Landscape series: 3

A review of Geology, Climate and Hydrology in Aruba

Photo by: Stan Norcom - Limestone Terraces along the Northeast shoreline
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The Aruban landscape has undergone many changes in history. This paper is part of the landscape series:
"Spatial Developments in the Aruban Landscape: A multidisciplinary GIS-based approach derived from geologic, historic, economic and housing information"

2016

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Aruba
2016

We would like to thank the following persons for their support and critical remarks:

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This paper is part of a series on the developments that relate to the Aruban landscape. To bring perspective to current environmental threats and developments we review in this paper the geological and (paleo)-climate history of Aruba. Good knowledge of present but also of past processes is vital to understanding the effects that urbanization and economic progress pose on land and marine ecosystems.

Geological history of Aruban landforms

The tectonic history of the Caribbean is not yet fully understood. Different models attempt to explain the different processes involved, in particular with respect to the position and origin of the Caribbean plate. The most popular theory explains the formation of the Caribbean Plateau by the entrapment and relative movement (in east-west direction relative to a fixed North American continent) in between the separating and westward migrating North- and South American Plates[1]. Ahead of the Plateau developed the Caribbean Great Arc by a series of volcanic eruptions, relatively pushed eastwards in between the separating North and South American continents, forming todays' Islands on the edge of the Caribbean Basin. An overview of this so-called *Pacific-origin model* is given by Pindell (2011) and Boschman (2014), and outlined below in order to gain better understanding of the history of Aruban geological features. Following an alternative, so-called *in-situ model*, originally proposed by James (2005), the Caribbean Great Arc never existed and the origin of the Caribbean Basin and the Islands in the region developed in-situ, i.e. they origin from a Proto-Caribbean Ocean crust at about the place where these situate now and not in the distant Pacific. However, evidence from Pacific type fauna in the Caribbean and from the complex distribution and pattern in geochemistry of old rocks against the South American continent favor the Pacific-origin model (references can be found in Lely et al., 2010). We describe the more popular models below.

'Great (Caribbean Islands) Arc'

~ 93Ma

In the Late Cretaceous, some 100-93 Ma (Mio yrs. ago; see endnote), a volcanic islands arc system formed, the '*Great Caribbean Islands Arc*' *(the later Caribbean Islands)*, *east of a subduction* zone where the Pacific Ocean crust (Farallon Plate) submerged under the Proto-Caribbean Ocean crust. As the North and South American Plates were separating and moving northwestwards this gap in between, the Proto-Caribbean Ocean crust, was so to say in collision with the Pacific Ocean crust. The volcanic basement of Bonaire (*Bonaire Washikemba Formation-BWF*) cropped out at the southern end of the Great Arc. Accordingly, the basement of Bonaire has in its earliest origin a different tectonic evolution then the Aruba - Curacao basement (Lelij, et al., 2010) that is argued to have its origin *more to the West* as part of a basaltic intrusion pushing upwards inside the Farallon Plate.

[1] The movement of the Earth's continents relative to each other is called continental drift; after Wegener, 1912. The Caribbean Plate was engulfed by westward migrating North and South Americas.

Basaltic Oceanic Plateau

~ 91Ma

A large basaltic flooding on the Farallon Plate, the *Caribbean Large Igneous Province (CLIP),* occurred below sea level, at approximately 91-88 Ma ago, at a location off the coast of present-day Colombia in todays' Pacific (White, Tarney, Klaver, & Ruiz, 1996). The Aruba-Curacao lava basement is a detached remnant part of this intrusion and the origin of both the *Aruba Lava Formation (ALF*) as well as the *Curacao Lava Formation (CLF*). In its relative movement eastwards it collided against the Proto-Caribbean Ocean crust and against the *Great Caribbean Islands Arc*.

Magmatic intrusions

~ 88Ma

As the Farallon Plate moved farther in between the North and South American Plates, there was a reversal of the subduction zone. The Proto-Caribbean Ocean crust went on now descending under the Farallon Plate and causing new magmatic activity, but now to the west of the subduction zone. Consequently, about 3 Mio years (~88 Ma) after the proto-Aruba Lava Formation had stopped intruding the Farallon plate and had been cooling, a new magmatic intrusion occurred on one section of the Oceanic Plateau, named the *Aruba Batholith* (see page 5). The Batholith is typical for Aruba and is not present in Curacao (or in Bonaire) (Lelij, et al., 2010).

The forces of the collision and magmatic intrusions caused metamorphic rock formations in the older *Aruba Lava Formation rocks* (see page 4). In time, the Aruba-Curacao basement moved on the edge of the new *Caribbean Plate* towards the southern margins and underwent a complex series of deformations against the South American continent. The Great Caribbean Island Arc moved further on the edge of the deformation zone north and southeast. The part that was to become the *Greater Antilles* moved all the way towards its current position, at the northeast border of the Caribbean Plate.

Collision with South American Plate

~ 75Ma

At about 75-73 Ma at the margins of the forming Caribbean Plate, accretion, convergence and thickening of the oceanic crust took place. As the north-eastwards migrating Caribbean Plate *collided with the South American Plate*, the submarine basement of Aruba and Bonaire (defined as discrete areas within a single Block) was deposited successively against the South American Plate (first Aruba at about 70-60 Ma ago and later Bonaire at ~50 Ma ago). The basements of Bonaire and Aruba/ Curacao had a different origin, but were positioned next to each other. Their distinct history from the collision, strike slip displacements and accretion against the South American Plate and renewed heating of the rocks (Lelij, et al., 2010) shaped a somewhat different landscape.

Uplifting

~ 70Ma

At the margin of the Caribbean Plate, Aruba was positioned in a very complex zone with tectonic interactions. The relative motion of the Caribbean Plate against the South American Plate caused a deformation zone with several plate fragments and blocks to strike and slip against the South American Plate. The *Aruba-Curacao-Bonaire Block* is such a block and estimated to be about

1,000 km long and 300 km wide. Along the thrust, strike and slip faults, moments of subsistence and land uplift occurred. Figure 1 gives an impression of the many faults that are still recognizable at the surface. The uplifting of the leeward Antilles occurred 70-60 Ma ago, about 500 km westwards from Aruba's current relative location. During the uplifting, parts of the original Basalt formation, came to the surface in all three islands. Evidence from paleo magnetic studies suggest that over subsequent displacements, the islands rotated clockwise at least 90° relative to a more stable South America continent (references in Boschman et al. (2014)).

Evidence is found today in the strike and slip fault patterns that run more or less parallel to the diffuse boundary between the two plates and evidence is also found in the direction of Quartz and calcite veins within the rocks (Beardsley & Avé Lallemant, 2005). Today, in Aruba, the strike and slip fault activity can still be felt from shocks and temblors on a quite regular basis[2].

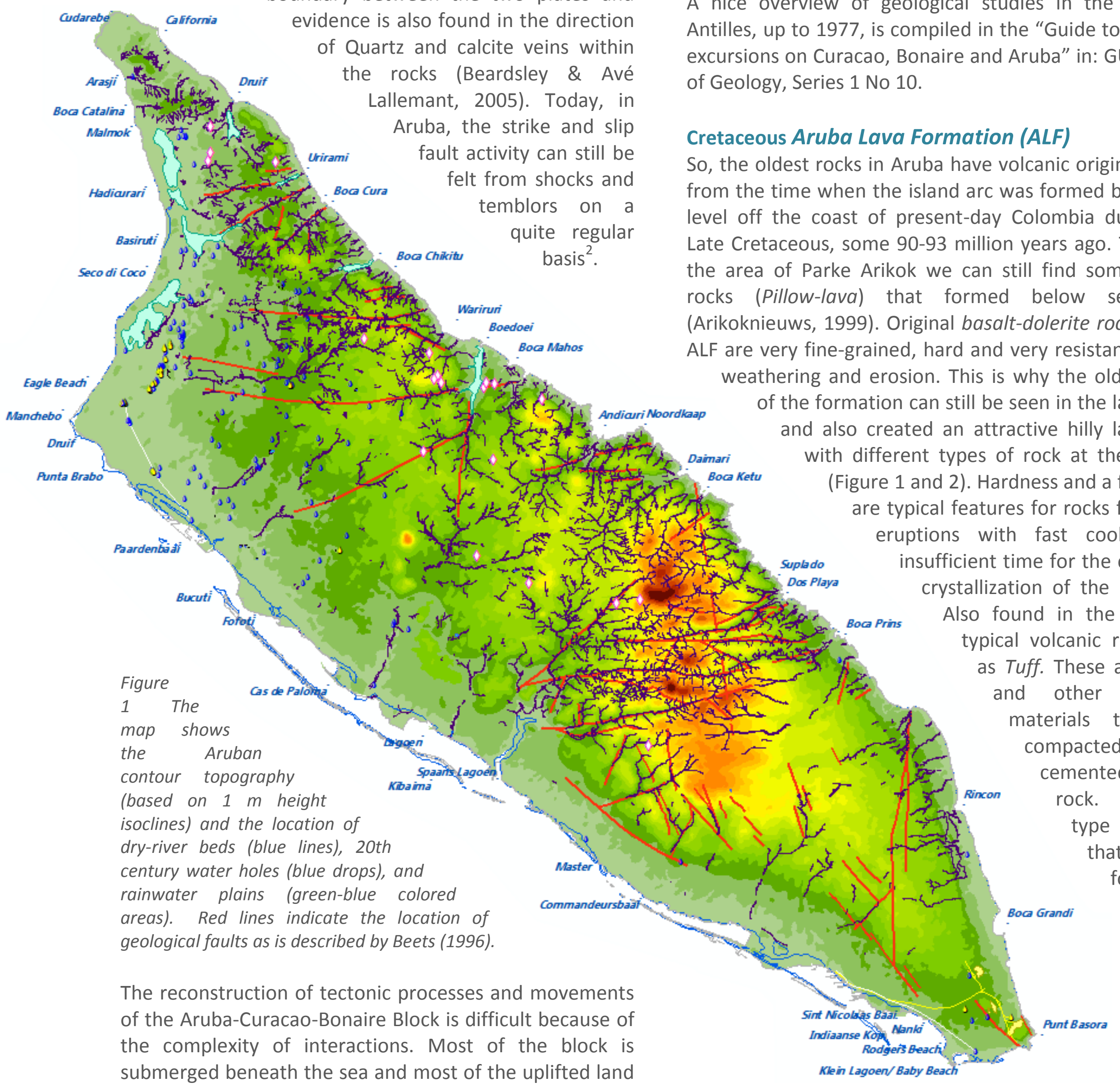

Figure 1 The map shows the Aruban contour topography (based on 1 m height isoclines) and the location of dry-river beds (blue lines), 20th century water holes (blue drops), and rainwater plains (green-blue colored areas). Red lines indicate the location of geological faults as is described by Beets (1996).

The reconstruction of tectonic processes and movements of the Aruba-Curacao-Bonaire Block is difficult because of the complexity of interactions. Most of the block is submerged beneath the sea and most of the uplifted land is under thick layers of sediments. Also there is still continental growth of South America as the South American Plate interacts with the Caribbean Plate (Curet, 1992).

Geomorphology of different rocks

Most of the Aruban basement consists of solidified molten rock from magma that has its origin deep below the surface of the earth crust during different episodes. These rocks are generally called *igneous rocks* with *volcanic* origin (when the magma erupted and quickly cooled as was the case with the Aruba Lava Formation) or *plutonic* origin (when later magmatic bursts remained within the earth's crust and cooled slowly, such as with the Aruban Batholith). Plutonic rocks are more coarse-grained than volcanic rocks and have larger crystals because with the slow cooling, the minerals had more time to move and crystalize. Grain size and chemical composition of the rocks is an important determinant for the resistance against later erosion.
A nice overview of geological studies in the Leeward Antilles, up to 1977, is compiled in the "Guide to the field excursions on Curacao, Bonaire and Aruba" in: GUA paper of Geology, Series 1 No 10.

Cretaceous *Aruba Lava Formation (ALF)*

~ 91Ma

So, the oldest rocks in Aruba have volcanic origin and are from the time when the island arc was formed below sea level off the coast of present-day Colombia during the Late Cretaceous, some 90-93 million years ago. Today, in the area of Parke Arikok we can still find some of the rocks (*Pillow-lava*) that formed below sea level (Arikoknieuws, 1999). Original *basalt-dolerite rocks* in the ALF are very fine-grained, hard and very resistant against weathering and erosion. This is why the old remains of the formation can still be seen in the landscape and also created an attractive hilly landscape with different types of rock at the surface (Figure 1 and 2). Hardness and a fine grain are typical features for rocks from lava eruptions with fast cooling and insufficient time for the complete crystallization of the minerals. Also found in the ALF are typical volcanic rock such as *Tuff.* These are ashes and other erupted materials that are compacted and cemented into a rock. Another type of rock that can be found are *Conglomerates* that are formed from loose particles and other clast sediments cemented together by the heat of pressure underneath the earth crust.

[2] http://es.earthquaketrack.com/p/aruba/recent

Most of these rocks however are transformed under the influence of pressure and heat[3] and become *metamorphic*[4] like *schist rocks.*

~ 88Ma

Cretaceous *Aruba Batholith*

The magma that cracked from under the partially solidified lava and intruded the older volcanic rocks is called the Aruba Batholith. Studies show that the batholith intrusion occurred in a sequence of several bursts not too long after the Aruba Lava Fm. stopped erupting (in less than 3 Ma) (Lelij, et al., 2010). Earlier magma had not been cooled completely yet (White, Tarney, Klaver, & Ruiz, 1996).

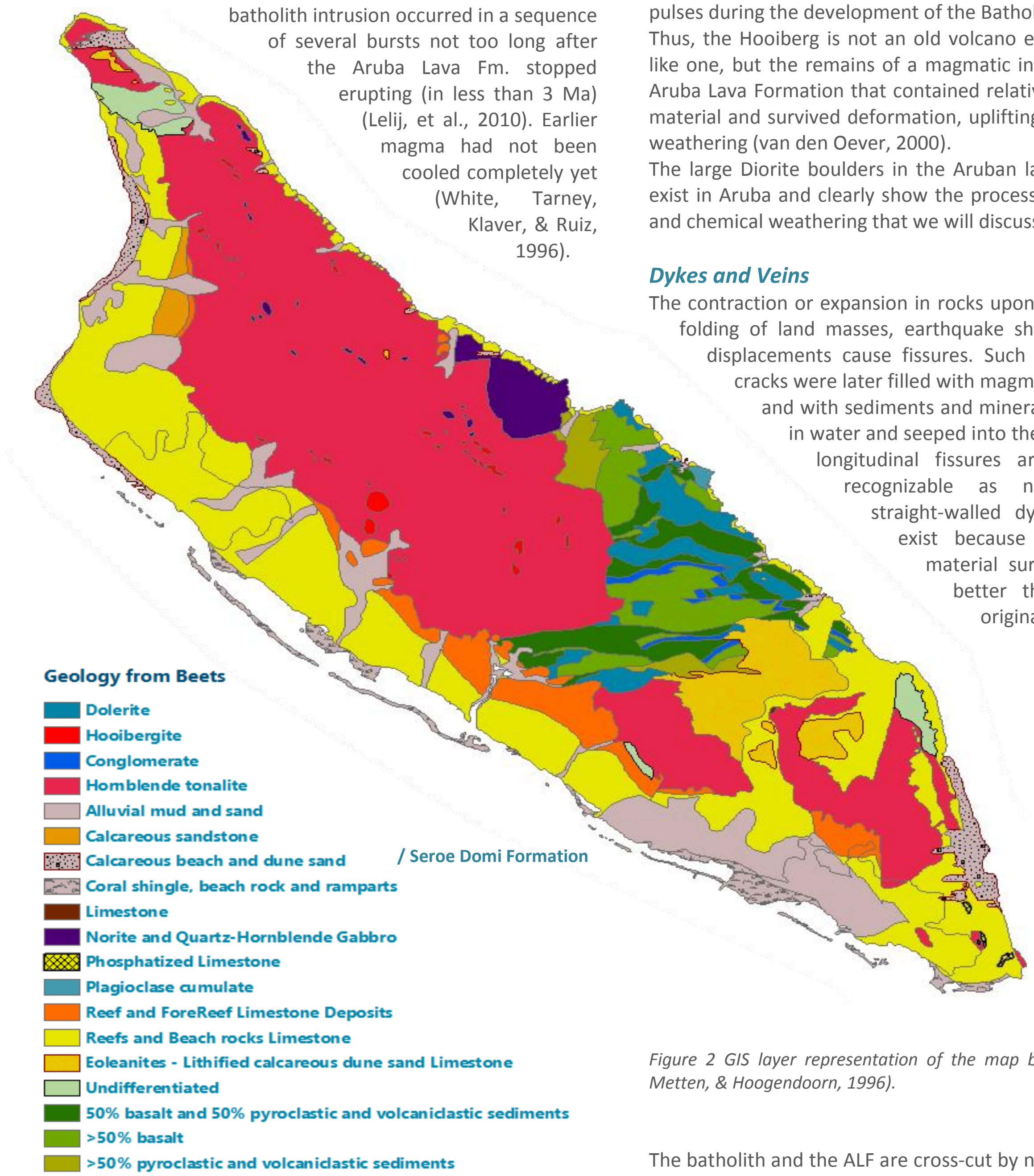

Figure 2 GIS layer representation of the map by Beets (Beets, Metten, & Hoogendoorn, 1996).

The big magmatic body, the Batholith, composes predominantly of *tonalite and quartz-diorite* rocks[5]. Earlier smaller intrusions with *Gabbro* (near Bushiribana and Matividiri) and later with *Hooibergite* (hornblende-rich diorite) are also part of the Aruba Batholith. Most of these rocks have about the same origin but differ in chemical composition and silicate (quartz) content.

The *Hooibergite* intrusion was one of the later thermal pulses during the development of the Batholith.

Thus, the Hooiberg is not an old volcano even if it looks like one, but the remains of a magmatic intrusion of the Aruba Lava Formation that contained relatively hard rock material and survived deformation, uplifting, erosion and weathering (van den Oever, 2000).

The large Diorite boulders in the Aruban landscape only exist in Aruba and clearly show the processes of physical and chemical weathering that we will discuss later.

Dykes and Veins

The contraction or expansion in rocks upon solidification, folding of land masses, earthquake shocks and line displacements cause fissures. Such fractures and cracks were later filled with magmatic intrusions and with sediments and minerals that solved in water and seeped into the cracks. Large longitudinal fissures are sometimes recognizable as narrow often straight-walled dykes that still exist because their harder material survived erosion better that than the original rock did.

The batholith and the ALF are cross-cut by numerous such *dykes* but also by *veins*. Veins are similar in origin but distinct because they have irregular, shorter and discontinuous shapes. The diorite embedded quartz veins in Aruba are known as they sometimes contain gold ores (van den Oever, 2000).

[3] A nice introduction to Petrology, the study of the origin, occurrence, structure and history of rocks, is found online: http://www.brocku.ca/earthsciences/people/gfinn/petrology/defn.htm

[4] Rock metamorphism occurs when the original rock has been subjected to high pressures and temperatures and has been transformed into another form.

[5] The difference is based on quartz or SiO_2 (Silica) content: **quartz-diorite** contains >5% quartz and **tonalite** contains >20% quartz.

~35- 24Ma

Paleogene (Eocene) Lime stone deposits

From the time of Late Cretaceous to Middle Miocene only an incomplete record of coral fore-reef debris and sediments from the South American mainland remained. The oldest remains of the erosion sedimentation are from Early Oligocene/Eocene (approx. 35 Ma), observable on the surface in Butucu. Slabs from a borehole in Oranjestad (Helmers & Beets, 1977) reveal Eocene Limestone sediments from Early Miocene (approx. 24 Ma).

~ 15- 0.5Ma

Neogene Seroe Domi Formation

More articulate are the uplifted layered thick carbonate sediment depositions with underneath different limestone deposits that date from Early/Middle Miocene until probably the Middle to Late Pleistocene (approx. 15 Ma-0.5 Ma). This is the so-called *Seroe Domi Formation* that typically consists of large flat multi-layers of limestone coral debris with eroded earlier Reef and Fore Reef from a Miocene high sea level stand. The Seroe Domi Fm. exists in Aruba, Bonaire as well as in Curacao where it is more visible in the landscape.

In Aruba, the areas northeast of Pos Chiquito, Savaneta and San Nicolas and an area east of Bubali Plas and at Seroe Cristal near the Northeast coastline (Figure 2) show the remains of *Seroe Domi Formation*. Like in Curacao, the stratification of these layers appears at some places clearly tilted. Today, it is the generally accepted view that the long-term processes of deformation and land uplift of the Aruba-Curacao-Bonaire block against the South American continental margin has been accompanied by a folding and tilting of the Seroe Domi Formation complex. There is, however, still some debate about whether these undulating limestone layers reflect the folding of a top earth crust (compression during early Pleistocene) or simply is the consequence of sedimentation along a dip in the original sea bedding. In his PhD Thesis (1979), Herweijer studied the Seroe Domi Formation and the likely occurrence of compression after deposition of the thick carbonate sediment layers on top of the heavily eroded Cretaceous basement (the remains of the ALF/Batholith complex).

~1.1- 0.1Ma

Quaternary Pleistocene Eolianite sanddunes

In the National Parke Arikok and the area of Jaburibari we find fossilized cliffs of Pleistocene eolianite[6] rocks, i.e. solidified grains of former wind-blown sand dunes. These lime-sands hardened and fossilized into the *eolianite limestone rocks*. They are a reminder of the rich shallow-marine life and coralgal communities with carbonate content that after depositing and surfacing have been blown by the winds into undulating sand dunes (Herweijer, 1979).

~ 0.6- 0.1Ma

Quaternary Late Pleistocene Limestone Terraces

The Pleistocene is commonly known for the alternating periods of advance and retreat of the Arctic and Antarctic ice cap. As a consequence of the advance and retreat of the ice sheets the sea levels slowly changed worldwide. The climate change came with *dryer and colder climate during Glacial* and *warmer and more humid climate conditions during Interglacial*. At the more regional level however, climatic conditions may have varied more abruptly followed by prolonged periods of change in regional temperature, precipitation and humidity.

A difference of approx. 120 m exists between the lowest seawater highstand only some 18,000 yrs. ago at the end of last Pleistocene glacial period and the highstand in current Holocene Interglacial (Lambeck, Yokoyama, & Purcell, 2002). Today, global sea levels are still rising, but less strong as in early Pleistocene and with only a few meters since the middle Holocene (over the last 5,000 yrs.) (Hodell, et al., 1991). The cause of this sea level rise is not to be confused with the very recent sea level rise caused by global warming and the buildup of greenhouse gasses in the atmosphere.

The subsequent sea level cycles in the Caribbean during Pleistocene (following the Glacial and Interglacial periods) with a continuous uplift of the land, have created a staircase of coral reefs banks by the interplay of land uplift and reef growth and erosion. The terraces surrounding the Aruba Batholith and the Aruba Lava Formation are the fossilized deposits and remains from these processes, cemented together into sedimentary limestone rock. Each of the raised shorelines is found to correspond to a specific period of highstand of the sea level (Eisenhauer & Blanchon, 2001).
In Aruba, only a few terraces have remained at different heights above sea level. Initial studies by Westermann (1932) and De Busonjé (1974) broadly discern a 'Higher', 'Middle' and 'Lower' Terrace surrounding the Aruba Batholith\ ALF complex. These limestone terraces are the remaining evidence of coral reef deposits during the final phases of different Pleistocene high sea level stands. The continuous uplifting of the ALF/Batholith has brought these Terraces above current sea level. The oldest terrace is situated on the highest grounds, but terrace building is a process that is still active today.

Based on a more complete record of Terraces in Barbados (Muhs, 2001), we know that in Aruba some terraces have not survived and must have been eroded completely. The thick Seroe Domi Fm. eroded and washed away for a large part. Along the southwest coast, where waters had been calmer, the Limestone deposits and erosion fields (and the remaining parts of the eroded Seroe Domi Fm.) however still cover most of the areas today. It is on the lowest and youngest of these terraces that most of the Aruban Aloe cultivation took place in early 20th century (see Figure 5).

Paleoclimate records

Little information is available about the more recent paleoclimate events that shaped the Aruban landscape.

[6] Eolianite refers not to a specific time period but to the type of process that formed the rock, that is, Eolianite rocks found their origin in compaction of sediments that have been accumulated by wind into for instance coastal dunes (formed into coastal limestone or sand dunes).

Sediment core records show that in the past the landscape must have been quite different.

A pollen record from a bore hole in Oranjestad (Helmers & Beets, 1977) shows spores of ferns and palms (A. Curet, pers. comm., 2015), possibly from early Miocene origin (23-15 Ma). Proxy[7] studies, like palynological research (pollen and spore research), oxygen isotope[8] and more recently x-ray fluorescence measurements of sediment components have shed some light on the paleoclimate history in the Caribbean. We describe some major findings, next.

Wet and dry periods

In a detailed study of sediment cores in Lake Miragoane, Haiti, published in Nature (Hodell, et al., 1991), changes in the lake water levels have been reconstructed on the basis of oxygen isotope[9] analyses. Information about past wet and dry conditions was compared with a corresponding analysis of vegetation communities, based on pollen zonation research. The overall pattern in the

~ 5400 BP

Haitian Lake samples shows that after the end of the last Glacial[10], from *early Holocene* at about 10,500 BP[11] up to about 5,400 BP, precipitation levels and climate temperatures had increased. Hence, the circumstances in the Caribbean have been (over thousands of years) much wetter than today. From about 5,400 BP onwards, from the mid to late Holocene up to today, climate turned to dry conditions.

Nearer to Aruba, in Bonaire, another study, by Giri (2013), shows similarly that *during mid-Holocene local climate was dominated by high and intense levels of precipitation, particularly during the summer*. These findings were based on oxygen isotope analysis from (marine) coral samples, off the coast in Bonaire.

Major deviations in the annual isotope ratios revealed fluctuations in marine salinity between summer and winter seasons. The process behind these fluctuations was argued to be intense rainfall during the summer seasons.

Today, in contrast to the situation in Mid-Holocene, marine hydrological conditions in the Southern Caribbean Sea are best characterized by the elevated evaporation in winter and the strong (wind-driven) oceanic surface currents that carry large freshwater concentrations from far away, from the seasonal discharge of the Orinoco and the Amazon rivers.

The dynamic relationship between the marine hydrology and the regional climate and the dominating effect thereof on local circumstances reflect a southwards shift of the so-called Inter Tropical Convergence Zone[12] (ITCZ) *throughout the Holocene*.

Aside from these general trends that we mentioned above, Hodell (1991) described in-between climate alterations that may have maintained over many years and that seem to have been stronger than might be expected on the basis of the annual shifts in the *received solar radiation*[13] alone. The study suggests that while long-term fluctuations in received solar energy dictate climate and sea level changes (Glacial and Interglacial Periods) and consequently propel regional changes towards dry or wetter conditions, additional forces such as a drastic shift in the salinity of sea currents may have created temporal alterations in local climate (Metcalfe, Barron, & Davies, 2015).

~ 8200 BP

One such abrupt variation in climate conditions (thus a large climatic change in a relatively short time span) occurred at about 8,200 yrs. BP, when conditions suddenly turned more humid due to an increase in precipitation (Hodell, Curtis, & Brenner, 1995). A rather abrupt onset of dry conditions occurred in Haiti at about 3,200 BP and again at about 2,400 BP. Based on the findings from the lake in Haiti, the ratio of precipitation/evaporation only switched back to the levels from before 2,400 BP at about 1,500 BP (500 AD), indicating the end of period of *temporary* drought that lasted 900 years (Hodell, et al., 1991).

~ 3200 BP

~ 2400 BP

Beside information about local climate variations, there is evidence that suggests a coincidence of climatic fluctuations across the Caribbean. Recent studies, for instance, confirmed that the fall of the Mayan Culture in Mexico was indeed consequential to repeated periods of a Caribbean-wide drought between about 1,240 BP (760 AD) and 1,090 BP (910 AD) (Peterson & Haug, 2005). During this time span there have been at least three

~ 1240 BP

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[7] Climate proxy studies are based on preserved physical characteristics of the past that enable scientists today to reconstruct the past climatic conditions. Definition: wikipedia.org

[8] Oxygen Isotope analyses is based on the difference in weight between the light oxygen atom ^{16}O (8 protons and 8 neutrons) and the heavy oxygen ^{18}O (more neutrons). Since water molecules with oxygen^{16} are lighter these molecules will evaporate more readily. The ratio between the two thus tells something about the conditions of evaporation or precipitation in the environment at the time of allocation in the sediments.

[9] Due to a difference in mass, differences in relative Oxygen isotope concentrations (O^{18}/O^{16}) express differences in evaporation relative to precipitation (H_2O^{18} is a fraction heavier and precipitates easier that the lighter H_2O^{16}).

[10] Ice ages (Glacials) typically occur in intervals of about 40-100 Ma. In between there are shorter interglacial periods such as the current one (Holocene) that are characterized by a retreat of the ice sheets and a warmer favorable climate. As the ice sheets retreat, sea levels rise first rapidly but then gradually up to the level of today. There is little change (3-5m) over the last 7,000 yrs. (Lambeck, Yokoyama, & Purcell, 2002) The general believe is however that human action contributes significantly to recent global warming and sea level rise

[11] BP indicates the timescale Before Present (dd. 1950) and is not to be confused with BC (Before Christ). 8,200 BP equals approx. 6,200 BC.

[12] The ITCZ is the area encircling the earth near the equator where the northeast and southeast trade winds come together. The location of the ITCZ varies over time influenced by the sun's position and the differentially warming hemisphere (Schneider, Bischoff, & Haug, 2014) (Haug, Hughen, Sigman, & Röhl, 2001).

[13] There is an annual shift in the *received solar radiation* that reflects the slow shift of the annual orbit of the earth around the sun. This movement dictates long-term but slowly varying levels in received solar radiation and these are largely responsible for the Glacial and Interglacial periods.

multiple-year periods of drought in the Yucatan Peninsula with an accumulation of the known social implications that led to the end of the Mayan Culture. The authors supported their conclusions on the basis of x-ray fluorescence measurements of trace elements and foraminifera data from cores in the Cariaco Basin, off the coast of Venezuela (at quite some distance from the Yucatan). Their data coincided with the earlier findings by Hodell in a lake in the Yucatan Peninsula, Mexico (Hodell, Curtis, & Brenner, 1995), and provided very detailed information about the shifts in precipitation and in marine salinity levels.

~ 1200 BP

The change towards generally dry conditions in the Caribbean in Late Holocene (approx. ~1,200 BP) is also supported by a study by Gregory et al. (2015) in two coastal lagoons in Cuba. Differential presence of specific foraminiferal assemblages reveals a shift in relative lagoon water salinity while a shift in the composition of trace elements in sediment core samples reveals a change in rainwater runoff into the lagoons corresponding to less precipitation.

A nice overview of the spatiotemporal pattern of climatic fluctuations across Central America and the Caribbean during the Holocene (including an overview of underlying studies), is given by Metcalfe (2015). The spatial, multi-annual, and even seasonal mapping of the climate in the Caribbean is complex, however. Their summary of studies suggests that wetter and drier conditions occur alternatively under the influence of factors, other than the decline in seasonal insulation and the displacement of the ITCZ alone. The authors reason, that the successive pulses of glacial ice water entering the region may have an impact on the climate as well. The occurrence of intense hurricane seasons, for instance, may also challenge a proper understanding of the paleoclimate conditions as these may mask periods with relative drought (Frappier et al., 2014; referenced in Metcalfe et al., 2015).

Unfortunately, paleoclimate information from Aruba is scarce. It would be interesting to reconstruct more precisely the climatic conditions that have dictated the vegetation growth and fauna abundance in Aruba for instance during recent Holocene and be able to understand the current landscape more precisely.

A pilot study in Aruba (Nooren, 2008), based on pollen analyses from sediment cores at the *Boca Prins bay inlet* (Northeast coast) and at a site in the *Spanish Lagoon* (Southwest coast), suggests a change in vegetation type and cover in line with described climatic fluctuations. The characterization of the sediment cores from the pilot study even suggests evidence that relates to the dramatic impact by man on the landscape from deforestation, grazing and heavy erosion in recent colonial times, as has been described in literature already (Hartog, 1953). In the youngest of sediment records from the Spanish Lagoon site, for instance, clastic material (seen as evidence for erosion) was observed together with charcoal[14] remains, whereas such type of sediment layer was absent from the periods before. The presence of charcoal and clastic sediments coincided with a peak in the occurrence of *Pal'i sia Cora* pollen (Bursera *simaruba*) in these layers. The high occurrence of '*Pal'i sia Cora'* pollen is indicative that there was a dry tropical forest in the surroundings of the lagoon up to that time. The timeframe clearly corresponds to the period of early *colonization* when deforestation occurred from the intense wood harvesting and the free-roaming of herbivore grazers. Consequential increased erosion seems in line with these events.

Such (preliminary) data also show that the inland bay in Spanish Lagoon was much larger in the past than it is today. Mangrove forests (Rhizophora *mangle*) were present already since approximately 7,000 BP. Pollen analyses of the old mangrove peat indicate relatively wet conditions (pers. comm. Nooren, 2015) with the presence of many fern spores, which were absent in the younger deposits.

Today, both bays are filled with sediments. The bay at Boca Prins is almost completely filled with erosion material from the hills in the hinterland. In the *Boca Prins bay inlet* there is only one thin organic layer found, at 3.3 m depth, that reveals a temporary presence of Mangrove forests (Rhizophora *mangle*), whereas the remainder of the sediment core is almost exclusively from mineralogical content. Slabs suggest that the Mangrove vegetation was displaced by a more terrestrial tree species, Buttonwood (Conocarpus *erectus*). Interesting is the fact that the core records from before the loss of Mangroves do also show spores of fern that were absent in all the younger records.

Such abrupt destruction of mangrove assemblages and the alteration of pollen spectra reveal a subsequent domination of more dry and open hinterland pollen types. Findings by Engel et al. (2009) in Bonaire suggest the occurrence of extreme wave events at about the same time. Whether there is any concurrence of events may be interesting to investigate in more detail. Such studies, however, suggest intense paleoclimate events that may have had a lasting impact on vegetation and landscape.

Data collected relatively near to Aruba, in the Cariaco Basin off the coast of Venezuela, show that dry conditions with precipitation minima occurred from 3,800 to 2,800 BP (Haug et al., 2001). The climate and vegetation cover then may accordingly have been different from today[15]. *~ 3800 BP*

Artifacts and large shell midden show that pre-ceramic people may already have visited Aruba incidentally in Mid-Holocene, i.e. since ~4,000 BP[16] (Versteeg & Ruiz, 1995). Preceramic Indian inhabitants in Aruba had a hunting/fishing and gathering lifestyle and mainly occupied the coastal areas, including the Spanish Lagoon.

[14] Micro-charcoal remains in sediments associate clearly with fires. The distinction between natural and anthropogenic fire regimes is however difficult to establish and are cause for debate.

[15] Based on received solar radiation today we typically live in a *relatively dry time zone*

[16] The **Preceramic period** in Aruba is estimated to start at about 4,000 BP and last until 1,000 BP. The **Ceramic period** is described to last from 1,000 BP to about 500 BP when Spanish colonization began.

~ 3500 BP

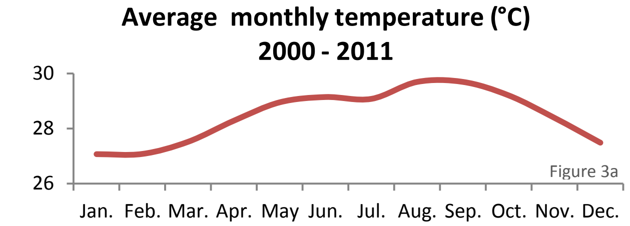
The oldest dated shell deposits associated with human occupation on the island were found in Rooi Bringamosa near the Spanish Lagoon. A charcoal sample from this shell layer in the pilot study of Nooren revealed an AMS[17] 14C date of 3,260 +/-35 BP (calibrated age of 3,500 +/-50 yr. BP at 68.2% probability) (pers. comm. Nooren, 2015, unpublished data). Nooren also confirms that fossil pollen and spores from that time span identify plant species that are now hardly found (pers. comm., 2015).

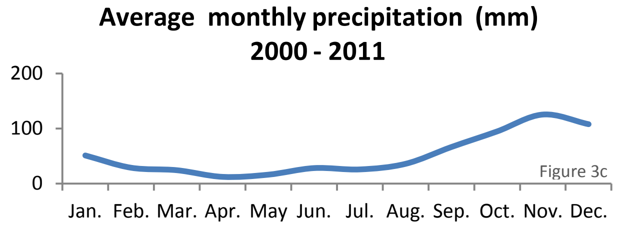
Interesting is the fact that Ceramic (Dabajuran) Indians arrived at about 1,200 BP (800 AD) in Northern Venezuela and at about 1,100 BP (900 AD) in Aruba (NAM, 1999). It is possible that climate change-induced migration (Gupta, Anderson, Pandey, & Sanghvi, 2006) (Laczko & Aghazarm, 2009) played a role here as well, and, that the onset of dryer climate conditions, such as occurred at about 3,800 BP and again at about 1,200 BP, was coincidental to the timing of settlement of the new arrivers.

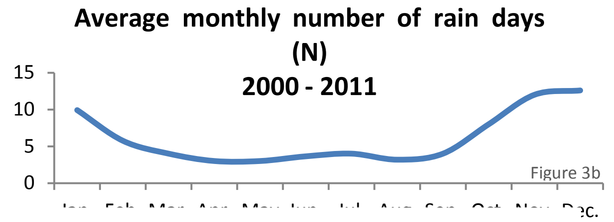
Current Climate Conditions

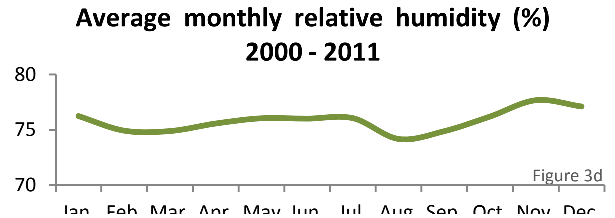
Regular monitoring of climatic conditions occurs since the early 20th century (Meteorological-Yearbook, 1933-1972). We present in figure 3 and figure 4 climate measurements from 2000-2011 at Reina Beatrix Airport in Aruba (Year reports Statistics of the Meteorological Observations in The Netherlands Antilles: 1955 - 1972). Earlier data can be found at www.meteo.aw.

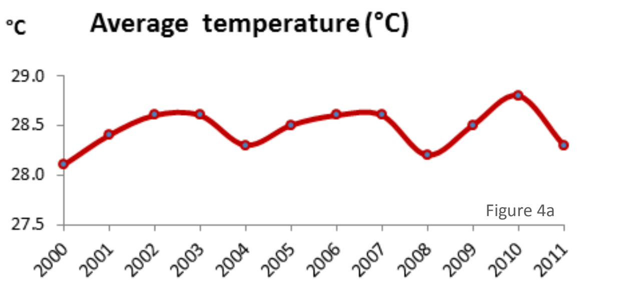
Figure 3 a-d (top) show climatological records collected at Reina Beatrix Airport during the period 2000-2011. The four graphs show the average monthly records for temperature, total precipitation, number of rain days and relative humidity.
Note: A rain day is a day with at least 1 mm rain.
Source: Statistical Yearbooks 2000-2011. CBS, Aruba
Figure 4 a-d (below) show climatological records collected at Reina Beatrix Airport during the period 2000-2011. The four graphs show the average annual records for temperature, total precipitation, number of rain days and relative humidity.

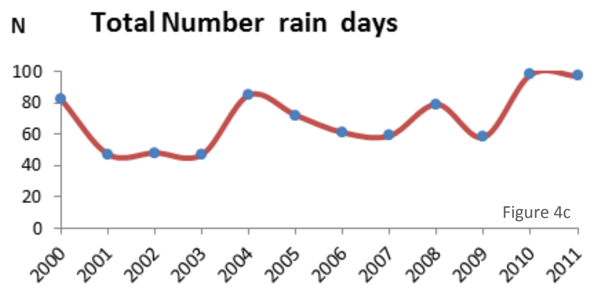


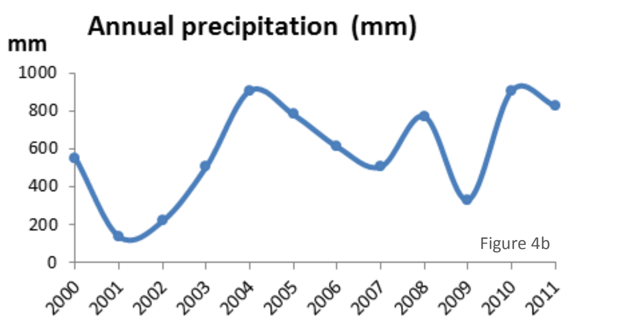


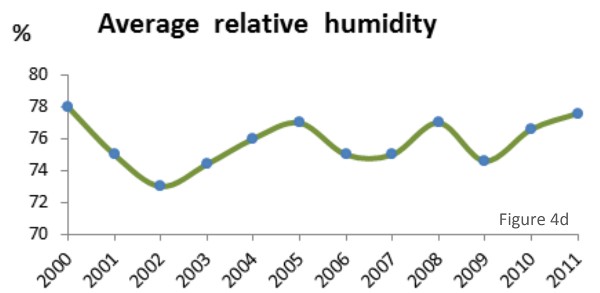












[17] Accelerator mass spectrometry (AMS) is a type of carbon dating technique.

Temperature

In Aruba, we observe little variation in daily temperature (Figure 3a). Values fluctuate between an average low of about 27 °C during the coldest months, January and February, up to 30°C during the hot summer months, August and September. Year averages remain quite uniform as well in the range of 28°C and 29°C (Figure 4a).

Precipitation

In contrast to the slight fluctuation in temperature the fluctuation in annual precipitation is more extreme (Figure 4b). Over the 10 year period, extremes occur in 2001 (137mm) and in 2004 (906mm). Considerable fluctuation exists between consecutive years. The latest decennium appears to have been quite wet at Queen Beatrix Airport, as we have to go back to the mid-50s to observe similar levels of rainfall. Rainfall in 1955 and 1956 (respectively 816 and 679mm average annual rainfall) is comparably high to the level of rainfall in 2004 (906 mm), 2010 and 2011 (respectively 906 and 826mm). The average annual rainfall over the period 2000-2011 is 587.9 mm and that is well above the long-term average of 410 mm over the long period 1953-1972.

Number of rain days

Precipitation is strongly influenced by the presence of tropical storms and/or hurricanes in the region. Therefore, it is important to realize that successive years with heavy rainfall as in the recent decade can be deceiving and do not necessarily represent a change in local climate conditions.

Rainfall generally peaks in November-December (rainy season), but in the rest of the year significant number of rainy days exist as well (Figure 3b and 3c).

For instance, August 2011 had 211.6 mm of rain but this is exceptional. The month of April is generally with the least rain, though it is not necessarily the driest month.

Interesting to note is that in contrast to the north-western Caribbean there are no distinct two rainy seasons. The precipitation pattern in Aruba is a unimodal late annual rainy season as described for south-eastern Caribbean islands.

> *August and September are considered the hot and dry summer months (March is considered dry as well) and November and December are the coolest and wettest months.*

Finkel and Finkel (1975) analyzed total rainfall per location and estimated rainwater drainage area. They suggested a descending gradient in rainfall from Southeast to Northwest in Aruba, in concurrence with the orientation of the Northeast Passat winds and the descending gradient in height topography of the island.

Humidity

Average annual humidity ranges between approx. 73% and 78% (compare Figure 4b, 4c and 4d) and roughly co-varies with annual number of rain days (ranges between 47 and 97 days) and annual precipitation (ranges between approx. 350 mm and 950 mm).

Over the period 2000 to 2011 the average monthly humidity was highest in the month November (77.7%) and lowest in August (74.2%), but the difference remains small (Figure 3d).

Sea surface temperature is an important determinant for precipitation (Karmalkar, 2013). Measurements of sea surface temperatures in the Southern Caribbean show that the highest annual sea surface temperature in the Southern Caribbean is in September[18] (no CBS data available), which is consistent with the timing of the onset of the wet season.

The descriptions of rainfall above provide no information about the intensity of rainfall. Commonly, rains pour down in heavy short showers. Under such conditions the runoff is strong and the effect of erosion on top soils severe. In particular when logging and land clearance has just taken place, heavy rains amass into large brownish runoff streams that carry topsoil and sediments towards the sea.

Hydrogeological structure

Next, we will review and describe some *hydro-morphological processes* in Aruba to better understand the effects of erosion, weathering and soil formation.

Earlier, we described how the Aruban geological formation has undergone tectonic *displacement, uplifting, sea level rises, and deformation activities*. Subterranean *temperature and pressure* regimes during its formation caused distinct differences between rocks in *morphology*, *mineral composition* and *physico-chemical characteristics*. These differences in resistance against the influences from sea, sun, wind and rain have shaped the relief patterns in the Aruban landscape as we know it today. We describe some of these relief patterns in the ALF/Batholith complex and Pleistocene terrace landscape and explain how processes of *erosion, weathering* and *sedimentation* created new opportunities for soil development and vegetation (Finkel & Finkel, 1975).

Watershed and Salt Spray Park

Interestingly, because of the elevated topography at the windward side, the *central watershed line*[19] (Figure 6) is at a close distance of only 0.6 km from the Northeast coastline and up to approximately 4 km from the Southeast coastline. With the exception of the more central area, the watershed line roughly defines the border of an intended *Salt Spray Park* that is envisioned to protect and cover the relatively still untouched natural environment along the Northeastern coastline (DIP, 2009). In the North and in the South, the watershed areas east of the *central watershed line* have little or no history in agricultural activity[20] and are still sparsely inhabited today. Current housing projects, however, develop beyond former agricultural terrain and advance towards the Northeastern coastal zone.

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[18] www.meteo.aw

[19] The watershed is an imaginary line that separates one drainage basin from another one. A drainage basin or catchment area covers the total land area that is drained by a single (dry-) river system.

[20] For information on the original agricultural extent in 1911, we refer to another paper in this landscape series (Derix R., 2016d).

The east coastal *Salt Spray* area is still characterized by nearly total absence of urban-based pollution in terms of contaminated rainwater runoff, sewage water, surface water, or even groundwater. The planning of a *Salt Spray Park* is, therefore, a unique opportunity to create a protected environment that stands in direct relation to the marine ecosystem along the Northeastern coast and the prospected *National Marine Park*. Besides, the area is still 'pristine' and offers the potential to enhance sustainable tourism.

More centrally along the Northeast coastline however, was quite some agricultural development in early 20th century. These Batholith soils are located east of the main watershed line, but are still protected from the salt-laden winds by for instance the hills of the Aruba Lava Formation (ALF) and the the Gabbro Formation ('Seroe Crystal' and 'Seroe Plat'). Today, the region has turned into new housing projects and economic activity, like most of the former agricultural lands. Consequential to the respective locations of these residential and economic activities there will be some degree of 'polluted' surface- and groundwater run-off east of the central watershed line into the coastal areas.

Figure 5 The map shows the main watershed line (red colored line) that delineates the rainwater catchment divide between southwest and northeast. The dry-river systems are not visualized in the map. The small plots (brown delineated light-colored plots) and the large plots (arced) represent respectively the areas where mixed agriculture and Aloe cultivation took place in 1911 (Werbata, 1913)

The different colors in the background represent different geological formations (from north to south respectively, the Aruba Batholith, the Gabbro Formation, the hills of the Aruba Lava Formation, the Limestone Formation and alluvial soils). Beach sands, beach rock and ramparts along the coast are not shown.

Figure 5 shows that the agricultural landscape in early 20th century is confined mainly to the areas west of the main watershed line, on the undulating quartz-dioritic soils of the Aruba Batholith and on the alluvial mud and sands of the dry-river systems at the Southwest coast.

Aloe production took place along the Southwest coast, on the Lower and Middle Limestone Terraces, but not immediately next to the sea.

A sharp demarcation reveals where agricultural subsistence in early 20th century situates that is in large *defined by the geology of the substrate* (Derix, 2016d). Today, these areas have largely been parceled and transformed into housing and economic development projects.

Differences in the drainage pattern of dry-river beds

Differences in chemical composition and resistance against weathering and erosion have in large determined the drainage pattern of dry-rivers (Finkel & Finkel, 1975). The location of these seasonal dry-gullies, better called *dry-rivers* or 'rooien' (in Dutch) is often defined by the location of the fracture lines and deep *geological faults* (see Figure 1).

Limestone Terraces

On the *Limestone Terraces* the main dry-rivers have carved up to the hard bedrock or sand and clay layers underneath the thick limestone layer and show little or no branching. Already in Pleistocene, during periods of sea level low stand, drainage systems created the deep cuts in the limestone coast that end in the small bays (locally called 'Boca's'); that still exist today. Limestone is highly permeable and the terraces are easily eroded. This is also why the watershed lines can only partially be determined in the Limestone landscape (Figure 5 and 6).

We observe few branches of dry-rivers on the Limestone Terraces.

The smaller run-offs disappear underground. There is little surface water and the majority of rainwater drains straight into the cracks of the porous limestone into the groundwater. Interestingly, despite the high permeability of limestone, trees in these areas seem to suffer less from periods of drought compared to the trees on the crystalline rock in the batholith. The cracks and cavities of the Limestone are filled with soils that consequently show a higher water-retention capacity than the upper soil layers on the semi-impermeable Batholith. The trees on the Limestone have the ability to reach these ground water sources during the dry-season (De Freitas, Nijhof, Rojer, & Debrot, 2005).

Batholith

In the *heavily weathered Batholith*, the pattern of the dry-river streams is *dendritic in nature (pers. comm. A. Curet, Figure 6)*. Most of the Batholith consists of a low rising and falling landscape with islands of naked impermeable rock amidst a thick layer of erosion breakdown material.

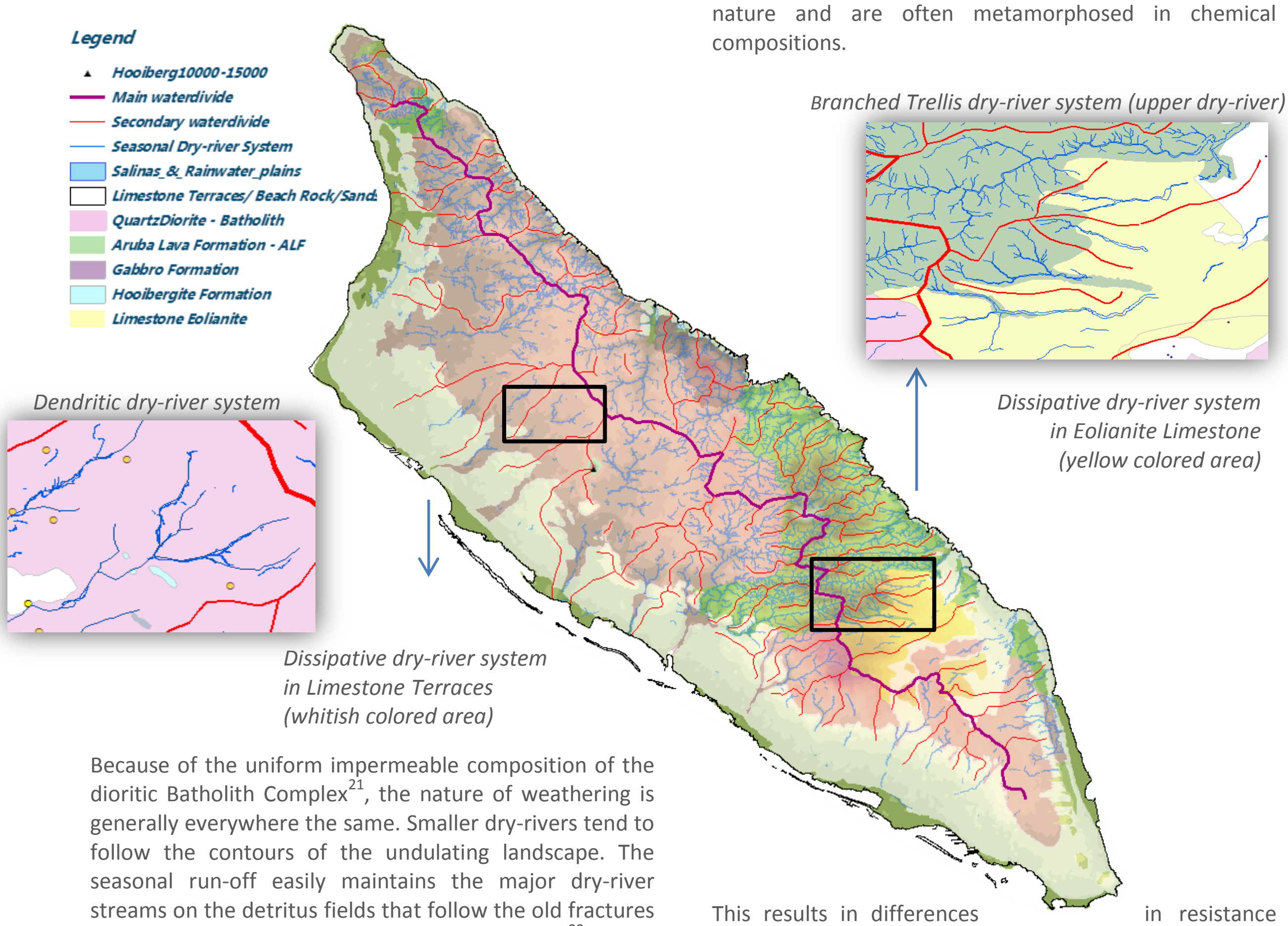

Figure 6 Hydrological features in the Aruban landscape

Because of the uniform impermeable composition of the dioritic Batholith Complex[21], the nature of weathering is generally everywhere the same. Smaller dry-rivers tend to follow the contours of the undulating landscape. The seasonal run-off easily maintains the major dry-river streams on the detritus fields that follow the old fractures and faults by the movements of the upper crust[22]. These major dry-rivers may carve deep as there is little resistance against erosion in these weathered parts of the crystalline rock (Finkel & Finkel, 1975).

Gabbro Formation (area of Seroe Crystal)

The Gabbro rocks are even more resistant against weathering and remain somewhat elevated in the landscape. In essence, the process of weathering and erosion, however, is similar as in the dioritic Batholith.

[21] The Batholith is differentiated in a wide variety of crystalline rocks but the time of solidification of the magma after eruption was too fast to enable crystallization into different rock types.
[22] The thrust and slide-slip faults cut the later Batholith intrusion occasionally up to the surface.

Aruba Lava Formation (ALF)

In contrast, the dry-rivers in the *Aruba Lava Formation* are strongly branched under a variety of often right angles[23] (Figure 6). This is a direct consequence of the different characteristics in physical weathering of the *basalt-based* rock (ALF) in comparison to the *quartz-dioritic/gabbro* rock (Batholith).
The rock formations in the Alf region are less uniform in nature and are often metamorphosed in chemical compositions.

This results in differences in resistance against weathering. In combination with the east-west orientation of many faults and dykes parallel ridges of resisting rock and resulted in a distinct pattern of the dry-river seasonal run-offs, a so-called *trellis pattern; pers. comm. A. Curet*.. Once carved, beddings of hard rock remain that lack the fertile soils as we find in the Batholith. The dry-rivers that carry sediments from the ALF are generally shallow and lack any good soils for agriculture (Finkel & Finkel, 1975).

Tanki's and Aquifers in the Batholith

Because of the low infiltration rate of the rock substrate and high coefficient of runoff (Finkel & Finkel, 1975) the Batholith is well suitable to catch surface rainwater. In the mid-20th century artificial wells and reservoirs or rainwater dams (Tanki) were constructed in the Batholith region specifically for agricultural purposes, to irrigate the fields, and even for domestic purposes (Grontmy & Sogreah, 1968).

[23] 'Trellised drainage patterns tend to develop where there is strong structural control upon streams because of geology' www.physicalgeography.net/fundamentals

Subsurface infiltration of the otherwise impermeable rocks occurs along the fault lines and the smaller fractures and cracks (Finkel & Finkel, 1975). Isolated shallow wells exist that each have their own water regime, based on the local hydraulic characteristics of the weathered zone. Small aquifers exist near the barrier where the Limestone Terrace layer meets the (underlying) hard Batholith rock and where the rainwater that easily seeps through the highly permeable limestone may get blocked by the harder rock and accumulates. In the early 20th century, water from small aquifers in the Batholith rocks was intensively exploited by man-dug holes and drilled wells (see also Derix R., 2016d). A natural freshwater spring exists in Fontein (at *Boca Prins*, see Figure 5) and derives its freshwater from a small local Limestone outcrop at the end of a large fracture in the hard rock bedding that also carries a dry-river 'Rooi Prins'.

Groundwater

Today, drinking water is industrially manufactured at the Balashi water production facility WEB[24] NV. But in the past, besides the seasonal water from man-made surface rainwater reservoirs (tanki's) or from man-build rainwater cisterns directly at the house, freshwater was retrieved from groundwater accumulations via drilled or man-dug wells[25] or directly from the freshwater spring in Fontein.

The wells that are situated in the Batholith or near the border with the limestone, generally tap from aquifers that are situated deep into the ground or directly from the groundwater. As argued already, the Batholith and Aruba Lava Formation consist of hard impermeable rock, and meteoric water (water that originates from precipitation) can only seep into the ground along subterranean fracture lines (i.e. faults) or can accumulate in the deep pockets where the rock is already heavily weathered. Also, underneath the deep beds of detritus and clay and sand particles, as occurs in some dry-river beds, water can accumulate on the deep impermeable rock. The composition of groundwater is generally brackish and influenced by the type of rock in the dry-river catchment-drainage basin. The wells that are situated more to the coast tap from the limestone aquifers and are easily polluted with seawater. When the pumping of well water is too intense, infiltration and mixing with seawater occurs and the water becomes too brackish even for agricultural use. A study by Sambeek, Eggenkamp and Vissers (2000) shows that the salinity of the groundwater in Aruba is high compared to neighboring islands. The authors also found that in only a *third of the wells* in Aruba (n=33), the water was suitable for irrigation purposes, as there is a risk on salinization of the land and a negative effect from the well-water's high sodium concentration that might influence the physical soil structure as well. Nonetheless, most of the well-water is still usable as drinking water for livestock.

Chemical and Physical weathering

Weathering of the rock material in the *Batholith* differs from the *Aruba Lava Formation* and the *Limestone Terraces*. Processes of physical and chemical weathering and erosion followed on each other differently. In general, under semi-arid conditions, soils are only infrequently moist and (chemical) weathering conditions are slow, which also limits the formation of rich soils.

Weathering in the Limestone Terraces

The most suitable soil formation for agriculture, in the *Limestone Terrace areas*, occurs only in dry-river beddings. Limestone, namely, does not weather down into soil, but consolidates and lithifies under wet conditions and may after dissolution and recrystallization of the carbonate components, easily wash away. Soil formation, however, does take place in the dry-river beddings in Limestone areas as these generally also carry mud, organic compounds, clay, and erosion remains of upstream rocks in the catchment-area (de Vries, 2000).
Accordingly, the seasonal dry river streams have easily cut through the permeable Limestone Terraces and have created fertile valleys where they open into the sea. Their sediments are high in carbonate content and contain mineral elements from the geological composition of the catchment-area (van den Oever, 2000). These dry-river beds contain relatively deep alluvial soils and have favorable hydrological conditions for agriculture (Finkel & Finkel, 1975). The maps in figure 2 and 5 respectively show the location of the alluvial mud and sand sediments and the areas, in particular near the southwest coast, that have been used most intensely for agricultural purpose in early 20th century. Historically, these dry-rivers often come with small bays and inlets that offer habitat for a number of plant (mangroves, etc.) and animal species (bird protection areas).

Pressure release, expansion cracks and weathering in the Batholith rocks

The solidification in Late Cretaceous of the Tonalite and Gabbro Batholith took place deep in the earth crust under high pressure and temperature regimes followed by a long period of cooling that has resulted in a homogeneous crystallization of the intruded rock material. Initial strain and ruptures took place deep under the earth surface as a result from physical stresses. The faults, dykes and veins that we can observe on the earth surface are the results of such processes and date back from early orogenesis[26].
In time, however, erosion of the top sediment layers exposed the Batholith rocks. With the removal of the mass on top there and consequent pressure release, more expansion cracks developed along relaxation and distension joints.
When water is able to infiltrate deep underground along the fault lines in the cracks and joints, processes of chemical weathering can take place.
Tonalite is high in silicate content and in contact with water hydrolysis takes place at the electrically charged crystal surfaces. This is a form of *chemical weathering* that

[24] www.webaruba.com

[25] Today, the water we consume is from imported bottles or from the water produced by the local Desalinization Plant (Web Aruba).

[26] The process of mountain formation by deformation of the Earth's crust

typically developed in the past in Aruba, when there were more humid and wet conditions than at present (Herweijer, 1979) and when rainwater was able to infiltrate inside the joints, deep in the rock underneath the surface (STINAPA, 1977)[27]. As the chemical weathering[28] continues, the disintegration of the rock material takes place. Joints turn into cracks and blocks of rock develop in a cube-like shape (typical for the joints in Granite or Quarts-Diorite rock). The chemical surface weathering is of course most intense at the edges and corners of the rocks (where the surface to volume ratio is largest). The result of the differential weathering is a boulder shape rock formation, as if they were placed and carved carefully to fit on top of each other. This type of weathering, however, takes place only as long as humidity (within the soil) is in direct contact with the rock. Once the 'rounded' Tonalite boulders surface, the loose weathered material in the cracks is taken by erosion. This explains why the rounded Diorite boulders have this shape and why they are still seen in large accumulations in the Aruban Batholith landscape. After exposure at the surface, the conditions, namely, turn too dry for chemical weathering and the further disintegration of the rock material takes place physically and under the influence of the sun.

Physical weathering

In the absence of water, most weathering in semi-arid environments is physical in nature. Rocks are bad heat conductors, but the alternation of intense heating during the day and cooling at night, in particular in combination with the alternation of wet and dry seasons, enables some level of physical weathering even at the hardest rock surface.

Sheeting of rock

The solar heat reaches up to millimeter or sometimes centimeters level deep into the rock. Different minerals expand differently when heated and, thus, under the influence of solar heat expansion cracks occur parallel to the rock surface. The daily sequence of expansion at day and contraction at night attacks the rock from all sides, but again, like is the case with chemical weathering, the strongest physical weathering occurs at the outer sharp edges where the surface to volume ratio is largest. Because of the homogeneity of the quartz-diorite rock components these rocks tend to peel off in time, layer by layer.

This process is called 'rock foliation' and creates an even more "spheroidal" appearance of the tonalite rocks. Due to the fact that some rocks still have a somewhat higher resistance against weathering than the remainder of the Batholith landscape, the final stage is an undulating landscape, typical for the Aruban Batholith with some accumulations of large rounded exfoliated Tonalite boulders.

In contrast, the rocks in the Aruba Lava Formation are more divers in the nature of composed material and tend to break apart piece by piece.

Stream sediments

Rainwater is only seasonally available and, therefore, most of the detritus and sediments remain largely unaltered in mineral composition at the surface. As a result of the accumulation of rainwater with humus and humic acids in cracks and crevices and in the dry river beds, some organic weathering and soil formation is manifested in these locations. Shallow soil is sufficient to provide new opportunities for vegetation that will accelerate rock decay and create even better conditions for soil formation. The hard and impenetrable rocks in the beddings of the seasonal streams in the Batholith only allow small puddles of water, however, where little organic compounds can collect and turn into soil.

A baseline study carried out in 2000 (van den Oever, 2000) shows that the stream sediments in the quartz-diorite Batholith are mainly *acidic in nature*. They have high silicate content, but are depleted of most metal elements and consequently offer relatively poor soils for agriculture. The Gabbro dry-river sediments have more metal ions and somewhat better soils, but the highest concentrations of metal elements are found in the ALF region. The hard rocks of the ALF, however, offer little opportunity for agriculture.

The dry-rivers that origin in the ALF region and end at the Northeast coast have almost no extent and have relatively narrow beddings. Those that have their downstream southwestwards, however, have large beddings that reflect the rich geology of their wider drainage basin and do provide relatively good soils for agriculture (see also Figure 2, 5 and 6) (Grontmy and Sogreah, 1967).

The interplay between hydrogeology, soil formation, climatic conditions and vegetation growth is elegantly portrayed by De Vries in Curacao (2000) and Van Den Oever in Aruba (2000). Even at some distance from the coast, under the harsh semi-arid local conditions, salt accumulation is likely to occur in the topsoil layers, influenced by the salt-laden Passat winds (de Vries, 2000). This process is called 'salinization'[29] and occurs when evaporation exceeds precipitation and the concentrations of soluble salts (sulphates and chloride of calcium, magnesium, sodium and potassium) in the upper soil layer increase until these eventually precipitate.

Today's influences on soil and groundwater

The deposition of weathered material is relevant for the formation of soils and delivers the nutrients for plant growth. However, it is not merely the type of parental material of the substrate from the watershed hinterland that determines the quality of the soil. Climatic conditions, local topology, vegetation type, human action, and also the presence (or allowance) of small insect fauna, etc., play a role in the process of soil formation.

[27] Reference made in De Vries (2000).

[28] Chemical weathering in contrast to physical weathering involves an alteration of the chemical and mineralogical composition of the rock material.

[29] Salinization will of course also be the case where salt spray accumulates and rainwater drain is limited. Under specific mineralogical conditions on the more calcareous grounds the same process is called 'calcification', i.e. when the accumulation and of precipitation involves calcium carbonate ($CaCO_3$).

Much topsoil have been washed away in Aruba already by seasonal rains or blown away by the trade winds after men exploited and the sun baked the land. Deforestation, overgrazing, and land clearances all had their impact. Loss of valuable soils we find elsewhere in the Caribbean (Ramjohn, Murphy, Burton, & Lugo, 2012) and worldwide (Howgego, 2015). In the mid-17th century large numbers of goats and sheep were free to roam and graze the land. The harvest of woods was already severe and was to continue for over three centuries in total (Hartog, 1953). In earlier century written accounts, the Aruban countryside is referred to as harsh, barren without much vegetation and with little or no topsoil (Teenstra, 1836).

Today, in many 'wildered' spots, we still find evidence of intense erosion, where the land has been cleared (or grazed), and nothing was put in place to retain the water or prevent the loss of valuable soils.

Photo: Ruud Derix, Sept 2015.

Soil enrichment and pollution in (sub) urban areas

Inside today's walled perimeters of the new densely inhabited areas new opportunities arise for soil formation, as these walls not only prevent a rapid rainwater runoff from the home gardens (or hotels, etc.) but also ease the accumulation of plant detritus in the garden enclosure. New (garden) ecosystems develop, sometimes added with irrigation during the dry season or with additional fertilization, albeit that the garden vegetation is frequently more exotic in nature with changed opportunities for local flora and fauna (Barendsen, 2008) (van Buurt & Debrot, 2012) (van der Burg, de Freitas, Debrot, & Lotz, 2012) (Maunder, et al., 2008).

The situation outside the landscaped garden environments can be completely different. Some urban areas may experience an increase in the incidence of flooding and sedimentation after heavy rains (Derix, 2016f) whereas in other places soil erosion is intense due to a rapid channeling of the rainwater runoff via the draining infrastructures. In particular when uninhabited land is 'cleared' for new construction (i.e. removal of 'wild' vegetation including topsoil layers with excavators) valuable soils are easily carried away (RuG/VROM, 2000). This is particularly the case during the rainy season (Perk, 2003).

As the suburbanization of the landscape[30] progresses, pollution from human activities plays a more important damaging role as well and influences the face of the landscape. Enriched soils not only provide more optimal circumstances for plant growth, but also may create new habitats where invasive species flourish best. The continual nutrient enrichment is also thought to have long-term consequences on the quality of ground- and surface waters and may even influence the marine ecosystems negatively via groundwater and surface water runoff (Cable, Corbett, & Walsh, 2002) (Day, 2010).

Besides from excessive fertilization of garden soils, additional contamination of soils, ground- and surface waters comes from the effluent of household sewage from shallow surface cesspools[31], the use of herbicides, pesticides, and alike, as well as the disposal of detergents and other discharges (Finkel & Finkel, 1975). These effectors accumulate in residential soils and are partly carried away with the seasonal rainwater runoff into the marine environment. Possibly phosphate (Sharpley, Daniel, Pote, & Sims, 1996) and more likely nitrogen enrichment (Cable, Corbett, & Walsh, 2002), and certainly chemical pollutants thus create a threat, not only to the local surface- and groundwater and freshwater in wells, but more importantly to the reef ecosystems[32] (Buurt, 2008). Coral bleaching and algal blooms along the coast have been described in other parts of the Caribbean already (Gast, 1998) and are a potential threat in Aruba as well that may even affect the tourism industry (Goreau & Thacker, 1994).

In conclusion

In this paper we have made an effort to summarize and show how geological and (paleo) climate events have set the boundaries for the natural development of the landscape. Today's suburban developments create a new type of landscape and habitat that differs as it tends to become more detached from its 'natural' settings. An overall loss in nature surface area and a human-induced impact on the local environment created a *multifaceted challenge for the prospected sustainable economy*. A good understanding of past history is significant to focus on the right efforts.

Weathering, erosion, soil formation, and the subsurface mixing and flow of fresh and marine waters is a continuous process and is active today as it was in the past. Changes on land indirectly influence the processes at sea, in particular in a small island setting when processes of eutrophication and contamination of ground- and surface waters occur. We must understand that the dynamics on land and at sea are inseparable. It is important to recognize the detail of spatial events as today's local events are in interplay with the geological formations of the landscape. The modern impacts and the challenges that we face will be different in different regions. In this paper we have made an attempt to help understand where these differences may be relevant and what these differences may include.

[30] We refer to a more detailed account in this series' paper No. 4, 'The suburbanization of the Aruban landscape' (Derix, 2016d).

[31] For a more detailed account of the location of household cesspools and public sewage systems we refer to this landscape series, paper No. 5 'Conflicts between the Economy and the Landscape in Aruba'

[32] An overview is presented by G. van Buurt during the WildAruba meeting in 2008, in Aruba: 'Nutrients on Coral Reefs', www.wildaruba.org.

Endnote:

Cretaceous 145-65 Mya
Ends with the extinction of dinosaurs

Paleogene 65-24 Mya
Evolution of first small mammals and birds

Early Neogene 24 Mya -1.8 Mya
First evolution of ape and man species

Quaternary Pleistocene 1.8 Mya - 11.000 year
Lasts until the latest Ice-age and is the time of saber-toothed cats, dire wolves, mammoths and stone-age man.

Quaternary Holocene 11.000 year – today
Man gatherer/hunting lifestyle turn to farming and the domestication of animals.

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