Soils and Paleosoils of the Galápagos Islands: What We Know and What We Don't Know, A Meta-Analysis[1]

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Abstract: Accessible information on Galápagos soils is very limited. Much of the existing, although still scarce, information is several decades old and not easily retrieved. The aim of this paper is to present a critical synthesis. Three local soil-forming factors (parent material, climate, and vegetation) are briefly highlighted, followed by a more detailed discussion of the hypsometric soil sequence on Santa Cruz, the only island where systematic information was recorded by a Belgian geopedological mission in 1962. Five zones are distinguished from the coast toward the top of the island: a dry coastal area, containing superficial and interstitial reddish, smectite-bearing soils between basalt blocks; a transition zone of brown, also smectite-bearing soils; and three subsequent higher zones covered by deeper, brown soils with probably andosolic characteristics. Trace element analyses point to a uniform composition of the parent material and a more progressed weathering on the higher slopes. Micromorphological characteristics of the soils are discussed. Soils of Santa Fé are comparable with those of the coastal zone of Santa Cruz but show higher amounts of P and S, probably of avian origin. Deeper, reddish clayey soils cover San Cristóbal and are at least partly pre-Holocene. On the younger islands, no soils seem to be present.

INFORMATION ON the soils of the Galápagos Islands is very scarce, and only a paper by Laruelle in 1966 seems to be known, as explicitly stated by Simkin (1984) and Sabau (2008). In reality more information was published, but it remains practically unknown in the scientific literature and is mostly not retrieved by Internet search tools.

The first scientific information on the soils of the Galápagos was gathered by the Belgian geopedological mission in 1962, organized by Ghent University. This mission, consisting of three scientists (J. Laruelle, P. De Paepe, and G. Stoops), made a systematic survey of the soil cover of the windward slopes of Santa Cruz Island and a part of Santa Fé

Island and sampled geological outcrops on several other islands (for more details about the expedition see Stoops and De Paepe in press). Based on the fieldwork and preliminary analytical results, Laruelle (1963, 1966) proposed a hypsometric distribution of soil types on the southern, southwestern, and southeastern slopes of Santa Cruz and later (1967) presented this in more detail, adding a rough sketch of the spatial distribution. These data were used in the soil map of Ecuador and the FAO World Map. More detailed analyses of the samples collected during the Belgian mission (Laruelle and Stoops 1967, Stoops 1972, 2013, Eswaran et al. 1973, Morrás 1974, 1975, 1976, 1977, 1978, Rodriguez Flores et al. 2006) gave better insight into the characteristics and genesis of these soils. Apart from this, only a hydrodynamic study on some samples from Santa Cruz and San Cristóbal by Adelinet et al. (2008) and a short geomorphological paper by Franz (1980) have contributed to our knowledge of the soils and paleosoils of the archipelago.

The aim of this paper is to present a synthesis of all available information on the soils of the Galápagos. A critical study of the report

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of Laruelle (1966) and other papers mentioned here, supplemented by new microscopic analyses of the samples collected in 1962 (Stoops 2013) allows a better understanding of soil genesis and paleoevironment on Santa Cruz and, by interpolation, the other islands of the archipelago.

MATERIALS AND METHODS

Because I participated in the only specifically pedological mission to the Galápagos organized to the present and much research has been done in my laboratory, most published papers and additional information were at hand. In addition a systematic literature search using Web of Knowledge, Google Scholar, and Scopus resulted in additional references being identified.

Most reported data were produced in the late 1960s and early 1970s. Analytical methods of that period are often different from those in modern use. A method for determination of allophane content was not yet available, and very little was published about soils on volcanic material, which were not considered as something special in those days. The same is true for the unpublished field descriptions made long before FAO and other guidelines were available. For the micromorphological descriptions the terminology proposed by Stoops (2003) is added in parentheses, where appropriate.

RESULTS

The Physical Environment

Parent material, climate, and vegetation are important factors of soil formation and therefore need to be highlighted to understand the distribution and genesis of the soil cover. The Galápagos archipelago is situated on the equator, 1,100 km west of Ecuador, rising 2,000 to 3,500 m above the seafloor (Figure 1). The highest point is the top of the volcano Wolf on Isabela Island, reaching 1,707 m above sea level. In general, the structure of the islands is that of coalescent and/or superposed lava streams in the lower parts and cones of different pyroclastic material in the higher parts, but exceptions occur. According to Banfield et al. (1956) a phase of effusive volcanism was followed by explosive pyroclastic eruptions. Some islands, such as Isabela, are formed of several coalescent volcanoes. The age of the islands increases from west to east due to the Nazca tectonic plate drifting away from the East Pacific Ridge to the southeast over a hotspot. The minimum age of the islands is at least 3.3 million yr (Simkin 1984, Gromme et al. 2010). In historic times, active volcanism has been recorded only on Isabela, Fernandina, Santiago, Pinta, and Marchena (Williams 1966).

The petrology of the Galápagos Islands in general has been studied by McBirney and Ken-ichiro Aoki (1966). They concluded that the lavas are tholeiitic, grading into alkaline basalts. Some islands (e.g., Daphne, Bartolomé) consist dominantly of palagonized hyaloclastites. Others (e.g., Santa Cruz) are covered by younger basaltic lava flows and cinders.

Although the Galápagos Islands are situated on the equator, they do not have 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'Ozouville 2010). Climate therefore not only varies between the different islands but is also strongly influenced by altitude. Data on temperature and precipitation are still rather scarce. Before the foundation of the Charles Darwin Research Station (CDRS) only occasional measurements were made during scientific expeditions, apart from systematic measurements during World War II on Baltra airport. Since 1962 the CDRS has systematically recorded climatic data at two locations on Santa Cruz (see Figure 2): at the CDRS station in Puerto Ayora and in Bellavista (www.darwinfoundation.org/datazone/climate/).

On the higher islands, such as Santa Cruz, a climatic zonation is observed, caused by the stratus cloud layer in the cool season: the dry lowlands gradually change to humid highlands and then to dry uplands. This is the case for the windward side of the islands, whereas the leeward slopes are much drier. The lower

Figure 1. General map of the Galápagos archipelago.

islands have an overall dry climate. During the short warm period (23°C–31°C) from February to March the coastal areas receive some rain, but this is not the case during the cool season. The lowest temperatures are measured in August and September (around 20°C). Precipitation is very variable, partly as a result of the El Niño effect (see case study of Santa Cruz following). On the windward slopes of the mountains a drizzly rain, called *garúa*, is responsible for continuous humidity throughout the cool season.

Information on paleoclimatic conditions on the Galápagos archipelago is scarce. The most important source of information comes from a paleobotanical study by Colinvaux (1972), supported by radiocarbon dates, of the sediments of El Junco crater lake on San Cristóbal Island. A reddish clayey sediment more than 10 m thick fills the lower part of the lake but is interrupted by a gyttja lens of about 0.5 m, too old to be dated by radiocarbon. Gyttja is a subaquatic fine humus form consisting of fine remains of plants and plankton. The clayey sediment is covered by 3.5 m of gyttja deposit. The bottom of this continuous gyttja deposit has a radiocarbon date of about 10.3 ka and is thus clearly Holocene, provided these old carbon data are correct. The presence of a permanent lake points to a mean precipitation exceeding evaporation. During its existence, periods of deep and shallow lake

Figure 2. Map of Santa Cruz Island (situation in 1962) with localization of profiles discussed. The east-west section through the island is approximately 43 km.

levels alternated, with some fluctuations superposed, as can be deduced from paleobotany. The underlying red, nonlacustrine clays were deposited in a period corresponding to the Würm glaciation (24–10 ka), under drier conditions. The intercalated gyttja lens probably corresponds to a less-dry interglacial period, more than 48 ka (Colinvaux 1972). The occurrence of red colluvial clay points to the erosion of soils formed before the glaciation, when the climate was wetter.

According to Sachs and Ladd (2010) there has been over the last 130 yr a trend toward a wetter mean climate; the driest period of the last 1,200 yr was apparently the end of the nineteenth century, corresponding to the end of the "Little Ice Age" in the Northern Hemisphere. Nevertheless, the current precipitation

is still lower than in the past, as can be deduced from the relatively high level of the El Junco water level during the last 1,200 yr (Steinitz Kannan et al. 1998). It should be noted that the El Junco crater lake is situated at an altitude of about 450 m, and results are therefore not automatically valid for coastal areas.

Since Darwin's time (1831), vegetation on the Galápagos has been studied by many scientists and from different points of view. With respect to soil studies, plant association patterns are most important. A first practical zonation for the "high islands" was described by Stewart (1911), distinguishing four botanical regions from the coast to the top: (1) *dry region*, in the coastal area of all islands and including the totally low-elevation islands; (2) *transition region*, situated between the dry region and the moist region, including the upper part of moderately high islands, such as Marchena, Santa Fé, and Pinzón; (3) *moist region*, bearing a forest vegetation; (4) *grassy region*, situated in the upper part of the islands. This zonation is only valid for the windward, thus southern, southwestern and southeastern slopes, not for the leeward northern slopes where the dry region extends to higher altitudes because of the influence of southeast trade winds. A more modern, detailed description of plant communities is given by Hamann (1981). See also Wiggins and Porter (1971).

Information on the soils of the Galápagos, before the Ghent University expedition of 1962, is practically nonexistent. Wolf (1895a, b) stated that basalt weathering results in thick, blackish-brown soils. Walle (1911) mentioned that in the lower part of the islands the lava is unweathered, whereas in the higher parts it is transformed to shallow, rich soils. According to Stewart (1911) the best substratum is basalt, the poorest pumice. He considered tuff to be good for scrub, not for trees, whereas grass grows best on ash, and cinders are generally bare (presumably because they are less altered, have minimal moisture retention, and are poor rooting material). Franz (1980) suggested that the red soils found on the coastal area of Santa Cruz and other islands are relicts of paleosoils covering vast marine terraces.

Adelinet et al. (2008) mentioned the existence of two unpublished reports on soils of the Galápagos, one dealing with the natural resources of the archipelago (Ingala, Pronareg, ORTSOM, 1989, Inventario cartografico de los recursos naturales geomorfologia, vegetacion, hidricos, ecologicos y biofysicos de las Islas Galápagos, Ecuador), the other with agricultural soils on San Cristóbal (Ipade, Fundar, 2003, Diagnostico fisico y quimico de los suelos agricolas de la Isla San Cristóbal, Galápagos, Ecuador). Both were not accessible to me. Only on Santa Cruz and a small area of Santa Fé were systematic pedological studies made in 1962 by the Ghent University expedition.

Case Study of Santa Cruz Island

GEOLOGY AND PARENT MATERIAL: Two distinct bedrock types can be distinguished: the "Platform Series" in the northeastern end and the larger "Shield Series" covering most of the island (Bow 1979 *in* Geist et al. 2011). The older Platform Series consists of submarine flows with limestone intercalations that contain fossiliferous beds pointing to a probable Pliocene or old Pleistocene age (Dall and Ochsner 1928). K-Ar dates yield an age around 1.3 Ma (Geist et al. 2011). Outcrops of this material are present near Cabo Colorado (Figure 2), in front of the Plaza Islands (see Figure 4), but no soil profiles were studied. The Shield Series, consisting of pāhoehoe and `a`ā, yields imprecise K-Ar data ranging between 590 ± 270 ka and 24 ± 11 ka (Geist et al. 2011). Cinder and scoria cones are visible in the landscape. A series of approximately east-west oriented fault scarps (the so-called "barrancos") is situated north of Puerto Ayora. In these barrancos, and in several collapse craters, such as Los Gemelos, neither soil formation nor weathering was observed between successive lava flows, indicating that the interval between the eruptions was too short, or the climatic conditions were not suitable for such processes.

According to De Paepe (1968) the lavas of Santa Cruz correspond to tholeiitic and alkaline basalts. Their fabric is almost always porphyric with large plagioclase and Mg-rich

olivine phenocrysts and abundant interstitial crystals of Ti-augite and small (titano)magnetite and ilmenite grains. Seventeen profiles sampled by the Belgian mission in 1962 were analyzed for major and minor elements by Rodriguez Flores et al. (2006). Correlation and cluster analysis indicated that there are no large differences between parent materials of the different profiles.

CLIMATE: As on all larger islands, the climate of Santa Cruz shows an altimetric zonation from dry at the coast to humid in the mountains. For the period 1965–2011 the mean annual precipitation at the CDRS (6 m altitude) was 464 mm with a minimum of 64 (1985) and a maximum of 2,739 mm (1983). For Bellavista (315 m altitude) the data are, respectively, 1,089 mm, 390.8 mm (1988), and 2,595 mm (1997). Houvenaghel (1973) mentioned data for precipitation in 1968 and 1969 for other localities: Caseta (200 m), 811 mm and 1,586 mm; Media Luna (600 m), 1,666 mm and 2,656 mm. Especially in the coastal area the interannual variability may be enormous (e.g., in May 1983, 660 mm were recorded, whereas in 1966, 1980, 1984, 1985, 2003, and 2007 no precipitation was measured). Dry periods (with a total of less than 1 mm precipitation) of more than 80 consecutive days were recorded both in the coastal area and in Bellavista. The maximum daily precipitation measured at the CDRS was 195 mm; in Bellavista it reached 163 mm. Because of its steep slopes and permeable subsurface zones, no permanent streams are found on Santa Cruz, in contrast to San Cristóbal where more than 30 streams exist.

VEGETATION: For soil scientists, the most practical altitudinal zonation of vegetation for Santa Cruz was established by Bowman (1963) as a tool for describing the environment of different Darwin finches. He distinguished six zones on the windward southwestern, southern, and southeastern slopes ranging from xerophytic in the coastal zone to forest covered by brow epiphytes on the middle of the slopes to a treeless pampa on the highest parts.

The leeward northern slope is much drier and its vegetation corresponds to that of the coastal area and the transition zone. Based on

a detailed survey of 33 sample sites, Hamann (1981) recognized more types (subformations) of plant communities along the altitudinal gradient on Santa Cruz.

SOILS: The Ghent University geopedological expedition in 1962 studied soils in the neighborhood of Puerto Ayora and along trails to Bellavista, El Occidente and Santa Rosa, Crocker Mountain, Camote and near Rambeck Mountain, and Table Mountain (Figure 2). Based on field observations (hundreds of auger observations, 58 profiles) and a few basic analytical data, Laruelle (1966) distinguished five soil belts on the windward side of the island between the coast and 500 m altitude, partly coinciding with Bowman's (1963) vegetation belts. In 1967 Laruelle published in a monograph on the archipelago a more detailed discussion on the soil morphology and a schematic map of the soil distribution (Figures 3 and 4). Because this paper was published in Dutch, its content did not get the attention it merited. The following paragraphs are based mainly on Laruelle (1966 and 1967) for the field data, Laruelle and Stoops (1967) for minor element analyses, Stoops (1972) for micromorphological descriptions and Eswaran et al. (1973) for chemical and mineralogical data, unless otherwise indicated.

First Soil Zone: In this zone, situated between the coast and 100 to 120 m altitude, Laruelle (1967) recognized two types of soils: shallow (< 15 cm) red *"lithosols"* interstitial between basalt lava blocks or on their surface (Table 1, Profile 58), and deeper (< 80 cm) interstitial clayey red soils (Table 1, Profile 17) occurring as patches, maximum a few tens of square meters (Figure 5). They were considered by Laruelle (1967) as remains of truncated *"latosolic"* soils. If in the shallow profiles an admixture of pyroclastic material dominates, *"regosols"* form. The pH_{H2O} of the soils ranged between 7.0 and 8.5, the pH_{NaF} between 9.8 and 11, and the base saturation between 90% and 100%. The clay content in the shallow soils was rather low (15%), whereas it exceeded 50% in the deeper soils. The clay fraction consisted mainly of halloysite and smectite, and NaOH extractable amorphous material totaled 35% to 40%. It
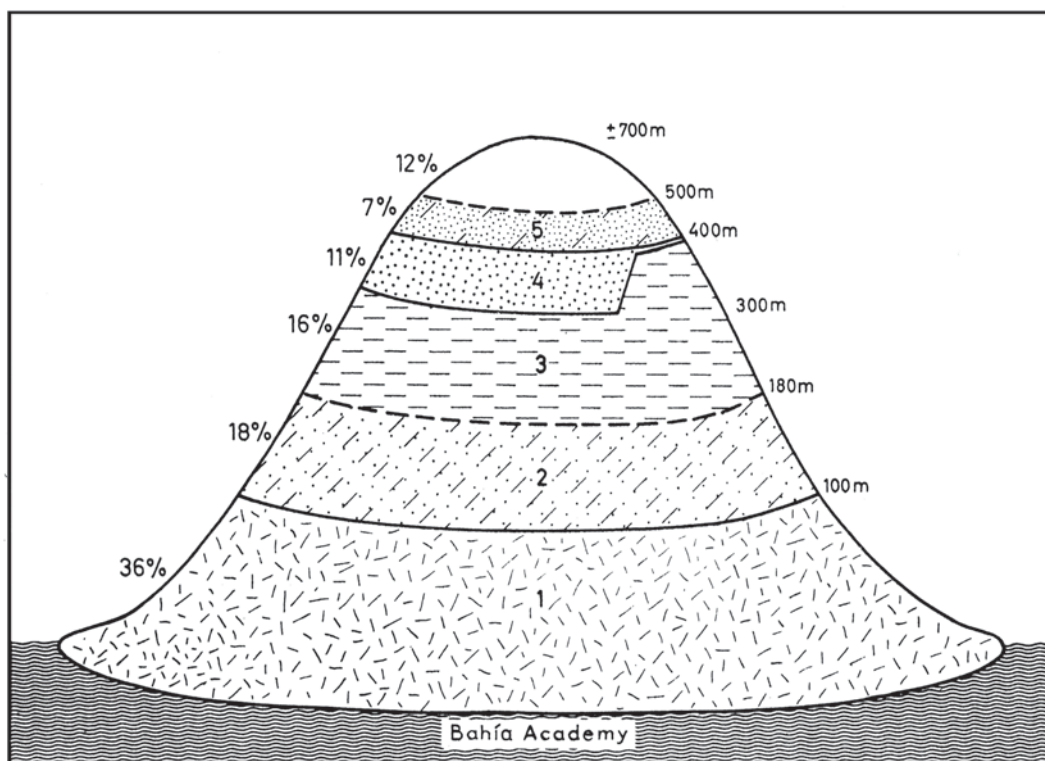
FIGURE 3. Diagrammatic representation of the five pedological zones on the windward slopes of Santa Cruz, with indication of the average area covered by each zone. Altitudes in meters above sea level. (Laruelle 1967).

is, however, well known that this method strongly affects poorly crystalline minerals and therefore is no longer considered as a measure for the allophane content. Fe_2O_{3DCB} (dithionite extractable free iron) ranged between 2.3% and 10%. Thin-section studies show the presence of fragments of limpid clay coatings, pointing to illuviation processes. Calcite nodules, lenticular gypsum crystals, and whevellite phytolites in plant remains are in agreement with a dry environment. Between crossed polarizers birefringent streaks are visible in the clay mass (well-developed striated b-fabric) in agreement with its smectitic nature and shrink and swell phenomena.

This zone, bearing xerophytic vegetation, corresponds to the "dry region" of Stewart (1911) and to the "arid coastal zone" and part of the "transition zone" of Bowman (1963).

Second Soil Zone: This zone is situated between 100 and 120 m and about 180 m alti-

tude and gradually merged into the third zone. The lower part of the AC profiles is always developed in basalt weathering products, with the weathering front never occurring below 70 cm depth (Table 1, Profile 3). In the upper part of the profile the influence of pyroclastic materials increased with altitude. The pH_{H2O} of these soils ranged between 7.5 in the top horizon to 6.5 in the solum, the pH_{NaF} between 9.2 and 9.8, and the base saturation between 70% and 85%. The clay fraction contained halloysite and smectite, with a minor amount of feldspars; the total NaOH extractable amorphous material amounted to 40%. Fe_2O_{3DCB} was about 6%. Micromorphology shows the presence of continuously oriented limpid clay coatings, pointing to illuviation processes, small iron oxide nodules related to short periods of hydromorphism and birefringent streaks (striated b-fabric) in the clay mass, in agreement
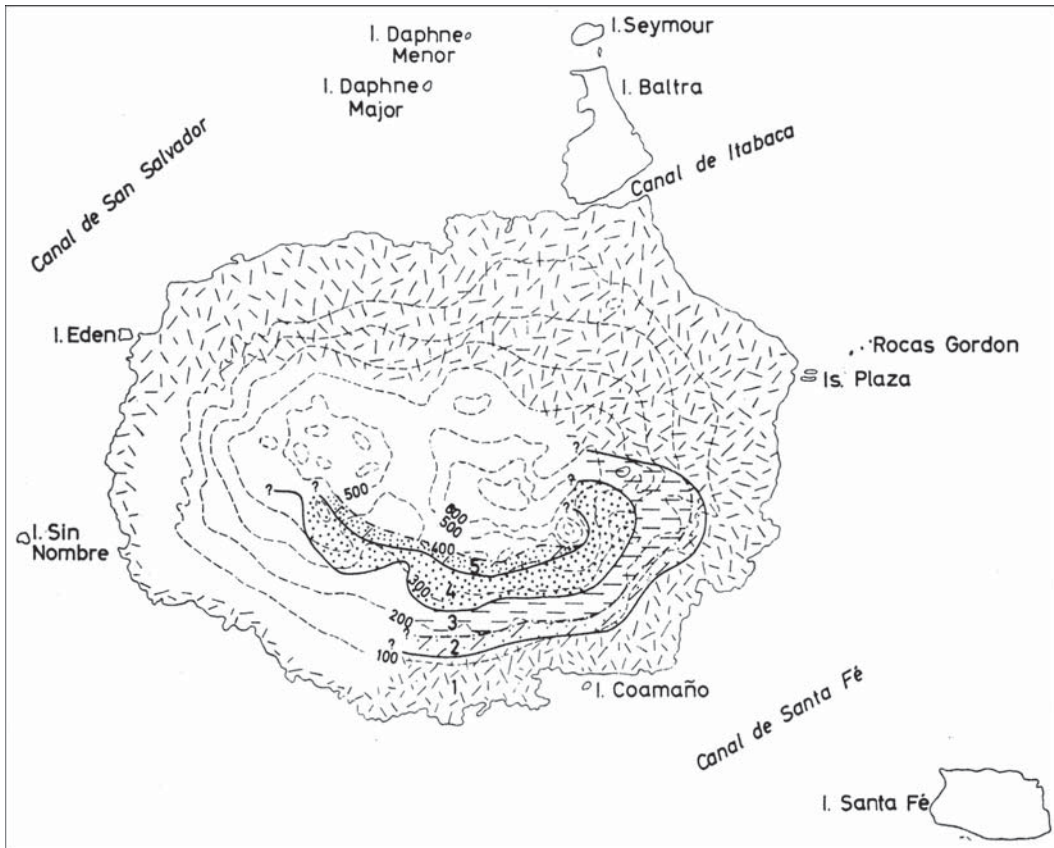
Figure 4. Sketch map of distribution of the five soil zones on Santa Cruz. (Laruelle 1967).

with the presence of smectite. The lower part of the profile clearly shows the characteristics of pedoplasmated material (Stoops and Schaefer 2010). Morrás (1974) described in rock fragments the weathering of plagioclase to gibbsite, through an amorphous phase.

This second zone corresponds to the "transition zone" of Stewart (1911) and is only a part of the "transition zone" of Bowman (1963), corresponding to a dense forest of mesophytic and xerophytic associations.

Third Soil Zone: This zone is situated between about 180 m and 300 m, locally up to 400 m. Laruelle (1966, 1967) distinguished two soil types: *"Brown Forest soils"* (sol brun) with A(B)C type profile (Table 1, Profile 9), and *"Gray-brown Podzolic soils"* (sol brun lessivé) with ABC profile (Table 1, Profile 53),

with weakly expressed Bt horizons. The soils have *"andosolic"* characteristics. Andosols have a bulk density less than 0.85, a dominance of amorphous material in the clay fraction, or more than 60% volcanic glass. The basaltic parent material can occur starting from 60 cm depth but does not occur deeper than 1 m.

Analytical data are almost lacking for this zone. The pH_{H2O} ranges between 7.5 (A_{11}) and 6.5 (C). Thin-section studies (Stoops 2013) show a mainly fine angular blocky microstructure, a completely isotropic clay mass (undifferentiated b-fabric), and the absence of pedofeatures, corresponding to the microfabric of soils on volcanic ash (Sedov et al. 2010). Stoops (1972) mentioned that soil structure has been changing in some areas as a result of the introduction of soil fauna from the South

TABLE 1

Field Description of Typical Profiles (Data from Geopedological Mission of Ghent University, 1962)

Profile 17. Coastal plain, north of Puerto Ayora, near barranco. Interstitial between basalt blocks, on a stony plateau covered by xerophytic vegetation (*Opuntia*) at about 20 m above sea level (Figure 5)

0–5 cm	A_1. Blocky structure with granular substructure; coatings along root channels; loamy clay; many small rock fragments; many roots. 2.5 YR 3/4 (dark reddish-brown) (moist), 5 YR 3/3–3/4 (dark reddish-brown) (dry)
5–80 cm	C_1. Coarse angular blocky structure, sometimes somewhat platy, covered by clay coatings; clayey; many small rock fragments; many roots until 40 cm. 2.5 YR 3/4–2/4 (dark reddish-brown) (moist), 2.5 YR 3/6 (dark red) (dry)
80–↓ cm	C_2. Parent rock, not or partly weathered

Profile 58. Superficial soil on and interstitial between numerous basalt blocks in the coastal plain west of Puerto Ayora with xerophytic vegetation

0–10/20 cm	A_1. Loose granular structure, moderately firm. 5 YR 5/6 (yellowish-red), locally 5 YR 3/2 (dark reddish-brown)

Profile 3. Brown soil on weak slope (maximum 3°) at the entrance of Bellavista, at an altitude of about 155 m

0–10 cm	A_{11}. Humiferous; crumb structure; no or very few coatings; loamy; 10 YR 2/2 (very dark brown)
10–25 cm	A_{12}. With humus infiltration and clear clay enrichment; coarse crumb structure; few clay coatings; loamy; 7.5 YR 3/2 (dark brown)
25–55 cm	$C_{(g)}$. In situ weathering clay; weakly expressed gley phenomena; compact; many clay coatings; clayey; 5 YR 3/3–3/4 (dark reddish-brown)
55–↓70 cm	Weathering basaltic rock; 5 YR 4/2–4/3 (dark reddish-gray to reddish-brown) (weathered rock) and 2.5 YR 6/2 (pale red) (weathering rock)

Profile 23. Plateau near Table Mountain, characterized by an alternation of small basins and ridges, similar to gilgai. The profile is on one of the small ridges covered with grass in the open forest, at about 365 m altitude (Figure 6)

0–3 cm	A_{01}. Humiferous; very coarse blocky structure; loamy, abrupt boundary; 10 YR 3/2 (very dark gray brown)
3–20 cm	A_{11}. Humiferous; weak columnar structure; clayey loam; no clay coatings; roots; 10 YR 4/2
20–30 cm	$B_{t(g)}$. Subangular blocky structure with some clay coatings; gley phenomena; clayey loam; roots; 10 YR 4/3 (brown to dark brown)
30–40 cm	C_{1g}. Weathering material, weak subangular blocky structure; clayey loam; gley mottles; no roots; 10 YR 4/3–5/3 (brown to dark brown) (pale zone), 5 YR 5/6 (yellowish-red) (rusty patches)
40–↓ cm	C.

Profile 53. Shallow depression in vast plain sloping about 3°, along the trail from Bellavista to the Pozos, at an elevation of about 240 m, covered with bamboo cane

0–7 cm	A_{11}. Humiferous; crumb to angular blocky structure; loamy clay; roots; 10 YR 3/2 (dark to very dark gray brown)
7–21 cm	A_{12}. With humus infiltration; crumb to angular blocky structure or more compact; loamy clay; roots; 10 YR 3/2 (dark to very dark gray brown)
21–110 cm	B. Weakly clayey horizon; more compact; roots; few, weakly weathered rock fragments between 60 and 80 cm, many below 80 cm; 10 YR 3/2–3/3 (very dark gray brown to dark brown)
110–↓ cm	Only slightly weathered vesicular basalt

Profile 9. At the foot of the Camote cone, where the steep slope (12–15°) starts, along the trail to the higher plain (pampa intramontana), at about 470 m altitude

0–5 cm	A_1. Humiferous; crumb to granular structure; powdery; clayey; few roots; 7.5 YR 3/2 (dark brown)
5–32 cm	B_1. Granular structure, powdery, slightly clayey, few roots, 10 YR 3/4 (dark yellowish-brown)
32–70 cm	B_2. Granular, powdery; more clayey; few roots; 10 YR 3/4–4/4 (dark yellowish-brown)
70–↓ 106 cm	C. Weakly developed granular, locally more compact; more clayey; interstitial between rock fragments; 10 YR 3/4–4/4 (dark yellowish-brown)

TABLE 1 (continued)

Profile 41. Weak slope (5–10°) on the trail before Santa Rosa at an altitude of about 410 m. Area is covered by ferns (*Pteridium aquilinum*)

3 cm	A_{11}. Humiferous, weak crumb structure, powdery; loamy; roots; 10 YR 2/1–2/2 (black to very dark brown)
3–9 cm	A_{12}. Humus infiltration; heterogeneous-sized aggregates, rather compact because wet; loamy; 10 YR 3/2–2/2 (very dark gray brown to very dark brown)
9–50 cm	C. Slightly compact; clayey loam; roots; 10 YR 4/3–3/3 (brown to dark brown)
50–↓ cm	Same but interstitial between weakly weathered scoria and basalt fragments

Profile 49. Weak slope (5° maximum) toward a ravine, at about 445 m altitude, along the trail from Bellavista to the central massif. Vegetation characterized by cacaotillo (*Miconia robinsoniana*) and ferns (*Pteridium aquilinum*)

0–4 cm	A_{11}. Humiferous; weakly crumb structure, powdery; roots; loamy, 2.5 YR 3/2–2/4 (dusky red to dark reddish-brown)
4–10 cm	C_1. Rubified tuff; massive structure, powdery; roots; loamy; 2.5 YR 3/2–3/4 (dusky red to dark reddish-brown)
10–40 cm	C_2. Tuff, massive structure, compact, locally powdery; roots; loamy clay; 7.5 YR 3/2–4/4 (dark brown)
40–63 cm	C_3. Stony, with interstitial soil, more compact, loamy to loamy clay; coatings on root channels; 10 YR 4/3–3/3, 7.5 YR 3/2 (dark brown)

FIGURE 5. Xerophytic vegetation consisting of *Opuntia echios* and scrub in the coastal zone. Soils occur interstitially between lava blocks. (Photograph by G. Stoops, June 1962.)

American mainland, disturbing the equilibrium reached by the endemic species. Kastendalen (1982) described how the endemic, 1-inch-long (2.54 cm) earthworm has been gradually replaced by a 4-inch-long (10.16 cm) species in the *Scalesia* forest. Originally soil structure was loose and powdery; after the introduction of the mainland species the topsoil turned into mud in the rainy season, becoming hard when the soil dried, and finally breaking up in clods. A stable granular microstructure is finally formed after rain.

Within the third zone, a group of azonal profiles occurs, not mentioned by Laruelle (1966, 1967). They are situated near Table Mountain in flat depressions with a gilgai-like microtopography (Table 1, Profile 23) (Figure 6). Gilgai is a hummocky microtopography with an alternation of microdepressions and microheights, usually a few centimeters or decimeters in height, on clayey soils subject to shrink and swell. The pH_{H2O} ranges between 5.8 (A_{11}) and 5.5 (Cg), the pH_{NaF} between 8.8 and 9.6, and the base saturation between 58.5% (A_{11}) and 16.5% (Cg). The clay fraction consists of smectite and halloysite and about 40% NaOH extractable amorphous material. Fe_2O_{3DCB} ranges between 6.5% and 8%. Micromorphological studies show the presence of many pale yellow limpid fine clay coatings, sometimes covered by thin colorless isotropic coatings, and many birefringent streaks (well-developed striated b-fabric) in the clay mass, in agreement with the smectitic nature of the clay fraction.

This zone, dominated by *Scalesia pedunculata* forest, corresponds to the lowest part of Stewart's (1911) "moist region" and Bowman's (1963) "Scalesia forest" zone. When the basalt is situated at more than 1 m depth, the *Scalesia* forest disappears. The origin of the gilgai-like microtopography is not clear. It

FIGURE 6. Depression near Table Mountain in the Third Soil Zone with gilgai-like microrelief. (Photograph by G. Stoops, August 1962.)

might be the result of biological activity, more specifically of the Galápagos tortoises using these ponds in the wet season (Stoops 1972).

Fourth Soil Zone: Situated above the third zone, it extends up to about 400 m. It is characterized by deep brown or reddish-brown soils formed in pyroclastic material, without basaltic substrate in depth (Table 1, Profile 9). Laruelle (1967) classified these soils, with AC profiles and often visible stratification, as "*andosols.*" The H_{H2O} is about 6.0, and the pH_{NaF} ranges between 10.5 and 11.5, pointing to substantial amounts of amorphous material (U.S. Department of Agriculture 1967). The base saturation is low, ranging between 32.7% (A11) and 11.4% (C). The clay fraction consists of halloysite and gibbsite and between 3% and 50% NaOH extractable amorphous material. Fe_2O_{3DCB} ranges between 13% and 16%. It is interesting that Adelinet et al. (2008) mentioned kaolinite, gibbsite, and hematite as components of the clay fraction, whereas Eswaran et al. (1973) mentioned halloysite and gibbsite, locally endelite (meta-halloysite). The presence of halloysite is more in agreement with the optical isotropic aspect of the clay mass (undifferentiated b-fabric) in thin sections. Micromorphology shows a blocky or granular microstructure, absence of pedofeatures, and an isotropic clay mass (undifferentiated b-fabric), typical for andosols on volcanic ash (Sedov et al. 2010). In the case of a granular microstructure, the granules commonly have a concentric fabric, sometimes even with a mineral nucleus.

This zone corresponds to part of the "moist region" of Stewart (1911) and the "Brown zone" of Bowman (1963), as far as the central north-south section is concerned. In other parts of the island the sequence of soil zones is not always so clear, and the Fourth zone can border the Second zone in the lower part, or the grassy zone, situated above the Fifth zone.

Fifth Soil Zone: It starts at 400 m and is characterized by soils developed in a mixture of pyroclastic materials and fragmented, fresh or weathered basalt fragments at less than 1 m depth. Two soil and vegetation types are distinguished: (a) between 400 and 500 m moderately deep brown to reddish-brown soils with no or weak horizon differentiation (comparable with the "*andosols*" of the Fourth zone) under brushwood composed of *Miconia robinsoniana* (Table 1, Profile 49); and (b) very shallow, brownish to grayish, partly gleyified soils with a dark A horizon under fern (*Pteridium aquilinum*) occurring above 500 m (Table 1, Profile 41). In this zone basalt lava flows locally occur at the surface. The pH_{H2O} is rather low, ranging between 4.7 and 5.5, whereas pH_{NaF} is high, ranging between 11.5 and 12.1 with a base saturation of 1.7% to 0.4% in the solum. Mineralogical and micromorphological characteristics are similar to those of the soils of the Fourth zone, although the amount of NaOH extractable amorphous material increases to 65%–77%. Fe_2O_{3DCB} ranges between 14% and 17% in the solum, and Al_2O_{3DCB} between 7.4% and 9%, whereas it is generally less than 1% in the soils of the lower zones.

The Fifth zone corresponds to the upper part of Stewart's (1911) "moist region" and part of his "grassy region," and to a combination of Bowman's (1963) "Miconia belt" and the fern-rich part of his "upland zone."

The upper grassland, with a presumably dryer climate, was not surveyed by the Belgian mission in 1962, and no information is available on those soils. From descriptions of botanists (e.g., Hamann 1981) it seems clear that locally thick peat areas occur; Histosols may thus be expected locally.

SOIL NAMES: Soil names, as present in literature, are summarized in Table 2. It should be noted however that classification has been assessed in all cases, except possibly for Adelinet et al. (2008), based on incomplete field descriptions and without access to the necessary analytical and climatological information and should be treated with caution.

SOIL CHARACTERISTICS IN RELATION TO ALTITUDE: From the preceding information, some general trends can be deduced. Soils of the higher zones are more weathered than those of the First and Second zones: they have a lower pH, a lower base saturation, a higher Fe_2O_{3DCB} value, and do not contain smectite. Laruelle and Stoops (1967), studying some minor elements in nine profiles from Santa Cruz by X-ray fluorescence, stated that Ti,

TABLE 2

Names Given to Soils of Different Zones Distinguished by Laruelle (1966, 1967)

Reference	First or Coastal Zone	Second or Transition Zone	Third or *Scalesia* Zone	Fourth or Brown Zone	Fifth or *Miconia* or Fern Zone
Laruelle (1966, 1967)	Lithosol, Regosol	Brown soil with AC profile	Sol brun or sol brun lessivé	Andosol	Andosol
Laruelle and Stoops (1967)[a]	Ustropept, Haplustult	Haplustoll, Hapludoll	Argiudol	Umbric Vitrandept	Andic Troporthent
Stoops (1972)[a]	Ustropept		Ustochrept[d]		
Eswaran et al. (1973)[b]	Ustropept		Hapludult[d]	Dystrandept	Dystrandept
Adelinet (2008)[c]		Lithic Argiudoll	Lithic Argiudoll, Agiudoll[d]	Lithic Dystrandept, Lithic Argiudoll	

[a] U.S. Department of Agriculture (1960).
[b] U.S. Department of Agriculture (1967).
[c] Soil zones and classification system used not specified in the paper.
[d] Atypical profile in depression.

Mn, Ni, and Ba are more abundant in the soils of the Third zone on, compared with those of the First and Second zones. Compared with the parent material (De Paepe and Stoops 1969) their Ni (102 ppm rock, 130 ppm soil), Cu (25 ppm rock, 57 ppm soil) and especially Zr (161 ppm rock, 262 ppm soil) content is higher, but their Sr content (379 ppm rock, 108 ppm soil) much lower. Analysis of the principal components of 17 profiles sampled by the Belgian mission in 1962 (Rodriguez Flores et al. 2006) showed a decrease of Si and an increase of immobile elements with altitude, thus an increase in weathering. Moreover the analysis showed that horizon differentiation is more pronounced in the higher parts than in the lower parts. Adelinet et al. (2008), studying the hydraulic conductivity of a series of soils on Santa Cruz (five samples) and San Cristóbal (seven samples), found a range of 1.5×10^{-3} to 1.7×10^{-6} msec^{-1}. Both hydraulic conductivity and porosity decreased systematically with altitude.

SOIL DISTRIBUTION AND GENESIS: In his papers, Laruelle (1963, 1966, 1967) considered only soils on slopes to develop his hypsometric zonality of soils on Santa Cruz. Azonal soils, such as those in depressions, were not discussed. His ideas were much influenced by the (then just published) vegetation zones of Bowman (1963) and the hypothesis that the island consists of a superposition of lava streams covered by younger volcanic ash on the higher slopes. The distribution of the red soils on the leeward side of the island (Figure 2) is a guess, not confirmed by field studies, and therefore may be excluded.

The deep red soils in the coastal area are considered to be remains of truncated latosols. This is most probably not the case; they rather resemble Terra Rossa soils (these are reddish, sesquioxide rich, only partly weathered soils formed in regions with contrasting climatic conditions; they are often paleosoils but still actively form in some regions), as found in Mediterranean areas, and the absence of saprolite suggests a colluvial material on marine plateaus, as suggested by Franz (1980) and Stoops (2013). Regosols in the coastal area are, according to Laruelle, caused by local colluvial material with an admixture of pyroclastic material. Stoops (2013) observed only exceptional small glass fragments in these materials, probably derived from airborne ash of other islands. There are no objective indications to consider these red soils as paleosoils. The hypothesis is based on color only but is contradicted by the fact that they are less weathered than soils on higher slopes. The presence of long dry periods in the coastal area, and the continuously moist conditions on the slopes, may explain the difference in color, as the rubification process takes place only in alternating moist and dry conditions. Grant (1981), studying tree rings on Santa Cruz, concluded that already in the

transition zone trees are less often water stressed than in the coastal area. Whitish soils were sampled in the dry coastal zone by Laruelle in 1964, both on and below the barranco, but not considered in his zonations. The andosolic properties of the soils in the Third through Fifth zones are not confirmed by physicochemical data. Their micromorphological properties do not always correspond to those of real Andosols as described by Stoops (2007) and Sedov et al. (2010).

A systematic micromorphological study of all 68 profiles sampled in 1962 suggests that the hypsometric zonation of the Third through Fifth zones is not that evident. This can be deduced also from Laruelle's (1967) ambivalent description of the Fourth zone mentioned earlier. No volcanic glass was found (Stoops 2013), which seems logical in view of the relatively old age of the island. Further studies on representative profiles of all zones collected in 1962 in progress at the Ghent University in the Laboratory of Soil Science (Director Prof. Dr. E. Van Ranst) will provide more information on these issues.

Large parts of the island remain unexplored with regard to soils: the drier upper grasslands, with inclusions of Histosols; the leeward side; and the region where the "Platform Series" form the parent rock. Saline soils near the coast and mangrove soil also remain unexplored. A study of the soils and sediments inside collapse craters (e.g., Los Gemelos) could yield more information on climatic changes because xerophytic vegetation occurs there, although they are situated in moist regions.

To date there is no proof of a polygenetic origin of the soils of Santa Cruz, except for the coastal soils, probably formed in colluvial soil sediments. This seems difficult to understand for an island 590 ± 270–24 ± 11 thousand yr old (Geist et al. 2011), taking also into account the substantial climatic and sea level changes during the Pleistocene, but one should bear in mind that the surface deposits (scoria, ash) in which the soils develop are younger than the basalts. It indicates that no drastic climatological changes have taken place since pedogenesis started.

Soils of Other Islands

During the 1962 geopedological mission some of the islands younger than Santa Cruz were visited only briefly, such as Bartolomé, Santiago, and Daphne, and no developed soils were detected. Nothing has been published on the soils of the larger, active volcanic islands, but it is unlikely that pedogenesis has taken place, considering their young age. On the older islands (e.g., Santa Fé, San Cristóbal, and Floreana), however, there is a better chance of finding soils.

Santa Fé

According to Simkin (1984), Santa Fé is between 2.6 and 2.8 million yr old, compared with 590 ± 270 Ka–24 ± 11 Ka for the Shield Series of Santa Cruz. The petrology and the vegetation of the coastal area are comparable with those of Santa Cruz. No meteorological data are available. During the Belgian geopedological mission of 1962 the coastal area was investigated and some analyses were published later (Laruelle and Stoops 1967, Morrás 1975, 1977, 1978). Profiles were sampled at four locations ranging between 90 m (tableland on Horst II) and 10 m (basin of Graben I) altitude. Soils at 70 and 90 m altitude were classified as Ustropepts, and those in the lower parts as Haplustalfs and Rhodustalfs (U.S. Department of Agriculture 1960). Morrás (1975, 1977) described clay orientations in the clay (striated b-fabrics), probably pointing to smectitic clays, but no clay coatings were described. It is however not excluded that due to swelling and shrinking, caused by alternating wet and dry conditions, former clay coatings are incorporated in the micromass. Yellowish, isotropic nodules in these soils were analyzed by Morrás (1978). X-ray diffraction analysis points to a poorly crystalline calcium phosphate, probably of animal origin (guano). No information is available on the soils of the higher slopes. It would be interesting to know whether the reddish soils extend to those higher areas, as they do on San Cristóbal.

San Cristóbal

This island is older than Santa Cruz and therefore weathering and soil formation should be much more advanced. Red soils seem to cover even the higher slopes, as mentioned by Franz (1980) and as can be deduced from the fact that erosion products of red soils occur at the bottom of El Junco crater lake at 450 m altitude (Colinvaux 1972). Adelinet et al. (2008) studied the hydraulic conductivity and clay mineralogy of a series of seven samples. The clay fraction of the soils at the lowest elevations is characterized by kaolinite and gibbsite; at higher elevations the clay fraction is characterized by gibbsite and kaolinite. In deeper parts of the profiles smectite occurs. The soils are classified as Vertic Haplustalfs, except the highest located profile, which is considered a Rhodudalf.

It is thought that Floreana also bears a soil cover, but no information is available.

DISCUSSION AND CONCLUSIONS

Although our knowledge of Galápagos soils is greater than supposed (Sabau 2008), it is still very limited. Only for the soils of Santa Cruz do we have systematic information, but even there we do not have details for all landscape units of the island, and the analytical results were derived using mostly outdated methods. It is strange that so little information is available (only six isolated samples) on the soils of San Cristóbal, the island with the longest agricultural history (e.g., the ill-famed sugarcane plantation El Progreso founded in 1832). On Floreana, also populated since 1870, no data exist at all. Knowledge of the soils of the Galápagos is not only of scientific interest but also of ecological and economic importance.

A better understanding of the genesis of soils and paleosoils on the Galápagos could help us in understanding past climates. For instance the reddish soils on Santa Cruz are restricted to the dry coastal areas and totally absent on the higher, always moist slopes, and therefore are considered a result of ongoing rubification. If they are comparable with the soils of San Cristóbal, it means that in the past, before the Holocene (see discussion on paleoclimates), a similar Mediterranean-type climate was present over the whole island, much different from the current situation. It is however also possible that the red soils on San Cristóbal are more weathered than those on Santa Cruz and have to be compared with more weathered red tropical soils. Many of these questions will remain until more information becomes available on the soils of the Galápagos.

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