soils in the coastal area are not considered as palaeosoils (roots of tropical soils), but as modern soils developed in colluvium on the lower slopes, which was deposited on totally eroded surfaces (marine terraces?). On the slopes the distribution of units is not only determined by hypsometric zones, as suggested in literature, but is rather clustered according to types of parent material. The soils on Santa Cruz are supposed to be formed after the last interglacial period, different from the red soils of San Cristóbal which are older.

RESUMEN

Se analizaron láminas delgadas de unos 200 horizontes o capas procedentes de 60 perfiles de suelos localizados en el área costera y en las laderas de barlovento de la Isla Santa Cruz (Islas Galápagos). En base a la contextura, la composición de la masa basal y la presencia de edaforrasgos en las capas individuales u horizontes, se realizaron clusters de material similar y se distinguieron 7 unidades y 3 subunidades. La demarcación de estas unidades en un mapa permite obtener una buena perspectiva de la distribución espacial de los distintos materiales de suelo, que expresan diferentes combinaciones de material parental y precipitación.

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En la zona costera y en las laderas más bajas, con un clima con verano seco, se observan, respectivamente, materiales rojizos o grisáceos y materiales pardos con una distribución relacionada c/f tipo porfídica y contexturas birrefringentes estriadas, y frecuentemente aparecen con revestimientos de arcilla iluvial fragmentados. El material grueso contiene principalmente fragmentos de basalto holocristalino, sin meteorizar en la zona costera, o minerales individuales derivados de basalto. La micromasa tiene una composición haloisítico-esmectítica. En las laderas más elevadas, con un clima permanentemente húmedo, los materiales también tienen una distribución relacionada c/f tipo porfídica o mónica fina, pero la contextura birrefringente es indiferenciada y no aparecen rasgos iluviales, los rasgos gibsíticos aparecen alguna vez y la micromasa está formada fundamentalmente por haloysita y gibsita. En este caso las subunidades se distinguen en función de la microestructura y la cantidad y tipo de material grueso. El basalto mesocristalino, a menudo vesicular, domina sobre el holocristalino, indicando la influencia de las escorias. Los suelos sobre las laderas más elevadas están más fuertemente meteorizados que los que se encuentran en las laderas más bajas y más secas y en las zonas costeras. En las depresiones de las zonas elevadas aparecen materiales con una micromasa de amarillenta a pardo grisácea con una contextura birrefringente estriada, y revestimientos de arcilla límpida iluvial bien desarrollados y nódulos de óxidos de hierro. La micromasa está formada por haloisita y esmectita.

Contrariamente a las hipótesis existentes, los suelos rojos en la zona costera no están considerados como paleosuelos (residuos de suelos tropicales) sino como suelos modernos desarrollados sobre materiales coluviales en las laderas más bajas, que fueron depositados sobre superficies totalmente erosionadas (¿terrazas marinas?). En las laderas la distribución de unidades no está solo determinada por zonas hipsométricas, tal y como sugiere la literatura, sino que está determinada sobre todo por el tipo de material original. Se supone que los suelos de Santa Cruz se han formado después del último periodo interglacial, diferentes de los suelos rojos más antiguos de San Cristóbal.

KEY WORDS
Andosols, basalt weathering, soils on cinders, soil on volcanic ash

PALABRAS CLAVE
Andosoles, meteorización de basalto, suelos sobre cenizas, suelo sobre cenizas volcánicas

PALAVRAS-CHAVE
Andosolos, meteorização do basalto, solos sobre cinzas, solos de cinza vulcânica

RESUMO

Lâminas delgadas de cerca de 200 horizontes ou camadas, que representam 60 perfis de solo na zona costeira e nas encostas de barlavento da Ilha de Santa Cruz (Ilhas Galápagos) foram analisadas. Com base na estrutura e composição do fundo matricial e na presença de pedocaracteres nas camadas individuais ou horizontes, podem-se estabelecer grupos de material semelhante e definir 7 unidades e 3 subunidades. Ao marcar estas unidades num mapa de levantamento, obtém-se uma boa perspectiva da distribuição espacial dos vários materiais do solo, que expressam diferentes combinações de material originário e de precipitação.

Na zona costeira e encostas mais baixas, com um clima com verão seco, observam-se respectivamente materiais avermelhados ou acinzentados e materiais castanhos, com distribuição relacionada g/f porfírica e tessitura-b estriada, e muitas vezes com revestimentos de argila iluvial fragmentados. O material grosseiro contém principalmente fragmentos de basalto holocristalino, não meteorizado na zona costeira, ou minerais individuais derivados do basalto. A composição da micromassa é haloisítico-esmectítica. Nas encostas mais altas, com um clima permanentemente húmido, os materiais têm também uma distribuição relacionada g/f porfírica ou mónica fina, mas a tessitura-b é indiferenciada, não se observam pedocaracteres iluviais, pedocaracteres gibsíticos ocorrem algumas vezes e a micromassa consiste principalmente de haloisite e gibsite. Neste caso as subunidades são definidas de acordo com a microestrutura e a quantidade e tipo de material grosseiro. O basalto mesocristalino, frequentemente vesicular, é dominante relativamente ao basalto holocristalino, indicando a influência de escória. Os solos das encostas mais elevadas são mais fortemente meteorizados do que os das encostas mais baixas e mais secas e os da zona costeira. Em depressões nas áreas mais elevadas, encontram-se materiais com micromassa cinzenta amarelada ou acastanhada, tessitura-b estriada, revestimentos de argila límpida iluvial bem desenvolvidos e nódulos de óxido de ferro impregnativo. O micromassa é composta por haloisite e esmectite.

Contrariamente às hipóteses existentes os solos avermelhados da zona costeira não são paleosolos (resíduos de solos tropicais), mas solos modernos desenvolvidos em material coluvial nas encostas mais baixas, que foi depositado sobre superfícies totalmente erodidas (terraços marinhos?). Nas encostas a distribuição de unidades não é apenas determinada pelas zonas hipsométricas, como sugerido na literatura, mas sobretudo determinada pelo tipo de material originário. Supõe-se que os solos em Santa Cruz se formaram após o último período interglacial, contrariamente aos solos vermelhos de San Cristóbal que são mais velhos.

1. Introduction

Although the study of the fauna, flora and geology of Galápagos Islands is rather popular amongst scientists, this is not the case for soils (Sabau 2008). Up to now it was only the Belgian geo-pedological mission of 1962 that made a systematic soil survey of the, at that time, accessible part of Isla Santa Cruz and Santa Fé (for details on the expedition see Stoops and De Paepe 2012, in press). Based on the field work and a few simple routine analyses, Laruelle (1963, 1964, 1966) discussed the distribution of different soil types, and later represented them on a provisional sketch map (Laruelle 1967) that was used in the soil map of Ecuador and the FAO World Soil Maps. A systematic evaluation of the existing knowledge on Galápagos soils was prepared by Stoops (2013). A preliminary micromorphological study of some profiles was presented during the Third International Working Meeting on Soil Micromorphology in Wroclaw (Stoops 1972), and some additional observations were published by co-workers (Eswaran et al. 1973; Morrás 1974, 1976).

Since then, understanding of soils on volcanic ash, and especially their micromorphology (Stoops 2007, Sedov et al. 2010) made enormous progress. Hence the aim of this paper is to present a global interpretation of the micromorphology of all samples collected 50 years ago, most of them not yet studied, according to modern concepts. This will allow to get a better insight in the formation and evolution of these soils from a micromorphological point of view, and to select profiles for further detailed chemical and mineralogical studies.

2. Geological and Geographical Setting

2.1. Geology

The Galapagos archipelago is situated in the Pacific Ocean on the equator, 1100 km West of Ecuador. It is a cluster of relatively young volcanic cones, increasing in age from west to east due to the SE drifting of the Nazca plate, away from the East Pacific Ridge, over a hotspot. Isla Santa Cruz belongs to middle aged islands and consists of a core of marine sediments, including hyaloclastites and fossiliferous limestone, the *Platform Series*, covered by basaltic lava streams, known as the *Shield Series* (Bow 1979, in Geist et al. 2011). In the higher parts of the island, many cinder cones are noticed. The study of marine fossils in the *Platform Series* revealed an Under Pliocene age (Dall and Ochsner 1928), and palaeomagnetic and K/Ar datings yielded ages between 1.47 and 0.28 Ma (Cox and Dalrymple 1966). The age of the *Shield Series* ranges between 590 ± 27 ka and 24 ± 11 ka (Geist et al. 2011).

A system of fault scarps north of Puerto Ayora, locally called "barranco", results in a stepwise aspect of the lower north-eastern slope.

De Paepe (1968a, 1968b) studied the petrography of the lava's of Isla Santa Cruz, including many samples collected in the soil profiles discussed below. The composition corresponds to that of tholeiitic and alkaline basalts. The lava has in general a porphyric fabric with phenocrysts of plagioclase and olivine. The plagioclase phenocrysts, always larger than the olivine, show clear albite twinning and strong zonation. Plagioclase is also common as microlites. Olivine is Mg-rich, colourless to faint green, and seldom zonated. In many cases iddingsitisation is strongly expressed. Sometimes iddingsite occurs as an internal quasi-coating in olivine, proving that the iddingsite is not the result of surface weathering but of deuteric alteration. Clinopyroxenes, Ti-augite, may compose 25% of the rock. Light coloured phenocrysts are observed only in a few cases of ophiolitic fabrics. Rarely uralitisation is noticed. Also opaque minerals are restricted to the groundmass, mostly isometric magnetite and titanomagnetite, and skeletal ilmenite. Based on trace element analysis of representative soils, Rodríguez Flores et al. (2006) concluded that soil parent material has a similar composition all over the island.

2.2. Climate

Although situated on the equator, the archipelago does not enjoy a tropical climate, because of the influence of interacting ocean currents and winds, governed by the movements of the Inter Tropical Convergence Zone and El Niño events (Alpert 1963; Trueman and d'Ouzoville 2010). Meteorological data are scarce, even inexistent for practically all localities. Precipitation is very variable between the years, especially taking into account the El Niño events. Since 1965 the Charles Darwin Research Station (CDRS) gathers systematically meteorological data for the coastal area, and since 1988 also in Bellavista. Daily meteorological data for these two sites are available (Charles Darwin Foundation Meteorological Database). For other stations (Santa Rosa or Devine and Media Luna) fragmental information could be found in literature (Figure 1).

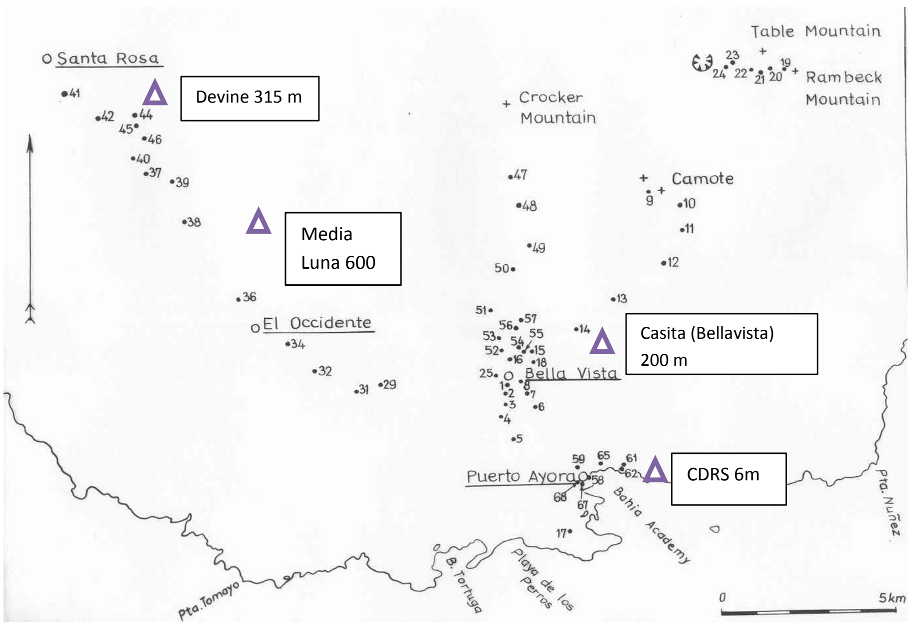


Figure 1. Sketch map of the southern part of Isla Santa Cruz with the location of the most important soil profiles and the meteorological stations (triangles) and their altitude.

The coastal zone and the complete northern (leeward) slope of Santa Cruz have a dry climate with typical xerophytic vegetation. During the cold season (May or June till December) several rain showers hit the coastal zone, whereas during the warm season (January till April or May) precipitation is rare. The windward slopes profit of an increasing higher precipitation with altitude, brought by showers in the rainy season, and by continuous fog and drizzly rain (garúa) in the dry season (Table 1). In the upper part of the island precipitation is again lower, but no data are available.

Table 1. Mean precipitation on different localities (see Figure 1) on the windward slopes of Santa Cruz in 1968 and 1969 (after Houvenaghel (1973). Note: Bella Vista was the troponin used at the time of the Belgian expedition in 1962; at present Bellavista is the official name

	CDRS	Casita (Bellavista)	Devine (Santa Rosa)	Media Luna
Altitude (m)	6	200	315	600
1968	165.7	810.7	784.5	1665.5
1969	469.7	1585.9	1901.7	2656.4

The mean annual temperature in the coastal area ranges between 29 to 32 °C for the (maximum), and 22 °C (minima) in the warm season and 27 to 24 °C and 21 to 18 °C in the cold season (Hoevenaghel 1973). In the higher areas temperatures will be slightly lower.

An analysis of the daily meteorological data provided on de CDF-website yields interesting results. Data on precipitation in the coastal area and Bellavista, summarized in **Table 2**, show that the interannual variability is high, especially in the coastal area, where the mean annual precipitation amounts 464 mm y^{-1} with a minimum of 63.6 mm y^{-1} (1985) and a maximum of 2738.2 mm y^{-1} (1983). For Bellavista these data are respectively 1054.8 mm y^{-1}, 390.8 mm y^{-1} (1988) and 2595.2 mm y^{-1} (1997).

Table 2. Monthly precipitation (maximum, average and minimum, mm) in Puerto Ayora (CDRS) for the period 1965 – 2011 and in Bellavista 1988 – 2011

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Puerto Ayora												
Max	396.3	342.9	322.6	442.3	660.2	635.5	278.2	25.6	25.7	38.6	124.9	508.6
Mean	56.3	76.5	77.9	75.7	51.0	31.3	17.7	11.7	10.4	10.7	12.2	32.6
Min	0.9	0	0	0	0	0	0.8	1.2	2.3	0.5	1.6	0.5
Bellavista												
Max	358.6	418.0	1263	687.7	302.7	172.4	138.6	113.8	120.2	137.9	347.3	609.8
Mean	92.5	134.9	149.0	129.6	65.6	49.2	68.9	71.5	67.7	64.5	74.2	87.2
Min	5.8	0.2	0	0	0	02.7	16.6	10.1	11.7	15.5	16.4	9.1

In geology and geomorphology it is generally accepted that exceptional events may have more influence on some processes than the average daily situations, such as for instance the contribution of tempestites to the formation of sediment layers. This understanding is less popular in soil science, but it is evident that exceptional meteorological situations may have a special impact. A few extreme data on precipitation on Isla Santa Cruz are summarised therefore in **Tables 3** and **4**.

Table 3. Five driest periods in the coastal area (since 1965) and in Bellavista (since 1988) with less than 1 mm precipitation in total

Coastal area (CDRS)		Bellavista	
period from - till	**Number of days**	**period from - till**	**Number of days**
06/03-27/06/1968	103	29/01-20/05/1988	111
03/03-02/06/2003	91	10/03-18/06/2003	100
06/02-05/05/1988	88	12/02-22/05/1994	99
12/02-05/06/1966	82	24/02-29/05/2006	94
22/03-11/07/1978	81	13/03-31/05/1996	79

Table 4. Five most rainy days in the coastal area (since 1965) and in Bella Vista (since 1988)

Coastal area		Bellavista	
mm	**date**	**mm**	**date**
194.6	03/06/1997	163.2	28/02/1990
176.0	13/05/1993	130.0	28/04/1998
147.8	07/05/1978	113.1	06/01/1995
141.7	25/02/1990	74.9	20/02/1991
137.6	17/12/19982	69.2	28/05/1995

Soils in the coastal area can dry to a considerable depth during the dry periods (Table 3), probably having impact on the rubification. In the transition zone prolonged dry periods are less numerous, and precipitation is higher and more equally distributed. From Table 4 it is clear that torrential rains may occur, both in the coastal area and the transition zone that can be responsible for strong erosion, especially taking into account the compact basaltic impermeable underground.

According to Colinvaux (1972) the climate on San Cristóbal was drier, even in the mountains, during the glaciation period, but became again less dry during the Holocene. The last 1200 years the level of the El Junco crater lake on San Cristóbal was much higher than now, pointing to wetter conditions, except during the Little Ace Age, till about 1880 AD (Sachs and Ladd 2010).

2.3. Vegetation and soils

Bowman (1963) distinguished 6 vegetation belts on the windward slopes:

- *Arid coastal zone* dominated by cacti (*Opuntia echios, Croton scouleri*), deciduous shrubs and dwarf trees, extending till about 30 m elevation;
- *Transition zone*, between 30 and 220 m;
- *Scalesia forest zone*, situated between 220 and 330 m, covered by a forest with *Scalesia pedunculata* trees and a dense undergrowth of shrubs;
- *Brown zone*, between 330 and 550 m, covered by a forest of *Psidium galapageium* and *Zanthoxulum fagara*; the most striking aspect is that almost all trees are covered by brown epiphytes (*Zycopodium dychotomum*);

- *Miconia belt*, reaching up to 630 m, consisting either of shrub, composed of 2 to 3.5 m high *Miconia robinsoniana* or of ferns (*Pteridium aquilinum*) fields;
- *Upland zone*, comprising the highest peaks, with a treeless pampa vegetation of low growing shrubs and ferns. Hamann (1981) describes small peaty areas in this zone. Colinvaux (1967) describes *Sphagnum* bogs, with a radio-carbon age of 1450 years at 5 m depth.

No information is published on the vegetation of the leeward side of the island.

Based on field observations, and having in mind the vegetation belts, Laruelle (1963, 1966, 1967) distinguished 5 soil belts on the windward (southern, south-western and south eastern) slopes of Santa Cruz: 1° the First Zone, with a xerophytic vegetation, comprises the lower area till 100 - 120 m altitude. Reddish soils occur either superficial (< 4 cm) or interstitial between basalt blocks. 2° the Second Zone, situated between 100 and 180 m altitude, is characterised by soils formed on basalt saprolite that occurs never at more than 70 cm depth; the upper part of the profile is influenced by pyroclastic material. 3° the Third Zone, situated between about 180 and 300 to 400 m, has ABC and A(B)C profiles in pyroclastic material on basalt, 4° in the Fourth Zone, till about 400 m deep soils in pyroclastic material with andosolic characteristics occur, and 5° in the Fifth Zone, between 400 and 500 m, soils developed in a mixture of pyroclastic material and basalt fragments, giving rise to andosolic soils under brushwood and gleyified AC profiles under fern. Soils in the higher part of the island were not investigated, even as those of the leeward slopes.

3. Materials and Methods

During the Belgian geo-pedological mission of 1962, on the base of a survey with single gauge auger, 58 Profiles were described and sampled on the windward slopes and the coastal area of the island (**Figure. 1**), and 10 additional profiles were sampled in the coastal area by J. Laruelle in 1964. For several representative profiles undisturbed samples were taken with Kubiëna boxes. Petrographic size thin sections were prepared in 1963 of air dried undisturbed samples or aggregates according to the technique described by Altemüller (1962).

A total of 457 petrographic size thin sections of 199 horizons, representing 65 profiles was systematically analysed and described applying the concepts and terminology proposed by Stoops (2003). Each horizon or layer was considered as an individual one, rather than part of a profile in order to obtain a “blind” description. Based on microstructure, c/f related distribution pattern, colour, limpidity and b-fabric of the micromass, type and weathering degree of the coarse material, organic matter and pedofeatures, clusters of material types were distinguished. These micromorphological clusters are provisionally named according to the concepts proposed by Stoops (1994), mentioning the texture, the composition of the coarse fraction (or its absence), the supposed genetic horizon type (e.g. argillic) and specific additional environmental features (e.g. hydromorphism). The colour is added in front of the name. The term “formation”, used in the original text, is replaced here by the more neutral “Unit”, and “syndrome” by “phase”. In a next step the distribution of units and subunits was plotted on schematic geographic maps of the island. Based on this information soil material formation, pedogenesis, and landscape evolution were interpreted.

4. Results and Discussions

4.1. The coarse material

As in all soils on basaltic material, all samples contain numerous fine opaque particles, mainly magnetite grains. They are coarser (± 5 μm) in basalt than in ashes (± 2 μm). Depending upon spatial distribution and weathering stage, following coarse components are distinguished: grains of olivine (O), often partly or totally transformed to iddingsite (I), plagioclase (P), augite (A) and magnetite, even as fragments of holocrystalline or mesocrystalline basalt. The holocrystalline alkali basalt (Bc) corresponds to the massive, deeper part of the lava streams, whereas the often vesicular mesocrystalline types (Bm), sometimes even tachylytic, correspond to the surface of the lava streams and cinders. Plotting Bc and Bm on a schematic map (Figure 2) shows that holocrystalline basalt is the main type of rock fragments found in the coastal area and the lower slopes (up to about 180 m), whereas Bm occurs on the middle and upper slopes, often mixed with Bc. This could indicate that in the lower zones basalt streams predominate, and that their pahoehoe surface is totally removed by weathering and erosion.

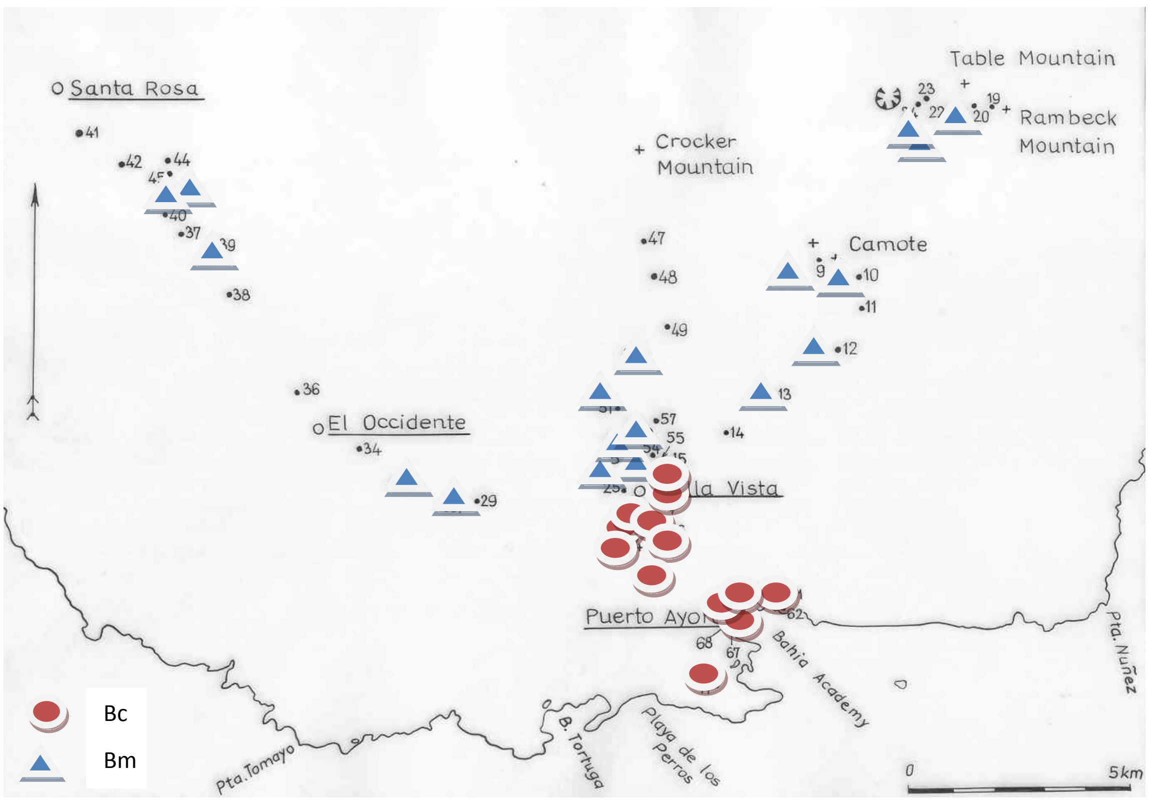
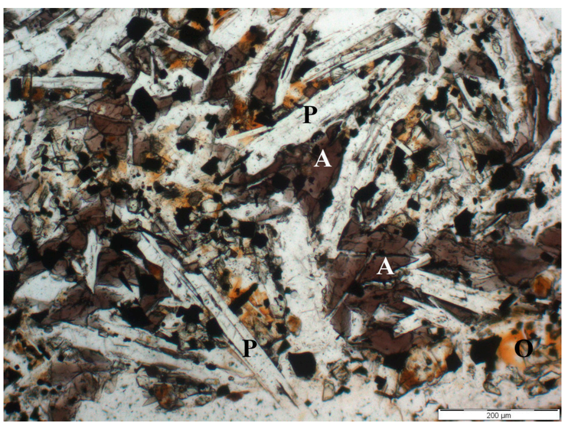


Figure 2. Sketch map showing occurrence of respectively holocrystalline (Bc) (ellipses) and mesocrystalline (Bm) (triangles) basalt fragments in soil profiles.

To indicate systematically the degree of weathering of the basalt fragments, following symbols are used in descriptions:

0: unweathered, except for cracks in the feldspar phenocrysts (Figure 3 a and b),
1: feldspars partly weathered, mainly to colourless isotropic material,
2: feldspars totally weathered,
3: feldspars and part or totality of augite weathered, olivine preserved (Figure 3 c and d; Figure 10 a and b),
4: feldspar, augite and olivine weathered,
P: after the symbols indicate pellicular weathering.

Example Bc2 means a holocrystalline basalt fragment with feldspar phenocrysts totally weathered to isotropic material. Bm1P means a mesocrystalline basalt fragment with a pellicular weathering rim in which feldspars are partly transformed to an isotropic material. Further subdivisions, even as specific cases, such as feldspar weathering to gibbsite (Morrás 1974) (Figure 4 a and b) or palagonitisation (Figure 4 c and d), are not discussed in detail in this paper. The arrangement of the opaque particles and iddingsite grains remains intact during weathering, even after total disappearance of all other minerals (Figure 10 a and b).



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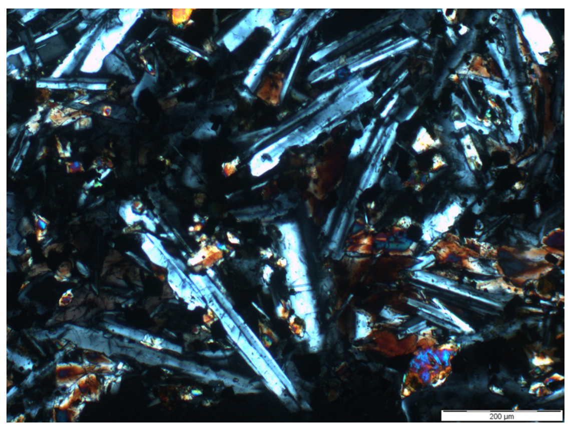

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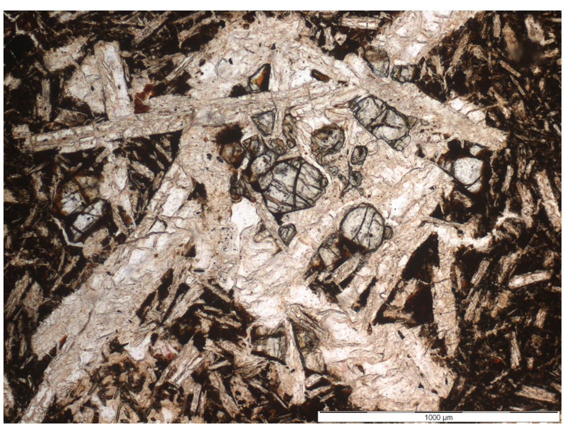

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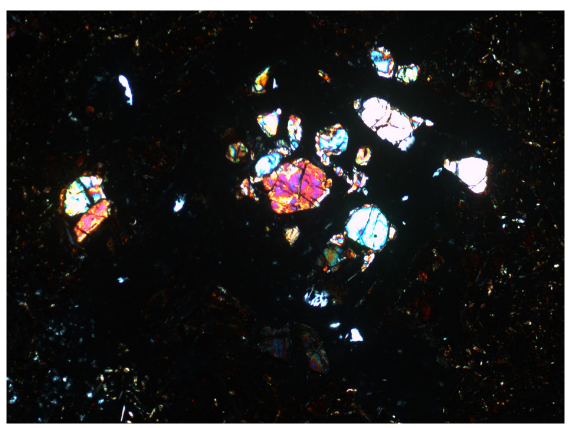
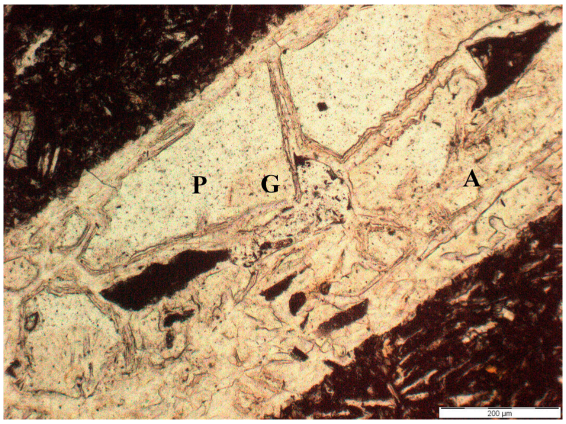


3 d

Figure 3. a) Fresh holocrystalline basalt (Bc0) with plagioclase laths (P), augite (A) and olivine (O) PPL; **b)** same, XPL; **c)** weathered holocrystalline basalt (Bc3) with transformation of plagioclase to colourless limpid amorphous phase. In the centre unweathered grains of olivine. PPL; **d)** idem XPL. Note isotropic nature of plagioclase pseudomorphs and fresh olivine. Rock fragment in lower part of Brown clayey isotropic weathered basaltic Unit.



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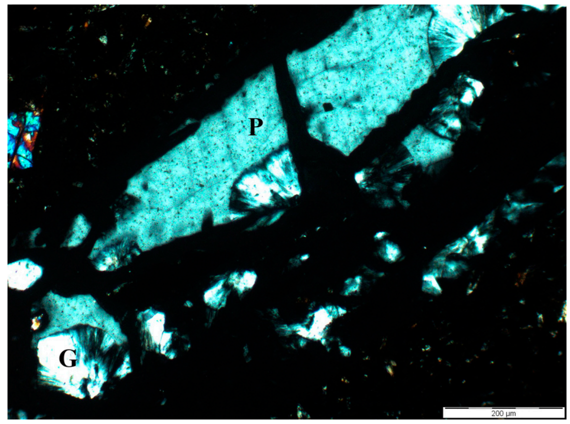

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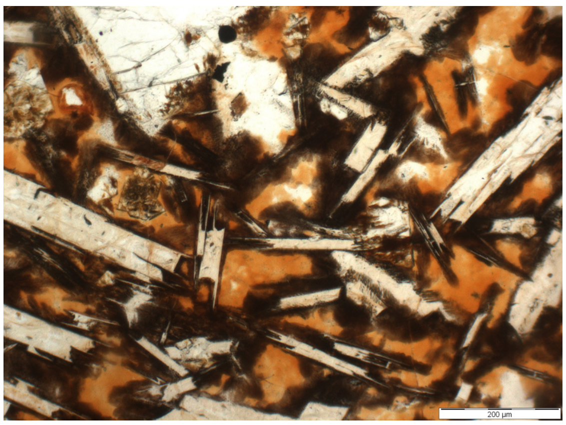

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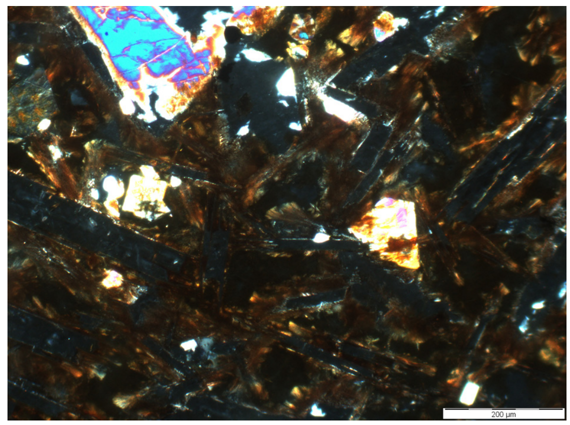


4 d

Figure 4. a) Plagioclase (P) weathered to amorphous phase (A) and gibbsite (G) in mesocrystalline basalt (Bm), Brown clayey isotropic iddingsitic Subunit. PPL; **b)** same, XPL; **c)** palagonite with plagioclase laths weathered to limpid colourless amorphous phase and unweathered olivine. PPL. Brown clayey isotropic granular Unit; **d)** same, XPL.

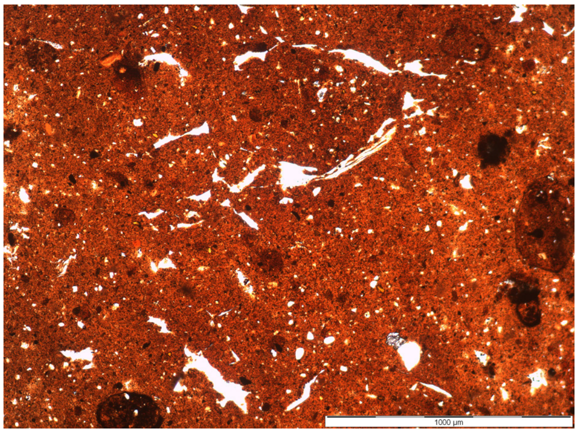
The increasing mineral weathering sequence in the basalt observed is: feldspar – augite – olivine. This sequence is also observed in the subsequent pellicular weathering rims. The fact that the sequence does not follow the series of Goldich may be caused by the relative large size of the olivine and the absence of cleavages. Iddingsite seems to remain stable.

Especially in some soils of the higher slopes yellowish to orange, limpid, optically isotropic mostly rounded particles of about 100-150 µm occur. They resemble palagonite, or weathering products as described by Gérard et al. (2007). Figure 4 c and d shows that plagioclases are less stable than palagonite.

4.2. Micromorphological Units

4.2.1. Red clayey striated fresh basaltic eoargillic Unit

This Unit is characterised by an open porphyric to fine monic c/f related distribution pattern, a reddish to reddish brown speckled micromass with a weak to very weak grano- and circular striated b-fabric superposed to an undifferentiated or speckled one. The unweathered coarse fraction consists of plagioclase, augite, olivine and iddingsite grains, Bc0, few Bm0 and some Bc1P. This almost unweathered coarse fraction is not in equilibrium with the apparently strongly weathered micromass. The occurrence of fresh rock fragments practically free of weathering is considered as an indication of colluvial material (Mücher et al. 2010). Limpid reddish clay coatings are rarely present *in situ*, but more common as stress deformed fragments (Figure 5).



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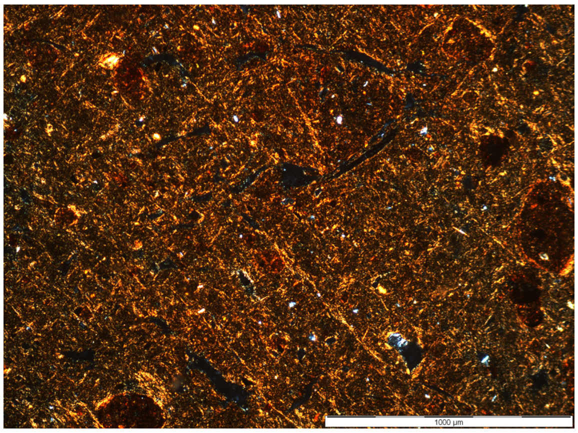
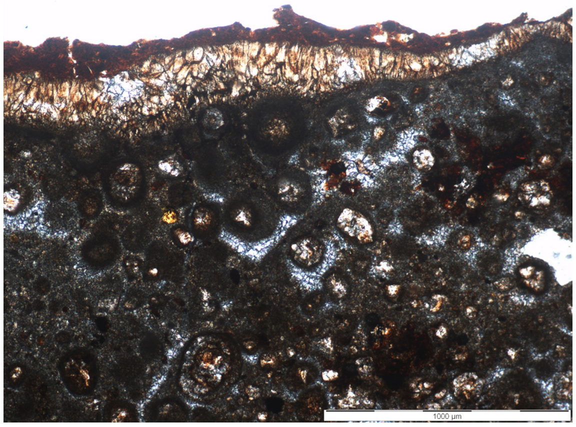


5 b

Figure 5. a) Red clayey striated fresh basaltic eoargillic Unit. Reddish groundmass with some iron oxide nodules and rare small fragment of illuvial clay coatings (left upper part). PPL; **b)** same material, XPL. Note cross-striated and granostriated b-fabric.

Additional pedofeatures are small (about 150 µm) iron oxide nodules, sometimes with concentric internal fabric, and calcitic features such as sparitic and micritic nodules and calcite coatings on weathered basalt even as some cytomorphic calcite. Locally siliceous phytoliths and orange limpid isotropic particles occur in surface horizons. The presence of calcitic features, shell fragments and whevellite phytoliths in organ residues is in agreement with a dry environment. An oolitic limestone fragment of a few mm was spotted in a thin section from a soil on the barranco (about 40 m altitude) but its origin could not be explained (Figure 6). A transport by sea birds is not excluded.



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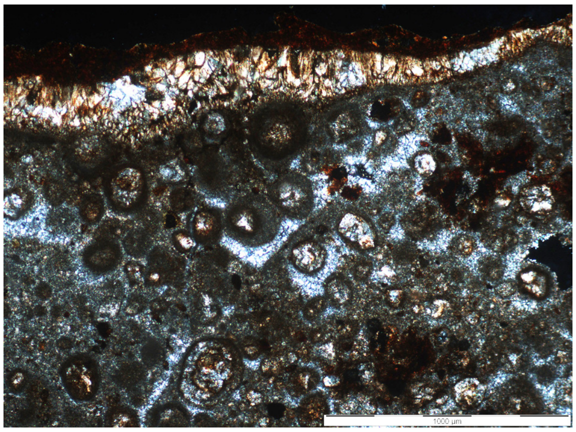


6 b

Figure 6. a) fragment of oolitic limestone with pedogenic coating of palisade calcite containing inclusions of the red micromass. PPL. Red clayey striated fresh basaltic eoargillic Unit, at 45 cm depth; **b)** same, XPL.

The name of this unit is based on its red colour, the fact that clay predominates, only fresh basalt fragments or minerals occur and small amounts of illuvial clay coatings/fragments are observed. The fabric and composition strongly resembles that of Terra Rossa soils (Rhodustalfs or Rhodoxeralfs) in Mediterranean regions with a Rothlehm fabric (Kubiëna 1948).

Eswaran et al. (1973) studied some of these red soils and noticed a pH ranging between 7 and 8.5, a CEC on fine earth ranging between 36 meq/100g and 100 meq/100g and a Fe_2O_{3DCB} content ranging between 3 and 10%. XRD indicates the presence of halloysite and smectite in the clay fraction, in line with the striated b-fabric observed in thin sections. The weak expression of this fabric is probably caused by the presence of large amounts of amorphous or randomly oriented components, such as halloysite. This also could explain why the striated b-fabric is superposed often to an undifferentiated one, rather than to a speckled as normally is observed, pointing to the absence of clay domains.

All profiles comprising this Unit are situated in the arid zone with a xerophytic vegetation, both in the coastal plain and above the 40 m high barranco, in a landscape where fresh basalt covers the surface (Figure 7). The shallow soils occur in interstitial positions between the basalt blocks, or form a thin discontinuous cover. No basalt saprolite is present.

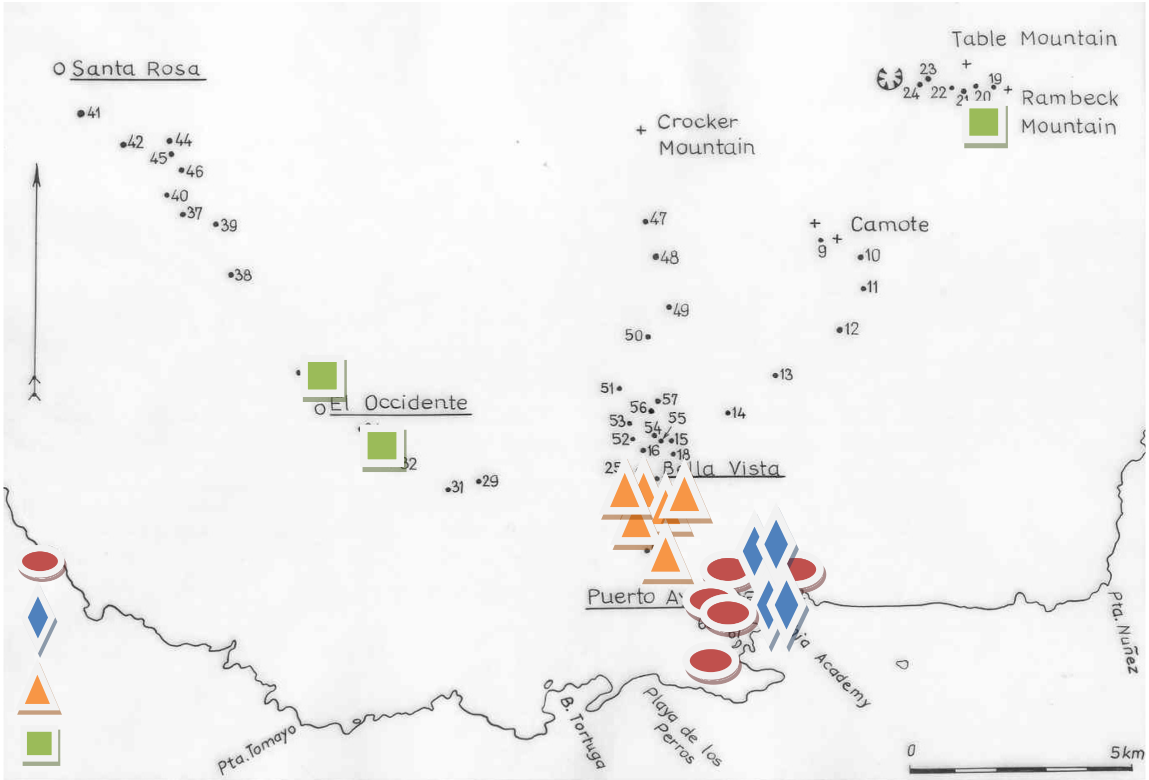


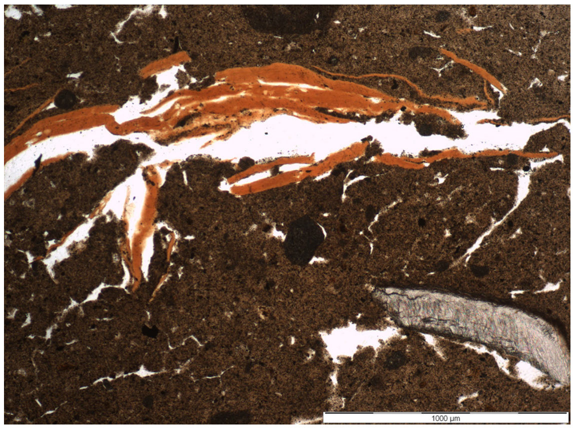
Figure 7. Sketch map showing occurrence of Red clayey striated fresh basaltic eoargillic Unit (ellipse), Grey clayey fresh basaltic Unit (lozenge), Brown clayey striated weathered basaltic Unit, at the surface (triangle) or covered by Brown isotropic Units (square).

Both the position in the landscape and the absence of weathered coarse fraction point to a colluvial material (Mücher et al. 2010) covering a fresh basalt surface. This means that the original weathering mantle must have been removed by erosion. There is no clear indication which process was involved: terrestrial or marine erosion. Whereas marine erosion would be quite acceptable for the coastal plain, as suggested by Franz (1980), this seems less probable for the soils on the summit of the barranco at 40 m of altitude, unless recent tectonic changes are considered. The red clay probably developed in erosion products of soils situated on the slopes.

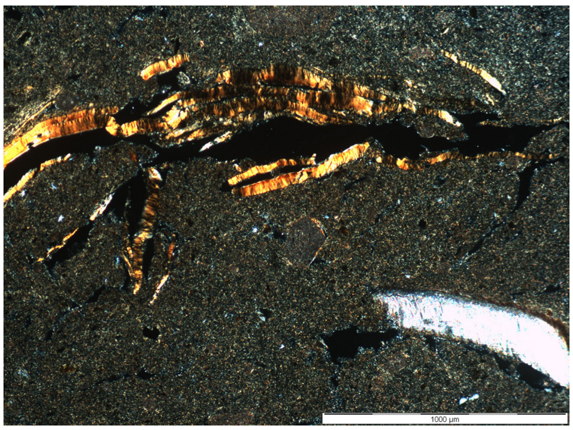
4.2.2. *Grey clayey fresh basaltic Unit*

The open porphyric to fine monic c/f related distribution pattern and the coarse fraction consisting of unweathered minerals and Bc fragments, resembles the Red clayey fresh basaltic eoargillic Unit. Different is however the greyish micromass, an often calcitic crystallitic b-fabric masking the weak striated one, and the local presence of more or less soluble features such as micritic nodules and lenticular gypsum crystals. Pure calcitic nodules or limestone fragments occur, even as some hard, concentric impregnative iron oxide nodules. A reddish clay coating showing kink-band fabric (**Figure 8**) points to the illuviation of clay from neighbouring reddish soils, the fact that reducing conditions are not active, and active swell and shrink processes deforming the coating. No chemical or mineralogical data are available on this unit. The name of this unit is based on the colour of the micromass and the unweathered coarse fraction.

Profiles of this unit are observed near the seismic station on the barranco and immediately below (**Figure 7**). The restricted, local occurrence of this unit, the deferrification of the micromass in the past, and the presence of calcite and gypsum points to local hydromorphic conditions (dissolution and removal of iron) in a confined position



8 a



8 b

Figure 8. a) Reddish clay coating on planar void in Grey clayey fresh basaltic Unit. PPL; **b)** same, XPL. Note clear kink-band fabric in coating and shell fragment in right lower part.

(accumulation of calcite and gypsum). The *Grey clayey fresh basaltic Unit* thus seems to be a local transformation of the *Red clayey striated fresh basaltic eoargillic Unit.* Another possibility would be to consider them as remains of (saline?) soils near the shore, as observed in the field but not sampled.

4.2.3. *Brown clayey striated weathered basaltic blocky Unit*

This unit has a blocky microstructure. The groundmass is characterised by a brown micromass with a weak circular-granostriated b-fabric, a double spaced porphyric to fine monic c/f related distribution pattern and a coarse material consisting of Bc0-3, P, O and I. Feldspar weathering in the basalt fragments to gibbsite, through an amorphous phase, was observed (Morrás 1974) (**Figure 4 a** and **b**). Limpid yellowish or reddish illuvial clay coatings with continuous interference colours occur in deeper parts, even as impregnative iron oxide nodules (about 150 µm). The material has a neutral pH, a CEC on fine earth around 50 meq/100g and a Fe_2O_{3DCB} of about 6%. The clay fraction contains besides halloysite also considerable amounts of smectite (Eswaran et al. 1973). Minor element studies (Laruelle and Stoops 1967) prove that this unit is chemically very similar to the *Red clayey striated fresh basaltic eoargillic Unit.* Different degrees of pedoplasmation of basaltic saprolite are observed. Several shallow profiles where the saprolite is reached are considered as truncated.

The Unit occurs mainly on the lower slopes north of Puerto Ayora, between the coastal plain and 180 m altitude and on the higher slopes in deeper parts of the profile where it is covered by *Brown clayey isotropic Units* (**Figure 7**).

4.2.4. *Brown clayey isotropic blocky Unit*

The general characteristics of this important unit are a blocky microstructure, an open porphyric to fine monic c/f related distribution pattern, and a brownish micromass with an undifferentiated b-fabric. As in all other units, fine opaque particles occur throughout the groundmass. Pedofeatures, apart from some excrements and passage features, are absent, except for rare gibbsite coatings or nodules (Morras 1976). Soils have a pH_{H_2O} below 6, a pH_{NaF} above 10.5 and a low to very low base saturation, but a high amount of Fe_2O_{3DCB}, reaching 10 – 16% (Eswaran et al. 1973). The clay fraction is dominated by halloysite and gibbsite according to Eswaran et al. (1973) or kaolinite and gibbsite according to Adelinet et al. (2008), but no information is available yet on the presence of allophane. Large amounts of Si and Al are extracted by NaOH (Eswaran et al. 1973).

This soil material covers the middle and higher windward slopes of the island, corresponding to a permanent humid environment (*garúa*). Depending on the amount and type of coarse material present, three subtypes are distinguished. The limits between these types are often gradual and in a same profile more than one unit can occur as different layers. Their distribution (**Figure 9**) is not related to a hypsometric zonation and probably determined by local changes in parent material. In earlier papers these soils were classified as Andepts and Argiudolls, based on field descriptions and a few simple analytical data (see above). From a micromorphological point of view no clear B-horizons appear.

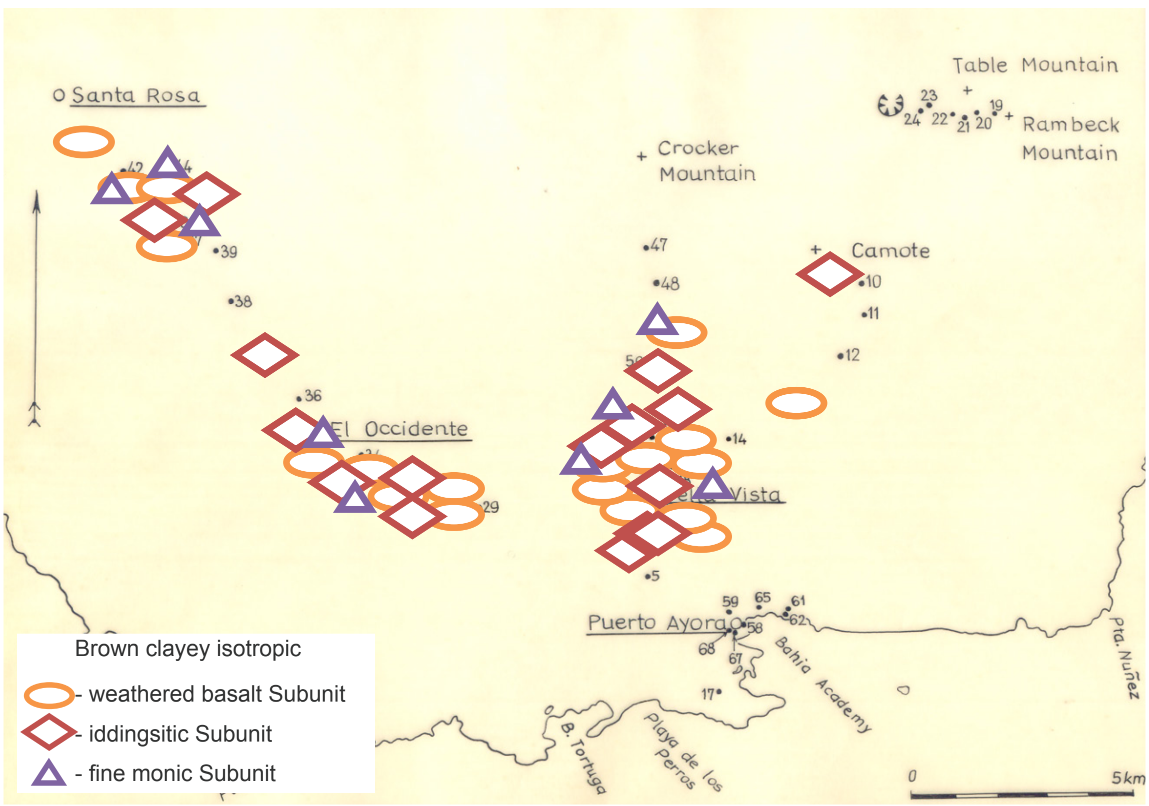


Figure 9. Sketch map showing occurrence of Brown clayey isotropic Unit and its three subunits: weathered basalt Subunit (ellipse), iddingsitic Subunit (lozenge) and fine monic Subunit (triangle).

4.2.4.1. *Brown clayey isotropic weathered basaltic blocky Subunit*

The coarse material of this subunit is composed of weathered basalt fragments (Figure 10 a and b), dominantly, but not exclusively Bm or tachylytic, and individual grains of augite, olivine, and especially small (< 50 – 70 μm) iddingsite. It originates from weathered basalt or scoria. Orange, limpid isotropic particles occur in some profiles (Figure 10 d).

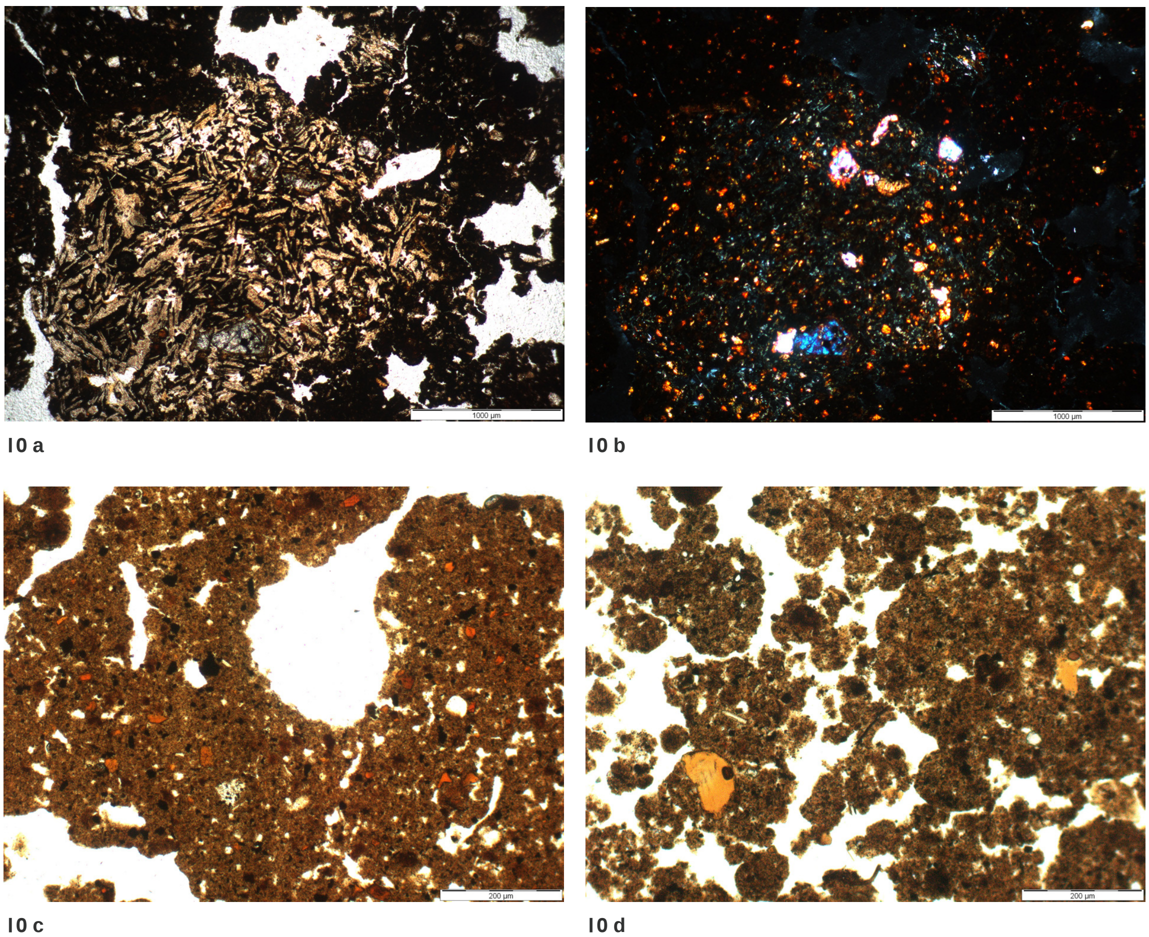


Figure 10. a) Brown clayey isotropic weathered blocky basaltic Subunit: weathered basalt (Bm3) with only small iddingsite and larger olivine grains preserved PPL.; **b)** same, XPL; **c)** Brown clayey isotropic iddingsitic blocky Subunit: iddingsite as only constituent in coarse fraction of the groundmass (PPL); **d)** Brown clayey isotropic granular Unit: orange, limpid isotropic particles in groundmass (PPL).

4.2.4.2. *Brown clayey isotropic iddingsitic blocky Subunit*

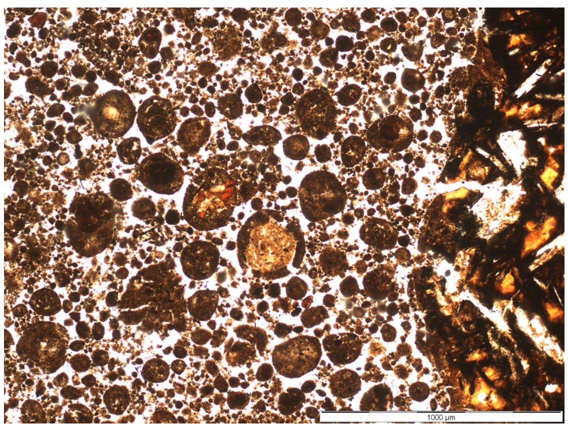
This subunit is characterised by a coarse material composed almost only of small (mainly 70 – 50 μm, but also smaller) grains of idddingsite, and rare larger (200 – 400 μm) grains of olivine. In a few cases totally weathered Bm fragments are observed where only iddingsite, and some rare grains of olivine, are preserved (Figure 10 c). The latter feature suggests that this subunit is derived from the total weathering of hard mesocrystalline basalt or scoria.

4.2.4.3. *Brown clayey isotropic fine monic blocky Subunits*

As mentioned in the name, this subunit is characterised by a fine monic c/f related distribution pattern. A coarse fraction is almost absent, except for the magnetite particles, mostly very small (1 – 2 µm), or limited to very rare grains of limpid isotropic orange particles, or iddingsite grains, and in a few cases phytoliths and/or diatoms. As both compact basalt and scoria contain resistant iddingsite, and as this complex "mineral" is almost absent, it is obvious that the parent material is of a different nature, and by exclusion of other possibilities, volcanic ash seems to be the most plausible material. This seems to be confirmed by the small size of the magnetite. This subunit seems to occur mainly on the higher slopes.

4.2.5. *Brown clayey isotropic basaltic granular Unit*

This unit is different from the former by its granular microstructure, although the groundmass is similar. Granules of about 500 µm occur individually (pure granular microstructure) or as clusters (crumb microstructure). Coarse material is rare, and comprises grains of olivine (up to 750 µm), small (mainly 75 – 50 µm, but also smaller) iddingsite grains and yellowish limpid isotropic particles. Exceptionally palagonite fragments (**Figure 11 a**) and gibbsite nodules occur.



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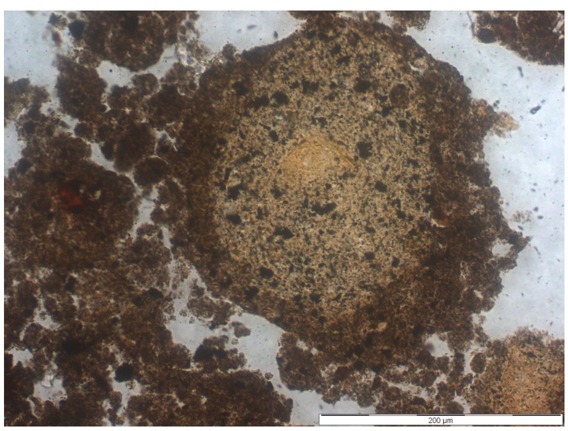


11 b

Figure 11. a) Granular microstructure with concentric granules, some with a nucleus (C-horizon) (PPL). Note fragment of palagonite at the right hand side; **b)** detail of concentric granule (B-horizon) (PPL). Brown clayey isotropic granular Unit.

A specific feature, rarely observed in other soils, is the concentric fabric in many granules, visible for instance by the arrangement of opaque microparticles (Figure 11 a and b). Moreover with very high light intensities a very weak concentric fabric is sometimes observed. In several cases these granules have a central core composed of a mineral or rock fragment. This feature strongly resembles armed pyroclasts, as described by petrographers, and could point to ashes formed during explosive volcanism.

This material was observed in all profiles in the neighbourhood of the Camote, a conic mountain, described in the field as a cinder cone, in the southeast part of the island, where the concentric variant is often observed (Figure 12). Also in profiles between Bellavista and Santa Rosa and Crocker Mountain this microstructure has been observed related to cinder cones, Media Luna and Crocker Mountain respectively. The distribution of the ashes is supposed to be determined by the direction of the trade winds (Itow 1971).

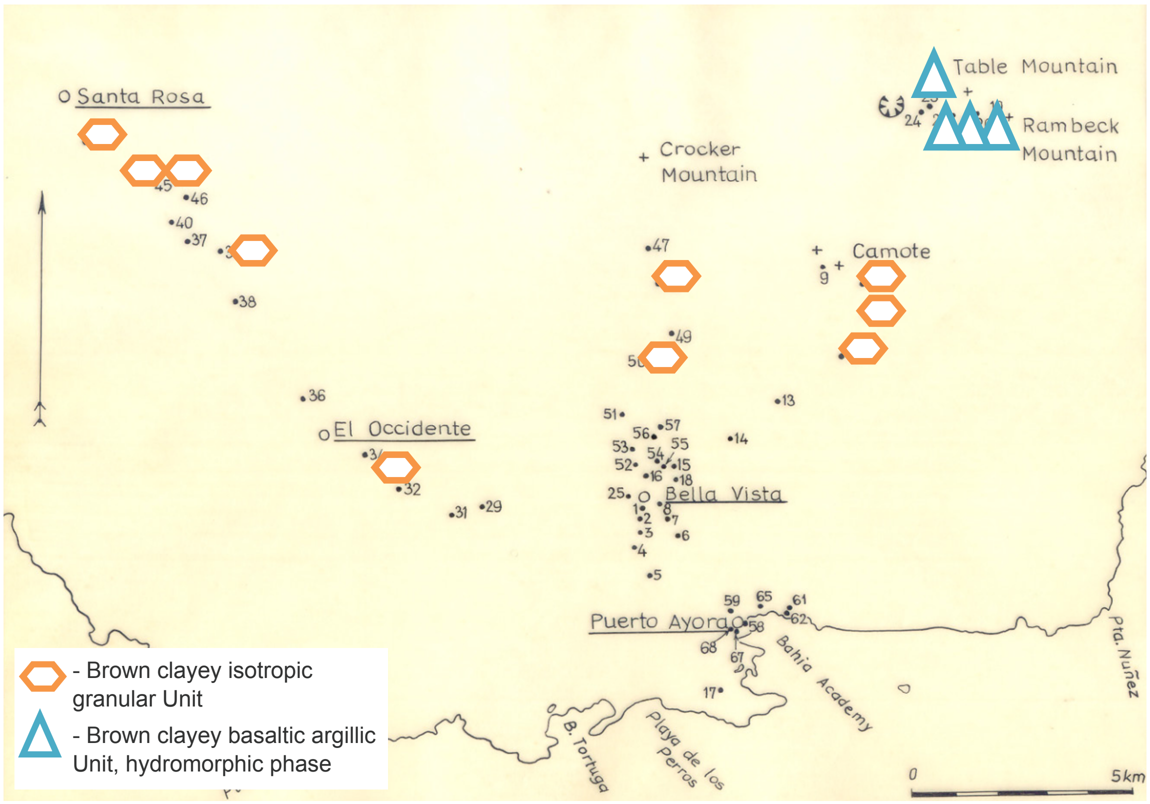
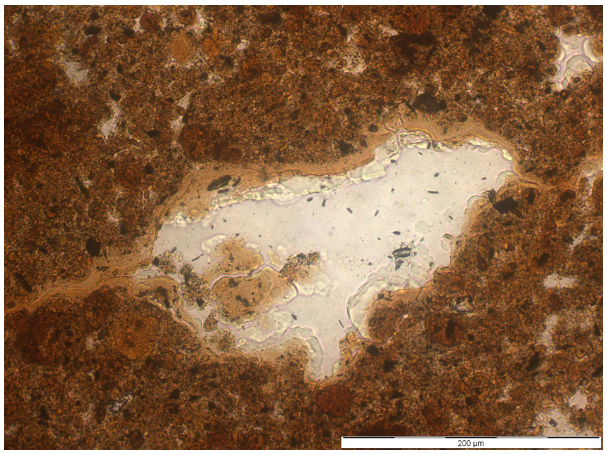


Figure 12. Sketch map showing occurrence of Brown clayey isotropic granular Unit (hexagone) and Brown clayey basaltic argillic Unit, hydromorphic phase (triangle).

4.2.6. *Brown clayey basaltic argillic blocky Unit, hydromorphic phase*

This unit has a blocky microstructure with a channel and/or vughy intrapedal microstructure. The groundmass is characterised by a double spaced porphyric to fine monic c/f related distribution pattern. The coarse material consists of fragments of Bm1-3 and individual grains of O and small I. Some samples contain small to considerable amounts of limpid orange, isotropic particles of about 100 µm, resembling palagonite. Most profiles contain relatively high amounts of phytoliths, especially in the surface horizons, but also in deeper horizons. This can even result in profiles with planosol-like aspects, when a fine sandy layer, composed of phytoliths, covers a clayey one (Van Ranst et al. 2011). The yellowish or brownish grey speckled micromass has a weakly granostriated b-fabric. Thin, limpid, pale yellowish nonlaminated clay coatings with a continuous orientation and first order interference colours cover channels and vughs in all subsurface samples. In a few cases colourless, hyaline isotropic coatings cover the clay coatings in the vughs (**Figure 13**). Brownish impregnative iron oxide nodules up to 500 µm are found in all samples and can reach even 40% by volume of the sample in the surface horizon.



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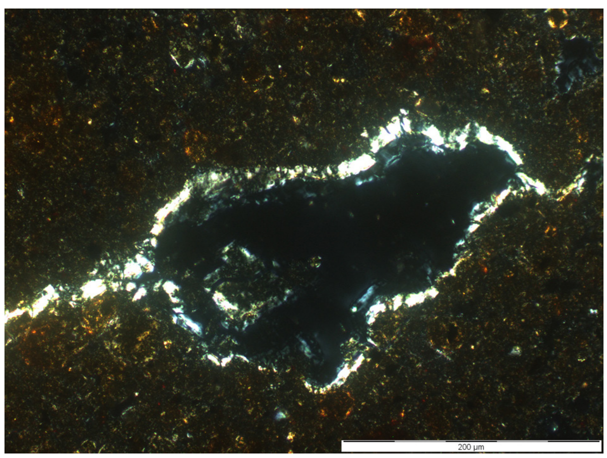

13 b

Figure 13. a) yellowish limpid, nonlaminated clay coating in vugh, covered by a limpid, colourless isotropic coating (PPL); **b)** idem, note isotropism of colourless coating (XPL). Brown clayey basaltic argillic Unit, hydromorphic phase.

The pH of one profile studied in this unit (Eswaran et al. 1973) ranges between 5.5 and 5.8, the CEC of the fine earth between 38 meq/100g (bottom) to 53 meq/100g (surface) and Fe_2O_{3DCB} is about 7%. XRD of the clay fraction points to the presence of halloysite and smectite.

The unit occurs in soils in flat areas near Table Mountain and Rambeck Mountain, on the east side of the island at an altitude of about 370 m (Figure 12). These flat areas are situated in shallow depressions with a very irregular microtopography, consisting of small (a few metres) ridges alternating with small hollows. It is not excluded that these small hollows have a biological origin, maybe created by the giant tortoises when the soil surface is muddy. All studied profiles were sampled on the ridges.

The geographic position of this area is east of the central part of the windward slope, and therefore probably less influenced by the *garúa*. No meteorological information is available. This could explain the formation of clay coatings by illuviation.

4.2.7. *Reddish Raw Humus Unit*

The basic microstructure of this unit is mostly a coarse monic to enaulic c/f related distribution pattern. It consists mainly of isotropic, reddish, brownish or yellowish rather fresh organ and tissue residues, and irregular aggregates of reddish, limpid isotropic material (Figure 14). Brownish and reddish ellipsoidal excrements point to an active mesofauna. Whevelite phytoliths commonly occur in the plant cells. The reddish organ and tissue fragments could be sclerenchyma of the *Opuntia* vegetation. In its most typical form this surface layer is restricted to the coastal area, covering the *Red clayey striated fresh basaltic eoargillic Unit*, but less typical examples were observed also rarely on the *Brown clayey isotropic blocky Units*, e.g. near Santa Rosa under *Miconia* and ferns.

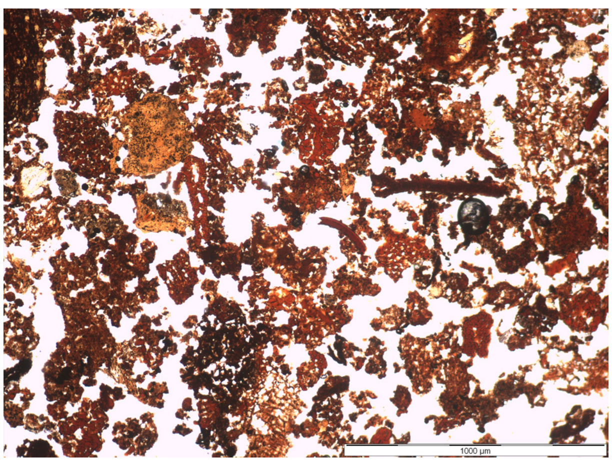

Figure 14. Reddish raw humus Unit. Note red organ and tissue residues and granules of red amorphous material (PPL).

5. Discussion

In the coastal area, and a zone above the barrancos, three micromorphological units are recognised: a dominant *Red clayey striated fresh basaltic eoargillic Unit*, locally covered by a thin *Reddish Raw Humus Unit*, and a *Gray clayey fresh basaltic Unit*. The clayey units seem to overlay directly fresh compact basalt, without a saprolite layer. Basalt fragments are unweathered, showing at maximum an incipient pellicular weathering and brown staining; feldspars and olivines too have a fresh aspect. The coarse fraction is not in equilibrium with the more weathered halloysite/smectite micromass. It is therefore suggested that the parent material is a colluvium, consisting of a transported fine fraction, deposited on an erosional surface, mixed with fresh coarser components from local origin. Due to steep slopes, impermeability of the underground and absence of rivers, strong erosion occurs during the torrential rains (**Table 4**). Minor element analysis (Laruelle and Stoops 1967) and clay mineralogy (Eswaran et al. 1973) prove that the soil materials of the coastal area and that of the transition zone are very similar. Therefore one can presume that the colluvium is essentially derived from the transition zone. Mainly the easily transported micromass would reach the relatively flat lower zone, whereas weathered coarse components are either destroyed or not transported. The chemical similarity (Laruelle and Stoops, 1967) with the weathering products on the lower slope (Brown clayey striated weathered basaltic blocky Unit) is not in favour of a later ash layer. Phosphatic nodules, observed in the coastal soils of Santa Fé (Morrás 1975, 1977, 1978) were not noticed in the coastal soils of Santa Cruz.

As the zone where rubified soils occur corresponds to the present dry climatic belt with prolonged periods without precipitation (**Table 3**), there is no reason to consider these red soils as a palaeofeature, as suggested by several authors (Laruelle 1966, 1967; Stoops 1972, Eswaran et al. 1973; Franz 1980). Moreover, all analyses show that they are much less weathered than the soils of the higher slopes, what would be in contradiction with an older age.

The absence of saprolite and mesocrystalline basalt (from pahoehoe lava surfaces or scoria) in the lower zones could be explained by weathering followed by the total removal of weathering products, either by terrestrial or marine erosion. The latter is however difficult to date in this tectonic active environment.

The similarity of soils below and above the barrancos (fault scarps) suggests the relative young age of this tectonic event. This is also confirmed by the fresh aspect of the natural outcrops observed in the barranco walls, as we observed in the field. Such tectonic up rise could explain the presence of an oolitic limestone fragment (**Figure 6**) in a thin section from a material above the barranco.

The distribution of the *Brown clayey striated weathered basaltic blocky Unit* is limited to the lower part of Laruelle's (1967) 2nd zone (transition zone) and the deeper part of some profiles higher on the slope (**Figure 7**). Its characteristics correspond to those of a pedoplasmated basalt saprolite (different stages are observed in thin sections) in a zone with wet and dry periods (Bellavista in **Table 2** and **3**), as confirmed by the presence of clay coatings, a striated b-fabric and the halloysite/smectite composition of the micromass. The quasi absence of mesocrystalline basalt suggests that the superficial part of the lava streams is totally weathered, and no scoria were present or totally weathered. Profiles are often shallow, with saprolite close to the surface, pointing to truncation by erosion. This zone was not eroded by marine erosion nor submerged, as lava tunnels (Stoops 1965) preserved their original aspect. Torrential rains do occur (**Table 4**) as discussed earlier, that can provoke strong erosion.

Long dry periods are less common than in the coastal area, and total precipitation is substantially higher. Moreover one must consider that before 1880 (Sachs and Ladd 2010) precipitation was higher, and maybe the sea-level probably lower in the early Holocene. This could explain the absence of rubifications compared to the coastal area.

The soils on the higher slopes, where, due to the *garua*, a continuous moist climate reigns, are all characterised by an undifferentiated b-fabric. This is in agreement with the nature of the clay fraction, composed of poorly crystalline halloysite, gibbsite and amorphous components. The composition of the clay fraction, the small amount of weatherable minerals present, the absence of volcanic glass and the physico-chemical properties point to strongly weathered materials, especially when compared with the soil material in the drier regions of the coastal area and the lowest slopes of the island. Where soils develop in altitude in flat areas or slight depressions with restricted drainage on the east side of the island, clayey soils with well expressed iron oxide nodules and clay illuviation features, striated b-fabric and smectitic clay form. The illuviation process is probably possible because garua is less intense and drier periods occur. It is generally accepted that for the formation of pedogenic clay coatings an alternative dry and wet season is needed.

6. Conclusions

All soil materials investigated on Santa Cruz formed on tholeiitic or alkali basalt lava flows, cinders or ash with very similar chemical composition. Weathering of the basaltic minerals does not follow the general scheme of Goldich (which is the reversed scheme of Bowen), as olivine seems to be more resistant than plagioclase and augite. Weathering of plagioclase gives rise to an amorphous phase that in strongly leached horizons is transformed to gibbsite. Plagioclase seems also less stable than palagonite (**Figure 4 c** and **d**). Iddingsite, mainly of deuteric origin, is together with magnetite the most stable component of basalt.

The existing ideas (Laruelle 1963, 1966, 1967; Stoops 1972; Eswaran et al. 1973) on the soil cover of Isla Santa Cruz are not all confirmed by the present micromorphological study of thin sections of 199 horizons or layers representing 68 profiles on the windward side of the island, neither from a pedogenic point of view, nor with regard to the distribution pattern. It was generally accepted that a clear hypsometric zonation determined the soil types present, depending upon a precipitation gradient and an increased thickness of a more recent ash cover on the higher slopes, where Andosols (even Vitrandepts) formed. In the coastal area roots of older red tropical palaeosoils (Latosols, Laruelle 1967) were supposed to have survived strong erosion. Fresh ash particles were observed only exceptionally in surface layers, probably accidentally derived from active volcanoes on other islands.

Based on the type and distribution of different types of soil material, described as micromorphological units, following general genetic picture of soil formation on Santa Cruz can be deduced: a general hypsometric zonation is present on the windward side of the island, comprising red soils on colluvium in the coastal area, followed by *in situ* formed brown soils on compact basalt with striated b-fabrics and a partly smectitic clay, and higher on the slopes brown soils with an undifferentiated b-fabric and a halloysite-gibbsite micromass, formed on scoria, pahoehoe surfaces and ash. Subdivision of the units on the higher slopes does not follow the hypsometric division, but is related to the local type of parent material. The Brown clayey isotropic granular Unit can be correlated with so called cinder cones in the landschape.

The reddish soils in the coastal area are most probably formed on an eroded surface in erosion products of the lower slopes, and their pedogenesis is in agreement with the present day climate (fragmented and stress deformed clay coatings, striated b-fabric, calcitic nodules, and rubification). There is no reason to consider them as roots of *in situ* tropical palaeosoils. Soils on the lower slope, north of Puerto Ayora, are formed in basalt saprolite, and most probably partly truncated. Their characteristics (clay coatings, striated b-fabric) are in accordance with the present climatic conditions. Soils on the higher slopes are strongly weathered except for those formed in depressions between the windward and leeward side of the island.

According to Kubiënas description (in Colinvaux 1967, 1972) red clays were found as erosion products at the bottom of the El Junco Crater on San Cristóbal at an elevation of 675 m. Also taking into account the observations of Adelinet et al. (2008) one can suppose that they cover the whole island. Based on radiocarbon datation of an enclosed gyttja lens, this sediment is considered more than 48 ky old, thus the red soils must have existed there already before the glaciations, when climate was more humid. There are no indications for a polygenetic origin of the soils of Santa Cruz. Taking into account the different climatic conditions during Pleistocene that gave rise to reddish soils all over the island of San Cristóbal, we can assume that soil formation on Santa Cruz took mainly place after the last interglacial period.

7. Acknowledegements

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REFERENCES

• Adelinet M, Fortin J, d'Ozouville N, Violette S. 2008. The relationship between hydrodynamic properties and weathering of soils derived from volcanic rocks, Galapagos Islands (Ecuador). Environ Geol. 56:45-58.

• Alpert A. 1963. The climate of the Galápagos Islands. In: Galápagos Islands. A unique Area for Scientific Investigations. Occasional Papers of the California Academy of Sciences 44:21-44.

• Altemüller HJ. 1962. Verbesserung der Einbettungs- und Schleiftechnik bei der Herstellung von Bodendünnschliffen mit VESTOPAL. In: Altemüller HJ, Frese H, editors. Arbeiten aus dem Gebiet der Mikromorphologie des Bodens. Weinheim: Verlag Chemie. p. 230-243.

• Bow CS. 1979. The geology and petrogenesis of lavas of Floreana and Santa Cruz Islands: Galápagos Archipelago, Ecuador. Unpub. PhD thesis. Eugene (Oregon): University of Oregon. 308 p.

• Bowman R. 1963. Evolutionary patterns in Darwin finches. In: Galápagos Islands. A unique Area for Scientific Investigations. Occasional Papers of the California Academy of Sciences 44:107-140.

• Charles Darwin Foundation Meteorological Database – Base de datos meteorológico de la FCD. http://www.darwinfoundation.org/database/climate.

• Colinvaux P. 1967. Environmental History of the Galapagos Islands. Washington D.C.: National Science Foundation. Report 2161-1.18 p. (stencil).

• Colinvaux P. 1972. Climate and the Galapagos Islands. Nature 240:17-20.

• Cox A, Dalrymple GB. 1966. Paleomagnetism and potassium-argon ages of some volcanic rocks from the Galapagos Islands. Nature 209:776-777.

• Dall WH, Ochsner WH. 1928. Tertiary and Pleistocene mollusca from the Galapagos Islands. Proc. Calif Acad Sci., 4th Series. Volume 17. p. 89-139.

• De Paepe P. 1968a. Bijdrage tot de kennis van de petrologie en van de petrografie van de Galápagos-eilanden. Ph.D. dissertation. State University of Ghent. 2 volumes. 326 p.

• De Paepe P. 1968b. Pétrographie et pétrologie de quelques îles situées dans la partie centrale de l'Archipiélago de Colón (Iles Galápagos). Abstract Volume of the International Symposium of Volcanology; 1968; La Laguna, Tenerife, Spain.

• Eswaran H, Stoops G, De Paepe P. 1973. A contribution to the study of soil formation on Isla Santa Cruz, Galápagos. Pedologie 23:100-122.

• Franz H. 1980. Old soils and land surfaces on the Galápagos islands. Geojournal 4:182-184.

• Geist D, Harpp K, d'Ozouville N. 2011. Field Trip Guide. AGU Chapman Conference on The Galápagos as a Laboratory for the Earth Sciences (Puerto Ayora, Galápagos, Ecuador, 25-30 July 2011). 24 p.

• Gérard M, Caquineau S, Pinheiro J, Stoops G. 2007. Weathering and allophane neoformation in soils on volcanic ash from the Azores. Europ J Soil Sci. 58:496-515.

• Hamann O. 1981. Plant Communities of the Galápagos Islands. Dansk Botanisk Arkiv 34, Bd. 2. 163 p.

• Houvenaghel G. 1973. Contribution à l'étude de l'écologie marine des Iles Galapagos. Koninklijke Academie voor Overzeese Wetenschappen, 19-1. 102 p.

• Itow S. 1971. A study of vegetation in Isla Santa Cruz, Galápagos Islands. Noticias de Galápagos 17:10-13.

• Kubiëna WL. 1948. Entwicklungslehre des Bodens. Wien: Springer Verlag. 215 p.

• Laruelle J. 1963. Exploration géo-pédologique de l'île Santa Cruz. Noticias de Galápagos 1:11-13.

• Laruelle J. 1964. Study of a soil sequence on Isla Santa Cruz (Galápagos Archipiélago, Ecuador). Galápagos International Scientific Project 1964, University of California, Symp. Pap., mimeographed.

• Laruelle J. 1966. Study of a soil sequence on Indefatigable Island. In: Bowman RI, editor. The Galápagos, Proceedings of Symposia of the Galápagos International Scientific Project. Berkeley, CA: U.C.P. p. 87-92.

• Laruelle J. 1967. Galápagos. Natuurwetenschappelijk Tijdschrift 47 (1965). 236 p.

• Laruelle J, Stoops G. 1967. Minor elements in Galapagos soils. Pedologie 17:232 258.

• Morrás HJM. 1974. La alteración y transformación de minerales primários en un perfile de suelo de la Isla Santa Cruz, Islas Galápagos (Ecuador). Rev Asoc Cienc Nat y Lit. 5:15-28.

• Morrás HJM. 1975. Algunas caracteristicas geneticas de los suelos de la zona arida de le Isla Santa Fe, Galápagos (Ecuador). Rev Asoc Cienc Nat y Lit. 6:43-48.

• Morrás HJM. 1976. Gibbsite glaebules of a soil profile from Santa Cruz Island, Galápagos (Ecuador). Pedologie 26:91-96.

• Morrás HJM. 1977. Analisis micromorfológico de dos perfiles de suelo de la zona árida de la Isla Santa Fé, Galápagos, Ecuador. Turrialba 27:93-98.

• Morrás HJM. 1978. Phosphatic nodules from a soil profile of Santa Fe Island, Galápagos. In: Delgado M, editor. Soil Micromorphology. Granada, Spain: Departamento de Edafología y Química Agrícola, Universidad de Granada. p. 1007-1018.

• Mücher H, van Steijn H, Kwaad F. 2010. Colluvial and mass wasting deposits. In: Stoops G, Marcelino V, Mees F, editors. Interpretation of Micromorphological Features of Soils and Regoliths. Amsterdam: Elsevier. p. 37-48.

• Rodríguez Flores R, Ferro Vazquez C, Stoops G, Martinez Cortizas A. 2006. Elemental composition of soils developed on volcanic materials of Isla Santa Cruz (Galapagos Islands). Abstracts of the EGU-General Assembly; 2006 April 2-7; Vienna, Austria. Abstract EGU06-A-04834.

• Sabau J. 2008. Unexplored Territory in the Galapagos Islands. Pacific Regional Society of Soil Sciences Newsletter 56:8-9. (www.prsss.ca/pdf/Newsletters/Newsletter56)

• Sachs JP, Ladd N. 2010. Climate and oceanography of the Galápagos in the 21th century: expected changes and research needs. Galapagos Research 67:50-54.

• Sedov S, Stoops G, Shoba S. 2010. Regoliths and soils on volcanic ash. In: Stoops G, Marcelino V, Mees F, editors. Interpretation of Micromorphological Features of Soils and Regoliths. Amsterdam: Elsevier. p. 275-303.

• Stoops G. 1965. On the presence of lava tunnels on Isla Santa Cruz. Noticias de Galápagos 5/6:17-18.

• Stoops G. 1972. Micromorphology of some important soils of Isla Santa Cruz (Galápagos). In: Kowalinski S, Drozd J, editors. Soil Micromorphology. Warsawa, Poland: Panstwowe Wydawnicto Naukowe. p. 407-420.

• Stoops G. 1994. Soil thin sections description: higher levels of classification of microfabrics as a tool for interpretation. In: Ringrose-Voase A, Humphreys GS, editors. Soil Micromorphology: Studies in Management and Genesis. Developments in Soil Science, Volume 22. Amsterdam: Elsevier. p. 317-325.

• Stoops G. 2003. Guidelines for Analysis and Description of Soil and Regolith Thin Sections. Madison, Wisconsin: Soil Science Society of America. 184 p.

• Stoops G. 2007. Micromorphology of soils derived from volcanic ash in Europe. A review and synthesis. European Journal Soil Science 58:356-377.

• Stoops G. 2013. Soils and Palaeosoils of the Galapagos Islands. What do we know? A meta-analysis. Pacific Science 68(1).

• Stoops G, De Paepe P. 2012. Vijftig jaar geleden. Een Belgische geo-pedologische zending naar de Galápagos eilanden (mei – oktober 1962). Mededelingen Zittingen van de Koninklijke Academie voor Overzeese Wetenschappen (in press). (www.kaowarsom.be/documents/57-58(2011-2012/Stoops.pdf)

• Trueman M, d'Ozouville N. 2010. Characterizing the Galápagos terrestrial climate in the face of global climate change. Galapagos Research 67:26-37.

• Van Ranst E, Dumon M, Tolossa AR, Cornelis JTh, Stoops G, Vandenberghe RE, Deckers RJ. 2011. Revisiting ferrolysis processes in the formation of Planosols for rationalizing the soils with stagnic properties in WRB. Geoderma 163:256-274.