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Highly Weathered Soil Landscapes of Costa Rica

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Abstract

Highly weathered soils, formerly known as lateritic soils, are currently classified according to the Soil Taxonomy as Oxisols and Ultisols. These soils have been identified in various landscapes of Costa Rica, developing under contrasting climatic conditions indicated by annual precipitation values between 1749 and 5778 mm. The chapter provides a concise description of five specific landscapes of Costa Rica, where Oxisols have been identified as dominant. The parent materials were grouped within four general categories: (1) Basaltic rocks from Jurassic-Miocene Oceanic Complexes, (2) Igneous materials of Paleocene-Pliocene ages, (3) Sedimentary materials from the Pliocene–Pleistocene ages, and (4) Volcanic materials from the Pleistocene. Despite this diversity in parent materials and climatic conditions, the stability of the geomorphic units is the common factor that allowed for the development of Oxisols and some great groups of Ultisols, corroborating the fundamental role of geomorphology in the origin of highly weathered soils.

Keywords

Costa Rica · Oxisols · Ultisols · Weathered soils · Geomorphology

21.1 Introduction

Highly weathered soils are usually understood as deep, red soils with high pedogenetic development and low activity clays. In Central America, soil characterization studies started in the twentieth century, with notable publications by Anderson and Byers (1930), Dóndoli (1943), Jaramillo (1969), Martini (1970), Macías (1969), Eswaran (1972). Previously, highly weathered soils were classified as "laterites" (Hardy 1970) until Soil Taxonomy came out (Soil Survey Staff 1975). Further, international committees were established to deal with taxonomic studies and aspects of these weathered soils, designating them as Oxisols (Buol and Eswaran 1988, 2000).

Soil-forming process includes factors that act together and independently over a parent material to modify it into a soil body. Jenny (1994) developed a mathematic function named "Universal equation for soil-forming factors" based on the combined effects of five forming factors: parent materials, relief (landforms), organisms, climate, and time, which depending on the magnitude and specific combinations between each other yield in different soils. The concept of these five forming factors remains valid up today, and they are the cornerstone for the main soil-forming processes: transformations, translocations, additions, and losses (Alvarado 1985; Buol et al. 2011; Targulian and Krasilnikov 2007), providing fundamental information to explain and understand the genesis of a certain soil. Within these soil-forming factors, landscape morphology becomes fundamental to understand the pedogenetic pathways forming highly weathered soils in the tropics. For instance, stability in geomorphologic units is required for Oxisols-forming processes, especially when dealing with materials and landforms formed during the Quaternary (Thomas 1994; Camacho et al. 2020, 2021).

Hence, the proper study and characterization of geomorphological landscapes and their features becomes essential in soil survey, genetic considerations, and classification of

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highly weathered soils. The present chapter focuses on five landscapes from Costa Rica, where climatic conditions and landform features allowed for the formation of Oxisols and Ultisols. Forming factors involved in pedogenesis will be also described. Our results are key to other tropical landscapes where highly weathered soils are present and which face similar environmental challenges as the ones presented in this chapter.

21.2 Landscapes with Highly Weathered Soils Development in Costa Rica

21.2.1 Mountains of Peninsula de Nicoya

Located in the Pacific Northwestern region of Costa Rica, these mountains were formed from the Nicoya Oceanic Complex (Jurassic–Lower Cretaceous), a geological formation mainly composed by igneous and sedimentary rocks, with some materials dated from 72 ± 4 to 30 ± 15 Ma (Alvarado et al. 1992; Denyer and Gazel 2009). This geological formation is considered among the oldest within the Costa Rican Territory. These mountains and their associated landforms are included within the large geomorphologic unit "Península de Nicoya". This unit (Fig. 21.1) is mainly composed by small hills, with evidence of intense weathering cycles of igneous and sedimentary materials (Bergoeing 2007). These weathering processes produce clay-rich weathering mantles, modeled by severe erosion processes which on steep slopes include solifluction, soil reptation, and landslides (Mora 1985).

The climate in this region (Fig. 21.2) is characterized by annual precipitation values of 1853 mm, with a bimodal distribution and peaks in May–June and August–October. This rainfall pattern includes a marked dry period between December and April (almost 0 mm), when the monthly average air temperature reaches the highest values (30 °C).

These climatic conditions restraint the number of plant species that cover this land, only allowing for the growth of species with drought resistant mechanisms, for instance coffee (*Coffea arabiga* L.) and orange (*Citrus sinensis* L.) have been successful crops. In addition, grasslands and cattle farms are possible within this area, and more recently orange production has become a cash crop (Fig. 21.3). However,

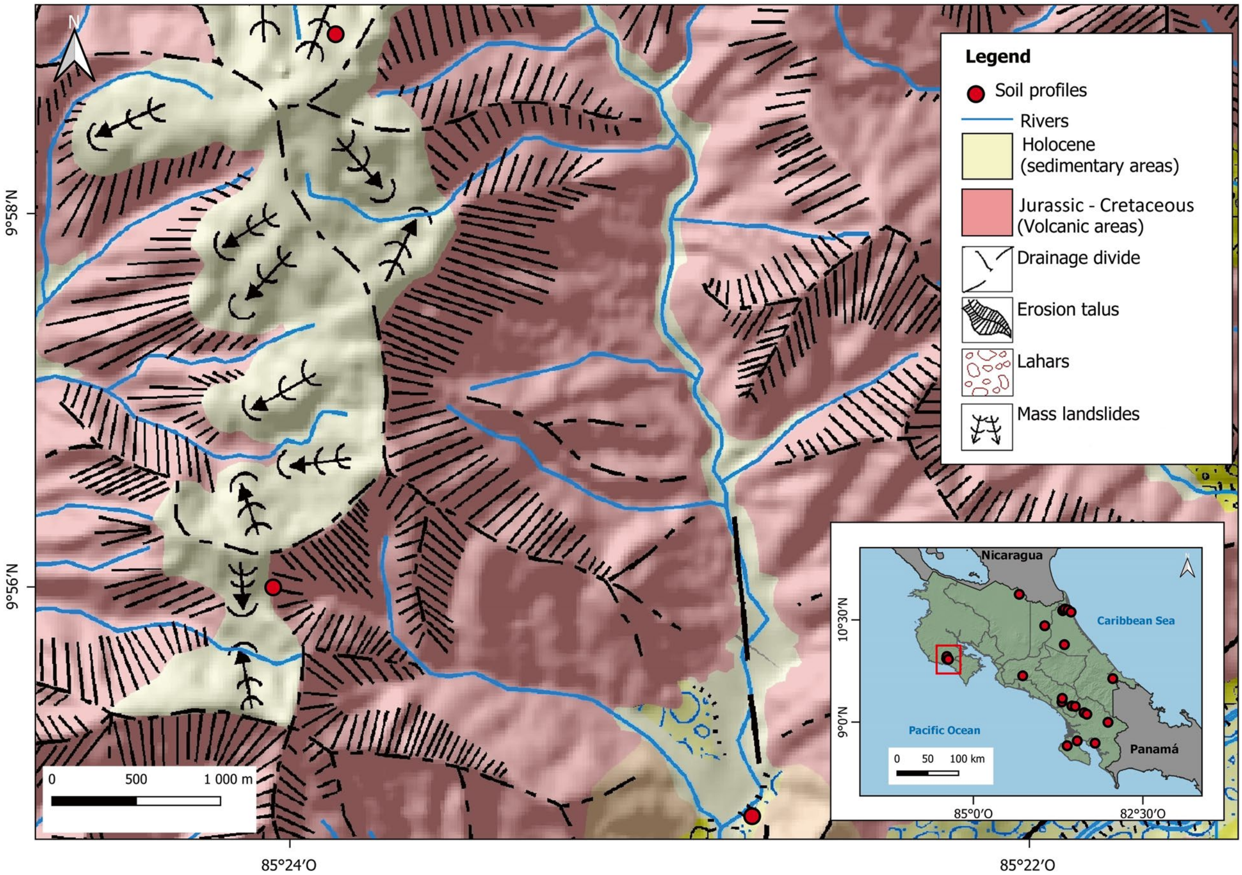

Fig. 21.1 Location, main geomorphologic features, and soil profiles observed in the Mountains of Peninsula de Nicoya. Adapted from Bergoeing and Brenes (2017)

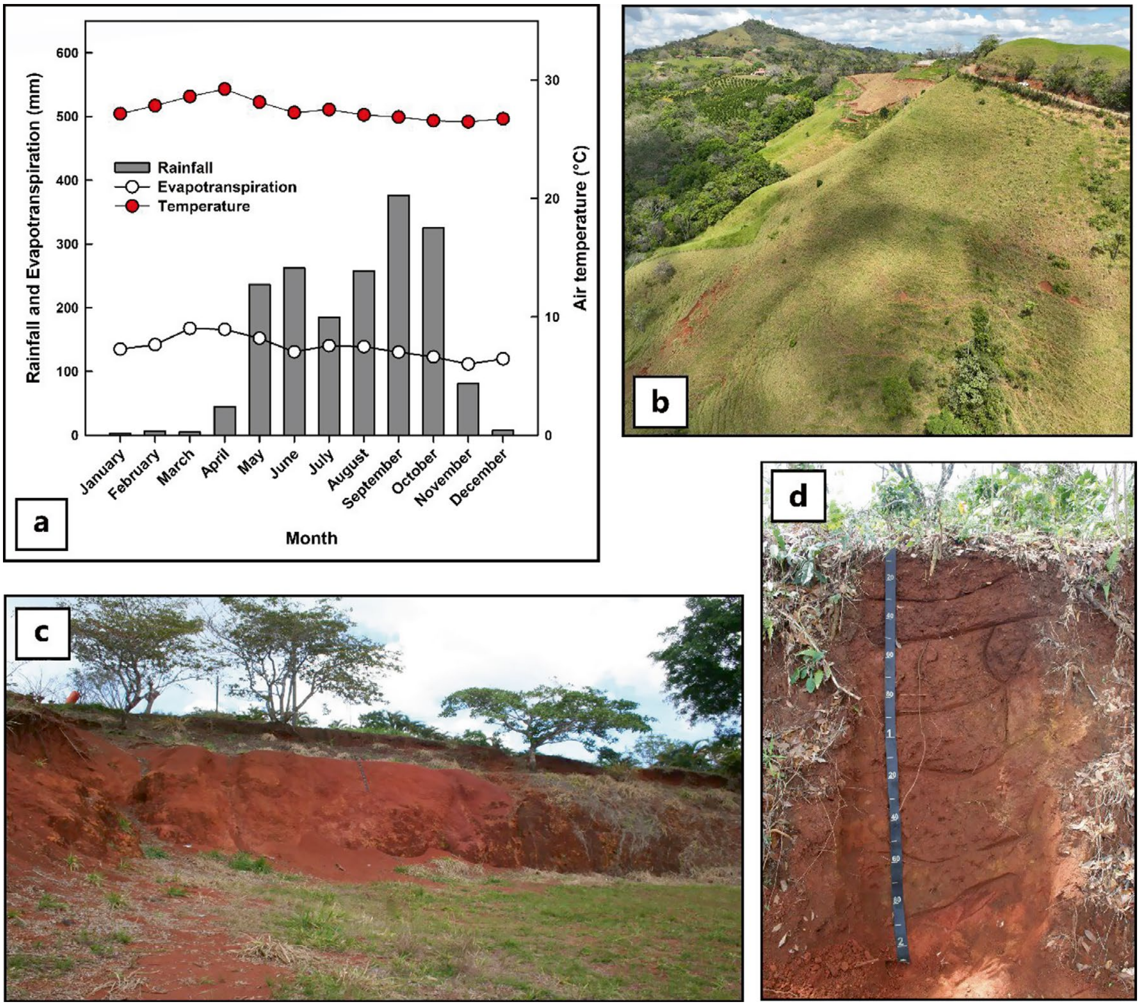

Fig. 21.2 Climate, landforms, and soils in the Mountains of Peninsula de Nicoya: **a** Atmospheric water balance estimated for the town of Hojancha, showing six months of water deficit; **b** Steep slopes and land denudation showing clayey reddish materials; **c** Red soil exposed in a soccer field, providing a complete view of the soil profile; **d** Typical soil observed in the highlands cultivated with coffee (*Coffea arabiga* L.)

the plant cover observed in this landscape can be classified as Lowland Semi deciduous Wet Forest, with tall plant species with clear defoliation during the dry season such as *Enterolobium ciclocarpum* and *Scheelea rostrata* (Vargas 1992). Likewise, the vegetation found in this region can be classified according to Holdridge's Life Zones as Premontane Wet Forest (wf-P) (Bolaños and Watson 1993), with secondary forest species such as *Cordia alliodora*, *Dalbergia retusa*, *Tabebuia rosea*, and *Lonchocarpus parviflorus*. (Soudre 2004; Granda 2015). In addition, quality tropical hardwood species like teak (*Tectona grandis* L.f.) has become an economic alternative due to its adaptability to dry conditions and timber high productivity (Fernández-Moya et al. 2014).

The soils in this landscape (Fig. 21.2) can be classified within the orders of Alfisols and Oxisols. Camacho et al. (2021), while studying soils in the highlands of Hojancha, classified the soils as *Kandiustalfic Eutrustox,* highly weathered soils with enough contents of exchangeable cations (> 35% base saturation) along all horizons and under an ustic soil moisture regimen. This soil order was previously described in this region by Wilcke et al. (1998), but these authors classified the soils as *Kadiudalfic Eutruduox* (Fig. 21.3), inferring a short drought period that is unlikely to occur under the aforementioned climatic conditions for this landscape. Interestingly, these Oxisols seem to be related with Alfisols, representing a transitional state between the orders Alfisols and Oxisols (as stated in the taxonomic Subgroup *Kandiustalfic*). This is consistent with the *Typic Rhodustalfs* found by Camacho (2016) just 4 km away from the Oxisols, and with other reports on Alfisols-Oxisols associations for other tropical and subtropical regions (Buol and Eswaran 2000). Despite those soils were classified as Oxisols (the most weathered soils within Soil Taxonomy), the exchangeable bases saturation was higher than 85%, in agreement with that found by Moura-Filho and Buol (1972), who described and

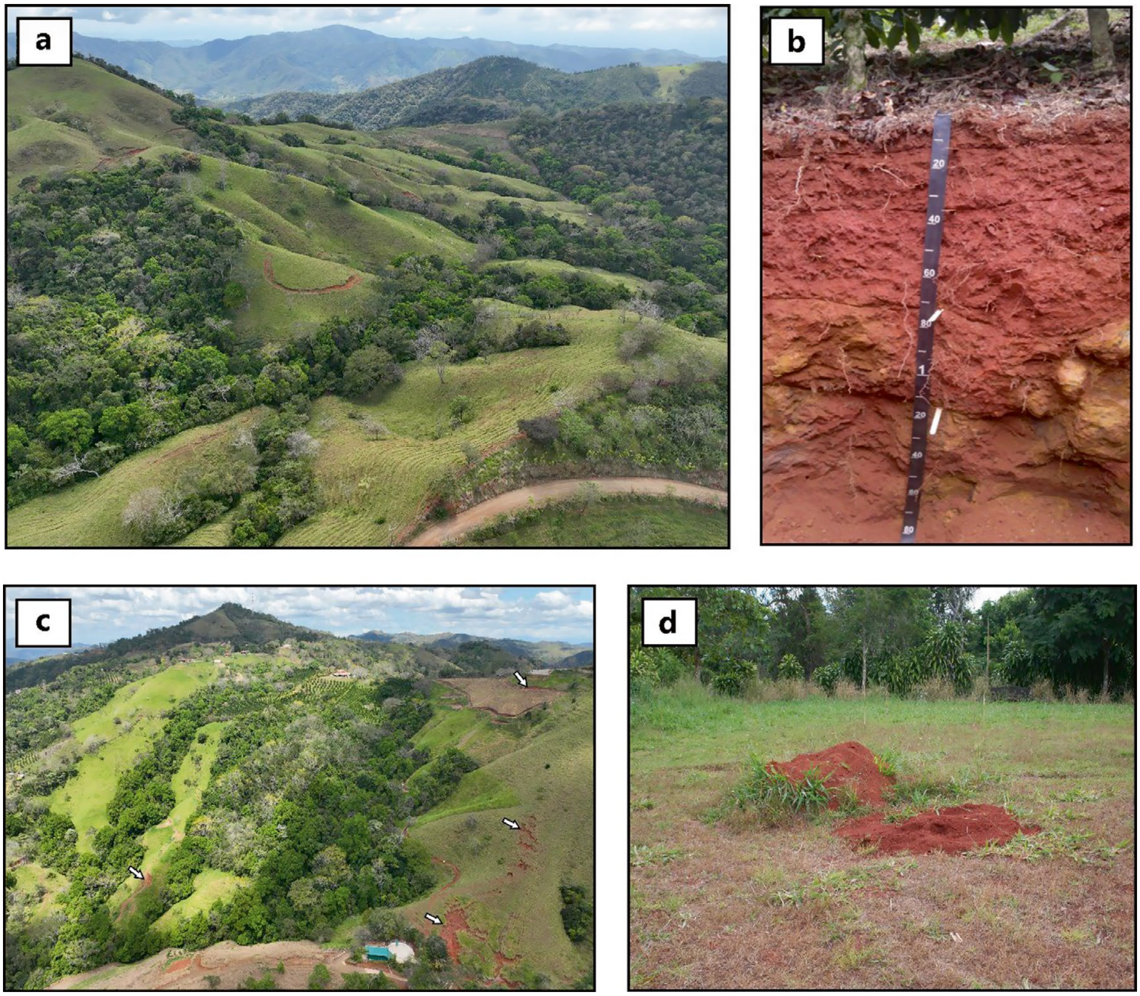

Fig. 21.3 Scenic views, landforms, and soils observed in the Mountains of Peninsula de Nicoya: **a** The mountains of Hojancha, with typical dissected relief and evidence of human activities like coffee (*Coffea arabiga* L.) and orange (*Citrus sinensis* L.) plantations and cattle farms; **b** The profile of a *Kandiustalfic Eutrustox* cultivated with coffee; **c** Steep slopes, road cuts and erosional scars showing clayey reddish materials (highlighted with white arrows); **d** Ant mounds of leaf-cuttler ants (*Atta cephalotes* L.) which show a reddish subsoil taken to the surface

classified "Latosolos Roxos" (*Eutrustox*) in Southern Sao Paulo and Brasilia in Brazil.

21.2.2 Alluvial Fans from Valle del General

Situated in the Central South region of Costa Rica, this landscape extends across the whole Río General Watershed, including the cities of San Isidro del General (Pérez Zeledón) and Buenos Aires de Puntarenas (Fig. 21.4). The current landforms observed developed from the progressive deposition of highly weathered old materials, deposited as alluvial fans during the Pliocene and the Quaternary (Kesel and Spicer 1985; Bergoeing 2011). These old alluvial fans present a clayey-red matrix, with some sandstones, andesitic rocks, and iron stones and duricrusts.

These old alluvial fans (Fig. 21.4) were formed due to extensive processes of deposition, associated with rapid deglaciation of the extensive glaciers that existed in the Cordillera de Talamanca during the Last Glacial Maximum (LGM). In addition, resulting alluvial fans have been modeled by high rainfall rates, high temperatures, and intense weathering processes (Camacho et al. 2020), which progressively have been molding the current fluvial landforms (Quesada-Román and Zamorano-Orozco 2019). In this regard, the rainfall distribution pattern observed in this landscape (Fig. 21.5) is characterized by annual precipitation values of 3050 mm, mainly from May to November. This rainfall pattern allows for a water deficit period (around −380 mm) from December to March, which represents an ustic soil moisture regime for most of the soils. The highest rainfall values occur in August, September, and

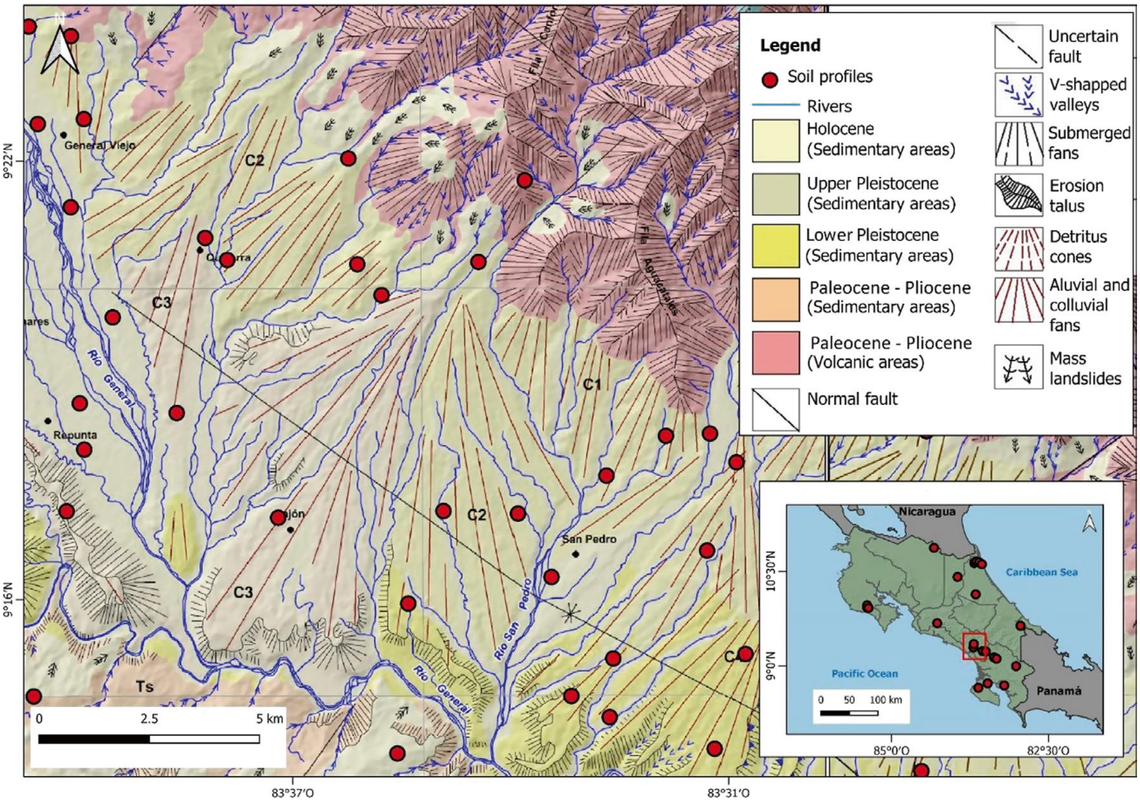

Fig. 21.4 Location, main geomorphologic features, and soil profiles observed in El Valle del General. Adapted from Bergoeing and Brenes (2017)

October (with average monthly values > 350 mm). In addition, the average air temperature reaches the highest values (25 °C) in March, and the lowest in November (21 °C), in agreement with the highest evapotranspiration value (Fig. 21.5).

Those climatic conditions allowed for the development of cash crops like sugarcane (*Saccharum officinarum* L.) (Fig. 21.6), or pineapple (*Ananas comosus* (L.) Merr.) (Fig. 21.7), which in addition to the population growth have been responsible for landscape transformation with time, extending the crop land across the whole area, enhancing land fires and even further formation of savannas (Budowsky 1963; Miranda 1983). Both cash crops represent a fundamental economic activity for this region, based on the high yields observed and the amount of people involved.

The soils of these valleys have been classified as Ultisols and Oxisols. Several literature reports indicate that highly weathered soils are dominant within these alluvial geomorphologic units (Kesel and Spicer 1985; Wilcke et al. 1998). For this region, Camacho et al. (2021) classified the soils as *Plinthic Kandiustox* and *Anionic Acrustox,* the latter being the most weathered soils of Costa Rica. These *Anionic Acrustox* are characterized by quite low values of effective cation exchange capacity (< 1.5 $\mathrm{cmol_c}$ kg clay$-^{1}$) within 150 cm from the soil surface, an ustic soil moisture regimen, pH dependent charge, and presence of lateritic bodies (Fig. 21.7).

Interestingly, those *Acrustox* developed over older alluvial fans (formed 85,000–45,000 y.a.), whereas the *Kandiustox* can be found over intermediate alluvial fans (formed 45,000–7000 y.a.). This difference in time of formation within the parent materials produces changes among the soil-forming processes, which results in different degrees of weathering within these soils classified as Oxisols (Camacho et al. 2020).

21.2.3 Lowlands of San Carlos

This landscape is located in the northern sector of Costa Rica, more precisely in the Central American Physiographic Province of "Nicaraguan depression" (Fig. 21.8; Marshall 2007). This region is characterized by *debris flows* and old alluvial fans deposition from the Guanacaste and Central volcanic ranges in the western sector, with the presence of red and highly weathered matrices (Fig. 21.9), mostly composed by kaolinitic clays (Bergoeing and Protti 2006).

The eastern sector of this landscape presents a diversity of volcanic materials, including some dacitic porphyries mounts, pyroclastic-felsic block deposits, and vitric welded

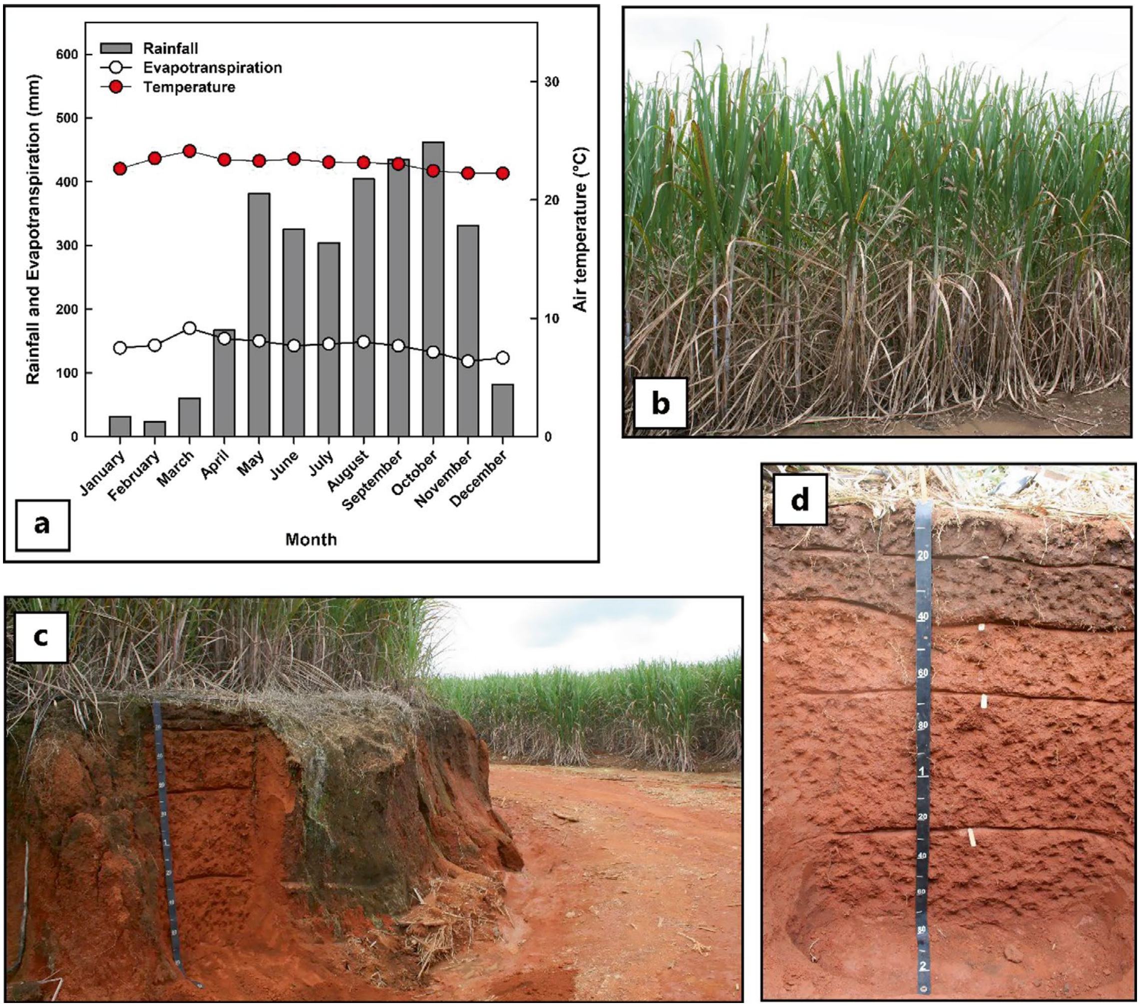

Fig. 21.5 Climate, crops, and soils observed in El Valle del General: **a** Atmospheric water balance estimated for the region of Valle del General, showing 4 months of water deficit; **b** Sugarcane (*Saccharum officinarum* L.); **c** Sugarcane growing over clayey reddish and highly weathered soils within old alluvial fans; **d** The profile of a *Anionic Acrustox* cultivated with sugarcane

tuffs limited by two quartz-stripes (Vargas and Alfaro 1992; Gazel et al. 2005). All these materials have been suffering from intense weathering processes, which are enhanced due the climatic conditions. Solano and Villalobos (2001) and Korpela (2014) described the region "Llanuras de San Carlos" as very rainy, with annual precipitation values around 3020 mm, with two months without rainfall (considered as a short drought period) (Fig. 21.9). This region presents an average air temperature of 23 °C, with minimum and maximum values of 20° and 31°, respectively. These climatic conditions promote the growth of a number of plant species typical of Tropical wet forest (wf-T), with heights that could reach 40–60 m. Among them are *Anacardium excelsun*, *Ceiba pentandra,* and other important forestry species like *Vochysia guatemalensis, V. ferruginea, Gmelina arborea,* and *Terminalia amazonia* (Fagan et al. 2015). More recently, the crop pineapple (*A. comosus*) has been extending within the northern side of this landscape, covering marginal areas, where cattle and forestry plantations were formerly established (Figs. 21.10 and 21.11). Other important crops (mostly in low input agriculture) found in this landscape are common red and black beans (*Phaseolus vulgaris* L.,), cassava (*Manihot esculenta* Crantz), and some extensive crops like orange (*C. sinensis* L.).

Soil development in this landscape reflects intense weathering processes acting over igneous materials, enhanced by hot and rainy environments which promote leaching and neoformation of sesquioxic and kaolinitic clay minerals. As a result, soils have been classified as *Plinthic Kandiudox*, *Typic Rhodudults,* and *Typic Haplohumults* (Fig. 21.9). Highlighted are these Oxisols, which present the development of plinthite within their bottom subsoil

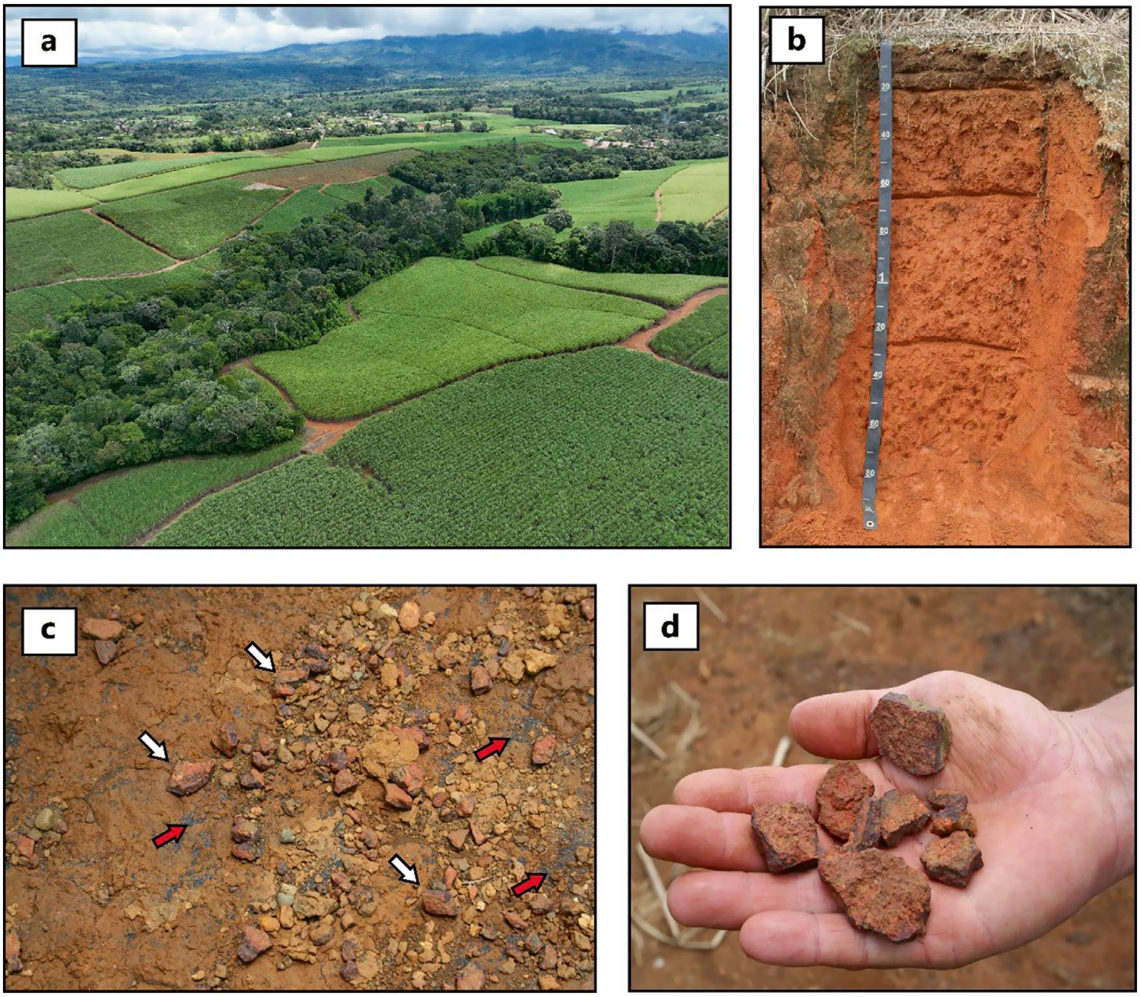

Fig. 21.6 Crops, soils, and special features observed on Quaternary alluvial fans: **a** Extensive areas cultivated with sugarcane (*Saccharum officinarum* L.); **b** A typical soil profile observed in the plantations of sugarcane; **c** Deposits of magnetite grains (red arrows), and iron-rich duricrust (white arrows); **d** Zoom picture of the iron-rich duricrust observed

horizons. This feature indicates (i) potential fluctuation of the groundwater table, allowing the differentiation of iron forms and further hardening, and (ii) changes within the landscapes which prevent erosion and degradation of plinthic materials (Eze et al. 2014).

In general, these weathered soils have low fertility (high soil acidity, low content of nutrients) which present a constraint for most of agricultural crop’s development, except the pineapple crop which is tolerant to soil acidity (Figs. 21.9 and 21.10). Nonetheless, there are some areas where the plinthite formation close to the soil surface represents a serious restriction for root growth and water movement, providing conditions for redoximorphic features development like glei colors (Fig. 21.11).

Consequently, it is not surprising that economic activities like agriculture and cattle production are limited in this landscape, constraining human settlement and therefore population growth and development. Nevertheless, in 1992, gold ores were discovered within the subsoil in the northern part of this area (Crucitas de Cutris), which could represent a potential economic activity. Indeed, Crucitas Mine Project (Fig. 21.11) was intended to start gold extraction in 1999, but the project was shut down due to a resolution from the Costa Rican Constitutional Court (Korpela 2014).

21.2.4 Mountains of Peninsula de Osa

This landscape is located in the southeastern part of Costa Rica, extending along the inner shore of Golfo Dulce and inward of the Peninsula (Fig. 21.12). This landscape is described as a litho-stratigraphic unit, composed by a sedimentary layer overlying basaltic materials, formerly associated with the Nicoya Oceanic Complex. Subsequently, these materials were reclassified as: (a) Golfito Terrain (90–64 Ma) mostly composed of basalts, breccias, and

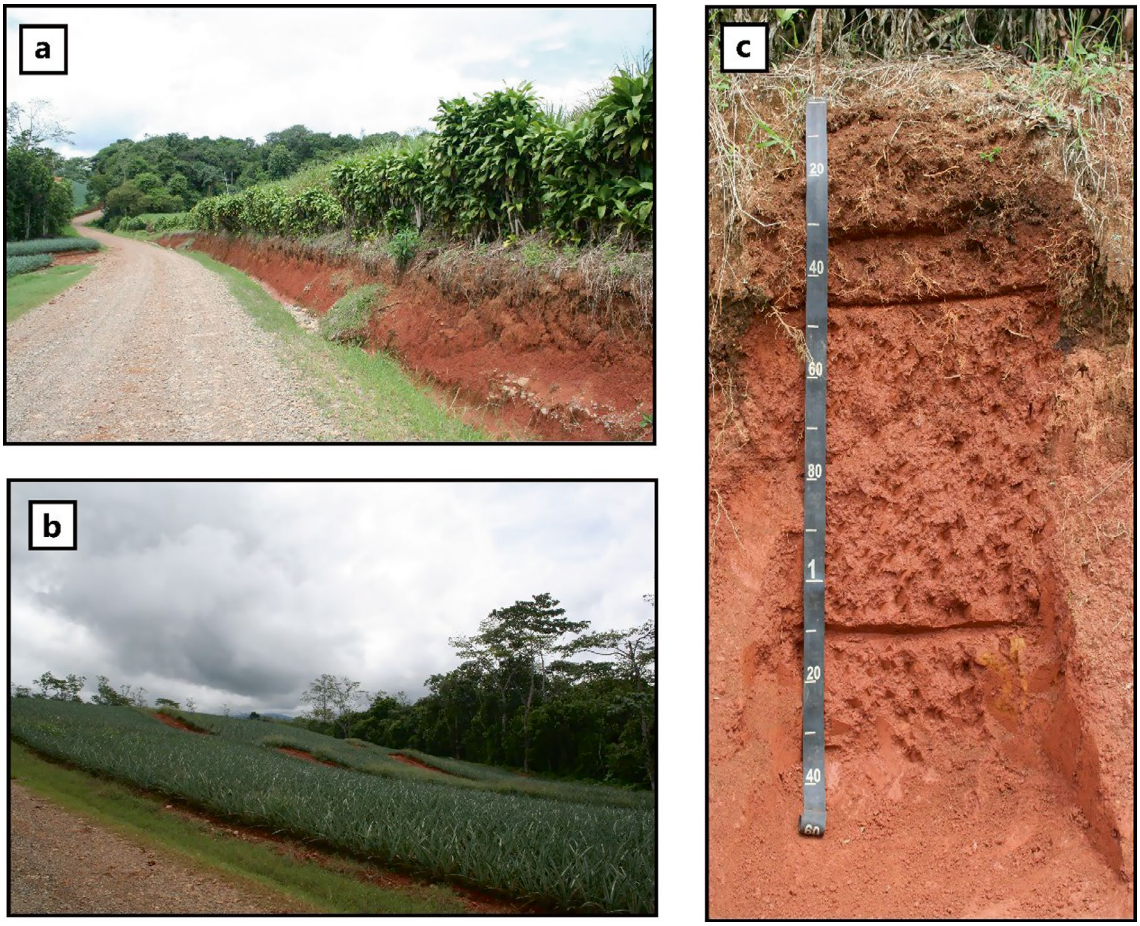

Fig. 21.7 Typical landscape with pineapple fields on Quaternary alluvial fans: **a** Road slope that extends along the whole field, exhibiting a distinct red soil; **b** Field planted with pineapple (*Ananas comosus* (L.) Merr.), in specific sowing beds arrangement; **c** The soil profile observed in this pineapple field, described as deep, reddish, and highly weathered soil

dolerites, with interbedded pelagic sediments from the upper Maastrichtian; and (b) Rincón Block (62–54 Ma) with accreted seamounts composed by basaltic materials (Denyer and Gazel 2009). According with Marshall (2007), the geomorphologic unit "Mountain range of Peninsula de Osa" belongs to the Central American Physiographic Province "Chorotega fore arc". This mountain range crosses the Peninsula from NW–SE, with rivers draining the mountains toward the flatlands and separating among tectonic and erosive geoforms, with highly weathered clay materials and saprolite exposed by landslide activity (Fig. 21.13).

Climatic conditions observed in this region are described as warm and wet (Solano and Villalobos 2001). For instance, total annual precipitation is 4282 mm (Fig. 21.14), with the highest monthly average values during August–October (more than 500 mm month^{-1}). This rainfall pattern also suggests a very short dry period (January and February), with a clear decrease of precipitation (< 200 mm month$-^{1}$). The annual average, minimum, and maximum temperature values are 27 °C, 23 °C, and 30 °C, respectively.

These particular climatic conditions allow for the growth of Tropical wet forest (wf-T) species according with Holdridge's Life Zones System (Bolaños and Watson 1993). Among these species, *Peltogyne purpure* Pittier (aka "Nazareno" or Purpleheart wood) is highlighted, a precious wood that currently is forbidden to cut down, being an endangered species. Despite this, the forest has been submitted to fractioning and deforestation, mostly associated to emerging development of extensive crops like oil palm (*Elaeis guineensis* JACQ) and cattle (Rosero-Bixby et al. 2002).

Within this landscape, the mountains and other elevated landforms present clayey deep soils with a characteristic reddish pattern (Fig. 21.15). These soils were previously described as Oxisols (Cleveland et al. 2003), but that study did not provide enough data to support this taxonomic classification. More recently, Camacho et al. (2021) studied and characterized the soils of Rincón de Osa, classifying

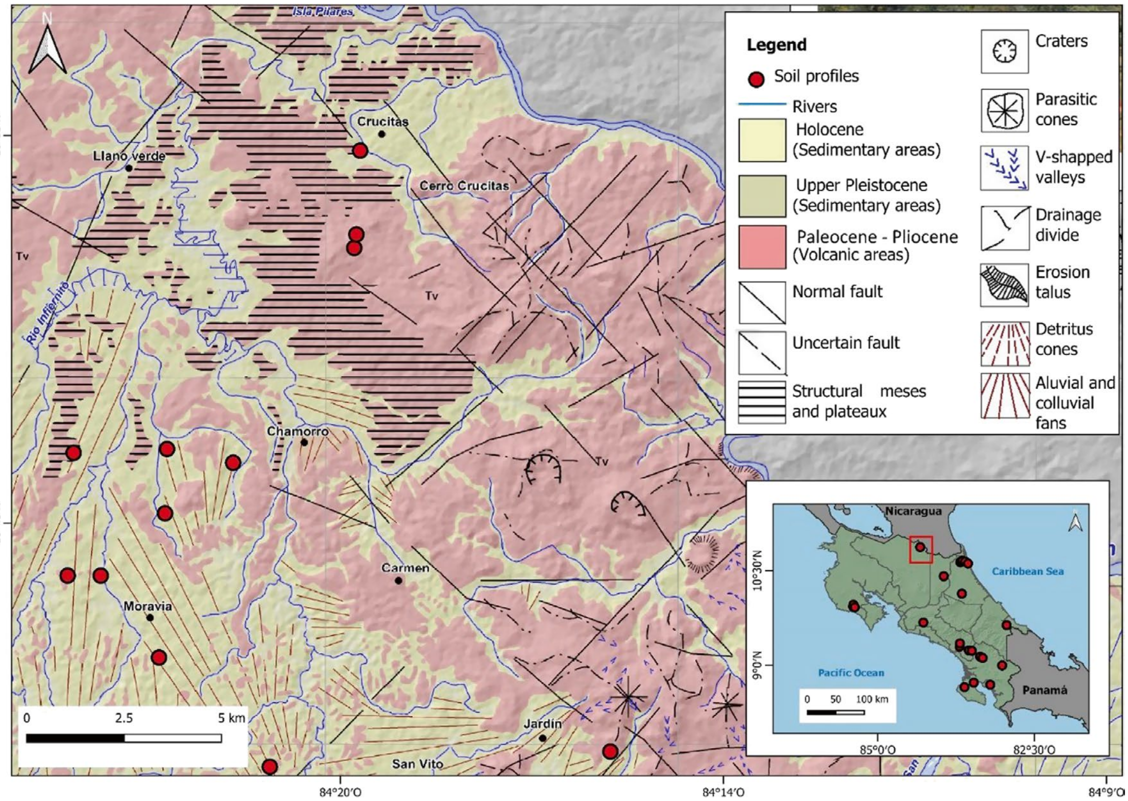

Fig. 21.8 Location, main geomorphologic features, and soil profiles observed in the Lowlands of San Carlos. Adapted from Bergoeing and Brenes (2017)

these soils as *Rhodic Kandiudox*, and confirming the presence of these highly weathered soils at Península de Osa (Fig. 21.15).

Rhodic Kandiudox is typically dark reddish soils (Hue 10R 3/6 or redder), with a kandic horizon where the content of weatherable minerals is less than 10%. These soils have normally a low exchangeable bases content (lower than $5\ \mathrm{cmol_c\ kg^{-1}}$) within the subsoil horizons, but present excellent soil physical properties (Camacho et al. 2021). These soil morphological patterns (clayey soils with reddish colors) were observed along the whole landscape (Figs. 21.14 and 21.15).

21.2.5 Mountains of Tortuguero-Barra del Colorado

The mountains of Tortuguero-Barra del Colorado are located in the northeastern part of Costa Rica, bordering the San Juan River delta with the Caribbean Sea (Fig. 21.16). These mountains are surrounded by lowlands composed by marine sediments and fluvial-volcanic deposits from the Quaternary (Nieuwenhuyse 1996). In general, these mountains are described as Quaternary conic-basalts with a dated age of 1.2 ± 0.4 Ma (Alvarado et al. 1992; Gazel et al. 2011). These basaltic cones are lower than 300 m asl and represent fissure eruptions (Fig. 21.17).

This landscape is included within the Central American Physiographic Province of "Chorotega back arc", described as an alluvial plain dissected by a network of rivers (Fig. 21.16) that drain waters from the elevations of the Central Volcanic Range to the Caribbean (Marshall 2007). The flatness of the coastal plain is abruptly interrupted by low-elevation mounts. For instance, highlights two mounts: (1) Cerro Cocorí (an ancient volcanic cone, dated from the Pliocene) and Cerro Coronel (an eroded volcanic cone, dated from the Pleistocene) (Nieuwenhuyse 1996). These mounts reaching elevations lower than 400 m asl, modifying the distribution of vegetation patterns and the course of the rivers that drain into the Caribbean coast providing differentiating conditions for soil formation (Figs. 21.17 and 21.18).

Climatic conditions observed in this region are particularly complex, described as hot and very wet (Solano and Villalobos 2001). The total annual precipitation is around 4860 mm (Fig. 21.17), where the highest monthly average values are observed from July to November (more than 450 mm month–^{1}). Because the rainfall surpasses the monthly average evapotranspiration during all twelve months, a clear dry period does not occur. Typically, there is a clear decrease in rainfall ($< 200\ \mathrm{mm\ month^{-1}}$) in March.

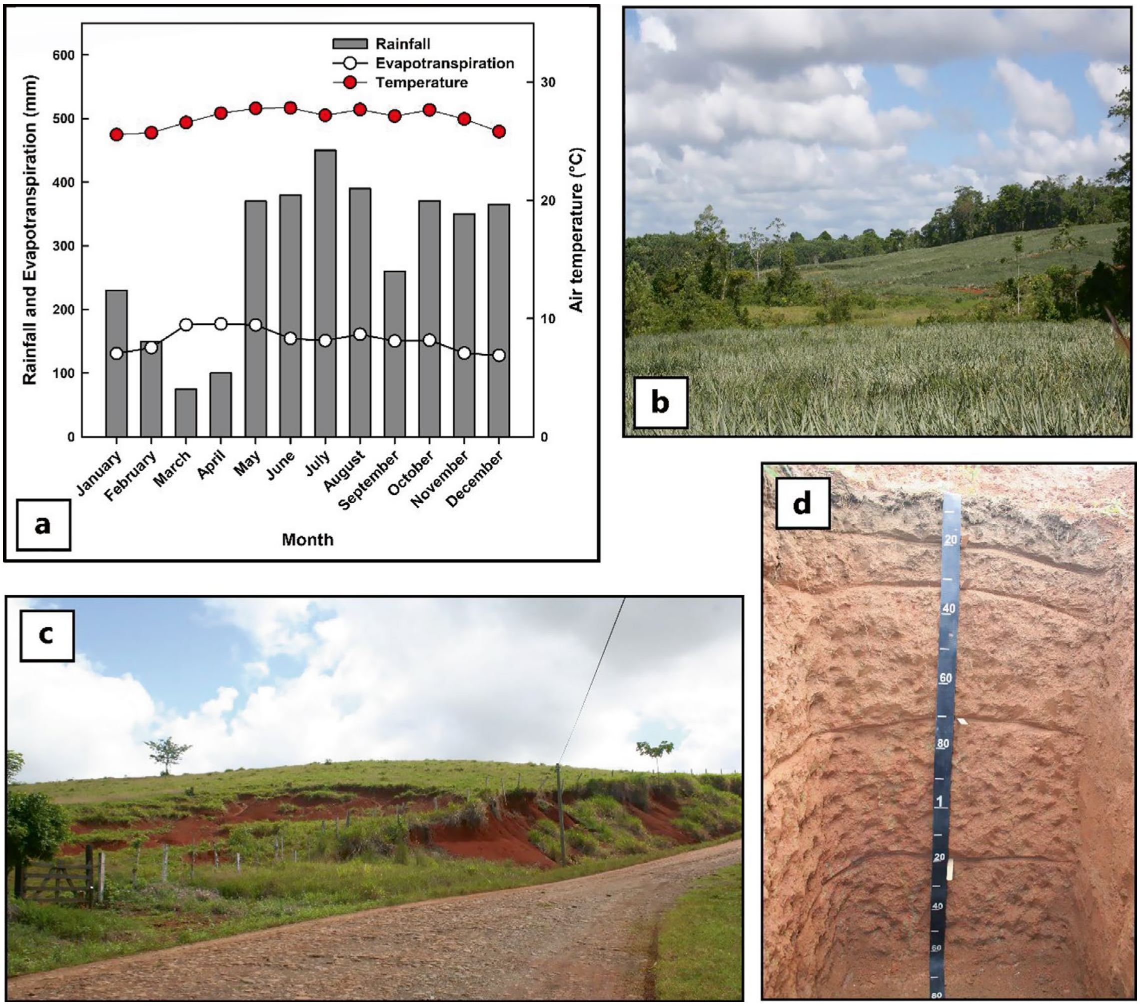

Fig. 21.9 Climate, crops, and soils observed in the Lowlands of San Carlos: **a** Atmospheric water balance estimated for the town of Crucitas de Cutris, with just two months of water deficit; **b** Field planted with pineapple (*Ananas comosus* (L.) Merr.), **c** Grassland with clayey reddish soils exposed in erosional scars; **d** The profile of a *Plinthic Kandiudox* studied in Crucitas de Cutris

In addition, the annual average, minimum, and maximum temperature values are 26°, 24°, and 28 °C respectively.

These climatic conditions allow to classify the vegetation within this landscape as Tropical wet forest (wf-T) according to Holdridge´s Life Zones System (Bolaños and Watson 1993). On the other hand, Vargas (1992) described this vegetation as low-height evergreen wet forest species, typical of lowlands forests. The key species include *Terminalia chiriquensis* Pittier, *T. amazonia* (Gmel.) Excell, and *Calophyllum brasiliense* Cambess (Figs. 21.18 and 21.19).

The soils within this landscape are contrasting. For instance, young alluvial soils (Inceptisols) have developed along the coastal plain, while highly weathered soils (Oxisols) have been observed in the elevations of lomas del Cerro Cocorí and Cerro Coronel (Fig. 21.17). The soils developed from the alluvial deposits have been classified as the following soil suborders: Aquepts, Udepts, and Aquents (Mata et al. 2022), all with very low degree of pedologic development, and saturation issues. More recently, Camacho et al. (2021) revisited the weathered soils previously described in the highlands of Coronel and reclassified as *Andic Haploperox* (Fig. 21.19). These soils developed within a perudic soil moisture regime, this meaning no soil water deficit (Fig. 21.19), but the soil does not saturate enough (due to high hydraulic conductivity) to get reduced iron forms. In addition, these soils present certain andic properties, like low bulk density values and high $PO_4{-}^{1}$ retention.

This landscape offers limited opportunities for agricultural activity, focused mainly on subsistence crops and small cattle farms, mostly due the climatic conditions and low fertility of predominant soils. However, scenic qualities of the area are worth emphasizing, including the delta of the San Juan River and the contrasts made by differentiated vegetation within the highlands and the lowlands (Fig. 21.17), in addition to high biodiversity in both flora

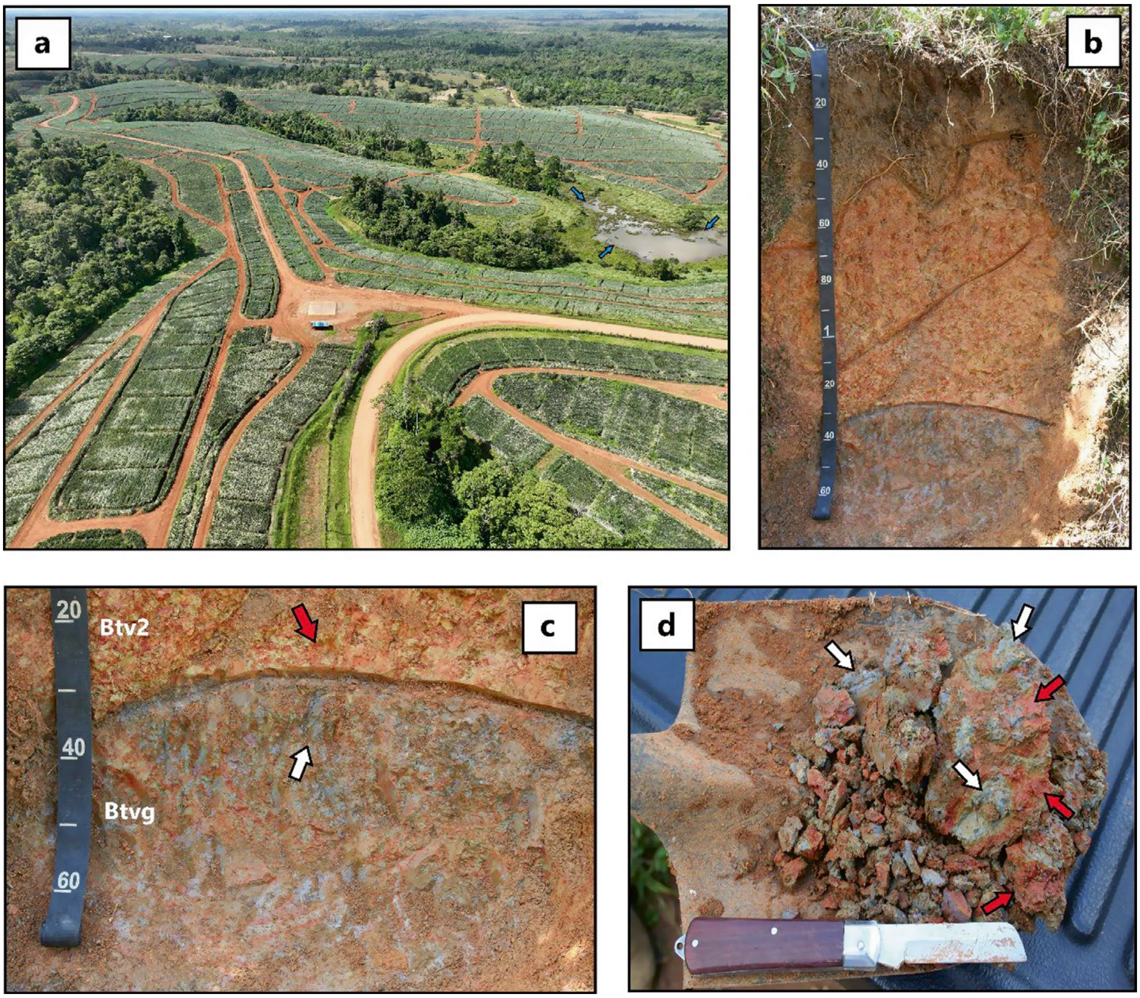

Fig. 21.10 Agricultural activities and typical soil features within the Lowlands of San Carlos: **a** Field planted with pineapple (*Ananas comosus* (L.) Merr) in El Concho de Cutris, with wetlands located in low-lying areas (blue arrows); **b** A soil profile observed in Crucitas de Cutris; **c** Boundary between contrasting soil horizons with plinthite Btv2 (red arrow) and bluish reduced iron conditions Btvg (white arrow) indicating possible fluctuation of water table; **d** Zoom picture of redoximorphic features observed in the horizon Btvg, showing reduced iron (white arrows) and oxidated iron forms (red arrows)

and fauna. These characteristics could be exploited through eco-touristic projects with a minimum environmental impact and considerable positive social impact, especially for this region with high poverty rate and low human development index.

21.3 Genesis of Highly Weathered Soils in Costa Rica

21.3.1 Parent Materials

Parent materials observed in landscapes presented above can be grouped according to their geologic features and ages within four main general categories: (1) Basaltic rocks from Jurassic-Miocene Oceanic complexes; (2) Igneous materials of Paleocene-Pliocene age; (3) Sedimentary materials of Pliocene–Pleistocene age, (4) Volcanic materials of Pleistocene age.

21.3.1.1 Basaltic Rocks from Jurassic-Miocene Oceanic Complexes

Bedrock presented in the mountains of Península de Nicoya and Península de Osa was originally classified within a great geological unit of "Nicoya Ophiolite Complex" (Berrangé and Thorpe 1988), but more recently, basaltic materials within these two landscapes were separated and reclassified, based on rock dating, into two main geologic units (Denyer and Gazel 2009): Nicoya Complex (Jurassic to Cretaceous, 139–83 Ma) and Rincón Block (Paleogene,

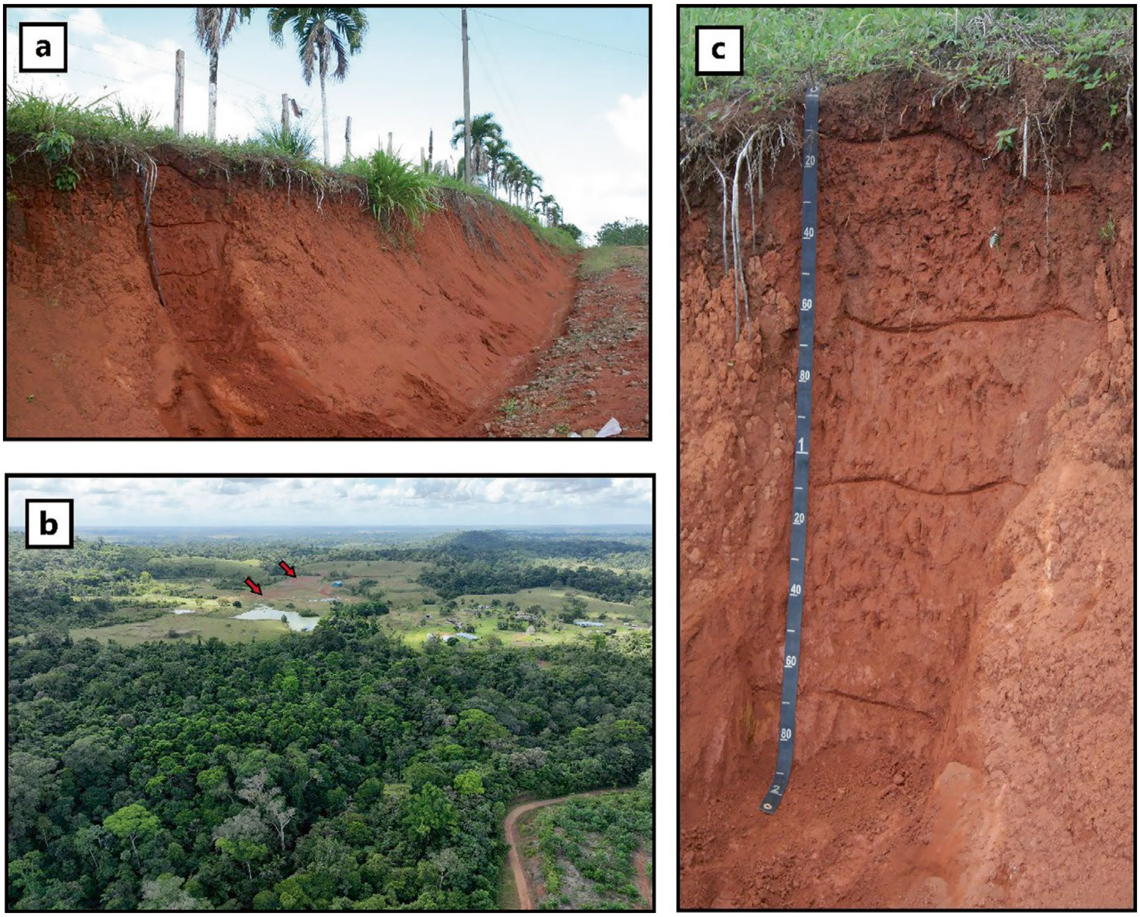

Fig. 21.11 Other human activities and associated soils observed in the Lowlands of San Carlos: **a** Road cut that extends along the whole road to Crucitas de Cutris, exhibiting a weathered reddish deep soil; **b** Headquarters of former Crucitas Mine Project, where red soils can be observed (red arrows); **c** The soil profile observed in the road cut (A)

55–62 Ma), respectively. This differential exposure of easily weatherable materials (e.g., basaltic, and ultramafic rocks) in time and space to non-uniform conditions has been described as a suitable background for the development of Oxisols and associated Alfisols and Ultisols (Buol and Eswaran 2000), in agreement with the taxonomic Subgroups observed in both landscapes (Camacho et al. 2021).

21.3.1.2 Igneous Materials of Paleocene-Pliocene Ages

The Paleocene and Pliocene in Costa Rica (65–2 Ma) were characterized by intense volcanic activity throughout the emerging regions, creating extensive areas of depositions of pyroclastic rocks, lahars, and further sedimentary materials (Bergoeing and Brenes 2017). In this regard, parent materials described within the landscape Lowlands of San Carlos are essentially pyroclastic rocks, dacitic and rhyolitic lavas, and welded tuffs (Alvarado et al. 1992; Gazel et al. 2005).

These old volcanic materials are highly susceptible to weathering processes, especially under the climatic conditions of the tropics. For instance, rhyolitic rocks include amphiboles, green hornblende, and plagioclase phenocrystals (Gazel et al. 2005), all of them easily weatherable, so that under the conditions of protracted exposure to humid tropical the development of Oxisols (Buol and Eswaran 2000), or other soil taxonomic orders like Ultisols (West et al. 1997), will take place.

21.3.1.3 Sedimentary Materials of Pliocene–Pleistocene Ages

These materials have been exclusively identified in Valle del General and linked with the glaciation during the LGM, which took place in this specific region of Costa

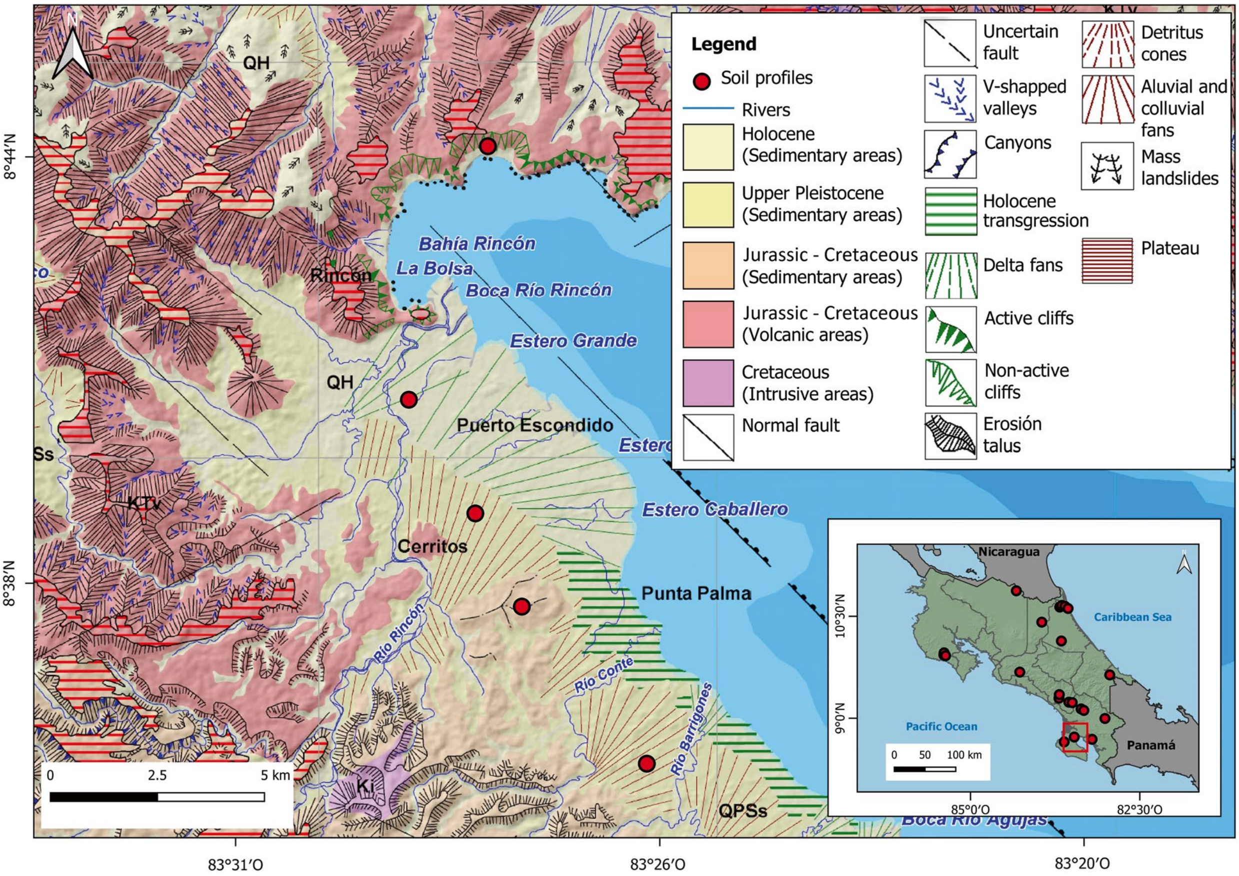

Fig. 21.12 Location, main geomorphologic features, and soil profiles observed for the landscape Mountains of Peninsula de Osa. Adapted from Bergoeing and Brenes (2017)

Rica (Quesada-Román et al. 2020, 2021). After accelerated deglaciation in the Talamanca Mountain Range (Quesada-Román et al. 2019), high volumes of sediments were deposited as massive alluvial fans along the whole piedmont (Camacho et al. 2020). These extensive geomorphic units are unique in Costa Rica (Quesada-Román and Zamorano-Orozco 2019).

Because these sediments were previously weathered and reworked during the transport, and they form very stable and extensive landforms, they allowed for the formation of highly weathered soils like Oxisols and Ultisols (Camacho et al. 2020), even within timespans shorter than 100,000 years. This relative geomorphic stability could have led to a feasible genetic process that gave rise to highly weathered soils such as Oxisols or Ultisols. Kesel and Spicer (1985) highlighted large clastic elements observed within these alluvial fans that have been turned into clay, which could indicate that weathering processes in both rocks and soils occurred in situ. Indeed, these clayey and red matrices commonly observed in old alluvial fans have become a pattern along this great landscape, where highly weathered soils like Oxisols and Ultisols have been identified (Kesel and Spicer 1985; Camacho et al. 2021). This is consistent with observations by Chen et al. (2015), who described Oxisols and Ultisols in Taiwan, genetically associated with Quaternary terraces formed from old alluvium.

21.3.1.4 Volcanic Materials of Pleistocene Age

The Quaternary history in Costa Rica (2.58–0 Ma) also included volcanic activity and associated deposition events (Bergoeing and Brenes 2017). For instance, Cerro Coronel and the corresponding mountain range are described as remnants of volcanic cones built of alkaline basaltic materials formed approximated 1.2 Ma and potentially extended up to Holocene age (Alvarado et al. 1992). These geologic materials support pedogenetic processes that result in highly weathered soils such as Oxisols and Ultisols. In this regard, Buol and Eswaran (2000) asserted that the development of Oxisols is likely when old volcanic areas within the Tropics are subjected to intensive climatic conditions, in agreement with the assessment provided by Camacho et al. (2021) for this region of Costa Rica.

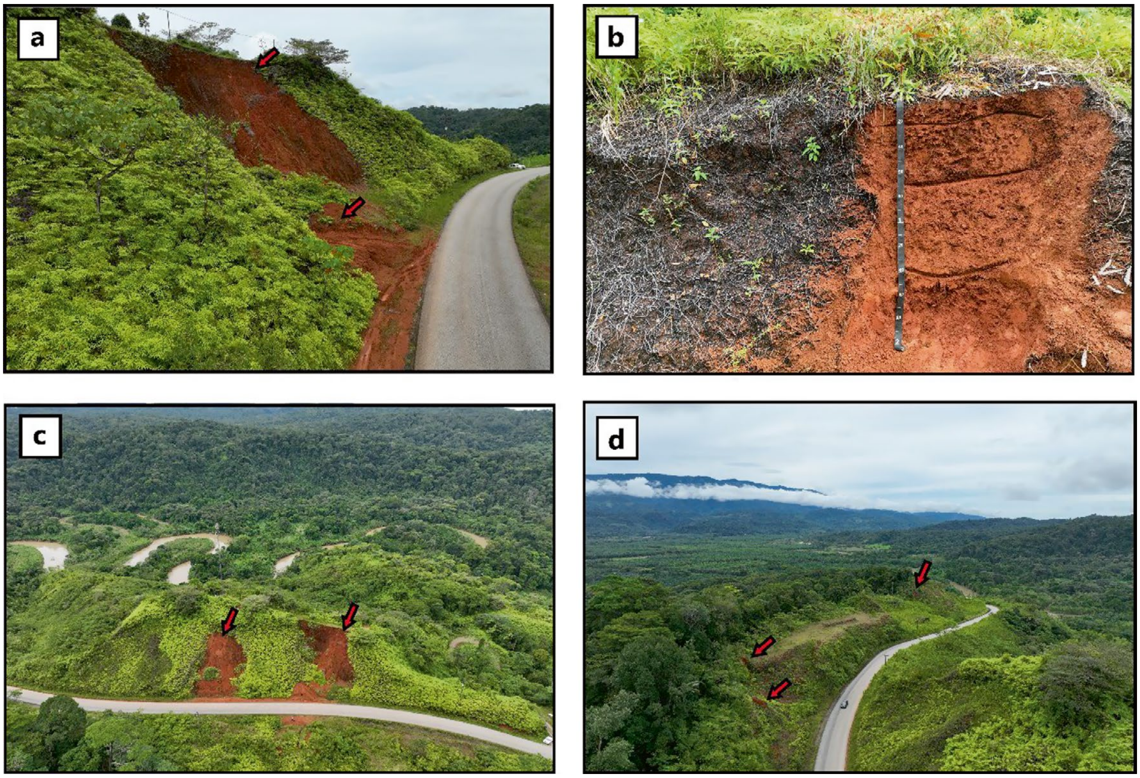

Fig. 21.13 Morphology and some landform features in the Mountains of Peninsula de Osa: **a** Slope next to the highway, covered by abundant vegetation which hides the parent material (visible after the landslide, and highlighted with red arrows); **b** A soil profile studied within these mountains, **c** River meanders behind a small elevation, where two landslides (30 m height) display the presence of a clayey matrix and reddish soils (red arrows); **d** A highway across the mountains, providing perspective about the elevations within this landscape in contrast with the Talamanca Mountain Range, with red soils observed in the top (red arrows)

21.3.2 Rainfall Distribution Within Landscapes and Neoformation Processes

Costa Rica has contrasting climatic conditions across its territory, which are indirectly modified by volcanic and mountain ranges, and the influence of both Caribbean and Pacific coast (Solano and Villalobos 2001). For instance, the province of Guanacaste is considered the driest region, with less than 1900 mm of annual rainfall distributed in 7 months, meanwhile the rainfall pattern in the mountains of Tortuguero-Barra del Colorado is such that more than 4500 mm of precipitation is distributed within 12 months.

Therefore, it is expected to find variations in the pedogenic processes, resulting in different soil taxonomic features. Indeed, different taxonomic subgroups (within Oxisols) were assigned to soils studied within these five landscapes. For example, when comparing *Kandiustalfic Eutrustox* from Península de Nicoya with *Andic Haploperox* observed in the mountains of Tortuguero-Barra del Colorado (Cerro Coronel), one can infer marked differences in fertility, in addition to soil water availability (Camacho et al. 2021).

These variations are associated with differences in the bases and Si leaching rates, and differential neoformation and ferratilization processes associated with changes in rainfall amount and distribution (Nieuwenhuyse and van Breemen 1997; Camacho et al. 2021). This last statement agrees with those results obtained by Pincus et al. (2017), who found in the Pacific Southeastern of Costa Rica that weathering rates could reach up to four times fold under annual rainfall values (higher than 4000 mm) when compared with rates in drier sectors (lower than 2800 mm).

21.3.3 The Fundamental Role of Geomorphology

When comparing these five landscapes, and despite variations in geologic materials and climatic conditions, there is a common factor that allowed for the development of highly weathered soils with similar morphologic features: *very stable geomorphologic units*. Buol and Eswaran (2000) explained the role of stable geomorphic surfaces in the genesis of Oxisols, where regardless the parent material (rock weathering or polycyclic sediments previously weathered)

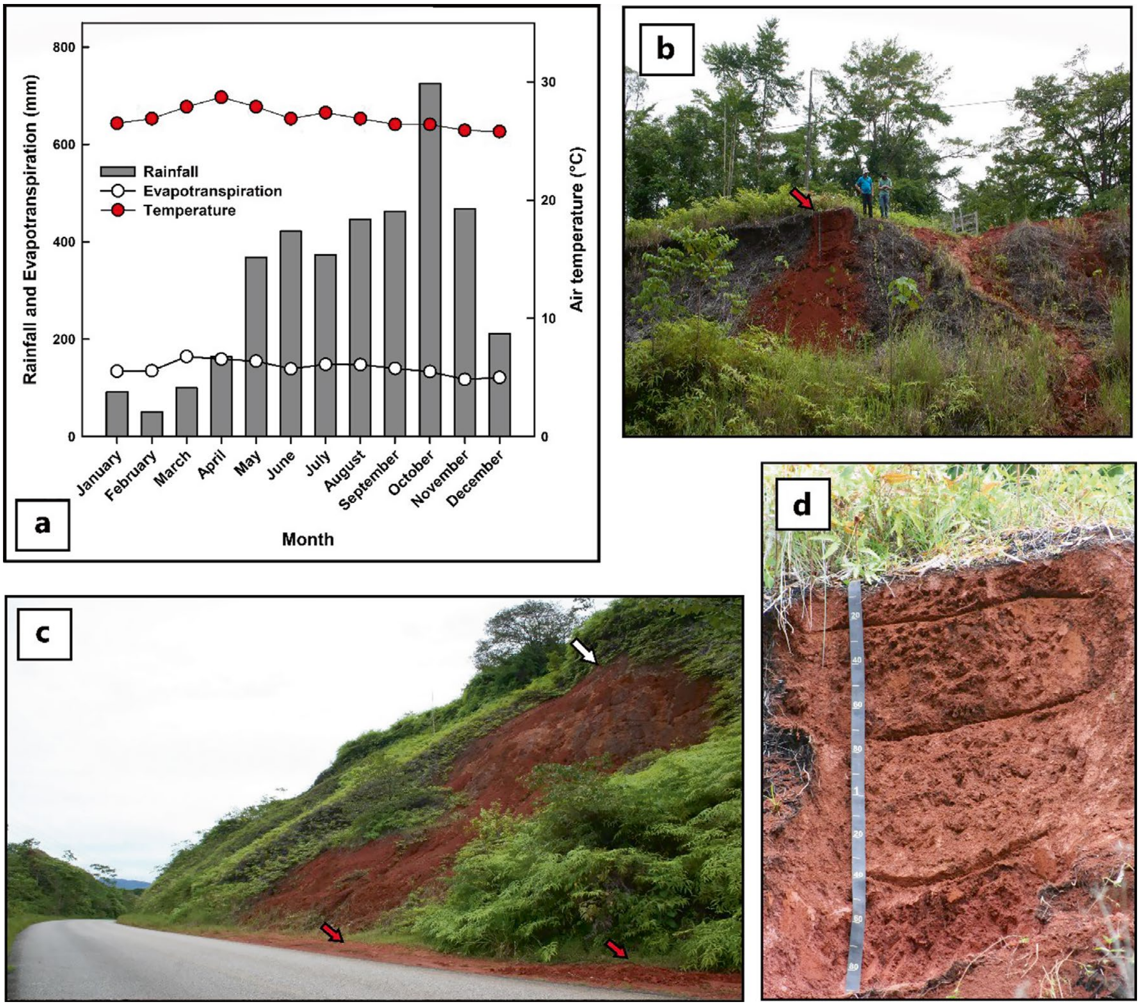

Fig. 21.14 Climate and soils observed in the Mountains of Peninsula de Osa: **a** Atmospheric water balance estimated for the town of Rincón de Osa, with three months of water deficit and high precipitation values from May to November; **b** Top of the mountain with an exposed soil profile (red arrow), and evidence of pluvial erosion along the slope **c** Deposits of red materials (red arrows) along the highway, which are products of landslides and further pluvial erosion from the top of the slope (white arrow); **d** Zoom picture of the soil profile assessed in the top of this mountain presented in panel A

and climatic conditions, this stability can control the occurrence of Oxisols within the landscape. Landscapes assessed in the present work represent diverse examples of stable geomorphic surfaces such as old alluvial fans from the Quaternary within El Valle del General (with higher occurrence of highly weathered soils), the mountains in both Península de Nicoya and Península de Osa, or lowlands in the northern part of Costa Rica (Bergoeing 2007).

Some of the Oxisols developed within the landscape "Alluvial fans from El Valle del General" are considered the most weathered soils of Costa Rica, classified as *Anionic Acrustox* (Camacho et al. 2021). Despite ages between 200,000 and 7000 years ago, these materials were weathered before their deposition as massive alluvial fans (Quesada-Román and Zamorano-Orozco 2019). Then, landform stability allowed for the genesis of highly weathered soils even within younger materials.

Conversely, in landscapes with older geologic materials under higher precipitation regimens, soils are consider highly weathered, but taxonomically they seem to be less weathered than those mentioned above. For instance, within the mountains of Peninsula de Osa, Oxisols developed from basaltic rocks (around 60 Ma) were classified as *Kandiudox*, which compared with the aforementioned *Acrustox, and* are considered less weathered soils (Camacho et al. 2021).

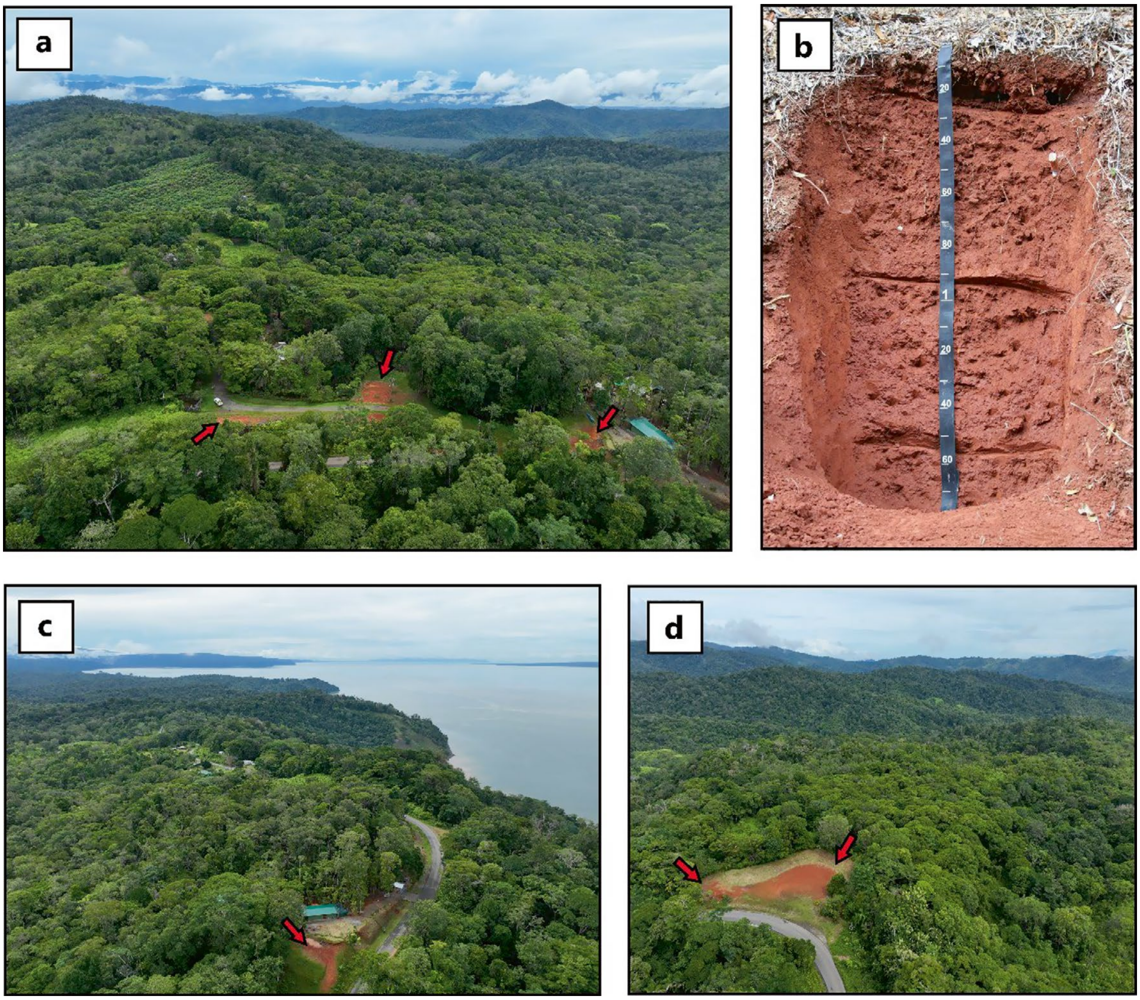

Fig. 21.15 Panoramic views and distribution of red soils within the Mountains of Peninsula de Osa: **a** Scenic view of the elevations in Rincón de Osa (foreground), diverging with Talamanca Mountain Range (background) and red soils (red arrows); **b** A *Rhodic Kandiudox*, studied in the elevation of Rincón de Osa; **c** The upper coast of Dulce Gulf contrasting the elevations with the presence of red soils (red arrow); **d** Cleared area within the mountains, where red soils are visible (red arrows)

21.4 Conclusions

Highly weathered soils (Oxisols and Ultisols) have been identified in diverse landscapes of Costa Rica. Despite this country has a "young geological age", there are other fundamental features that allowed for the development of highly weathered soils, similar to regions which are geologically much older. Diversity in parent materials (various Cenozoic igneous and sedimentary rocks), contrasting climatic conditions and specific geomorphologic features provided the stage for different genetic pathways that resulted in different taxonomic Subgroups found within the five landscapes studied in present work, ranging from *Eutric* Oxisols to the most developed taxonomic groups among the Oxisols: *Acrustox*.

The comparative analysis highlights the fundamental role of geomorphologic features in the development of weathered soils, where highly stable landforms are required

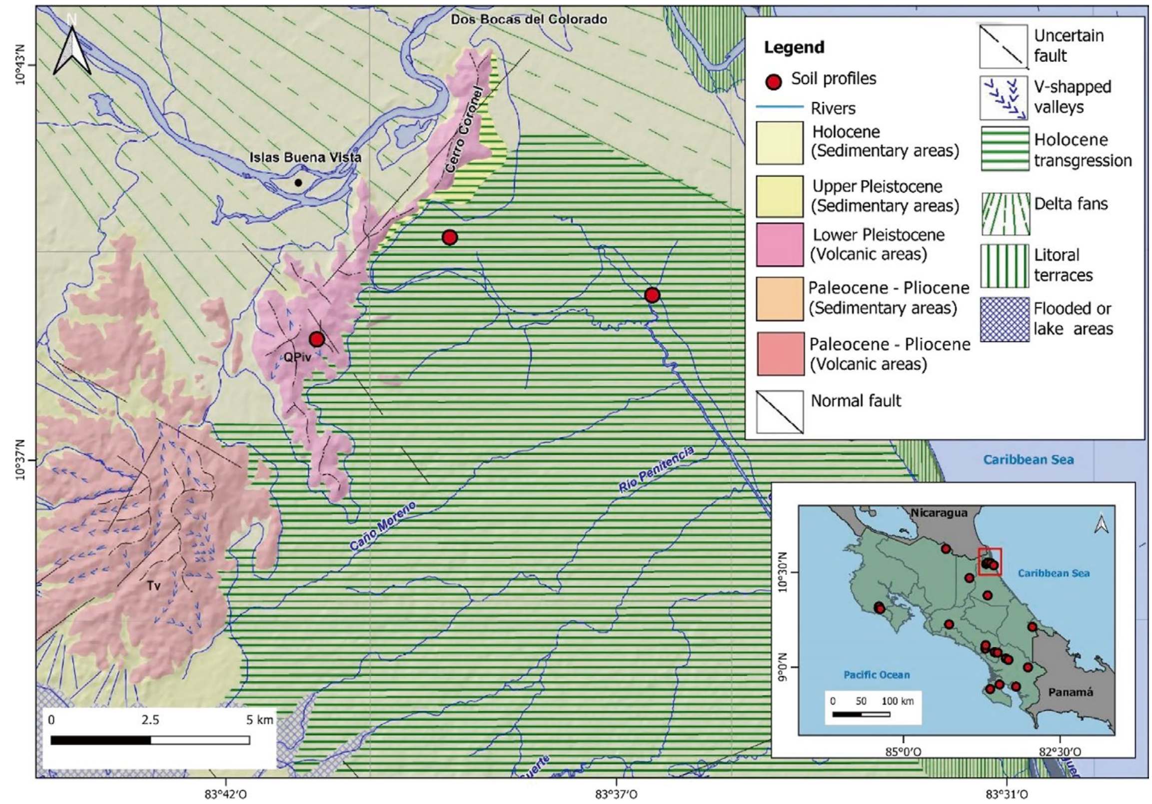

Fig. 21.16 Location, main geomorphologic features, and soil profiles observed in the mountains of Tortuguero-Barra del Colorado. Adapted from Bergoeing and Brenes (2017)

to achieve diverse forming processes (additions, losses, transformations, and translocations) even though the other forming factors are favorable. From economic perspective, these stable landforms allow important cash crop establishment, including coffee and pineapple, which becomes profitable under a proper soil management.

A concise review of soil-forming factors becomes fundamental to understand the origin of soils and their further fate, allowing not only for their taxonomic classification but also better soil management and conservation. All this information should be considered in land-use planning, considering the limitations, trade-offs, and advantages of soil taxonomic subgroups within the landscapes assessed, aiming to optimize the use of available resources with minimum ecological impact.

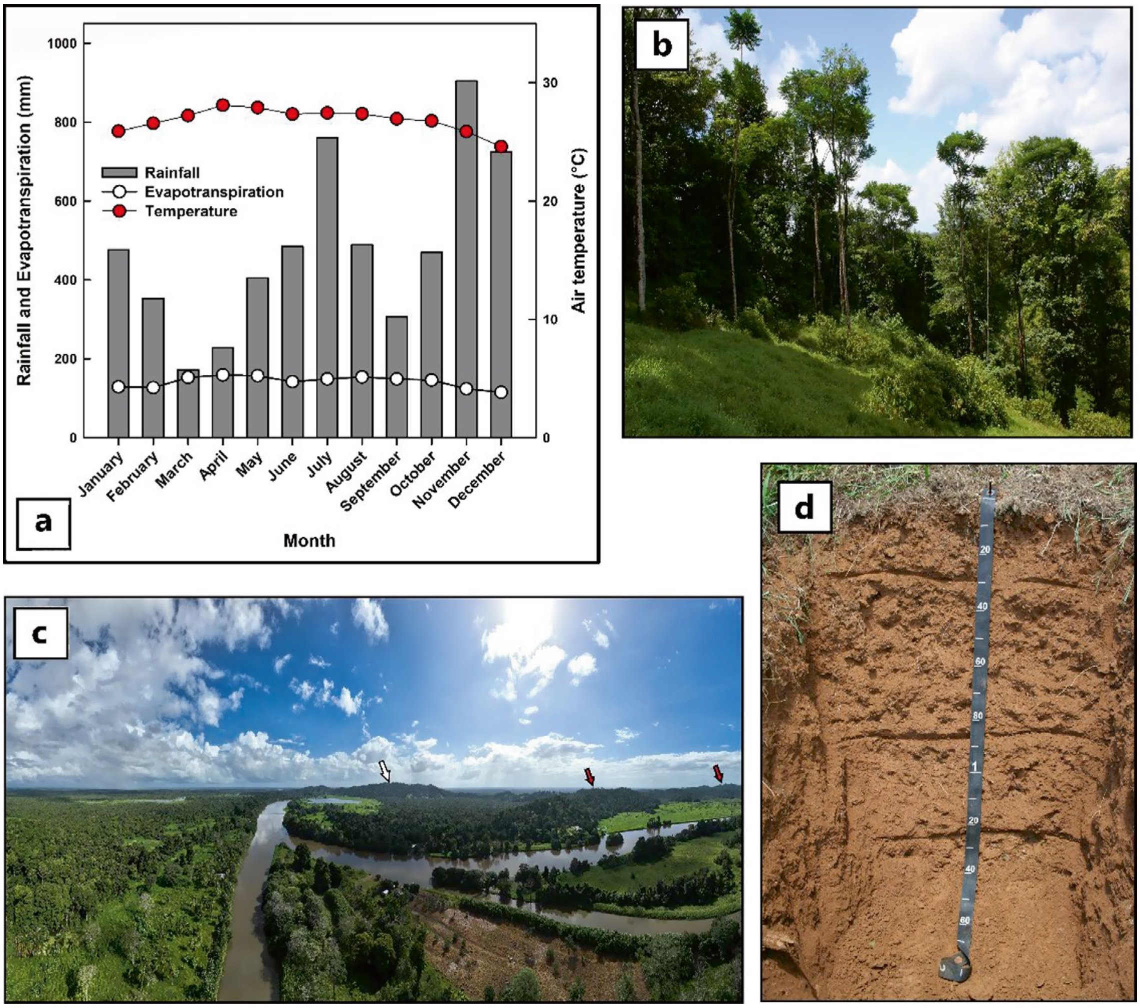

Fig. 21.17 Climate, vegetation, and soils observed in the Mountains of Tortuguero-Barra del Colorado: **a** Atmospheric water balance estimated for the Barra del Colorado, showing no water deficit, and high values of monthly precipitation in July, November, and December; **b** Evergreen vegetation corresponding to Tropical wet forest in Cerro Coronel; **c** Panoramic view of Barra del Colorado, with distant elevations of Cerro Coronel (white arrow) and Lomas del Cerro Cocorí (red arrow); **d** Typical soil observed on the top of Cerro Coronel

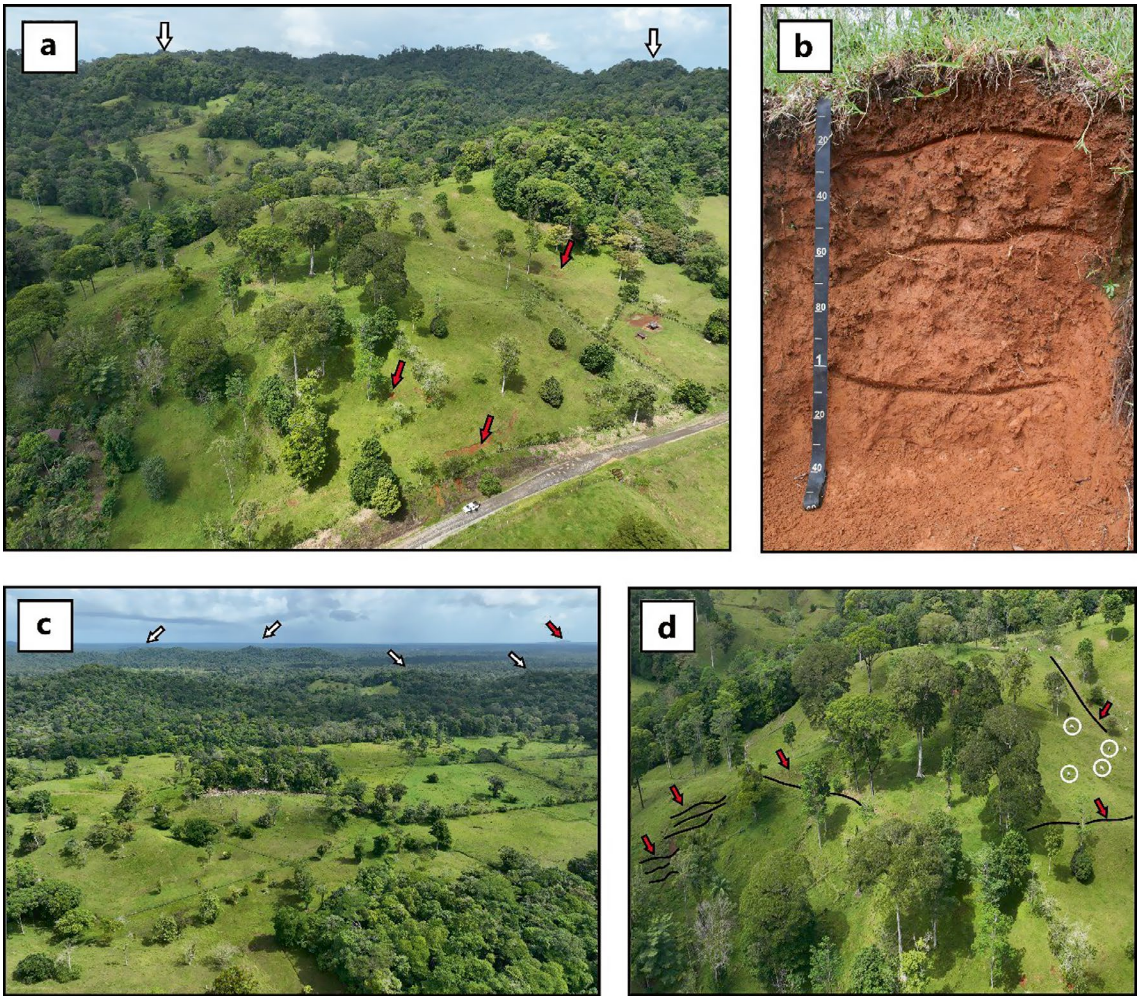

Fig. 21.18 Landscapes and landforms observed in the region of Tortuguero-Barra del Colorado: **a** Mountains covered by abundant vegetation (white arrows), and associated elevations that have been cleared to grasslands, with the presence of deep clayey reddish soils (red arrows); **b** A reddish soil profile studied at the same elevation as shown in panel A, **c** Lowlands punctuated by low hills (white arrows) with contrasting vegetation due difference in land-use (forest versus grassland), and distant view of Cerro Tortuguero (red arrow); **d** Terracettes and lanes (black lines and red arrows) observed in grasslands due to cattle movement (cattle in white circles)

Fig. 21.19 Highly weathered soils in the Mountains of Tortuguero-Barra del Colorado: **a** Road cut that extends along the road to Barra del Colorado, exhibiting weathered reddish deep soils (white arrows); **b** A soil profile observed in these same road cut (2 m depth between the red arrows); **c** Zoom picture of the soil profile observed in the road cut (panel B), and classified as *Andic Haploperox*

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