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GUIDE

TO THE FIELD EXCURSIONS ON CURAÇAO, BONAIRE AND ARUBA, NETHERLANDS ANTILLES

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G U I D E

TO THE

FIELD EXCURSIONS ON CURAÇAO, BONAIRE AND ARUBA, NETHERLANDS ANTILLES

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C O N T E N T S

C O N T E N T S (continued)

OUTLINE OF THE CRETACEOUS AND EARLY TERTIARY HISTORY OF CURAÇAO, BONAIRE AND ARUBA

D.J. Beets; H.J. Mac Gillavry

Introduction

Curaçao, Bonaire and Aruba form the western part of the Aruba - La Blanquilla chain, an E-W-running row of small islands and atolls on the Venezuelan continental borderland in the southern Caribbean (fig. 1). The Bonaire Trench with a depth of over 2000 m separates the central part of this island chain from the mainland. The Los Roques Trench and Curaçao Outer Ridge lie between the islands and the oceanic Venezuela Basin. The Venezuelan borderland with its ridges and trenches forms part of a broad orogenic belt of Mesozoic and younger age at the boundary of the Caribbean with the South American plate. The main, emerged part of this belt is the Caribbean Mountain System of Northern Venezuela.

The geology of the Leeward Netherlands Antilles is characterized by strong magmatic activity during the Cretaceous and mobility during Cretaceous and Early Tertiary. The Middle Eocene to Recent history, in contrast, shows remarkable stability.

The Cretaceous and Early Tertiary history falls apart in two episodes.

1. An Early Cretaceous - Coniacian phase with abundant submarine volcanism of the tholeiitic series (Santamaría & Schubert, 1974; Donnelly et al, 1973; Beunk & Klaver, Vol. of Abstracts). The Curaçao Lava Formation (more than 1000 m of basalt only), Washikemba Formation of Bonaire (5000 m of submarine arc volcanism with lavas ranging in composition from basalt to rhyodacite), and the diabase-schist-tuff formation of Aruba (mainly basalt) have been formed in this phase (fig.2). Terrigenous detritus, if present, is all volcaniclastic debris.
2. A late Senonian - Paleocene phase with less magmatic activity, and an increase in clastic sedimentation (fig. 2). Igneous rocks of this phase belong to the calc-alkaline series (Santamaría & Schubert, 1974; Beunk & Klaver, Volume of Abstracts). Detritus during this phase comes from various source areas. In addition to volcaniclastic debris, sialic detritus occurs, indicating the proximity of the South American continent. Stratigraphy of the late Senonian on Curaçao suggests that sedimentation during this phase is largely controlled by faulting. No sediments of this phase are found on Aruba; emplacement of the quartz-diorite batholith occurs in this interval.

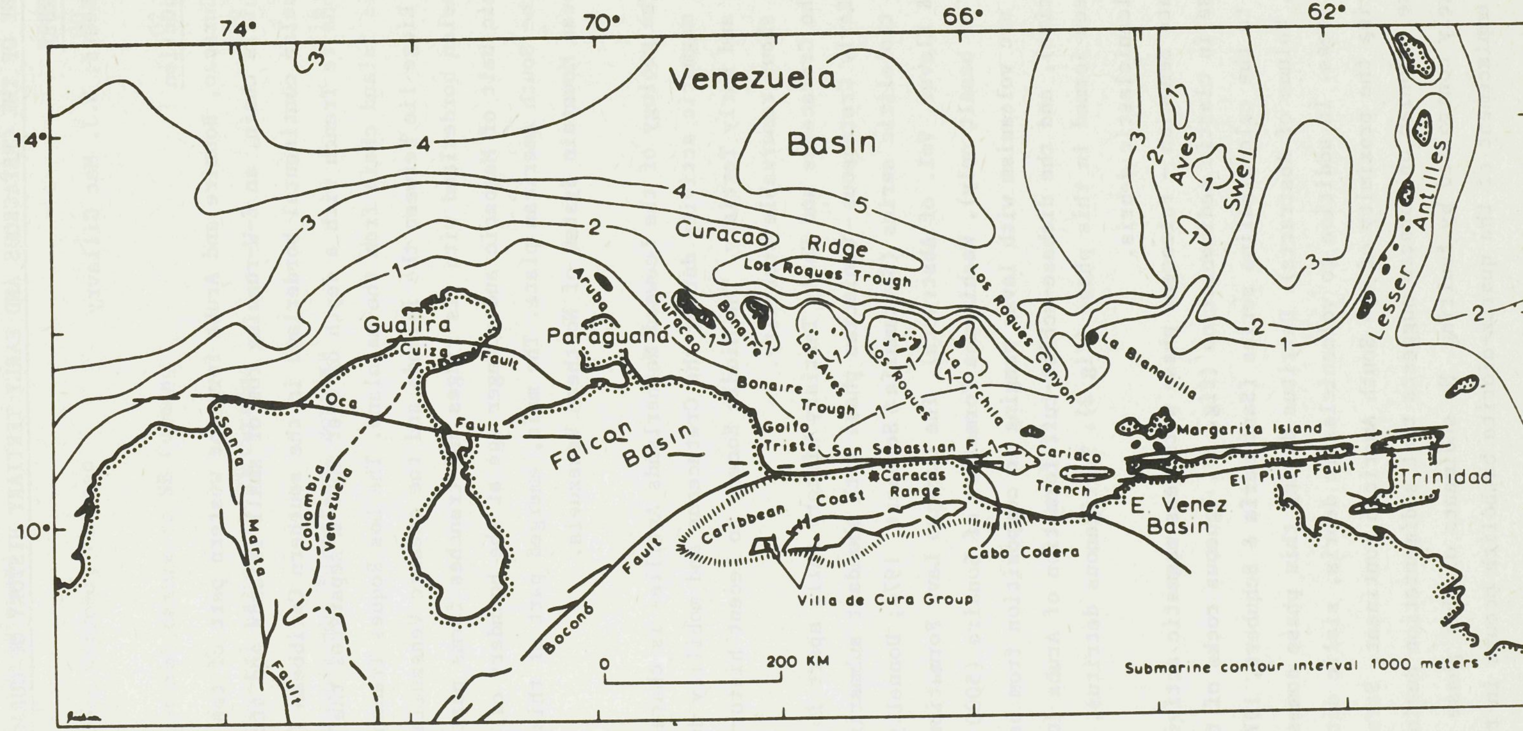

Fig. 1. Venezuelan Borderland (from Silver et al., 1975, Geol. Soc. Am. Bull., 86, 213-226)

A stratigraphic break, due to emersion of the Curaçao Lava Formation and uplift and tilting of the Washikemba Formation (fig. 2) separates the two phases.

Phase 1. Early Cretaceous - Coniacian submarine volcanism: volcanic arc or spreading ridge; collision with South America.

The first question with regard to this phase is whether volcanism represents a compressional or an extensional environment (Mac Gillavry, 1970).

Curaçao Lava Formation and diabase-schist-tuff formation consist of thick piles of basaltic rocks only. Trace element data (Donnelly et al, 1973; Beunk & Klaver, Volume of Abstracts) indicate that the basalts belong to the group of low-potassium tholeiites (LKT) or abyssal floor tholeiites, thought to be derived by shallow melting of depleted mantle. Both data favour an extensional environment.

The Washikemba Formation of Bonaire, on the other hand, is made up of about equal amounts of intermediate (andesite - rhyodacite) and basic volcanites; main and trace element data show them to belong to the so-called island-arc tholeiites (Beunk & Klaver, Volume of Abstracts). In other words: a compressional environment.

Assuming that the Washikemba Formation indeed represents island-arc volcanism, it leaves us two alternatives for Curaçao Lava Formation and diabase-schist-tuff formation: (a). the development of Curaçao and Aruba during this phase is basically different from that of Bonaire; (b). low-potassium tholeiites (abyssal floor tholeiites) may also occur in a compressional (island-arc) environment.

We prefer the latter alternative, although the arguments are scant. Most important argument is that both on Curaçao and on Bonaire this phase of volcanism ends with emersion; a coincidence which is difficult to reconcile when assuming a divergent development (on Aruba, however, there already was temporary emersion during this phase). A second argument is, that in the Danian a land area existed north of the present island of Curaçao which supplied partly metamorphosed detritus of mid-Cretaceous diorites and andesites (Beets, 1972, 1975). Although this does not prove that the Curaçao Lava Formation represents island-arc volcanism, it gives considerable constraints to any reconstruction which assumes the sequence to be ocean floor.

A third argument is given by Maresch (1974) in his plate tectonic reconstruction of the Caribbean Mountain System.

Maresch showed convincingly that the medium- to high-pressure

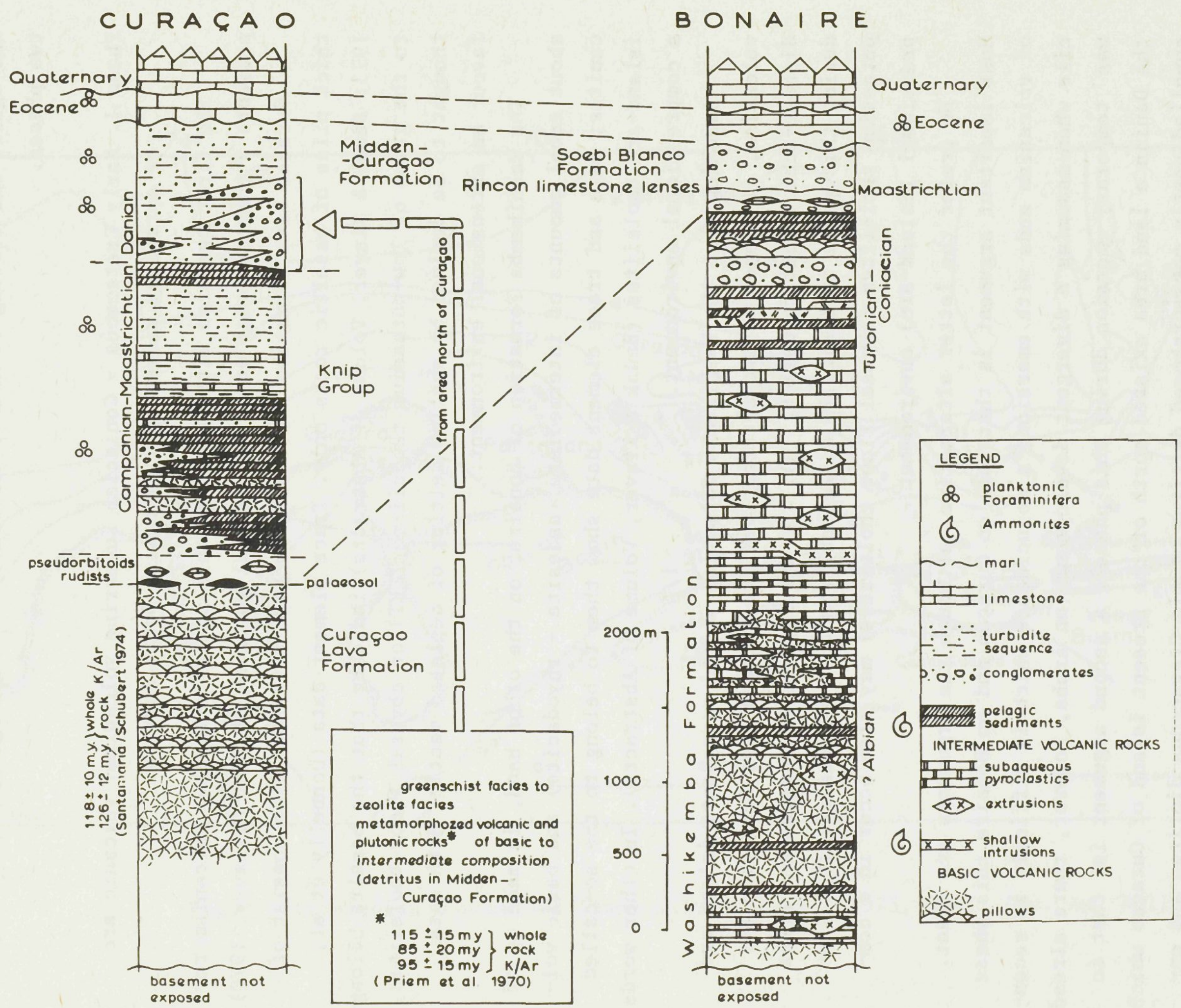

Fig. 2. Simplified stratigraphic columns of Curaçao and Bonaire.

type of metamorphism of the rocks of the Caribbean Mountain System can best be explained by collision of an island-arc with the continental margin of northern South America in late Cretaceous time. He suggested that the Curaçao Lava Formation formed part of this island-arc, and its emersion the actual collision.

Adapting this thought-provoking idea of Maresch, one of us (Beets, 1975) gave a different version with regard to timing of the collision. Mainly based on the assumption that the Washikemba Formation of Bonaire represents continuous sedimentation and volcanism from the Albian to the Maastrichtian, Beets placed collision pre-Washikemba Formation, in the early Cretaceous. The Maastrichtian age was based on rudists and planktonic Foraminifera from the Rincon limestones and marls, which were thought to be intercalated in the Washikemba Formation. This is now considered to be erroneous: paleontologic evidence shows that the Washikemba type rocks adjacent to the Rincon carbonates are of Coniacian age. Accordingly we must now assume that the Rincon carbonates were deposited unconformably upon the Washikemba Formation and that the present remnants have been faulted or folded into the surrounding Washikemba rocks (Mac Gillavry & Beets, Volume of Abstracts). This new age range of the Washikemba Formation fits perfectly in Maresch's reconstruction. It shows that a volcanic arc was present north of South America, and that collision took place in the interval Coniacian-Campanian.

Phase 2. Late Senonian - Paleocene: cordilleran-type island arc.

After collision of the island-arc and continental margin, convergence continued and a southward-dipping Benioff zone developed north of the continental margin. The igneous rocks of the calc-alkaline series of Late Senonian and Tertiary age found on most islands of the Aruba - La Blanquilla chain as well as in the Caribbean Mountain system (Santamaria & Schubert, 1974), represent island-arc magmatism above this Benioff zone. The composite tonalite batholith of Aruba and the (quartz)andesitic necks, sills and tuffs of Curaçao belong to this arc. Isostatic readjustment from the earlier collision may have taken place during this phase causing vertical movements, development of flysch basins and gravity sliding (Bell, 1971, 1972; Maresch, 1974; Bellizzia, 1972).

Selected references: Beets, 1972, thesis Amsterdam; Beets, 1975, Prog. Geod., Royal Neth. Ac. Arts Sc., Amsterdam, 218 -233; Bell, 1971, Geol. Soc. Am. Bull., 130, 107 - 118; Bell, 1972, Geol. Soc. Am. Bull., 132, 367 - 386; Bellizzia, 1972, Geol. Soc. Am. Bull., 132, 363 - 368; Beunk & Klaver, 1977, VIIIth Car. Geol. Conf., Vol. Abstracts; Donnelly et al., 1973, In. Rep. DSDP, 15, 989 - 1011; Mac Gillavry, 1970, Proc. K. Ak. Wet. A'dam, 73, 64 - 96; Mac Gillavry & Beets, 1977, VIIIth Car. Geol. Conf., Vol. Abstracts; Maresch, 1974, Geol. Soc. Am. Bull., 85, 669 - 682; Santamaría & Schubert, 1974, Geol. Soc. Am. Bull., 85, 1085 - 1098.

CRETACEOUS AND EARLY TERTIARY OF CURAÇAO

D.J. Beets

Introduction

On the basis of lithology and folding phases the Curaçaoan succession can be roughly divided into three parts, from old to young:

1. A strongly folded Cretaceous - Danian volcanic-sedimentary sequence of more than 3000 m thickness. Folding occurred in the interval Danian - middle Eocene.
2. A few remnants of limestones, marls, sandstones and clays of Eocene age, which unconformably overlie the older sequence. These deposits are tilted or weakly folded.
3. Limestones of Neogene and Quaternary age, exposed in a zone of varying width along the coastline and covering about 1/3 of the island. The limestones have not been affected by folding.

Cretaceous and early Tertiary sequence

In main lines the structure of the sequence is relatively simple: two large anticlinoria, forming the northwestern and southeastern part of the island, respectively, separated by a synclinorium in the central part (plates 1 and 2). Smaller folding, faulting and thrusting complicate the structure in detail. Thrusting is towards the south.

Stratigraphy

The sequence has been subdivided into three main units, from base to top: A) Curaçao Lava Formation, B) Knip Group and C) Midden-Curaçao Formation (fig. 3). Because of rapid vertical and lateral facies changes the Knip Group has been split up into 9 formations; the Midden-Curaçao Formation has been subdivided into 4 members.

A) Curaçao Lava Formation

The Curaçao Lava Formation is exposed in the cores of the two anticlinoria and in a third, smaller outcrop area in the extreme northwestern part of the island (plates 1 and 2). It is a more than 1000 m thick, monotonous succession of submarine extruded, altered tholeiitic basalts with subordinate some intercalations of reworked hyaloclastites, and perhaps some doleritic dikes and
F, G sills. Pillow structure is very common. Pillows usually do not contain vesicles, which suggests extrusion of the lavas at depth below 800 m.

Reworked hyaloclastites form a subordinate constituent of the formation. They are fine grained (grainsize usually smaller than 1 mm), occasionally show graded bedding, and consist of angular fragments of brownish coloured palagonitic glass and grains of plagioclase and clinopyroxene. The glass

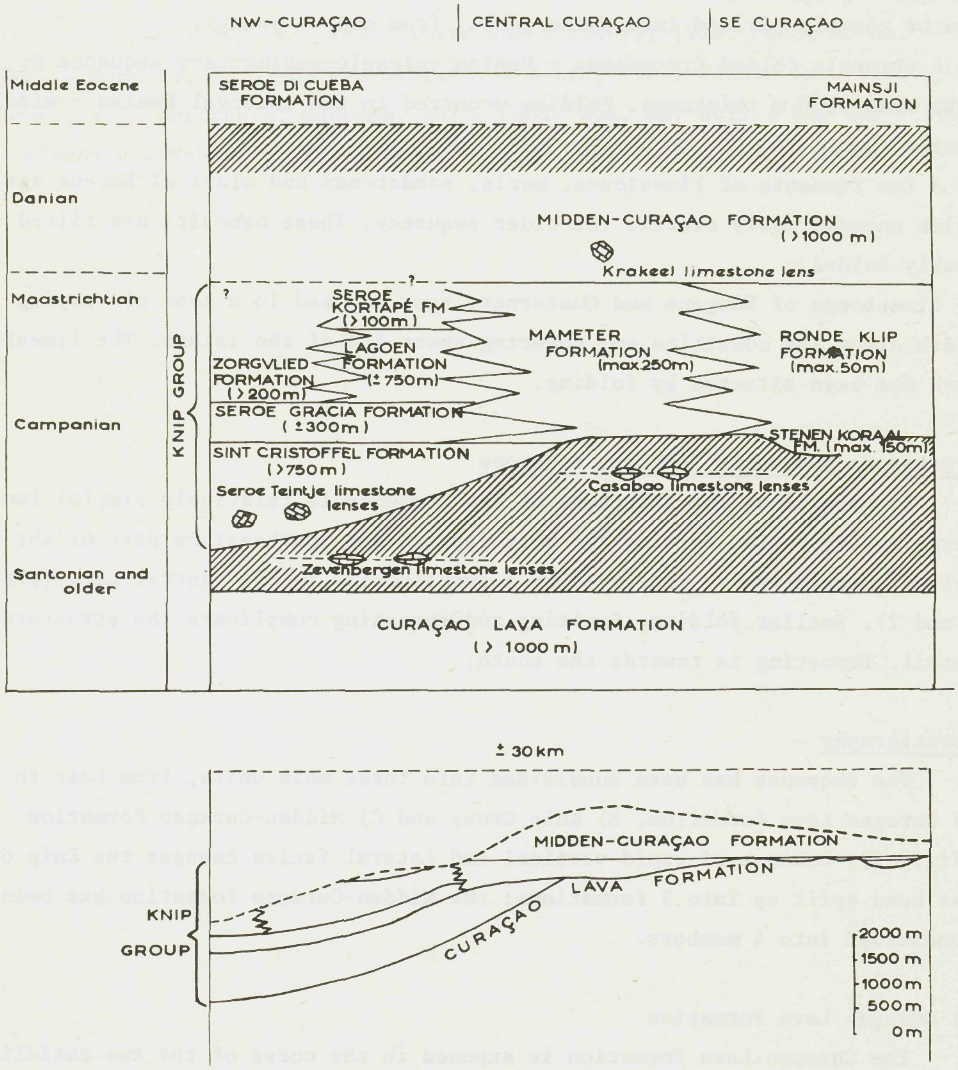

Fig. 3. Stratigraphic table of the Cretaceous and Danian of Curaçao. The relative thickness of the units are given in the section below, which uses the top of the Knip Group as base level (vertical exaggeration 2x).

fragments may contain some vesicles, but they lack the characteristics of pumiceous glass shards from explosive eruptions. Except for these hyaloclastites, the Curaçao Lava Formation lacks any vertical or lateral variation in rock-types, despite its thickness and relatively large outcrop area. Differences between the lavas are so small that no individual flows could be distinguished.

No fossils were found which could be used for dating. K/Ar whole rock dating of two dolerites (Santamaría and Schubert, 1974) gave ages of 118 ± 10 and 126 ± 12 my, which would place this unit in the early Cretaceous. RE-pattern and other trace element data indicate that the basalts of the Curaçao Lava Formation belong to the group of the abyssal floor tholeiites.

The Curaçao Lava Formation is separated from the overlying Knip Group by an unconformity. Main evidence for emersion of the Curaçao Lava Formation is the local occurrence of shallow water limestones on top of the
E, J formation (Zevenbergen and Casabao limestone lenses, see below). During the emergent interval the basalts were strongly weathered which resulted in a discontinuous level of brecciated lavas on top of the sequence (in-situ breccias) and the local occurrence of jasper lenses at the boundary of Curaçao Lava Formation and Knip Group.
Whether the break between Curaçao Lava Formation and Knip Group is an angular unconformity or not is unknown, because of the absence of data on bedding plane attitudes in the Curaçao Lava Formation.

Zevenbergen and Casabao limestone lenses

Two groups of small limestone lenses occur at the boundary of the
E, J Curaçao Lava Formation and the Knip Group, the Zevenbergen limestone lenses in the northwestern part of the island (fig. 3), and the Casaboa limestone lenses in the central part. The limestones are calcarenites and calcirudites. Organic remains in the Zevenbergen limestone lenses are fragments of algae, rudists, corals, gastropods and crinoids. Rudists and rudist fragments were identified by H.J. Mac Gillavry as Torreites cf. tschoppi MAC GILLAVRY, Plachioptychus sp. and Radiolitidae. The Torreites is smaller than Torreites tschoppi described from Loma Yucatan, Cuba (Mac Gillavry, 1932), and could be a new species. The Casabao limestone lenses consist predominantly of remains of larger Foraminifera, algae, bryozoan, crinoids and some oysters. The larger Foraminifera are Sulcoperculina sp. and Pseudorbitoides

curaçaoensis KRIJNEN (Krijnen, 1967, 1972, p. 10) a primitive form of this group.

The absence of pseudorbitoids in the Zevenbergen limestone lenses suggests that this limestone is older than the Casabao limestone. Based on phylomorphogenetical studies Krijnen (1967) concludes to a Campanian age for the latter. A late Santonian - Campanian age range for the Zevenbergen limestone lenses is based on the association of Torreites tschoppi with Pseudovaccinites inaequicostatus in the Loma Yucatan limestones, Cuba.

B) Knip Group

The Knip Group consists almost exclusively of sediments both pelagic silica-rich rocks and clastic sediments. Variation in supply and sources of the detritus are largely responsible for the vertical and lateral facies changes in the unit.

The sequence has its most extensive development in the northwestern part of the island, where it attains a thickness of over 2000 m. It thins rapidly towards the S and SE, and in the central and southeastern part it is reduced to less than 100 m thickness (plates 1 and 2, fig. 4). Thinning is probably largely due to a time-lag between submersion of the northwestern part of the island and the central and southeastern part. However, differences in rate of sedimentation and submarine erosion at the upper boundary of the group are also important factors.

Volcanic rocks form a minor constituent in the group: basaltic flows in the lower half and (quartz) andesitic tuffs in the upper part. However, most of the detritus in the group is epiclastic volcanic debris. In the upper half this is associated by detritus derived from a sialic source. This is the first indication in the Curaçaoan section of the proximity of the South American continent.

It is assumed that the Knip Group is of late Senonian age, based upon age of the underlying Zevenbergen and Casabao limstone lenses, the Danian age of the overlying Midden-Curaçao Formation and the presence of single- and double-keeled globotruncanids in a few thin-sections of cherty limestones of the group.

Subsidence started at the site of the northwestern part of the island
G, E, J (fig. 6), and here an up to 1000 m thick succession of boulder beds, slump breccias, pebbly mudstones, turbidites and silica-rich pelagic sediments, the Sint Christoffel Formation, was deposited (fig. 5). Downward movement is

rapid and probably controlled by faulting. Rapid, because the basal beds on top of the unconformity are cherts and slump deposits, considered to be characteristic for somewhat deeper water. Subsidence in the northwest is accompanied by uplift in the source area (central and southeastern Curaçao, fig. 6), as is indicated by the large amount of very coarse grained and angular basalt debris deposited at the foot of the basin slope. There submarine fans built up, mainly consisting of rock fall deposits (boulderbeds and slump breccias) debris flows, pebbly mudstones and turbidites with a relatively large amount of pelagic intercalations: cherts, radiolarites, cherty mudstones and cherty limestones.

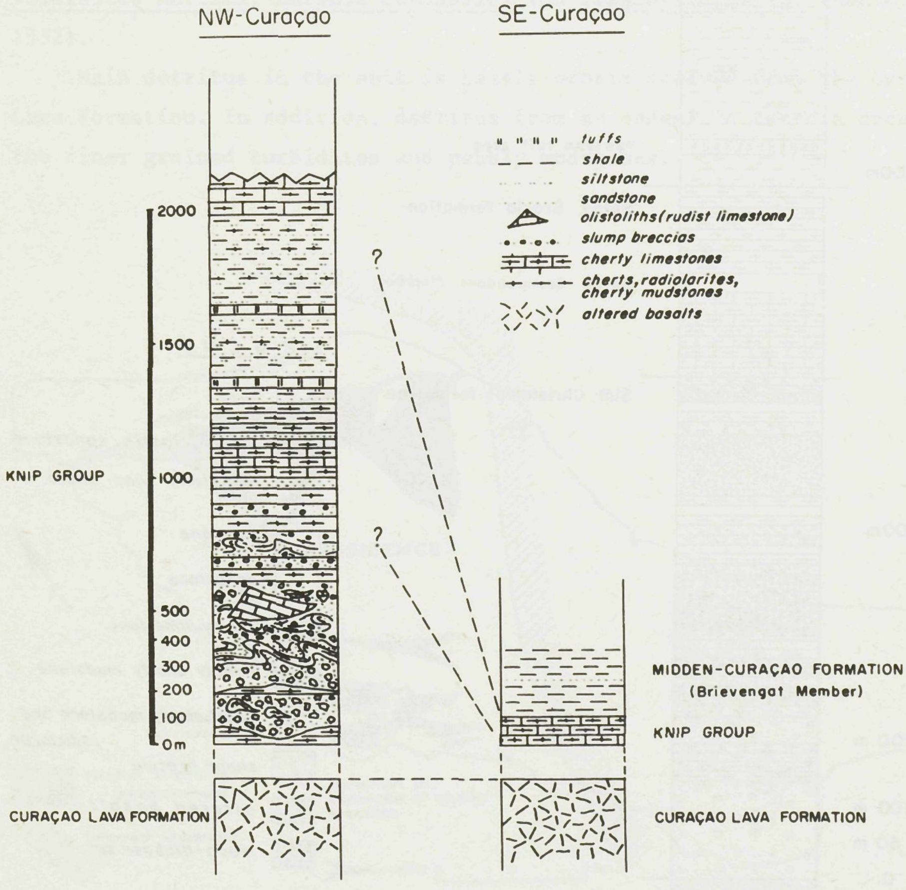

Fig. 4. Simplified sections of the Knip Group in northwest (left) and southeast (right) Curaçao, showing the great difference in thickness, and the presumed correlation.

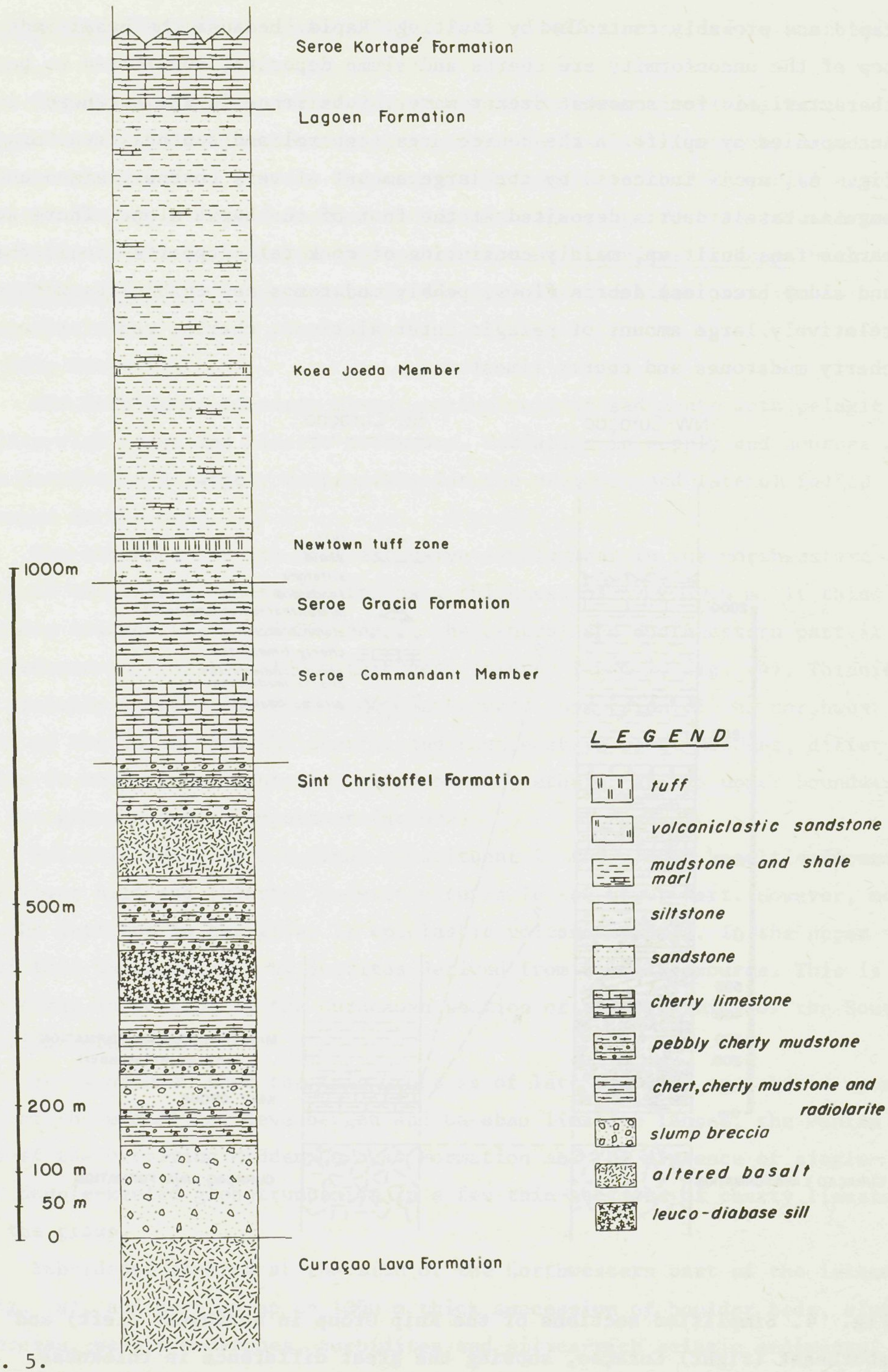

Fig. 5.
Simplified stratigraphic column of Knip Group in northwestern Curaçao.

The presence of pelagic deposits in the proximal realm of the fans suggests that clastic sedimentation is spasmodic, and due to catastrophic events in the source area and along the basin margin rather than to a more or less continuous supply of detritus by draining beach drift or river systems. Large scale sliding and slumping of the chert-rich sediments, coarseness and angularity of the debris and the presence of up to 500 m large blocks of a shallow water limestone in this sequence confirm this view. These latter limestone blocks are the Seroe Teintje limestone lenses,
G a reefal limestone with remains of rudists, corals, stromatoporoids, algae, gastropods, pelecypods and echinids. The rudists were identified as Pseudovaccinites martini, Durania curasavica and Plagioptychus sp. (Mac Gillavry, 1932).

Main detritus in the unit is basalt debris derived from the Curaçao Lava Formation. In addition, detritus from an andesitic terrain occurs in the finer grained turbidites and pebbly mudstones.

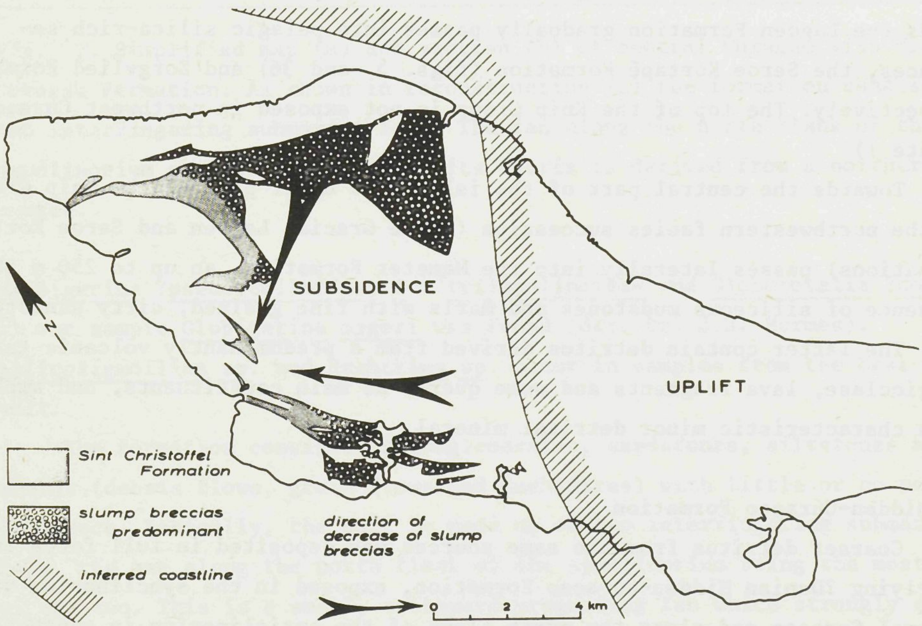

Fig. 6. Distribution of coarse grained breccias in Sint Christoffel Formation, and inferred paleogeography.

Towards the top of the Sint Christoffel Formation the amount and grain-
E, J size of the detritus decreases rapidly and the unit grades into an up to
300 m thick succession of cherty limestones, bedded cherts and radiolarites,
the Seroe Gracia Formation. Central and southeastern Curaçao became flooded,
as no basalt debris is supplied anymore. The Seroe Gracia is a pelagic de-
posit with the exception of one intercalation of an up to 30 m thick vol-
caniclastic sandstone, the Seroe Commandant Member (figs. 5 and 36). This
sandstone consists predominantly of debris of volcanites of intermediate com-
position (roughly 50%) and exotic detritus: metamorphics (quartzites, schists
and amphibolites) and acid plutonic rocks. The Seroe Gracia Formation is con-
formably overlain by the Lagoen Formation, which is an approximately 750 m
G thick outer fan - basin plain turbidite succession consisting of fine sand-
stones, siltstones, mudstones and marls with intercalations of tuffs and a
G volcaniclastic sandstone, the Koea Joeda Member. Composition, grainsize and
structures of the latter are identical to that of Seroe Commandant volcan-
iclastic sandstone. The detritus in the turbidites is a quartz-muscovite-
albite association, indicating a sialic source. Upwards and laterally north-
wards the Lagoen Formation gradually passes into pelagic silica-rich se-
quences, the Seroe Kortapê Formation (figs. 5 and 36) and Zorgvlied Formation,
respectively. The top of the Knip Group is not exposed in northwest Curaçao
(plate 1)

Towards the central part of the island the upper part of the Knip Group of the northwestern facies succession (Seroe Gracia, Lagoen and Seroe Kortapê Formations) passes laterally into the Mameter Formation, an up to 250 m thick sequence of siliceous mudstones and marls with fine grained, dirty sandstones.

The latter contain detritus derived from a predominantly volcanic terrain: plagioclase, lava fragments and some quartz as main constituents, and amphibole as a characteristic minor detrital mineral.

C) Midden-Curaçao Formation

Coarser detritus from the same sources was deposited in full force in the overlying ?Danian Midden-Curaçao Formation, exposed in the synclinorium of central Curaçao and along the north flank of the anticlinorium in southeast Curaçao (plates 1 and 2). The formation conformably overlies the Knip Group, although submarine erosion may be considerable. The Danian age is based on poor fauna's of ill-preserved planktonic Foraminifera found in 4 samples of shales from various levels in the formation. Three of the samples contain

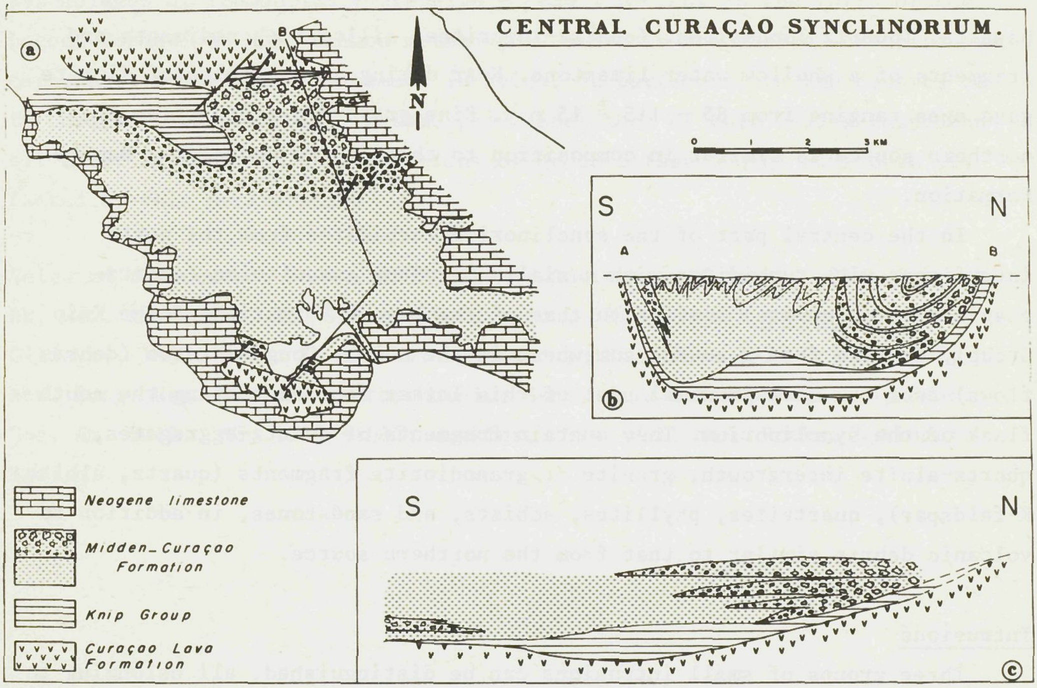

Fig. 7. Simplified map (a) and section (b) of central Curaçao with Midden-Curaçao Formation. As shown in reconstruction (c) the formation consists of two interfingering submarine fans. The fan along the north flank of the synclinorium progrades southward; its debris is derived from a northern source.

Globigerina ?pseudobulloides, G. ?triloculinoides and Globorotalia ?compressa, in one sample Globigerina mageri was found (det. Dr. J.J. Hermes). Silicosigmoilina sp. and Rzehakina sp. occur in samples from the base of the unit.

The formation consists of conglomerates, sandstones, siltstones and shales (debris flows, grain flows and turbidites) with little or no pelagic influence. Basically, the unit is made up of two interfingering submarine fans, the one along the north flank of the synclinorium being the most distinct of the two. This is a small, southward prograding fan which strongly scours the underlying Mameter Formation, reducing it to almost zero near profile A-B (fig. 7). Conglomeratic part of this fan is thought to represent innerfan and midfan, passing southward into a turbidite sequence of the outer fan realm. The detritus of this fan is derived from a nearby source in the north and consists mainly of debris of non-metamorphic and greenschist-facies metamorphic basalts, (quartz-)andesites, (quartz-)diorites, silica-rich sediments and fragments of a shallow water limestone. K-Ar dating of 3 pebbles of diorite gave ages ranging from 85 - 115 $\pm$ 15 m.y. Fine grained detritus from this northern source is similar in composition to that of the underlying Mameter Formation.

In the central part of the synclinorium turbidites from the north interfinger with turbidites with a sialic detritus association (quartz-plagioclase-muscovite) similar to that of the Lagoen Formation of the Knip Group), derived from a source somewhere in the south. Conglomerates (debris flows) from the more proximal part of this latter fan occur along the south flank of the synclinorium. They contain fragments of quartz-aggregates, quartz-albite intergrowth, granite or granodiorite fragments (quartz, albite, K-feldspar), quartzites, phyllites, schists, and sandstones, in addition to volcanic debris similar to that from the northern source.

Intrusions

Three groups of small intrusions can be distinguished, all belonging to the calc-alkaline suite, and all of Campanian or younger age.

1. Oldest group are plugs of (quartz-)dioritic composition intrusive into basalts of the Curaçao Lava Formation in the extreme northwestern part of the island about 2.5 km east of Westpunt. Radiometric dating gave an age of 72 $\pm$ 7 m.y. (whole rock K-Ar, Priem, 1967); it is thought that they are contemporaneous with the tuffs of the Lagoen Formation.
2. A group of small sills and dikes of (quartz-)andesitic composition preferentially intrusive along fault planes in rocks of the Knip Group outcropping along the southflank of the northwestern anticlinorium (surroundings of Santa Marta Bay). Despite their peculiar position the intrusions have not been affected by faulting which suggests emplacement in the interval Danian - Eocene.
3. Small andesitic and doleritic dikes in the rocks of the Midden-Curaçao Formation in central Curaçao and a larger dolerite sill in similar rocks in southeast Curaçao. It is assumed that they represent the same event as group 2.

Metamorphism

The sequence has been metamorphosed under conditions of the zeolite facies (laumontite-chlorite zone of Winkler, 1974). Well-developed mineral assemblages of laumontite + prehnite + chlorite occur in the tuffs of the Lagoen Formation. Most common metamorphic minerals are albite, chlorite and carbonate. Pumpellyite is common in veins, in particular in the basalts of the Curaçao Lava Formation. Metamorphic conditions of this facies lasted until after folding, as the intrusions of group 2 (see above) have been affected by this metamorphism.

Selected references: Beets, 1972, thesis Amsterdam; Krijnen, 1967, Proc. K. Ak. Wet. Amsterdam, 70, 144 - 164; Krijnen, 1972, thesis Amsterdam; Mac Gillavry, 1932, Proc. K. Ak. Wet. Amsterdam, 35, 381 - 393; Priem, 1967, Ann. Prog. Rep. ZWOlab. Isotopengeol.; Santamaría & Schubert, 1974, Geol. Soc. Am. Bull., 85, 1085 -1098; Winkler, 1974, Pet. Met. Rocks, Springer Verlag.

GEOLOGY OF THE CRETACEOUS AND EARLY TERTIARY OF BONAIRE

D.J. Beets, H.J. Mac Gillavry and G. Klaver

Introduction

The Bonaire succession consists of 5 main lithologic units, from base to top (plate 3, fig. 2):

1. The Washikemba Formation, a more than 5 km thick, submarine volcanic arc succession of (?)Albian - Coniacian-Santonian age.
2. The Rincon Formation, an up to 30 m thick succession of limstones and sandy marls of late Senonian age.
3. The Soebi Blanco Formation, an up to 400 m thick sequence of fluviatile conglomerates and sandstones, younger than the Rincon Formation and of the same age or older than Eocene limestones, which overlie the formation.
4. Eocene conglomerates, limestones and marls.
5. Neogene and Quaternary limestones, similar to those of Curaçao. (see Herweijer, de Buisonjê and Zonneveld, this guide-book).

With the exception of the latter unit, all rocks have been tilted. Regional strike in the Washikemba Formation is roughly N120 with a dip of 30 - 60° toward the northeast. Tilting gave rise to some small-scale folding and faulting in well-bedded sequences of cherts and (cherty) limestones of the Washikemba Formation, but large structures are absent.

Stratigraphy

1. Washikemba Formation

A detailed remapping of this unit has been started in 1976, and data given below are preliminary and based on Pijpers (1933), Beets & Mac Gillavry, 1974 and later work of the authors. Base and top of the formation are not exposed; the main section of the unit is situated in northwest Bonaire where a gently dipping section of more than 5 km thickness is exposed between the Wecũa in the south and Saliña Matijs in the north (figs 8 and 9).

The formation is a submarine volcanic-arc succession mainly consisting of flows and shallow intrusions of basalt, andesite and dacite, pyroclastic equivalents of the two latter rock types, pelagic cherts and (cherty) limestones, and volcaniclastic boulderbeds, conglomerates and sandstones. The three latter rock-types only occur in the upper part of the formation and are the first indication in the section of islands. As will be discussed, it is assumed that eruption centra were submarine throughout the greater part of the succession.

Trace element data, in particular RE-patterns, indicate that the volcanics belong to the island-arc tholeiitic suite (see Beunk et al., volume of abstracts). Andesites, dacites and their pyroclastics, at a rough estimate, form about 60% of the volcanic rocks of the formation; basalts and diabases about 40%. High percentage of intermediate volcanics and the RE data render it unlikely that andesites and dacites are fractionation products of the basalts.

Age:

The age of the Washikemba Formation ranges between ?Albian and Coniacian.

Ammonites have been found in cherty sediments in the lower half of the formation (figs 8 and 9) in northwest Bonaire. The fauna was identified by Cobban (pers.comm. 1974) who states: 'The general aspect of these bits of crushed ammonites suggest an Albian age (probably middle or late). This age assignment is based on the presence of Mariella associated with small ammonites that are interpreted as possible juveniles of Mortoniceras and Pervinquieria.'

In (cherty) limestones in the upper part of the formation in northwest Bonaire an abundant fauna of inoceramids has been found in 5 localities (fig. 8) situated roughly at one stratigraphic level. Kauffman (pers. comm. 1975) has identified the inoceramids from three localities near Saliña Matijs and arrived at a Coniacian age for the fauna. He gives the following species list:

Mytiloides sp. cf. M. striatoconcentricus
Inoceramus sp. aff. I. vancouverensis
Mytiloides striatoconcentricus striatoconcentricus
Mytiloides sp. aff. M. angustiundulatus
Mytiloides lusatiae
Inoceramus sp. cf. I. rotundatus
Inoceramus waltersdorfensis hannovrensis
Mytiloides dresdensis labiatoidiformis
Mytiloides sp. cf. M. fiegi mytiloidiformis
Didymotis variabilis
Inoceramus "vancouverensis" parvus
Mytiloides striatoconcentricus carpathicus
Mytiloides n.sp. aff. M. striatoconcentricus.

The late Senonian (Maastrichtian) age for the top of the Washikemba as reported by Beets & Mac Gillavry (1974) and Beets (1975) was based on a mis-

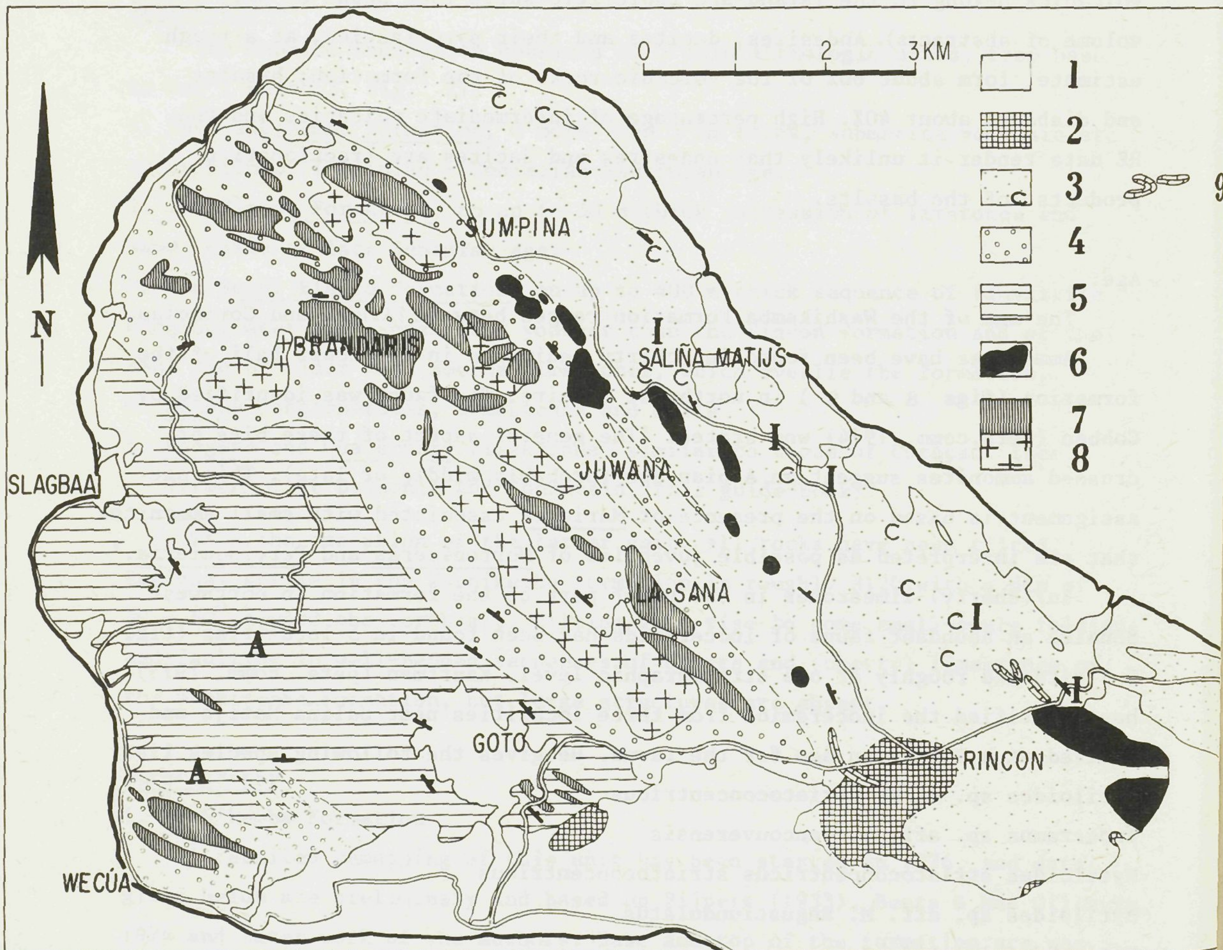

Fig. 8. Preliminary geologic map of northwest Bonaire.
1. Neogene and Quaternary limestones; Eocene conglomerates and limestones;
3. - 8. Washikemba; 3. cherty limestones, pillowed basalt, and ash tuffs with c. volcaniclastic boulderbeds, conglomerates and sandstones; 4. agglomerates and lapilli tuffs (subaqueous pyroclastic flows); 5. basalt and diabase (shallow intrusions, lapilli and ash tuffs, chert; 6. diabase (dolerite) plugs; 7. flows of andesitic and dacitic composition; 8. sills and laccoliths (shallow) of andesitic and dacitic composition; 9. Rincon limestones.

I - inoceramids

A - ammonites

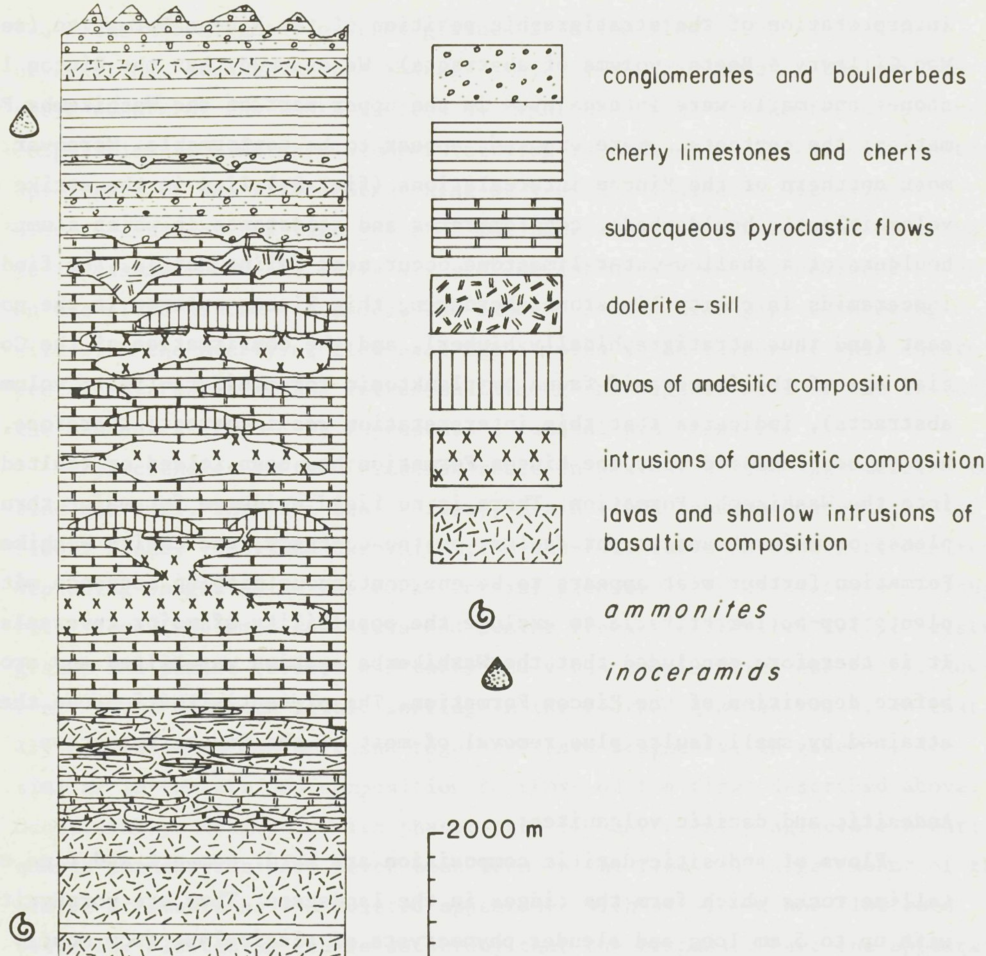

Fig. 9. Simplified stratigraphic column of Washikemba Formation in northwest Bonaire between Wecúa and north of Saliña Matijs.

interpretation of the stratigraphic position of the Rincon Formation (see Mac Gillavry & Beets, volume of abstracts). We assumed that the Rincon limestones and marls were intercalated in the upper part of the Washikemba Formation; the contacts, where exposed, appear to be conformable. Moreover, the most northern of the Rincon intercalations (fig. 8) lies in the strike of volcaniclastic boulderbeds, conglomerates and sandstones in which slump boulders of a shallow water limestone occur near Salina Matijs. The find of inoceramids in cherty limestones bordering this Rincon outcrop in the northeast (and thus stratigraphically higher), and the confirmation of the Coniacian age of the inoceramid fauna by planktonic foraminifera (Smit; volume of abstracts), indicates that this interpretation was incorrect; therefore, it has to be concluded that the Rincon Formation has been folded or faulted into the Washikemba Formation. There is no field evidence for major thrust planes or major transcurrent faults; on the contrary, the entire Washikemba Formation further west appears to be one continuous dipping sequence with plenty top-bottom criteria to exclude the possibility of major reversals.
It is therefore concluded that the Washikemba section was tilted and eroded before deposition of the Rincon Formation. The present situation can then be attained by small faults plus removal of most of the Rincon Formation.

Andesitic and dacitic volcanites:

Flows of andesitic-dacitic composition are hard, compact and fine crys-
talline rocks which form the ridges in the landscape. They are porphyritic
with up to 5 mm long and slender phynocrysts of plagioclase (now mostly
albite) in a felsitic groundmass of predominantly plagioclase, some quartz
A,K,L and chlorite and ore as accessory constituent. Phenocrysts of mafic minerals
have not been found. Individual flows may become as thick as 100 m and more
than 1 km long in cross-section. Usually, however, they are smaller. The
flows often show a crude foliation parallel to the bedding plane; spacing of
the foliation planes is in the order of several decimeters. It is thought
that these are shear planes formed by laminar flow of the magma. Columnar
jointing is very well developed. Vesicles up to several centimeters in dia-
meter and filled by quartz, chalcedony and/or chlorite mineral are common
throughout the flows.

L Sills and ?necks of andesitic-dacitic composition accompany the flows
in northwest Bonaire (fig. 8). The sills attain a thickness of 200 - 300 m.

The rocks are slightly coarser grained than the flows, but still finely crystalline. Because of the coarser grain of the groundmass, the porphyritic nature of the rocks is less distinct than that of the flows; mineral composition is similar. Columnar jointing is common; vesicles occur in the upper part of the sills. Stretching of vesicles indicates high viscous flow. Because of the fine grain of the rocks and the presence of vesicles it is assumed that the sills are shallow intrusions in the sediment cover on the slope of the volcanoes. The find of a 20 m wide pipe connecting a sill with the overlying flow near the Sumpiña is in favour of this interpretation. Possibly, the intrusion forming the highest hill of the island, the Brandaris (fig. 8), represents a central pipe conduit.

A,K,L Pyroclastics in the formation range in grainsize from agglomerates to fine ash tuff. They are debris flows, grain flows (subaqueous pyroclastic flows, Fiske, 1963) and turbidites; no air-fall tuffs have been recognized. Depending on grainsize the rocks consist predominantly of blocks of porphyritic lava (agglomerate), lava and pumice fragments (lapilli tuff), crystal grains and pumice (course ash tuff) and glass shards (fine ash tuff). However, there has been little sorting in the coarser grained rocks, so that all constituents can be found together. Lava fragments, in general, are similar in texture and composition to those of the flows described above. Occasionally, fragments with phenocrysts of quartz and plagioclase occur; quartz phenocrysts have never been seen in the flows. A large amount of the pumice fragments have a twisted appearance with stretched and flattened vesicles. Flattening can be so strong that the fragments have the appearance of collapsed pumice. Direction of flattening not necessarily coincides with the bedding of the rocks, and it is obvious that twisting of the fragments and flattening of the vesicles originated during eruption. Plagioclase (now mostly altered to albite) forms the majority of the crystal grains; occasionally quartz occurs. Grains of mafic minerals are absent. Glass shards occasionally have the beautiful Y-shaped outline from classical tuffs; more commonly, however, they have an irregular shape.

Individual subaqueous pyroclastic flows vary in thickness from about 20 to a few meters. They are ill-sorted with large blocks floating in finer grained material. Nevertheless, the thicker beds show a crude normal grading; in exceptional cases from blocks near the base to fine ash dust at the top. A faint and widely spaced parallel lamination occurs in the coarser grained portions. The fine grained upper part (coarse and fine ash) show parallel lamination, climbing ripples and convolute bedding. Ill-sorting of the coarse grained portions suggests debris flow (sluggish movement downslope of mixed granular solids, dust and water in response to gravity) as main transport mechanism. Structures of the finer grained upper parts suggest a transition to turbidity currents. Often debris flows alternate with sequences of ash tuff turbidites with distinct grading (fig. 23). Monomict character of the pyroclastics, angularity of the debris, and high amount of pumice fragments and glass shards suggest that the eruption centra were submarine.

Basalt and diabase:

Three types occur: pillow basalt, shallow sheets intruded in still
soft and pliable sediment, and coarser crystalline, hypabyssal diabase
A,K,L (dolerite) laccoliths. Pillow basalts are vesicular with baked siliceous
and calcareous sediment between the pillows. Shallow sheet intrusions are
L best exposed along the shore of Saliña Slagbaai (figs 8 and 45) where they
intrude subaqueous pyroclastic flows. The sheets, which may attain a thickness of over 50 m, are layered. Layers vary in thickness from 5 to 25 cm. Both pillow lavas and sheets have intersertal to intergranular texture with plagioclase (now albite), clinopyroxene and chlorite as main minerals. Laumontite, prehnite and pumpellyite are common low-grade metamorphic replacement products. Replaced glass with forked and hollow plagioclase microphenocrysts embedded in a chlorite aggregate forms the pillow rims and occurs as small, irregular lumps in the layered sheets. Layering is mainly due to a concentration of these lumps in the lower half of the layers, and of zeolite-filled vesicles in the upper half. Lumps are embedded in a coarser grained intergranular framework of plagioclase lath and clinopyroxene. The presence of vesicles in the upper part of the layers excludes an origin of layering by crystal settling from a liquid. By want of better explanation we assume at present that layering is due to multiple intrusion.

L Laccoliths of medium grained diabase (dolerite) with intergranular to subophitic texture are thought to be hypabyssal equivalents of the basalts. These intrusions are common in the area between the Sumpiña and Rincon (figs 8 and 47).

Pelagic sediments:

Well-bedded silica-rich sediments with Radiolaria predominate. Cherty mudstones, from which the Albian ammonite fauna has been collected, occur in the lower part of the section (fig. 8): cherty limestones with Radiolaria, planktonic Foraminifera and Inoceramids in the upper part. In the latter rocks early diagenetic limestones concretions are common. In most of the pelagic sediments fish scales can be found.

Volcaniclastic deposits:

In the upper part of the formation in northwestern Bonaire volcaniclastic boulderbeds, conglomerates and sandstones are intercalated between cherty limestones and pillow basalt. They are the first indication in the section of islands. Debris in the rocks is almost entirely of volcanic origin: andesite-dacite fragments predominate, but highly vesicular basalt fragments also occur. Lava fragments are strongly impregnated by red coloured iron compounds. Glass and pumice fragments are present in fine grained conglomerates and sandstones, but are far less common than in the subaqeous pyroclastic flows. In addition to this volcanic debris a few fragments of gabbro and two large boulders of a shallow water limestone have been found in a boulderbed near Saliña Matijs. Pijpers (1933), moreover, describes coral fragments from the conglomerates. Conglomerates and boulderbeds are ill-sorted, massive and thick-bedded slump deposits (debris flows), which channel into the underlying cherty limestones. Volcaniclastic sandstones are turbidites. Localy, thin graded layers of well-sorted plagioclase and amphibole grains embedded in an carbonate matrix, are intercalated in the cherty limestones. These are considered to be redeposited washed beach sands, because of the find of limestone ooïds among the detritus,

Vertical and lateral variation:

Andesites and dacites on the one hand and basalt and diabases on the other, tend to occur at different levels in the formation and form more or less distinct facies associations. The andesite-dacite association consists entirely of flows, shallow intrusions, agglomerates and lapilli tuffs, and represents deposition on the slope of highly active volcanoes with central eruption point. Basalts and diabases are usually associated by pelagic cherts and cherty limestones, and tuffs, ranging in grainsize from lapilli to dust. The latter represent the more distal parts of agglomerates and lapilli tuffs of the andesite-dacite association. Andesitic flows do occur in these sequences, but are scarce and small in comparison to those in the andesite-dacite association. The presence of tuffs in both indicates that the two associations are lateral facies equivalents: the andesite-dacite association proximal in regard to volcanic cones, and the basalt-diabase association more distal to these cones in the basins separating the volcanoes. Consequently, the alternation of these facies successions in the Washikemba Formation points to a change in the position of the andesitic-dacitic eruption centra in time, and not, as was formerly assumed, a general change in the nature and composition of volcanism.

Metamorphism:

The rocks of the Washikemba Formation have been metamorphosed under conditions of the zeolite and prehnite-pumpellyite facies.

2. Rincon Formation

A number of isolated outcrops of rocks of the Rincon Formation occur in
A,K the central part of the island in the surroundings of the village of Rincon (plate 3, fig. 8). The outcrops are enclosed by cherty limestones of the Washikemba Formation, and occur at roughly two levels in this latter unit, one in the village of Rincon and one to the north between Ceru Grita Čabai and Sta. Maria near to Boca Onima. As discussed above (age of the Washikemba Formation) it is inferred that the Rincon Formation unconformably overlies the Washikemba Formation; the present position of the formation is thought to be due to small-scale folding or faulting.

The Rincon Formation consists of limestones, marls and calcareous sandstones. Because of its faulted contacts stratigraphy and thickness are not known. The limestones contain a shallow water fauna of rudists, algae, larger Foraminifera, gastropods and pelecypods. Prebarrettia sparcilerata, Titanosarcolites alatus, Plachioptychus sp. and Durania sp. were found in the limstones near Ceru Grita Cabai (see Mac Gillavry, volume of abstracts), and were associated by Sulcoperculina sp. and Pseudorbitoides (?Rhabdorbitoides) sp. Marls and calcareous sandstones of the formation are locally rich in planktonic Foraminifera. Marls from the outcrop in the village of Rincon yielded the following fauna (det. Kuhry).

Globotruncana elevata (BROTZEN)
Globotruncana sp. aff. G. rosetta (CARSEY)
Globotruncana conica WHITE
Globotruncana sp. cf. G. gansseri BOLLI
Globotruncanella havanensis (VOORWIJK)
Rugoglobigerina rugosa (PLUMMER)
Rugoglobigerina sp. aff. R. marcrocephala BRONNIMANN
Rugoglobigerina scotti (BRONNIMANN)
Rugoglobigerina rotundata BRONNIMANN
Rugoglobigerina spp.
Globigerinelloides sp. gr. G. volutus (WHITE)
Pseudotextularia sp. cf. P. deformis (KIKOINE)
Heterohelix sp. cf. H. planata ((CUSHMAN)
Heterohelix spp.

According to Kuhry the fauna points to the Globotruncana gansseri zone or the Abathomphalus mayaroensis zone (middle - late Maastrichtian). Detritus in the calcareous sandstones is all volcaniclastic debris probably derived from the Washikemba Formation.

3. Soebi Blanco Formation

The Soebi Blanco Formation, 400 m thick, a fluviatile sequence of conglomerates, sandstones and shales (mudstones), is exposed on the southeast flank of the Ceru Largu in central Bonaire (plate 3). The rocks strike roughly E-W and dip towards the north. Age of the Soebi Blanco Formation is ill-known. Pijpers (1933) states that the unit is younger than the Rincon Formation as he found pebbles of the limestones of this sequence as pebbles in the conglomerates. The Soebi Blanco Formation is overlain by Eocene limestones, so that its age must be Eocene or older. The Soebi Blanco Formation contains a large amount of exotic pebbles, which it has in common with the Danian Midden-Curaçao Formation (depositional environment - turbidites versus fluviatile deposits - , however is strongly different). All dated Eocene deposits on the island lack exotic debris, indicating that the islands were isolated. For that reason we tend to think that Soebi Blanco Formation is older than Eocene.

Most conspicuous feature of the Soebi Blanco Formation is the presence of a large amount of coarse grained exotic debris.

Gneissose granoblastites (for nomenclature see Winkler, 1974) mainly consisting of perthitic microcline, plagioclase (occasionally antiperthitic) and quartz, form the majority of the exotic pebbles. The rocks have flaser texture with quartz in lenses or ribbons. Relics of garnet armoured by chlorite have been found in some of these pebbles. In one, sillimanite occurs. Diagnostic mineral assemblages of the hypersthene zone, however, have not been found.

In addition to these, pebbles of quartzites, schists, and sandstones occur. Large cobbles and boulders of an algal limestone were found in all outcrops of the formation.

Pebbles of volcanic rocks, probably for a large part derived from the Washikemba Formation, forms the majority of the detritus.

Selected references: Beets, 1975, Progr. Geod., Royal Neth. Ac. Arts & Sc., 218 - 233; Beets & Mac Gilalvry, 1974, Trans. VIIth Car. Geol. Conf.; Beunk & Klaver, 1977, VIIIth Car. Geol. Conf., Vol. Abstracts; Fiske, 1963, Geol. Soc. Am. Bull., 74, 391 - 406; Mac Gillavry, 1977, VIIIth Car. Geol. Conf., Vol. Abstracts; Mac Gillavry & Beets, 1977, VIIIth Car. Geol. Conf., Vol. Abstracts; Pijpers, 1933, Thesis Utrecht; Smit, 1977, VIIIth Car. Geol. Conf., Vol. Abstracts; Winkler, 1974, Petr. Met. Rocks, Springer Verlag.

GEOLOGY OF THE CRETACEOUS OF ARUBA

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Introduction

The Cretaceous of Aruba consists of two main units (Westermann, 1932):

1. The diabase-schist-tuff formation, a metamorphic sequence of predominantly basic volcanites of (late) Cretaceous age.
2. A composite tonalite batholith of late Senonian age.

The outcrops of the diabase-schist-tuff formation can be interpreted as roof-pendants of the batholith (plate 4).

The two units are unconformably overlain by Tertiary and Quaternary deposits, mainly limestones (Mac Gillavry, p. 36 and Herweijer et al., p. 39, this excursion guide).

The age of the diabase-schist-tuff formation is based on ?Turonian ammonites found in a sedimentary intercalation in the formation near Dos Playa (MacDonald, 1968). The late Senonian age of the batholith comes from radiometric dating (Priem et al., 1966; Priem et al., Vol. of Abstracts; Santamaría & Schubert, 1974)

1. The diabase-schist-tuff formation

Remapping of this unit started in 1976 and is still in progress. The stratigraphy is still little known. Basalt and diabase are the main rock-types. They are associated by volcaniclastic conglomerates and sandstones, accretionary lapilli tuffs, hyaloclastites and, subordinately, pelagic cherty limestones. Most of the rocks are submarine extrusives or marine deposits. However, the formation includes also continental deposits. In what way the two are related stratigraphically, is not yet known.

Basalt and diabase form the greater part of the formation, and occur roughly in equal amounts. The basalts often show pillow structure, indicating submarine extrusion. Pillows commonly have vesicular rims. At a few localities, as for instance along the coast between Dos Playa and Boca Prins, pillowed basalts are associated by reworked, sandy hyaloclastites, largely consisting of angular fragments of glass. Pillowed basalts show variolitic texture along rim and intergranular texture in the core of the pillows.

The diabases are fine to medium-grained and show intergranular to subophitic texture. Intrusive contacts have locally been seen as, for instance near Ceru Jamanota and Ceru Arikok. It is not known whether all diabases are indeed intrusions. It may be possible that some represent thick flows protected from the contact with seawater by a top layer of pillowed basalt.

Basalts and diabases belong to the group of low-potassium or abyssal floor tholeiites (LKT; see Beunk & Klaver, Vol. of Abstracts).

Volcaniclastic conglomerates and sandstones consist entirely of debris of basalt and diabase. Most of the sediments are marine, and either turbidites (volcaniclastic sandstones) or slump conglomerates. Good exposures of these sediments occur between Boca Prins and Dos Playa, and near Ceru Arikok. Often they are associated by pillowed basalt and by accretionary lapilli tuffs. The latter rocks consist of up to 1 cm. large concentric spheres of volcanic ash embedded in a matrix of ash and sand. Such accretions are formed in eruptive clouds of subaerial volcanoes, according to Moore & Peck (1962).

In addition to these marine volcaniclastic sediments,?fluviatile conglomerates, made up of basalt fragments only, occur in an isolated exposure southeast of Boca Prins. Rounding and sorting of the debris strongly suggest current- or wave-action. The conglomerates are underlain by a paleosol of weathered basalt with well-preserved exfoliation structures.

Two levels of cherty limestones were found intercalated between pillowed basalt in a section south of Ceru du Chef in the southern part of the outcrop area of the formation in central Aruba.

All rocks of the formation have been metamorphosed under conditions of the greenschist or prehnite-pumpellyite facies. Metamorphism is thought to be largely due to heating by the intrusion of the tonalite batholith. However, in addition to contact metamorphism, a cleavage develops in the sedimentary intercalations, in particular in those of the southern part of the outcrop area in central Aruba. Here, in some of the rocks a schistosity develops because of the parallel orientation of newly formed amphibole and chlorite. In this area, dikes accompanying intrusion of the batholith may be sheared also, suggesting that cleavage in part is contemporaneous with, or postdates early stages of intrusion.

Locally, at the contact with the batholith, the country rock shows small-scale partial anatexis. Westermann (1932) describes hornblende-gedrite schists (Andicouri), and hornblende-diopside-plagioclase rocks (Rincon, Arikok and N. of Savaneta), from the contact with the (quartz)norite and tonalite.

The majority of the rocks in the northern part of the outcrop area in central Aruba is little affected by metamorphism; magmatic minerals are often largely preserved.

2. The composite batholith.

2.1. Introduction

The composite batholith constitutes the backbone of the island. It is fairly well exposed, on many places as gigantic corestones.

For the description of the plutonic rocks, the nomenclature introduced by Streckeisen (1973) will be used. Consequently some names are different from those given previously by Westermann (diagram 1). For dike rocks, neutral, current names will be used.

The main member of the batholith is a hornblende tonalite with schlieren of trondjemite and granitic pegmatite. The (quartz) norite to quartz-hornblende gabbro massifs constitute an older, separate intrusion and are now roof-pendants of the tonalite. The diabase-schist-tuff formation, the (quartz) norite massifs and the tonalite are crossed by numerous dioritic to semi-lamprophyric and felsitic dikes. The so-called hooibergites are late members of the igneous series and interpreted as either water-saturated basic clots or the intruded product of partially melted country rock fragments (Helmers, Vol. of Abstracts).

During the cooling hydrothermal alteration became very important.

2.2 The (quartz) norite to quartz-hornblende gabbro

The largest outcrop of these rocks forms the Matividiri. Many smaller outcrops occur west and northwest of this hill, in part as blocks within the tonalite. The assumption that these bodies are part of a separate, older intrusion, is strengthened by the following observations:

a. Westermann describes the invasion of gabbro by tonalite near Bushiribana;

b. The present position of the igneous lamination, which is indicated by parallel orientation of tabular plagioclase crystals, is about EW with a steep S dip. Coarse layering shows the same orientation. This points to tilting of the mass because the phenomena are due to gravitational differentiation within the crystallising melt.

c. Rock compositions intermediate between gabbro and tonalite are absent (see diagram 1).

d. Some larger, gabbro blocks are cut by semi-lamprophyric dikes which are truncated at the contact with the surrounding tonalite.

Microscopically, the rocks grade from norite with about equal amounts of hypersthene and augite and a colour index of about 45 to quartz-hornblende gabbro, with relictic augite, more quartz and a colour index which may drop to 35. The oscillatory, euhedral zoning of the large plagioclase crystals ranges between An_{64} and An_{52}. Occasionally, these have rounded cores of up to An_{75}. The plagioclase crystals are accompanied by hypersthene and some large augite crystals; in the rims hypersthene prisms can be included. The hypersthene shows exsolution lamellae of clinopyroxene parallel to (100). These crystals may be regarded as the cumulus phase. The zoning of the plagioclase may be due to the presence of crystals in the melt before the magma took its final space. Crystallization continued by mantling of hypersthene by augite and development of a plagioclase, ranging between An_{52} and An_{47} (very locally down to An_{33}) along rims of existing crystals and as interstitially developed new crystals. The hornblende and biotite start to develop by reaction of pyroxene and magnetite with the water-enriched melt. Poikilitic quartz and K-rich feldspar fill the remaining interspace. Probably, the quartz content is also determinated by the amount of hornblende and biotite grown at the expense of pyroxene, as the latter contains more SiO_2.

2.3 The tonalite, trondjemite and pegmatite.

In the diagram 1. no compositional separation in two distinct groups exists. The trondjemite occurs in schlieren in the tonalite, boundaries are commonly sharp but may be gradual. The schlieren have a width of 20 cm. to more than 50 m. Small pegmatite veins occur as a rule within or near to the trondjemite schlieren. Westermann (1932) describes banding with E-W orientation in the tonalite north of Savaneta. Probably this is flow layering. Gneissose structures, which are among others present near Miralamar, may be due to shearing in the crystallized parts of the batholith because of movements in the still liquid, central parts of the batholith. Dark inclusions are common. They are of three types:

a) "basic"clots, which originate from the synneusis of the early crystallized minerals magnetite, hornblende (up to 50% of vol.) and plagioclase, commonly of small size.
b) hornblende gneisses or amphibolites, which are contact metamorphic inclusions of basaltic composition. They consist mainly of small subhedral crystals of hornblende, plagioclase and quartz, commonly showing parallel orientation.
c) angular or slightly rounded fragments of gabbro, mafic dike-rocks and tonalite (Westermann 1932). The latter probably derived from the already crystallized outer part of the batholith.

Near Altovista, the inclusions are so abundant that they form a magmatic breccia. Here, the inclusions are mainly of type b, together with some dike rocks.

Only locally, tonalites and trondjemites may contain a higher amount of K-rich feldspar and grade into granodiorites or leuco-granodiorites.

Microscopically, the tonalites are mainly composed of plagioclase crystals, showing features of magmatic crystallization as synneusis structures, euhedral and oscillatory zoning (An_{58}-An_{37} locally going down to An_{25}; occasionally with rounded cores of up to An_{75}) and magmatic corrosion. A few magnetite and clinopyroxene crystals are early crystallization products. The large brownish green hornblende prisms crystallized in part subsequent to the plagioclase, as appears from small plagioclase grains in the hornblende. Dark brown biotite encloses the hornblende. The anhedral quartz crystals show an interstitial, locally poikilitic development, similar to a few K-rich feldspar crystals. Quartz amounts commonly to 30% of vol.

Light coloured trondjemite often shows a well-developed banding, due to a concentration of biotite in layers of about 1 cm. across. The layers may truncate one another. Thicker layers, which show differences in amount and grainsize of the biotite plates, also occur. No inclusions are observed.

Microscopically, plagioclase (An_{42}-An_{22}) is the main mineral. The crystals may contain bipyramidal quartz inclusions in the outer rim. Usually, the dark mineral is a brown biotite. Quartz and K-rich feldspar show an interstitial to poikilitic development. Locally hornblende may occur.

The small pegmatites show either a rim in which oligoclase and quartz occur in micrographic intergrowth or have an aplitic rim. The central part is composed of quartz and microcline-perthite in coarse crystals. Locally, the feldspar is developed as green amazonite. Limonitized large hematite crystals were found locally. A few biotite plates occur along cleavage planes of the feldspar. Small epidote prisms may cover the large crystals.

2.4 The hooibergite.

The hooibergite is a mela-tonalite with hornblende prisms up to 5 cm. in length, which is veined by numerous white trondjemite veins, locally of pegmatitic appearance. They may contain large hornblende gneiss inclusions. They are not intruded by semi-lamprophyric dike rocks. Presence of mylonite zones in the border zone and in neighbouring tonalite points to a late ultimate emplacement. Microscopically they contain small clinopyroxene prisms, partly enclosed by large brownish green to green hornblende prisms. Plagioclase crystals, which only locally show clear features of magmatic crystallization, range in composition between An_{50}-An_{22}. Frequently, plagioclase and quartz grow between the existing other minerals. Micropegmatitic intergrowth exists.

2.5 The dikes

Mafic and felsic dikes from 1 dm. up to 40 m. wide accompany the intrusion of the tonalite. Their composition ranges from gabbroic to trondjemitic. They intrude the diabase-schist-tuff formation, the (quartz) norite to quartz-hornblende gabbro and the tonalite.

The mafic dikes may be classified as (quartz) diorite-porphyr and semi-lamprophyre. As a rule they follow joint systems. Their contemporaneity with the tonalite intrusion is strongly suggested by the following observation:

a) angular fragments of dike rocks occur in the tonalite and fragments of gabbro which contain their own crosscutting dike are observed.

b) mafic dikes intrusive into the tonalite grade in the direction of the strike into a magmatic breccia.

c) other dikes of the swarm show common dilatation phenomena in the tonalite.

In the mafic dikes phenocrysts of plagioclase (An_{70}-An_{30}) are accompanied by phenocrysts of hornblende and/or clinopyroxene. Plagioclase may show euhedral recurrent zoning and magmatic corrosion, the elongated hornblende prisms a preferred orientation. Very locally, quartz phenocrysts occur which show a well-developed reaction rim with clinopyroxene or hornblende.

The matrix is composed of a second, (very fine-grained) generation of these minerals, with the exception of the clinopyroxene in various types of intergrowth. The felsic dikes are tonalite porphyr to quartz albitite. They may be slightly later than the mafic ones. Phenocrysts of plagioclase may be present. Some altered biotite is locally observed. The matrix consists of a quartz-feldspar intergrowth. Dikes may contain sulfides. The gold-bearing quartz veins of Seroe Crystal, Miralamar and other places, may be related to the felsic dikes.

2.6 Hydrothermal alteration.

All rocks of the batholith are intimately crossed by hydrothermal alteration zones, composed of a central veinlet filled with epidote and quartz of 1 mm. across, rimmed by a bleached zone of about 5 cm. across. On every exposed square m. one or a few may be observed, but outside these zones, alteration is also present. The main reactions observed are:

- plagioclase alters to oligoclase or albite, epidote and colourless mica
- biotite gives intergrowths of chlorite and titanite
- hornblende alters to either biotite, epidote and quartz, actinolite, hematite and albite, or chlorite, epidote and albite
- clinopyroxene alters to actinolite and epidote, or hornblende (in acicular crystals) and hematite
- K-rich feldspar gives chess-board albite
- hypersthene alters to talc, and/or chlorite.

Typical products of weathering are excluded. The conditions point to amphibolite and greenschist facies of metamorphism, roughly between 580° and 450°C and most probably represent the higher temperature subsolidus part of the cooling history of the batholith.

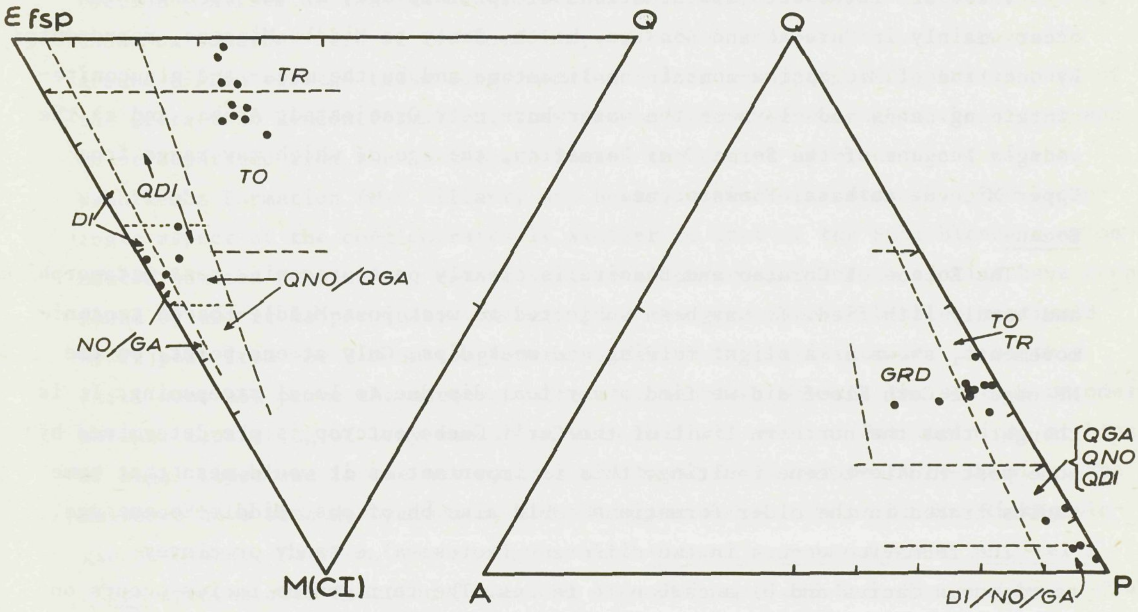

Diagram 1., showing point-counting results of 15 representative plutonic rocks of the batholith of Aruba. Nomenclature after Streckeisen (1972).

P-	plagioclase (An>5),	NO-	norite
Q-	quartz	GA-	gabbro
A-	alkalifeldspar	GDR-	granodiorite
M-	mafic minerals (Colour Index)	QDR-	quartz diorite
TO-	tonalite	QNO-	quartz norite
TR-	trondjemite	QGA-	quartz gabbro
DI-	diorite		

Selected references: Beunk & Klaver, VIIIth Car.Geol.Conf., vol.abstracts; Helmers, 1977, VIIIth Car. Geol.Conf., vol.abstracts; Moore & Peck, 1962, J.Geol. 70, 182-193; Priem et al., 1966, Geol.Mijnb., 45, 188-190; Priem et al., 1977, VIIIth Car.Geol.Conf., vol.abstracts; Santamarìa & Schubert, 1974, Geol.Soc.Am.Bull., 85, 1085-1098; Streckeisen, 1973, IUGS.Syst.Ign.Rocks; Westermann, 1932, thesis Utrecht.

TERTIARY FORMATIONS

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Introduction

There are three sets of formations of Tertiary age: a) the Eocene which occurs mainly in Curaçao and Bonaire, b) the Early to Middle Miocene, represented by one find of Miogypsina-containing limestone and by the mica- and glauconite-containing sands and clays of the water bore near Oranjestad, Aruba, and c) the younger Neogene of the Seroe Domi Formation, the age of which may range from Upper Miocene to basal Pleistocene.

Eocene

The Eocene of Curaçao and Bonaire is clearly post-orogenic, post-metamorphism, and hardly lithified. It has been subjected to weak post-Middle-Eocene tectonic movements, shown as a slight folding and weak dips. Only at one point, on the NE edge of Ceru Kloof did we find a vertical dip due to local steepening. It is thought that the northern limit of the Cer'i Cueba outcrop is pre-determined by some post-Middle-Eocene faulting; this is important as it would mean that some faults traced in the older formations could also be of post-Middle-Eocene age.

The formation occurs in two different facies: a) a sandy or clayey terrigenous facies and b) a carbonate facies. The terrigenous facies occurs on Curaçao at Ceru Blancu and Ceru Mainsjie in the southeast and at Ceru Kloof in
D,H, the northern half of the island; the carbonate facies at the Cer'i Cueba and at the mouth of a cave in the seaward cliff cut in the Middle Terrace near the north coast (Cueba Bosã) 1). Another outcrop near the north coast, on the plantation Patrick, between Kloof and Cer'i Cueba has the terrigenous facies at the base overlain by conglomeratic algal limestone; possibly this outcrop represents the transition between the two facies. On Bonaire the terrigenous facies is found around the village of Rincon and southward to Pos Dominica, all other occurrences being in carbonate facies (SW of Montagne near Goto; E rim of the Rincon cirque; near Port Spanjo; and SE of Ceru Largu). On both islands, accordingly, the carbonate facies occurs towards the present seaward side, on Curaçao to the northwest, on Bonaire to the west, northeast and east of the terrigenous facies.

1) The cave is formed in the Eocene and is roofed by the conglomeratic base of the Middle Terrace deposits (Dr. P.H. de Buisonjé, pers. comm.). It is reputed that the name Cer'i Cueba actually refers to this cave but that the name has been transferred by mistake to the present Cer'i Cueba in which no caves are found.

At Ceru Mainsjie and Cer'i Cueba the marine facies directly transgresses upon older rocks with a basal conglomerate, at Ceru Mainsjie accompanied by a thin layer of platy gypsum. A more terrestrial basal facies is found at Ceru Kloof and at Rincon on Bonaire. In both cases the lower part of the exposed section consists of layered conglomerates with well developed foreset bedding;
A, K those on Bonaire, west of Pos Dominica, are often red coloured. In the plain around Rincon village these conglomerates had been mapped by Pijpers as part of the Cretaceous Rincon formation; they are now known to belong to the Eocene and to be separated from the Cretaceous Rincon carbonates by black chert of the Washikemba Formation (Mac Gillavry and Beets, volume of abstracts). The lithologic aspect of the conglomerates is similar to that of the Subi Blanco conglomerates but the pebbles are entirely of local derivation and no exotics have been found by us. It is possible, however, that the granodiorite pebbles mentioned by Pijpers from the Rincon conglomerates derive from this Eocene; if so this still does not prove the presence of exotic pebbles. Upwards the section becomes marine, consisting of limy sandstone with Molluscs west of Pos Dominica, or blocks of algal limestone in the new roadcut southwest of Rincon south of Dochila. The Molluscs have been determined by B.C. Sliggers and G. Spaink of the Rijksgeologische Dienst, Haarlem, who recognize a.o. *Clementia peruviana* and *Turritella chira* species also found on Curaçao at Ceru Mainsjie and Ceru Blancu (Jung, 1974).

At Ceru Kloof on Curaçao the incoming of marine conditions is marked by an increase in sphericity of the pebbles, followed by a hardground and a layer with serpulite-coated pebbles, after which the terrigenous marine facies sets in with micaceous sandy and clayey deposits with limy concretions, exposed along the road (Mac Gillavry, 1970, Tectonophysics 9, p. 386). These deposits contain small nummulites.

D, H The carbonate facies is described in the excursion to Cer'i Cueba.

Most of the literature on the Eocene is of paleontologic nature. Schaub gives a lithologic description of a type section for the carbonate facies on the southwest point of the Cer'i Cueba and for the terrigenous facies on Ceru Mainsjie.

A complete list of fossils can not be given in this summary. Those of Bonaire are listed by Pijpers; Molluscs from the Eocene of Curaçao are listed by Jung; the larger Foraminifera by Pijpers and by Rutten and Vermunt. The fauna of larger Foraminifera is curious because of the abundance of *Lepidocyclina sp. sp* and the absence of *Discocyclina*. The consensus of opinion is that the age of the Antillean Eocene is late Middle Eocene, as presently defined (Hermes; Hunter).

Early Miocene

The only occurrences of Early Miocene mentioned in the literature are: a) the section penetrated by the water bore of 1942-1943 of Oranjestad, Aruba, consisting of some 130 m. of glauconite-bearing sands and clays overlying another 130 m. of unfossiliferous micaceous sand, and b) a limonitic layer, about one meter thick at a maximum, with dark-grey limestone concretions at the landward side of the Tafelberg, Santa Barbara; these concretions contained Miogypsina ex. gr. globulina (C.W. Drooger det.).

Selected references

Eocene: Hermes, 1968. Geol. & Mijnb., 47,4,280; Hunter, V.F., 1977, VIIIth Carib. Geol. Conf., vol. abstracts; Jung, P., Verh. Natf. Ges. Basel, 84, 1, 483; Pijpers, P.J., 1933, thesis Utrecht; Rutten, M.G. & Vermunt, L.W.J., 1932, Proc. K. Ned. Akad. Wet. Amsterdam, 35, 2, 228; Schaub, H.P., 1948, Bull. Am. Assoc. Petr. Geol., 32, 7, 1275; Mac Gillavry, this excursion D, H.

Early Miocene: P.H. de Buisonjé, 1974, thesis, Amsterdam, p. 174-176; J.H. Westermann, 1951, Proc. Kon. Akad. Wet. Amsterdam (B) 54, 2, 140.

Younger Neogene

For the Younger Neogene of the Seroe Domi Formation, see Herweyer, de Buisonjé, Zonneveld, this volume.

NEOGENE and QUATERNARY GEOLOGY and GEOMORPHOLOGY

J.P. Herweijer *, P.H. de Buisonjé, J.I.S. Zonneveld.

From early-Neogene times onward the ABC-islands show the effects of slow discontinuous emersion. Indications for this emersion are found in the limestone coastal ranges where elevated terraces occur and emerged submarine reeftalus are present. Along the windward coasts mainly accumulative terraces are present. The emerged reeftalus - mainly found along the leeward shores - show locally marine denudational terraces, sub-horizontally eroded from the seaward dipping limestones of the Seroe Domi Formation. Reeftalus ,originally deposited below the lower limits of coral growth, show even in their elevated state the original dips of the talus-slumps.

SEROE DOMI FORMATION

F The more or less continuous caps of the Seroe Domi Formation consist of limestones and dolomitized limestones. The toplevel as well as the basal plane of Seroe Domi Deposits show a seaward dip, mostly between 15° and 25°.

The limestones consist almost completely of detrital elements derived from coral reefs and calcareous algae, mixed with locally changing quantities of terrigenous material. The Seroe Domi Formation can be divided into three separate units:

1. The Older Seroe Domi Formation: Strongly dolomitized algal limestones poor in macro-fossils and devoid of terrigenous, non-calcareous detritus.
2. The Middle Seroe Domi Formation: Rather rich in macro-fossils of hermatypic origin and containing well-rounded pebbles of older, non-calcareous rocks.
3. The Younger Seroe Domi Formation: Bedded limestones often containing large quantities of terrigenous pebbles together with macro-fossils, often showing strong changes in faunal content.

The Older and Middle Seroe Domi Formations are of Middle and Upper-Miocene to Pliocene age. A Quaternary age is ascribed to the Younger Seroe Domi Formation judging from the fossil content.

* WOTRO

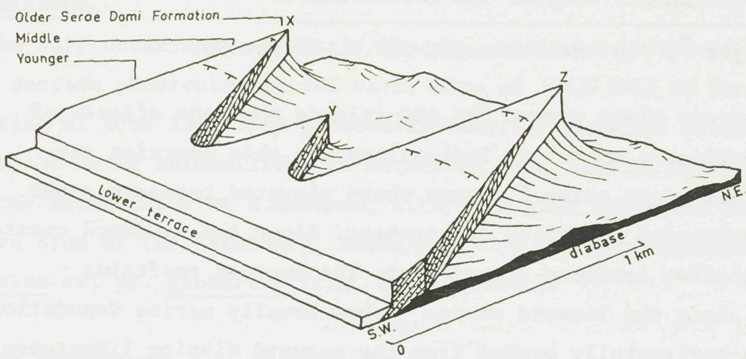


Fig. 10
Schematic diagram of erosional remnants of Seroe Domi Formation resting unconformably on Curaçao Lava Formation. The fore-reef deposits dip steeper than the basal plane. Only the Lower Terrace is indicated, Higher Terraces are not given in this diagram

The three units of the Seroe Domi Formation are all considered to represent submarine talusslopes, their detrital elements derived from hermatypic reefs which occured on a higher level. The absence of terrigenous material in the Older Seroe Domi Formation and the increasing amounts in Middle and Younger Seroe Domi Formation indicate a gradually rising above sea level of ever larger areas with older non-calcareous rocks outcropping in a reef complex.
Arguments for the conclusion that Seroe Domi Formation represents submarine reeftalus still showing their orginal dips are:

- absence of corals in position of growth;
- arrangement of elongated coral-detritus in the direction of the dip;
- mixture of faunal elements from different ecological niches;
- lateral wedging out of individual strata within short distances;
- near absence of wash-out phenomena;
- indication of rapid deposition of individual strata in which both valves of pelecypoda and echinids with their spines are present but not in living position with respect to the stratification;
- strike of the Seroe Domi Formation following the present coastlines;
- dips - always seaward - hardly ever exceeding 32^{o};
- sedimentary fillings of burrows and shells of Lithophaga and Gastrochaenidae still with horizontal top-surfaces when fillings were incomplete.

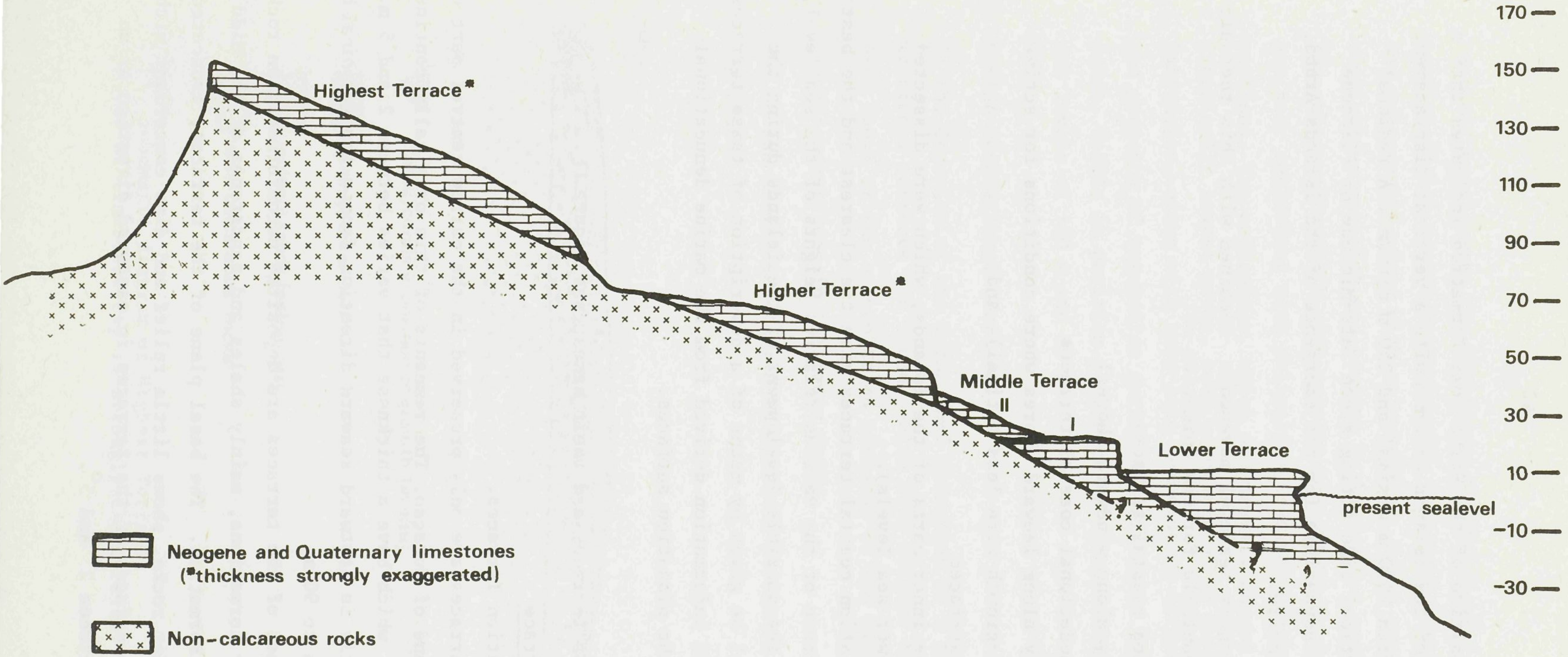


Fig. 11
Highly schematic diagram of the Quaternary accumulation terraces. Horizontal extension is approximately 1,5 km. N.B. Both vertical scale and thickness of terraces is strongly exaggerated. Slope of top level and basal plane is in reality nearly horizontal.

The present position of the Seroe Domi Formation indicates that a relative rise of the islands occurred with a vertical displacement estimated between 2000 m maximal and 250 m minimal. A regional tectonical vertical rise acting since late-Miocene or Pliocene times is held responsible for the emergence of the islands Aruba, Curaçao and Bonaire.

Eustatic Quaternary sealevel movements combined with this tectonic rise were accountable for the formation of:

a. accumulation coastal terraces
   (mainly along windward shores)
b. marine denudational coastal terraces
   (mainly along leeward shores where conditions for active coral-growth were less optimal) and
c. planation surfaces
   (in the inner parts of the islands, which were dissected at lower sea levels).

As the accumulation coastal terraces give the clearest and the best specified evidence of the various relative heights of the sea level, an outline of the possible development of the islands during the Quaternary will be given by means of a description of these terraces, with additional information derived from the marine denudational terraces and the planation surfaces.

For the various terraces and their names, see figure 11.

F,G I. Highest Terrace

a. Accumulation Terraces.

These terraces are only preserved in the narrow central part of the island of Curaçao. The remnants of this originally continuous terrace, which have a thickness that varies between 2 and 5 m, dip gently in eastward seaward direction from a topographical height of 150 m to 90 m.

Limestones of the terraces are deposited unconformably on rocks of older formations, mainly shales and sandstones of the Midden Curaçao Formation. The basal plane of the terraces, truncated from older rocks, shows little relief and dips concordant with the top-surfaces of the terraces in eastward direction at an angle between 2^{o} and 5^{o}.

In their basal parts the limestones of the Highest Terrace consist of ill sorted macro-fossils (casts of corals, gastropods and pelecypods) mixed with calcarenites. Small quantities of terrigenous material are present in sand-sized grade.
The calcarenites both with respect to sorting as well as rounding are near equivalent with eolianites, occurring higher in the sections. The eolianites, which are usually absent in the topographically lowest parts, have a horizontal or gently undulating lamination, often with tube-like cementation structures, indicating the presence of vegetation during deposition of the calcareous dune-sands. Corals in position of growth are encountered sporadically (at levels of 150 m and 90 m).

b. Marine denudational terraces.

In the deposits of the Seroe Domi Formation at a few places erosional terraces are found, which have heights that correlate with those of the accumulation terraces of the Highest Terrace.

c. Planation surfaces in the inner parts.

Due to sub-aerial denudation no distinct planation surfaces are found.

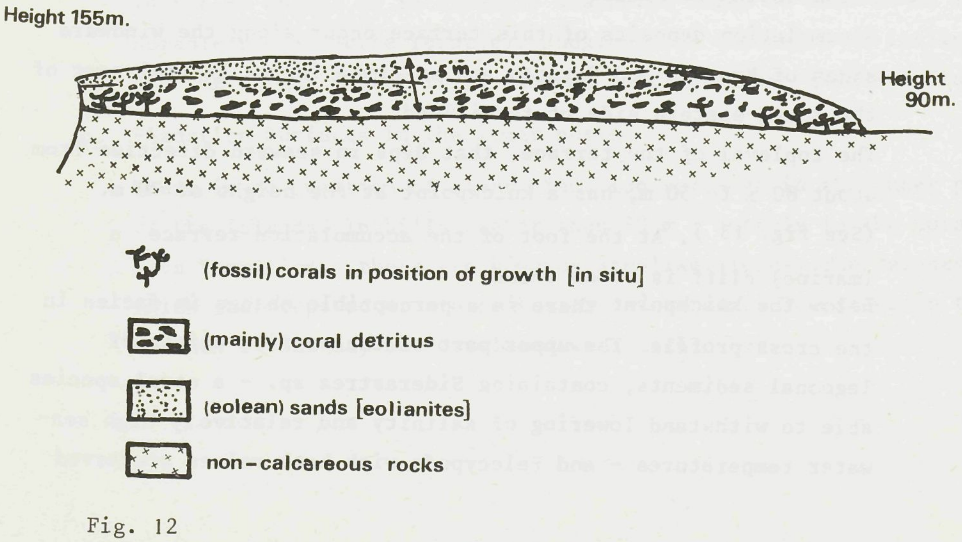


Fig. 12
Highly schematic diagram of Highest Terrace.
Thickness of limestone cap is strongly exaggerated.

Geological History of the Highest Terrace

From the presence of corals in situ at 150 and 95 m it may be deduced that the sea level underwent a relative change of 55 metres.

The sediments in the basal part of the Highest Terrace-section are considered to be beach ridges, such as those found nowadays for instance on Bonaire. The deposits of the Highest Terrace may be best explained by a regression; in a relatively rising area the shingles of the regularly and newly emerged barriers are constantly blown over and covered with dunes of calcareous sands which are afterwards cemented into eolianites.

Age of the Highest Terrace

The deposits of the Highest Terrace are covering truncated limestones of the Seroe Domi Formation near the western side of Grote Berg and Kleine Berg, thus the age of the Highest Terrace is considered to be younger than the truncated strata of the Seroe Domi Formation. The Highest Terrace contains Acropora cervicornis, which supposedly is a coral species exclusively occuring post-Pliocene in the Caribbean area.

II. Higher Terrace

a. Accumulation terraces.

Accumulation deposits of this terrace occur along the windward sides of Bonaire and Curaçao and on Aruba in the central part of the south-eastern side of the island.

The toplevel of the terrace, that dips in seaward direction from about 80 m to 50 m, has a knickpoint at the height of 70 m. (See fig. 13). At the foot of the accumulation terrace a (marine) cliff is often found.

Below the knickpoint there is a perceptible change in facies in the cross profile. The upper part of the profile exists of lagoonal sediments, containing Siderastrea sp. - a coral species able to withstand lowering of salinity and relatively high seawater temperatures - and Pelecypods with both valves preserved in living position. In the lower part of the profile Acropora palmata occurs in living position, indicating rather turbulent and shallow conditions during deposition. The fact that Acropora cervicornis - a species indicative for lower energy levels than A. palmata - is locally found, is considered to be diagnostic for an open fore reef facies.

Both in vertical as in horizontal sense there are only minor quantities of non-calcareous, terrigenous material. During deposition of the Higher Terrace non-calcareous products derived from inland exposures were only locally mixed with the mainly fore reef limestone sediments.

The marine sediments of the Higher Terrace are locally covered with eolianites. The eolianites present on top of marine deposits in the upper part often show steep fore-set lamination. Eolianites on top of the lower part of the terrace are laminated horizontally or possess a gently undulating lamination.

b. Marine denudational Terraces

At several places at a height of 80 metres very smooth areas are found, slightly dipping in seaward direction and which are in some instances covered with thin eolianite caps.

Typical for these areas is that they are found in less resistant (Seroe di Cueba) or in strongly weathered rocks as well as in more durable rocks (Seroe Teintje). Judging from the angle of inclination and the slight relief it is assumed that these are abrasive flats.

c. Planation Surfaces in the inner parts

There is no question of clear planation surfaces in the inner parts of the islands. In hills higher than 80 m - notably in the Curaçao Lava Formation - there are however steplike slopes. The heights at which the steps occur are comparatively regular. The steps in the various slopes may be correlated with each other.

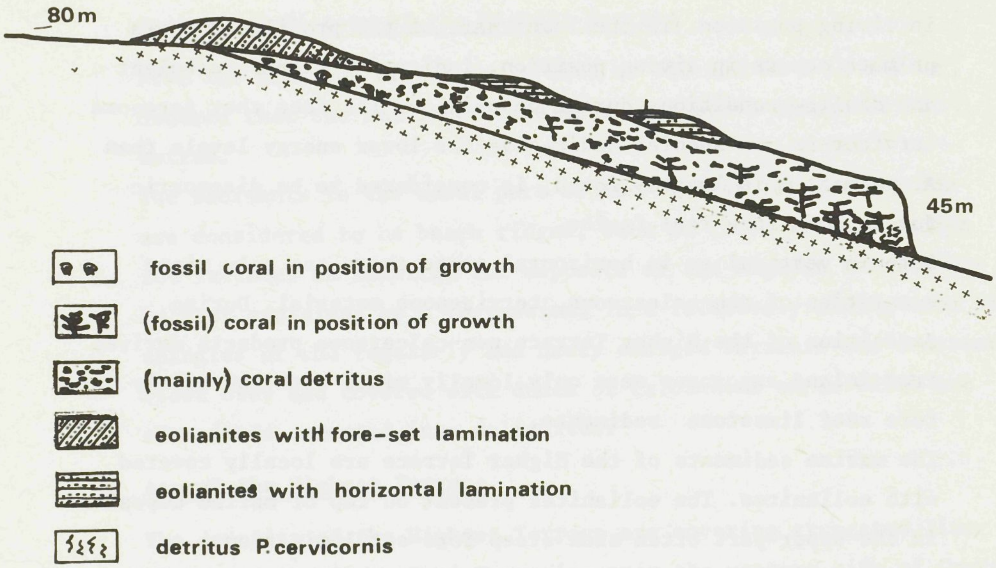


Fig. 13, Highly schematic diagram of Higher Terrace. Thickness of limestone is strongly exaggerated.

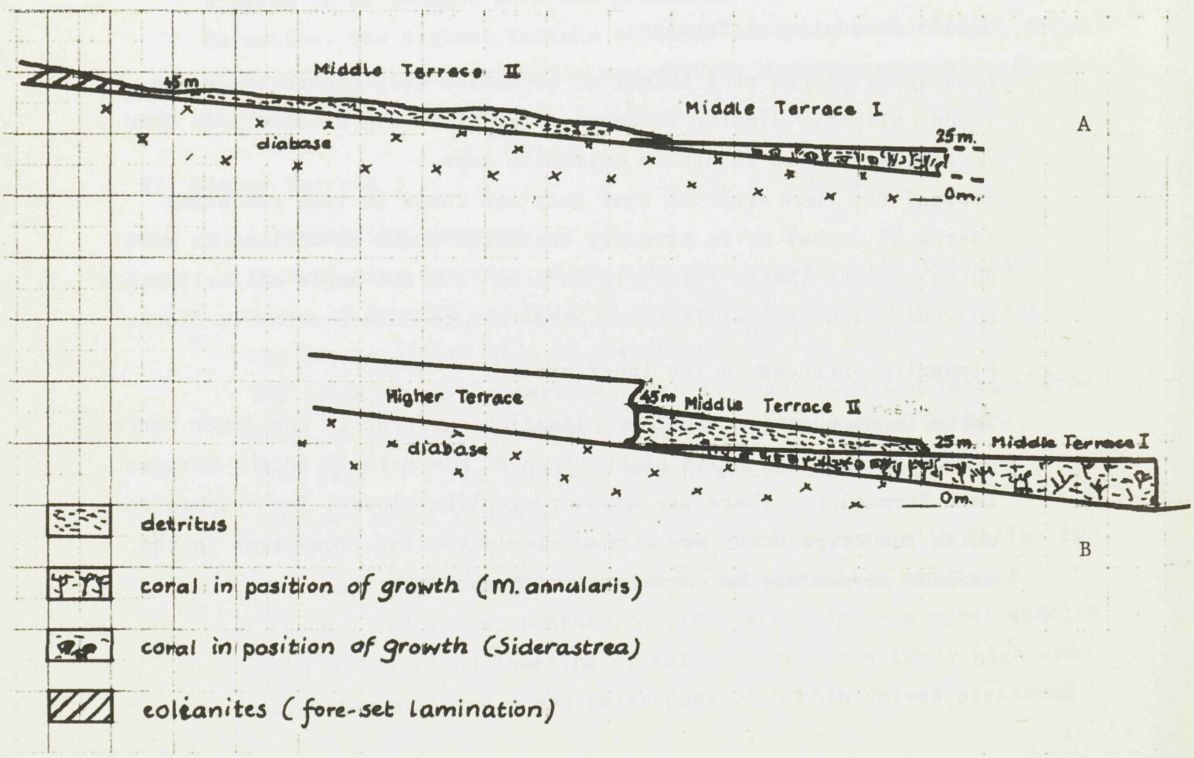


Fig. 14, Schematic diagrams of Middle Terrace I and II.
A.: Middle Terrace II, landinward of Middle Terrace I, lying on Curaçao Lava Formation.
B.: Middle Terrace II on Middle Terrace I.

The geological history of the Higher Terrace

It is most probable that after the regressive phase of the Highest Terrace the relative height of the sea level has remained constant for a prolonged time. During this period marine denudational terraces were formed and the central parts of the islands were denudated.
The stage with constant sea level was succeeded by a period in which regression took place at a rather quick rate. Deeper parts of fore-reef growth zones constantly suffered from marine erosion and were replaced by coral growth zones characteristic for heavy surf and shallow environment. In places newly emerged parts of these shallow deposits were covered by thin eolianites. Real lagoonal development - typically associated with rising sea level - never became a large-scale phenomenon during the regressive Higher Terrace development.
The steplike slopes in the inner parts are indicative for interruptions in the denudative processes, probably caused by fluctuations of the climatological circumstances and/or of the speed of the relative sea level lowering.
The differences in lamination of eolianites correlated with the High Terrace deposits lead to the conclusion that between the formation of the upper -earlier - part and the lower - later - part climatological conditions changed.

Age of the Higher Terrace

The age of the Higher Terrace is intermediate between the -Quaternary - Highest Terrace and the younger - also Quaternary - Middle Terrace. This can be concluded from the facts that:
- no deposits of the Highest Terrace resting on the Higher Terrace are found;
- there is a steep cliff at a height of 50 - 45 m, below which no deposits of the Higher Terrace are found, owing to marine erosion during the formation of the Middle Terrace.

III Middle Terrace

The Middle Terrace consists of two parts (Fig. 14):
1. Middle Terrace I, with a toplevel at about 25 m and
2. Middle Terrace II, with a baselevel at 25 m and at about 45 m its top.

1. Middle Terrace I

a. Accumulation terraces.

These are essentially found at the windward sides of the ABC islands. The topographical height of these very gently in seaward direction sloping toplevels is about 25 m.
The in cross-section wedge-shaped deposits of Middle Terrace I are rather strongly recrystallized massive limestones.
The limestones can be divided into two facies:

i a biozone with predominantly Montastrea often in position of growth and other corals such as Acropora palmata and Diploria, mainly as detritus.
This zone is of lagoonal origin.

ii a biozone with predominantly Siderastrea together with Strombus gigas as the most conspicuous of the Mollusca.
This Siderastrea-zone is of lagoonal origin and is indicative for conditions with lower salinities and higher temperatures.

Both zones do not have a continuous basal conglomerate.

b. Marine denudational terraces

These are mainly found along the leeward sides of the islands, usually eroded in the limestones and the dolomitized limestones of the Seroe Domi Formation at a level of about 25 m above the present sea level.

c. Planation surfaces

Rather extensive areas of the islands have dissected planation surfaces, that probably can be correlated with the Middle Terrace I.

2. Middle Terrace II

a. Accumulation terraces

Accumulation terraces are particularly found along the windward sides of the islands. The toplevels of these terraces dip from 45 m to 25 m in seaward direction (See fig. 14).

The Middle Terrace II limestones lie on the Middle Terrace I deposits or in a landward direction of them in which case the basal plane is made up of non-calcareous rocks. The often massive limestones contain no - or very few - corals in position of growth and are almost exclusively made up of coarse detrital fragments. At several places extensive eolianite-complexes are found, which can be related with the formation of the accumulation terraces of the Middle Terrace II.

b. Marine denudational terraces

These are mainly found along the leeward sides of the islands, usually eroded as - gently dipping from 45 to 25 m - planes in the limestones and dolomitized limestones of the Seroe Domi Formation.
A distinct knickpoint between the marine denudational surfaces of Middle Terrace I and II is often lacking.

c. Planation Surfaces

Various remnants of planation surfaces in the hinterland can - possibly - be correlated with Middle Terrace II.

Geological history of the Middle Terrace

The geological and geomorphological evidence obtained from the Middle Terrace points at:

a. a phase with a slow relative rise in sea level.
b. a phase with a more or less constant sea level.
c. a phase with a relatively rapid transgression.

From the lagoonal bio-zones in the Middle Terrace I can be deduced that there has been a barrier- or fringing reef at the seaward sides of these zones. The

presence of for instance detritus of Acropora palmata could be an argument in support of the occurence of a barrier zone. A slow relative sea level rise is deduced from the fact that the corals growing in the barrier zone were able to keep up with the rise, so that the lagoonal nature was not disturbed at the landward side of the barrier during the rise of sea level. (A process more or less identical with the process described for the Lower Terrace).
Geomorphological evidence, for example the presence of marine denudation terraces and the extended planation surfaces, indicates a prolonged stable relative sea level. This constant sea level was relatively 25 m above the present sea level.
The Middle Terrace II is made up of rather chaotic detritus. This form of sediments is supposed to be the result of high energy circumstances during deposition. These circumstances could prevail during a period of rapid rise of sea level.
De Buisonjé (1974) is of the opinion that the absence of a karst-development on top of Middle Terrace I where this top-surface is covered with sediments from Middle Terrace II and also the absence of beachrocks on top of Middle Terrace I, is caused by a rather swift rise in relative sea level, immediately after the relative stable sea level at the end of the lagoonal period.
Attention must be drawn to the fact that during sea level rise(s), associated with the deposition of the Middle Terrace, the cliffs bordering at the landward side, were constantly eroded. As a result we have no information on the older limestones of the Higher Terrace that prior to the Middle Terrace development occurred below the 45 m isohypse.
Before and also after the deposition of the Middle Terrace the relative sea level must have reached levels below the present one. During the relatively low sea levels, the islands would be dissected by possibly periodical streams. Later relative rise(s) in sea level caused drowning of the lower parts of the stream courses. At present these drowned stream valleys are preserved as lobate inland waters or inland bays.
Knickpoints in submarine slope profiles indicate possible sea levels at approximately minus 80 m, minus 50 m and minus 35 m below present sea level.

Age of Middle Terrace

The age of the Middle Terrace is intermediate between the Higher Terrace and Lower Terrace.
This can be concluded from the facts that:

- no deposits of the Higher Terrace resting on the Middle Terrace are found;
- a cliff at the foot of the Higher Terrace indicating marine denudation during the formation of the Middle Terrace of the Higher Terrace;
- a cliff at the foot of the Middle Terrace pointing to a marine denudation of the Middle Terrace during the formation of the Lower Terrace.

The fact that the deposits of Middle Terrace II are on top of Middle Terrace I, indicates that Middle Terrace II is of a younger age.

IV. Lower Terrace

The Lower Terrace is the lowest terrace of the series present in the ABC-islands.

a. Accumulation terraces.

These terraces have a width of about 600 m along the windward sides (Curaçao and Bonaire) and about 200 m along the leeward coasts and almost completely encircle the three islands. Moreover Lower Terrace deposits are found in the lobate-shaped innerbays.
The height of the almost completely horizontal - in cases even slightly landinward dipping - top-surface, is about 10 m above the present sea level. In the smaller "boca's" - outlets of periodical streams through limestones - the wedgeshaped cross-sections of the Lower Terrace are excellently exposed. (see fig. 15).
Based on the occurrence of macro-fossils three facies, more or less parallel to the present coast, are discernible, often gradually merging into each other.

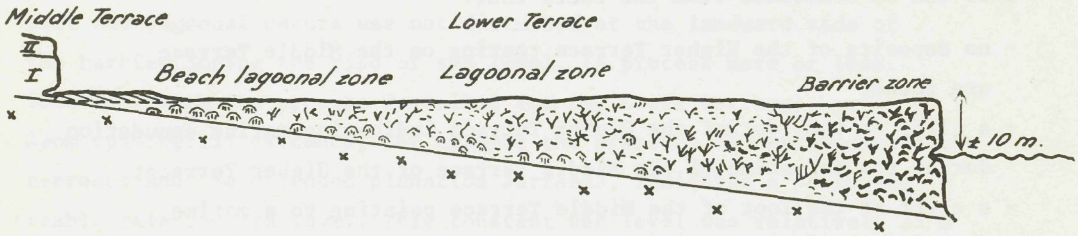


Fig. 15. Schematic cross-section of Lower Terrace.

The three bio-zones, situated between the open sea and the cliff, separating the Lower Terrace from higher limestones, are:

i. Barrier Zone
Consisting of large colonies of Acropora palmata in position of growth and of colonies of Diploria sp. and Meadrina meandrites. Nowadays these coral species are typical for a strongly surf swept environment. Along the leeward sides of the islands the barrier zone as described above, is lacking. Here corals of the lagoonal zone from the windward side occur as barrier-builders.

ii. Lagoonal Zone
With Montastrea annularis as the most conspicuous macro-fossil in position of growth and often in large, branching colonies with a tree-like development. Such diagnostic colonies are often surrounded by detritus of smaller species such as Acropora cervicornis, also an inhabitant of the Montastrea annularis zone. In places, especially near the barrier zone, large fragments of Acropora palmata may be incorporated in the lagoonal sediments.
Conglomerates of terrigenous material occur sporadically, but non-

calcareous sand may be present in small quantities. The deposits are only subordinately influenced from landinward side.

iii. Beach-lagoonal Zone

With colonies of Siderastrea siderea and Siderastrea radians in position of growth and sometimes other corals in small growth forms. Pelecypoda with both valves in original position occur frequently together with the large gastropod Strombus gigas. All these fossils are enclosed by calcarenites.

The deposits of this zone indicate that rather frequently influx of fresh water from landinward side occured.

In several places the two lagoonal zones and sometimes even the barrier zone are completely covered with beachrock. Over long distances the zones bordered along the landinward side against a cliff, eroded from higher situated Middle Terrace limestones.

b. Marine denudational Terraces.

Sporadically erosion surfaces, associated with the + 10 m level of the Lower Terrace, are present in non-calcareous, older formations. They consist of very small abrasion-ledges.

c. Planation surfaces.

Planation surfaces in the central parts of the islands, at a level of about 10 m and formed in the older formations, occur in the ABC-islands on a rather large scale. The planation surfaces are in several cases covered with a thin layer of sediment.

<u>Geological history of the Lower Terrace</u>

The geological and geomorphological evidence obtained from the Lower Terrace leads to the following possible conclusions:

1. The Lower Terrace developed during a relative sea level rise;
2. This sea level rise was of such a nature that - at least from about - 20 m to + 10 m with respect to the present sea level - robust coral

growth in the barrier zone could keep up with rising sea level. As a result the barrier kept growing on the original spot in a vertical direction and landinward of this barrier an ever widening lagoon was formed. The tree-like branching colonies of Montastraea annularis suggest a rather rapid relative rise of sea level in certain times.

3. Within this broad lagoon two processes of quite different character took place: on the one hand a cliff developed in the older, higher limestones of the Middle Terrace along the landward side of the lagoon; on the other hand deposition took place within the lagoon: corals with species adapted to a shallow, low energy habitat throve especially in the lagoonal parts directly bordering the barrier zone. Detritus of such corals, together with fragments of more robust species, torn loose from the barrier and swept during severe storms into the lagoon, accumulated between the living corals of the lagoonal zone (Montastrea zone).
4. At the extreme landinward side, bordering the cliff in higher situated limestones or bordering against older, non-calcareous formations, the circumstances for vigorous coral growth were absent. Here influx of fresh water and rather strong changes in temperature of the extremely shallow lagoon excluded coral growth almost completely. Only species of Siderastrea could withstand the extremes, together with Pelecypods and Gastropods.
5. The beachrock completely covering the Lower Terrace indicates that in the final phase, starting at the landinward side, the lagoon was filled with calcareous sands, derived from organisms living in the lagoon. These sand beaches gave rise to dune formation, preserved as eolianites against or on top of Middle Terrace limestones, as for instance near San Pedro (Curaçao).
6. A relative sea level lowering exposed the upper parts of the Lower Terrace deposits.

Age of Lower Terrace

The Lower Terrace is younger than the Middle Terrace as indicated by the marine denudational cliff eroded in the Middle Terrace during the formation of the Lower Terrace.

As to the age of the Lower Terrace development some radiometric data are present: An age between 30.000 and 40.000 years B.P. is concluded on ^{14}C measurements of Strombus gigas shells for the upper parts of the Lower Terrace sediments (de Buisonjé 1974).
A completely different age is attributed by Murray 1969 to the Lower Terrace, obtained from radiogenic dating of unaltered Aragonite corals and conch-shells yielding an age of 103.000 ± 5000 years.

Selected references: Buisonjé, P.H. de, 1964, Proc. Kon. Ned. Ac. Wet. (B), 67 (1), 60 -79; Buisonjé, P.H. de, 1974, thesis Utrecht; Murray, R.C., 1969, J. Sed. Petr., vol. 39, no. 3, 1007 - 1013.

GEOMORPHOLOGY and DENUDATION PROCESSES

J.I.S. Zonneveld, P.H. de Buisonjé, J.P. Herweijer *

Most of the geomorphological processes that were active during the geological evolution of the islands, still can be studied in the present landscape. Although these processes will be described here seperately, it must be stressed that they are acting in most cases in intricate combinations. Main processes and their effects in the ABC-islands are:

WEATHERING

The degree of weathering of the rocks is closely connected with the climatological conditions that reigned during the successive geological periods. Although it can not be stated that chemical weathering is restricted to tropical climates, one may assume that especially in the humid tropics the chemical weathering is very important and reaches down to considerable depths (some tens of metres; cf Strakhov, 1967).

Chemical weathering is favored by warm-humid climates. It is less effective in warm and dry climates. The present climate of the ABC-islands is semi-arid and it must be assumed that the deep weathering that has taken place in the islands, where the regolith shows effects of disintergration to a depth of 15 m, has to be attributed to former periods with more humid climates.
The degree of weathering and also the depths that are reached depend on the nature of the rocks, for instance on the chemical and mineralogical composition, on the occurrence of diaclases and the massivity. So are for example rocks like quartzite and silicified shales, present in the Knip Formation, resistant against weathering.
Where deep weathering and subsequent denudation occurred, the massive parts stand out as inselbergs and core-stones are left behind in the shape of tors. It is a well known fact that in tropical regions rock-

* WOTRO

masses protuding above the surface are often much less attacked by chemical weathering than those that are still in contact with the soil moisture. Under subaerial conditions the rock surface dries up quickly after a shower has passed. Most of the time, exposed rock surfaces are therefore in "arid" conditions, such in contrast with the situation of rock surfaces below ground level.

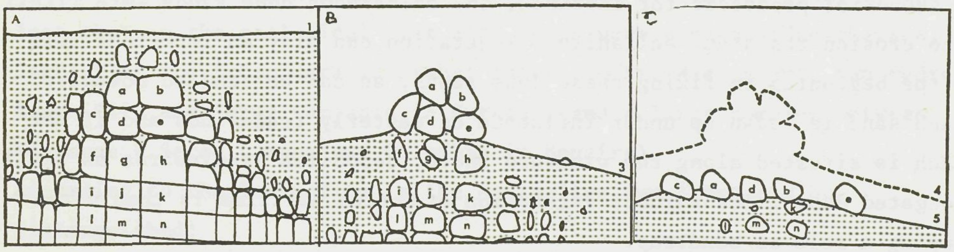


Fig. 16, Schematic representation of the development and decay of quartz-dioritic tors. (Thomas,1975)
A.: Weathering in soil;
B.: Denudation of finer material, and weathering;
C.: Present situation.

Due to the very constant, easterly trade winds a peculiar type of weathering occurs in the giant quartz-dioritic boulders that are present in Aruba. Originally more or less globular boulders weather here to hollow forms, called tafoni. These cavities practically always occur at the leeward, western sides of the boulders. Moisture was apparently accumulated there during showers and wet conditions remained longer in the leeward side than in the - more quickly drying - windward side of the boulders. In the cavernous sides a flaking takes place of weathered material.
Considered as a whole, the chemical weathering of plutonic and magmatic rocks, present in the ABC-islands is the most extreme and reaches the greatest depths. More resistant are the Cretaceous and early-Tertiary sedimentary rocks, as well as the relatively thin limestones that cover older formations.

LITHIFICATION and SOLUTION PROCESSES in LIMESTONES

Most of the Neogene and Quaternary limestones were originally deposited as loose materials, that under subaerial and/or submarine conditions mainly through solution and recrystallisation of carbonates, were lithified and consolidated.
By subaerial processes for instance, the calcareous dune sands were lithified into erosion resistant eolianites. Vegetation can play an important role in the beginning in fixing these dune sands, as can be studied nowadays: beach sand is blown up under influence of easterly tradewinds and if the beach is situated along the windward shore, deposited landinwards as small elongated dunes. The shrubby vegetation of Surina maritima is then often playing a role as sandtrap.

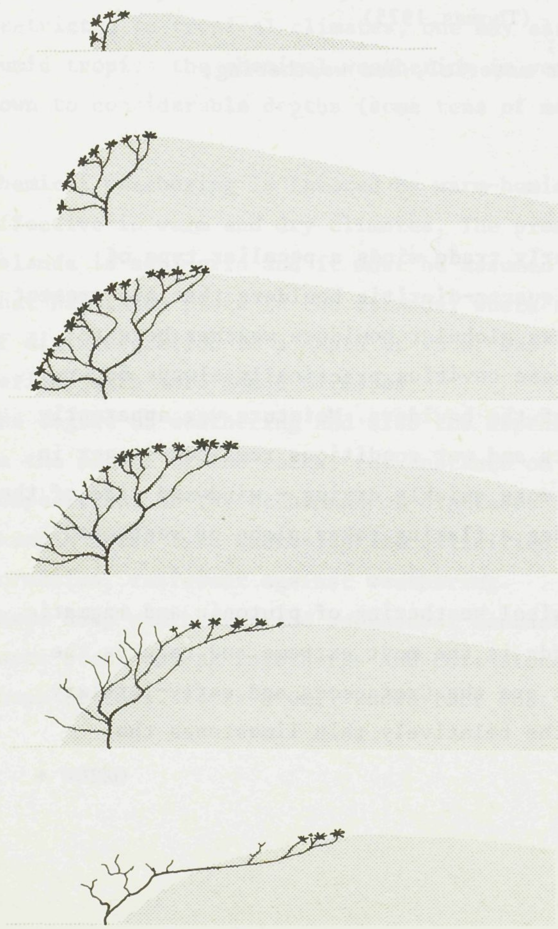


Fig. 17,
Schematic representation:
the role of Surina maritima
in trapping dune sands.

One of the larger recent dune complexes of the islands is situated near Hudishibana (NW Aruba). Other smaller dune complexes occur near Daimari, Dos Playa, Boca Prins and Boca Grandi in Aruba and near Playa Chikitoe and Manparia Goetoe in Bonaire. The dune sands in SE Aruba are party deposited against and on top of the Middle Terrace limestones, in Bonaire exclusively on top of the Lower Terrace.

In many parts of the ABC-islands occurrences of eolianites point to the fact that in the geological past also dunes were present (Hudishibana, Seroe Plat and Droemidera in Aruba; Tafelberg St. Hieronymus, San Pedro, Ronde Klip and Seroe Companie in Curaçao; and a large complex between Montagne - Seroe Largoe and Colombia in Bonaire).

According to the lamination in the eolianites two types can be distinguished:

- a type with a horizontal or almost horizontal lamination, connected with the presence of a vegetation cover during deposition of the original calcareous dune sand and probably corresponding with more humid conditions than those that prevailed during the formation of the second type;
- a type with fore-set lamination, attributed to dune formation of purely physical nature in the absence of a vegetation cover.

A subaerial effect caused by rainwater on limestones is the development of a karst surface. Solution of limestones plays an important role in this process and the limestones acquire a rough surface with lapies up to several decimeters in height with hollows of corresponding depths in between. This solution, that might have been more intense under more humid climates than under the present semi-arid climate, has caused moreover a general lowering of the whole top surface of the limestones, especially the older ones.

It is not easy to calculate the exact amount of this lowering. But an impression of its importance can be acquired from the following observation: near Boca St. Marie in Curaçao, a huge limestone block, fallen from the Middle Terrace and lying on the surface of the Lower Terrace, locally protects this surface against immediate moistening by rain water.

The block is now lying on a "piedestal". Apparently the whole surface of the Lower Terrace, except the area protected by the rock, was lowered over a vertical distance of about one meter since the block took up its present position.

The subterraneous solution of limestone has caused the development of caves. This effect is thought to be related with former ground water levels. The often longitudinal shaped caves, more or less perpendicular to the Quaternary coastlines, can be studied in several places in Higher Terrace, Middle Terrace and Lower Terrace-limestones. Moreover they occur in corresponding levels in the limestones of the Seroe Domi Formation. The caves were formed at or near ground water levels in emerged limestones. Arguments for correlating the cave formation with at least two periods with humid conditions, occurring:

- after the emergence of the Higher Terrace but prior to the final phase in Middle Terrace sedimentation and
- again after emergence of the Middle Terrace and prior to Lower Terrace deposition and
- the simple fact that during humid climate more subterranean water is transported and therefore solution effects can be expected.

Groundwater flow played an important role in the formation of the caves, as is suggested by longitudinal shape, down-dip course, and the occurrence on particular levels within the limestone covers.
The nature of the first deposits that accumulated within the caves immediately after their formation by solution. These first cave deposits are always in the shape of reddish "flowstones", complexes of almost horizontally layered dripstones. They often contain teeth and bones of rodents (Megalomys curazensis Hooijer, Thomasomys sp., Oryzomys sp. sp. etc.), found encrusted in phosphate material between the flowstones. They are indicative of more humid climates.

Only later on, the environment within the caves became less humid and stalactites and stalagmites developed, the latter resting on top of the flowstones.

- the fact that cave development, deposition of flowstones and formation of stalactites and stalagmites within a certain terrace was completed and never reactivated before the next lower terrace was formed.

Caves and their dripstone deposits are cut vertically in the cliff-fronts between Lower and Middle Terrace and between Middle and Higher Terrace. Terrestrial vertebrate faunae have more stratigraphical value: Megalomys and Thomasomys are restricted to caves in Higher Terrace limestones (or caves of identical height in Seroe Domi limestones) and Oryzomys almost exclusively occurs in caves from the Middle Terrace.

Considered as a whole it must be stressed that the process of solution and swift redeposition of $CaCO_3$ under influence of rainwater are of extreme importance for the formation of relatively thin limestone caps that effectively protected underlying rocks against weathering and transportation of the weathering products.

TRANSPORT of WEATHERING PRODUCTS

Under the present climatological and vegetational conditions the weathered materials on hill slopes are transported by sheetwash and splash erosion. Sheetwash and splash erosion can give rise to the formation of very smooth slightly sloping areas. In Curaçao, Bonaire as well in Aruba these planated surfaces can be found. In Aruba the quartz-dioritic area has assumed the character of denudational plains in elevations between 10 and 35 m above sea level clearly adapted to base levels coinciding with the Middle and Lower Terrace. Inselbergs and tors are present in those places where more resistant rocks did not yield to weathering and denudation in the same degree as the majority of the quartz-dioritic masses elsewhere did.
From geomorphological point of view this lowered area differs greatly from the terrains where the diabase-schist-tuff formation comes at the surface or those areas where less resistant rocks are covered by the Neogene or Quaternary limestones. In the latter places sometimes very conspicuous mesa- and cuesta-like forms are developed.

The non-calcareous land surface is drained by a multitude of drainage basins that are characterised by periodic streams, known as "rooien" (arroyos).The braided beds of such rooien consist of ill-sorted material, that is transported during the sporadic times that water is carried in the beds.

In the limestone caps a different drainage system is developed. Rooien are only exceptionally developed and rainwater mainly penetrates first vertically in the porous limestones and then flows off following the dip of the boundary plane between limestone and the underlying rocks. (When the permeability of the limestones in question is sufficiently low, subterranean rainwater flow is retarded in such manner that at favourable spots, mostly in lower situated cliff fronts, a constantly flowing well is established).

As already stated limestones mostly are desintegrated by solution. Only where limestone caps are undermined in the foot hills of cuesta's or table mountains, limestone blocks break off from the cuesta scarp and may be transported gradually as smaller fragments via the drainage system to the open sea.

In some places the limestone caps function as base level of denudation of the inland. Drainage basins of the inner parts of the islands discharge through or underneath the limestone.

In other cases the inland drainage basins discharge into lobate inland bays, the partly drowned lower parts of larger drainage systems that were established during periods of low sea level(s), below the present one. From geological observations, for instance the increasing amount of non-calcareous pebbles in the terrace limestones where lobate inland waters have a connection with open sea, it can be concluded that the larger drainage basins already in early Quaternary times had a connection with open sea at the same spot where the limestone coast-ranges are nowadays dissected.

COASTAL PROCESSES

A number of interacting circumstances, for instance the easterly trade-winds, vigorous hermatypic coral growth and an arid or semi-arid climate, together with eustatic sea level changes, are the main causes for a peculiar coastal development in the ABC-islands.
Only for short stretches, not exceeding a few kilometers in length, the coast consists of non-calcareous rocks: in Aruba near Noordkaap the rocks of the schist-tuff formation are in immediate contact with the sea. In practically all other cases the coast line is in calcareous material, either as cliffs in elevated coral limestones or as beaches consisting of coral shingle or calcareous sands. In most cases the coast-line proper is accompanied in seaward direction by living hermatypic coral reefs.
The importance of differences in wave attack are very conspicuous when comparing the windward coasts with those in the more sheltered leeward sides of the islands. The latter coasts are exposed to wave action in a much lesser degree.
Fig. 18 shows a generalised profile as it can be observed in many places along the windward coasts where over long distances cliffs are developed in the elevated Lower Terrace limestones.
The ridge indicated 'a' consists of loose blocks that during extremely stormy weather broke off from the cliff and were accumulated in a distance of some tens of meters from the coastline proper. Zone b is the sprayzone. During normal wind conditions the limestone of this zone is kept moist by salt sea water spray. The constant moistening favors the solution of the limestone which shows here very conspicuous, relative large lapies and clints. If during periods with little wind the spray can not reach this part of the coast, water in the depressions between the lapies is evaporated and salt crusts originate. The extremely strong solution activity in zone b causes a general lowering of the zone, which in several places results in a complete absence of the vertical part c of the cliff.

In other cases however, for instance where socalled "boca's" (mouths) dissect the limestone cliffs perpendicular to the main coastline, the vertical part c is still present or re-established by breaking off of huge, protruding limestone masses.
The notch d is developed as a result of biochemical action. Algae and other organisms living in this environment cause conditions favourable for chemical degradation of the limestone. Moreover a kind of "bio-mechanical" abrasion is active here: organisms as Chitonidae and Patellidae move over the algal surface of this constantly wetted part of the profile and feed on this algal vegetation covering the surface with a slimy layer. During this grazing they rasp with their radula the limestone material away and new, fresh limestone is exposed.
The terrace-like zone e stands in marked contrast with the notch just above. Here no chemical or bio-mechanical erosion occurs. This part of the cliff profile on the contrary is protected by living calcareous algae and other lime-secreting organisms which prefer a living position in the turbulent water of the surf. These organisms also form limestone incrustations, sometimes in the shape of rims around "sawah"-like terraces, each consisting of a small basin that is constantly filled with fresh sea water as long as the waves can reach it. The growth of the lime-secreting organisms in the rims constantly occurs predominantly in places where sea water flows over the rim to lower places.
From the moment the water becomes less turbulent in a certain coast section, the lime-secreting organisms, originally effectively retarding abrasion of the cliff in the terraced part e, die and their calcareous skeletons and the whole protruding part e disappear.
Below the terraced bench a second notch f is present. This notch results partly from abrasive action of waves carrying sand and cobbles, partly also from the chemical and bio-chemical abrasion caused by (other) living organisms. Diving expeditions during extremely quiet weather along the windward coasts revealed that in this zone, amongst other, living echinids play their role in the abrasive influences (Focke, personal communication).
In places where the surf and the waves are weaker, a profile develops as shown in fig. 18. The most important differences are the absence of

the terraced bench and the elements a (ridge of storm swept blocks) and b (the extremely developed marine "karst" caused by sea water spray). The notch d and f coalesce in that case.
The above mentioned differences and peculiarities in coastal limestone cliff development are of great importance when considering the palaeo-environments that reigned immediately in front of the several emerged cliffs, now separating the elevated terraces along the windward sides of the islands.

In several places the recent coastal cliffs show interruptions where the limestones are dissected more or less perpendicular to the main coast line.
Mostly such inlets in the coast line coincide with places where rain water from the interior of the islands discharges in open sea. The inlets are called "boca", literary "mouth".
In some cases such "boca's" not only dissect completely the Lower Terrace limestones, but also older terraces or the deposits of the Seroe Domi Formation. The larger boca's exist since early Quaternary or even late Tertiary time on or near their present place and are almost exclusively the narrow, natural connections with the lobate, hand-shaped inland bays, the drowned lower parts of older drainage basins that developed in connection with stands of the sea level below the present one.
According to the fact that the valleys in these drainage basins are much shallower and wider in the less resistant rocks inland than in the hard and massive limestones of the coast-ranges, the boca's of the lobate bays are narrow, relatively deep and steep-sided.
In some cases the seaward parts of lobate bays have been closed by the formation of a bay mouth bar, consisting of coral shingle, transported by beach drifting (Goto and Slagbaai in Bonaire; Jan Thielbay and Boca St. Marie in Curaçao). But large bays inland are still open (Sint Joris bay and Schottegat in Curaçao). As a matter of fact, the island of Curaçao owes its important harbour function to the existence of the open Schottegat.
In the case of most other drainage basins, especially the smaller ones, dissecting the Lower Terrace limestones or flowing off subterraneously to open sea, the terrace shows an inlet, again called "boca". The side

walls of such boca's show the profile as given in Fig. 18. The part where the rooi enters the boca is generally characterised by a small beach, consisting of recent calcareous sand and coral shingle, mixed with changing quantities of terrigenous material, transported inland weathered products.

Beachrock is a very common phenomenon in these beaches.

Beaches are not exclusively confined to the heads of the boca's. Some beaches are present along larger coast-sections as for instance in NW and SE Aruba. Here along the windward side a more or less continuous coral reef is present at some distance from the coast proper. Between this reef and the coast a shallow lagoon is present. The coast consists of calcareous sand exclusively, derived from calcareous organisms living in the lagoon. In their turn the beach sands are the source area of the calcareous dunes, mentioned already earlier.

The northwestern part of Aruba has also sandy beaches over long stretches of the leeward side. Here the sand beaches have developed in connection with an extremely extensive submarine platform with a depth of only 20 m, more than one kilometer wide, situated between the shore and the open sea. As the tradewind is off shore, no dunes developed here.

In Bonaire the Lac is a partly landlocked lagoon, seperated from open sea by a living coral reef and possessing sandy shores in the shallow landward side. A large part of this sand consists of fragments of the algae Halimeda sp.. The lagoon is subjected to a gradual colmatation by this sand and by calcareous mud.

Already during Middle Terrace development as well as during Lower Terrace deposition, the whole southern part of Bonaire over a width of about five kilometer, showed extensive shallow lagoonal development behind coral reefs and with some islands built up of coral detritus.

Especially during the Middle Terrace lagoonal development, being of exceptional width, the extensive dunes between Montagne - Seroe Largoe and Colombia were formed, derived from beaches in the final lagoonal stages.

The Lower Terrace lagoon has also been filled up since and has changed into a broad, extremely flat plain with large residual salt pans, now exploited artificially by letting in sea water periodically.

Along the leeward sides of the islands long coastal sections have the character of narrow and steep beaches, built from coarser material: shingle derived from the coral colonies growing immediately seaward of thecoastline. A very common coral species here is Acropora cervicornis, a rather fragile type, living in less turbulent conditions. It is no wonder that the beach material for the greater part consists of the well-rounded shingle, recognisable as bleached detritus from Acropora cervicornis.

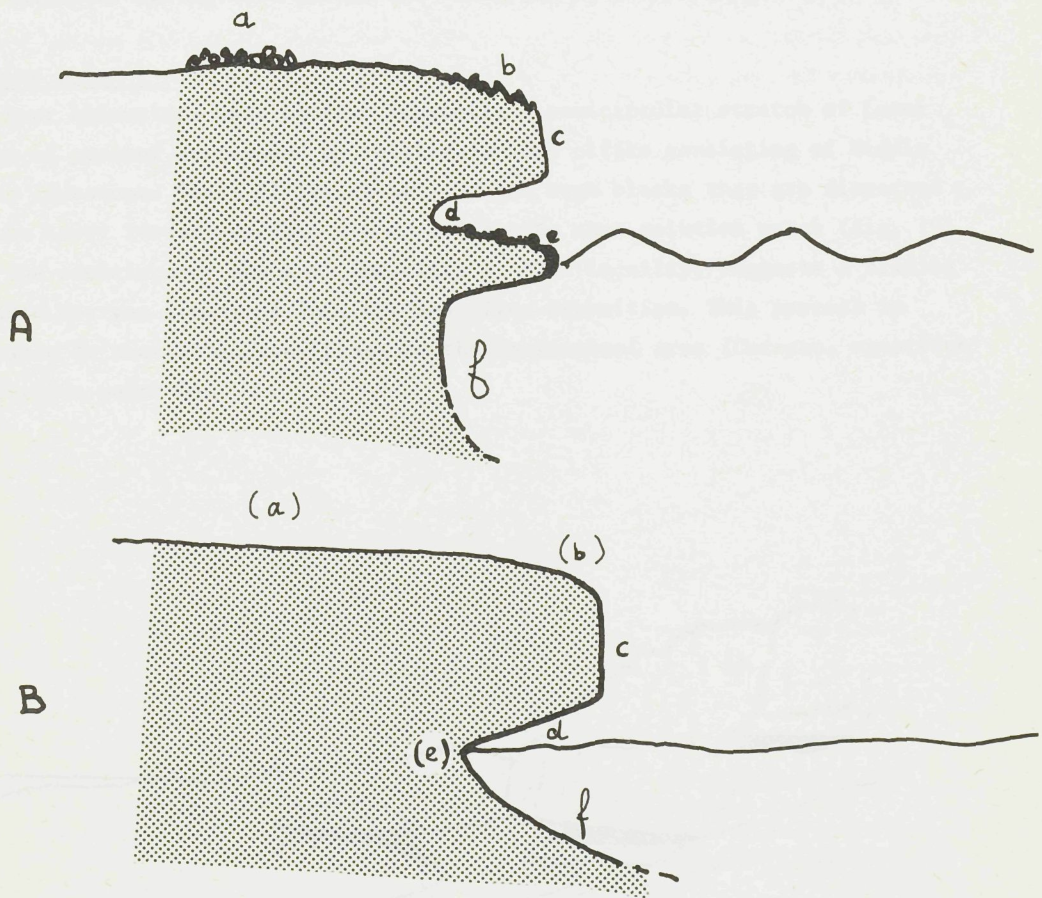


Fig. 18, A: Profile of a limestone coast with strong wave action; a.: ridge consisting of loose blocks; b.: lapieszone; c.: steep cliff; d.: notch, caused by biochemical solution and biomechanical abrasion; e.: "Sawah-bench", characterized by calcareous encrustation; f.: niche, caused by mechanical as well as biomechanical abrasion.

B: Profile of a limestone coast with only slight wave action. The elements a, b and e are absent or only weakly represented (indicated by "( )"). The elements d and f are connected and form a more or less deep notch.

Selected references: Buisonjé, P.H. de and J.I.S. Zonneveld, 1960, Nieuwe West Indische Gids 40, 121 - 144; Buisonjé, P.H. de, 1964, Proc. Kon. Ned. Ak. Wet. (B), 67 (1), 60 - 79; Buisonjé, P.H. de, 1974, thesis Utrecht; Strakhov, N.W., 1967, Oliver and Boyd, Edinburg; Thomas, M., 1975, MacMillan, London.

FIELD TRIP OF A GENERAL NATURE TO BONAIRE (A = K).

From airport by bus via Kralendijk towards Goto in the northwestern part of the island (plate 3). Road leads over Quaternary limestones of Lower and Middle Terrace. Solution notches occur in the cliff of the Middle Terrace limestone. The most distinct, roughly 10 m. above sealevel, was formed during deposition of the Lower Terrace limestone. Relatively narrow vertical width of the notch indicates little wave action and therefore probably a lagoonal environment.

Excursion point 1

Four kilometers east of Goto (Karpat), a semicircular stretch of Lower Terrace is present surrounded by relatively high cliffs consisting of Middle Terrace limestone. These cliffs as well as the huge blocks that are dispersed over the Lower Terrace surface are marked by the same solution notch (fig. 19).

The semicircular shape of the cliff at this locality, suggests a sliding of Middle Terrace limestone into the sea after deposition. This process is comparable to that which took place in the Caracasbaai area (Curaçao, excursion F, excursion point 4).

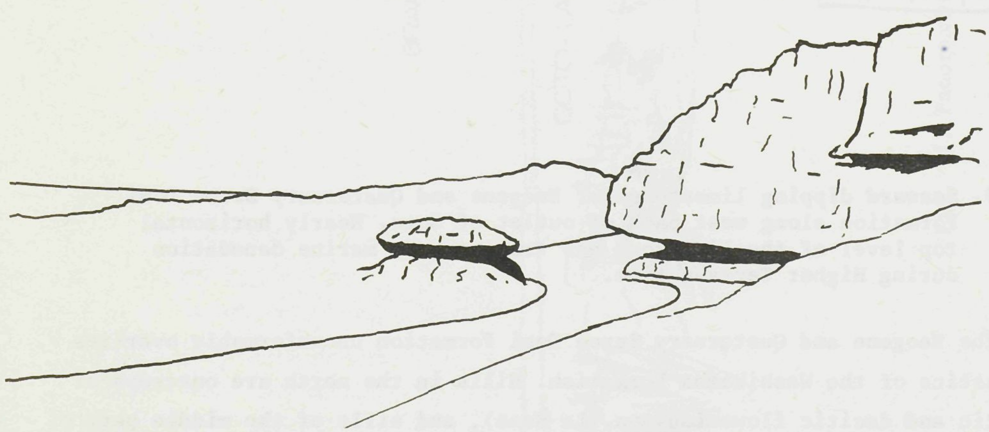


Fig. 19, Solution notch in the Middle Terrace limestones near Karpat. Block on left side of road fell down because of undercutting and obtained a solution notch at similar height .

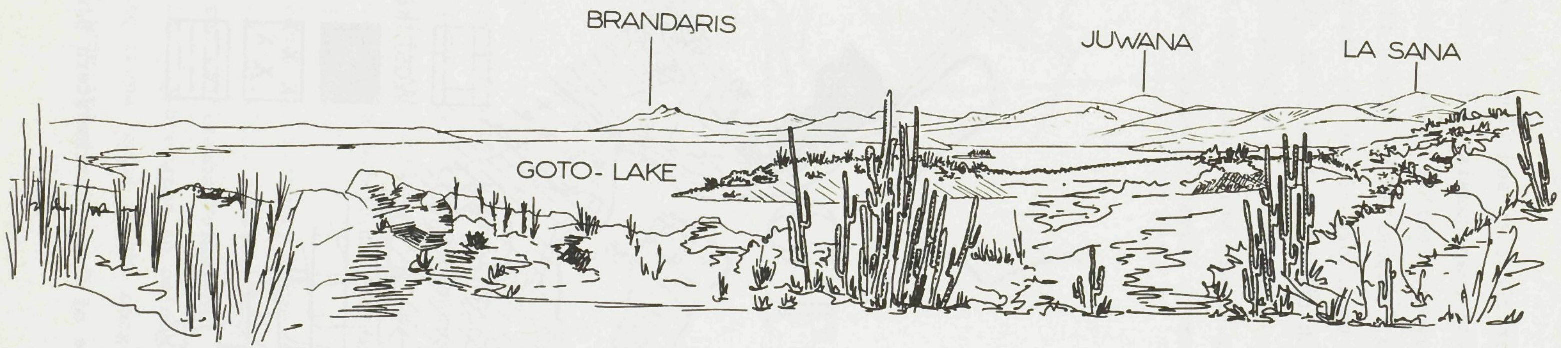
Not far from the spot the head of a submarine valley could be mapped. But the available data do not yield special evidences for a slide like that of Caracasbaai, which however is not astonishing. If really a slide went down here the event must have taken place before deposition of Lower Terrace. In the time that elapsed since then, traces could have been effaced.

Excursion point 2: Lake Goto

Goto is a lobate bay: a drowned valley system incised into the less resistant pyroclastics and diabases of the Washikemba Formation during lower base levels of erosion. The more resistant Seroe Domi limestone, exposed along the south shore of the lake, is accountable for the steep and narrow outlet (fig. 20). Subsequent to the last relative rise in sealevel the outlet was closed by a bar of coral shingle.

Fig. 20. Seaward dipping limestones of Neogene and Quaternary Seroe Domi Formation along west bank of outlet of Goto. Nearly horizontal top level of the limestone was truncated by marine denudation during Higher Terrace time.

The Neogene and Quaternary Seroe Domi Formation unconformably overlies pyroclastics of the Washikemba Formation. Hills in the north are outcrops of andesitic and dacitic flows (Juwana, La Sana), and sills of the middle part of the Washikemba Formation (figs. 8 and 21). The Brandaris, the highest hill of the island, is a large intrusive andesite neck, possibly a central pipe conduit. The relatively flat area on the northeastern side of Goto is an outcrop area of basalts and diabases (fig. 8) of lower half of the formation. Elevation of this area is that of the middle terrace. Basalts and diabases are lateral facies



Fif. 21. Panoramic view on Goto from parking. View is to the NNW.

equivalents of andesitic pyroclastics and flows exposed on this side of Goto. Most of the section along the road consists of up to 5 m. thick coarse grained pyroclastic flows (predominantly lapilli) which alternate with graded ash tuff. Pyroclastic debris has been redeposited by debris flow and turbidity currents. Good exposures occur along the shore of the bay directly north of the parking and at the base of the thick andesitic lava about 150 m. northwest of the parking (figs. 22 and 23). Andesites and dacites in the section are lavas with well-developed columnar jointing. Basic volcanics higher in the section are intrusions. Small remnants of lower terrace limestone occur at a few places along this side of the shore.

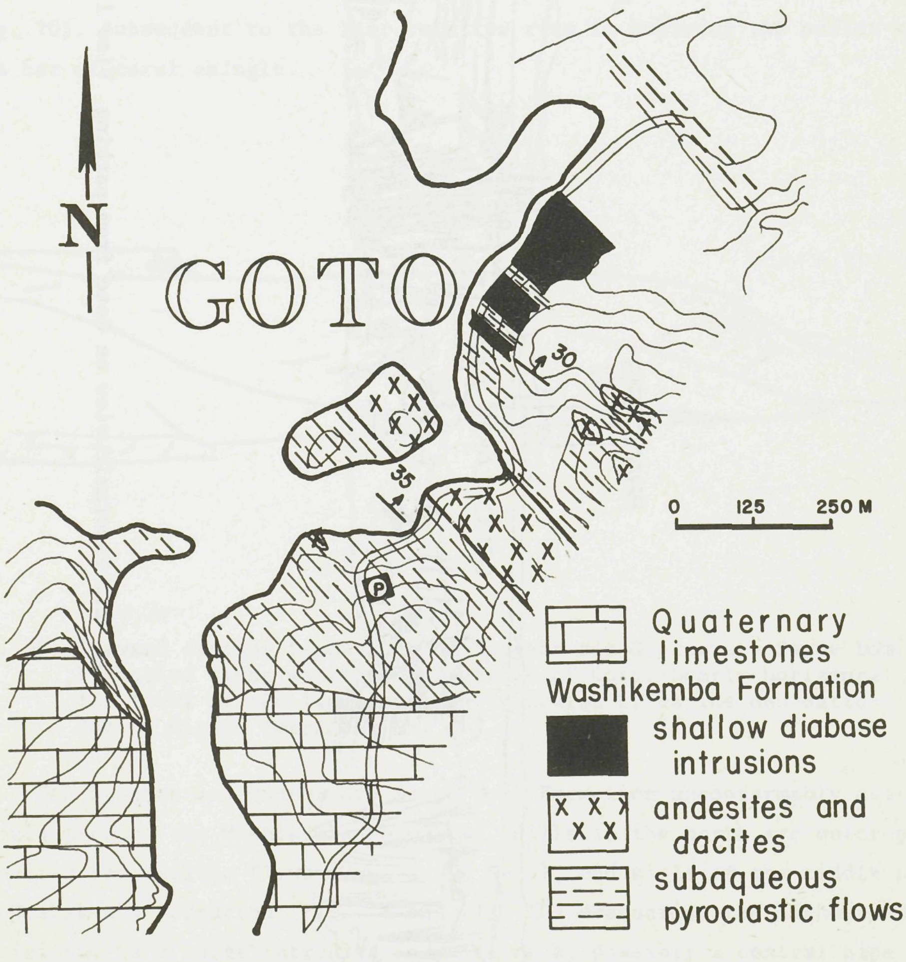


Fig. 22, Map of east shore of Goto, northwestern Bonaire

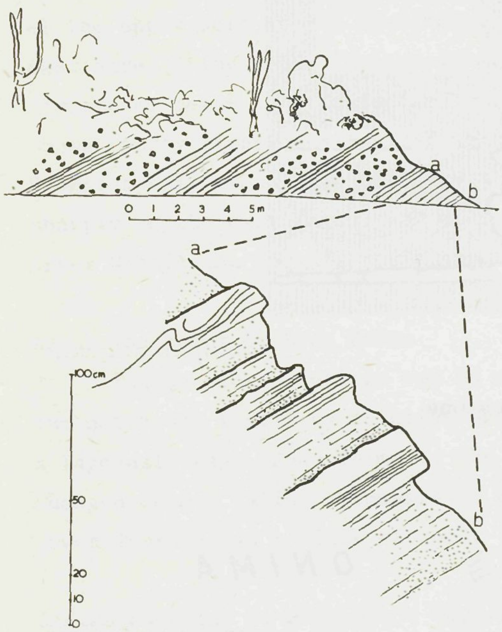


Fig. 23,

Sketch of outcrop of subaqueous pyroclastic flows and turbidites along east shore of Goto, 150 m. northwest of the parking and about 4 m. below base of thick andesitic lava.

From Goto eastward through middle part of the Washikemba Formation to drainage basin of Rincon (plate 3).

Excursion point 3: Pos Dominica

Almost flat-lying to gently dipping limestones of the Seroe Domi Formation border the southern and eastern side of the Rincon basin. The limestones have a steep escarpment and form a cuesta landscape. As shown by Blume (1969), sapping and headward erosion took place in a more humid climate; at present, cuesta formation is at a standstill.

Eocene conglomerates cover a relatively large area in the Rincon basin. They outcrop as part of the cuesta. Detritus consists mainly of pebbles of andesites and dacites from the Washikemba Formation; no exotic pebbles were found. Pijpers (1933) considered the conglomerates to belong to the Late Senonian Rincon Formation. The marine mollusc fauna found in the conglomerates at this side, however, appears to be of Eocene age.

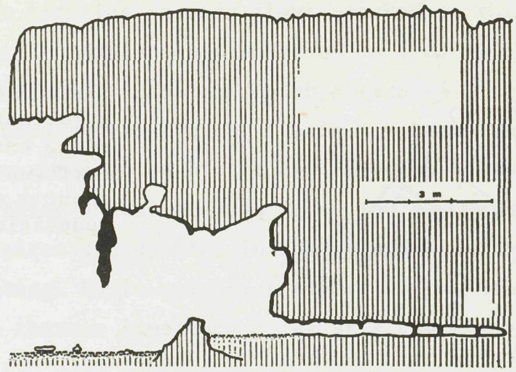


Fig. 24.
Cross-section of Middle Terrace limestone
with stalactites in notch.

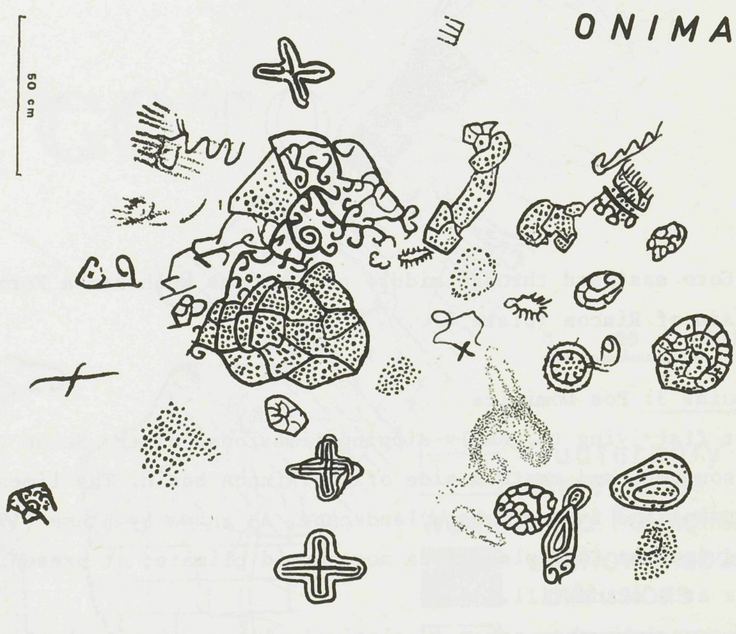


Fig. 25.
Indian paintings at ceiling of notch.
From: P. Wagenaar Hummelinck, 1972, Uitg. "natuurw. werkgroep Ned. Ant.", Curaçao, No. 21 - Rotstekeningen van Curaçao, Aruba en Bonaire IV.

From Subi Rincon back to the village Rincon and along the main road Rincon - Kralendijk to excursion point 4 at Boca Onima. About 1625 m. northeast of Rincon, near Ceru Grita Cabai, cherty limestones and volcaniclastic turbidites of the upper part of the Washikemba Formation outcrop in a small quarry at the east side of the road. Inoceramids and planktonic Foraminifera from the cherty limestones point to a Coniacian age. On the west side of the road a small outcrop shows cherty limestones faulted against calcareous sandstones of the late Senonian Knip Group (Mac Gillavry & Beets, abstract volume). Where the road turns sharply to the east (about 400 m. northeast of quarry), pillow basalts of the upper Washikemba Formation are exposed in a small gully aside from the road.

Excursion point 4: Boca Onima

Indian rock paintings can be observed in a notch in Middle Terrace Limestone. The notch was formed by solution during the period that the Lower Terrace was in a lagoonal stage. Boca Onima is the mouth of a very small lobate bay, that has changed into a saliña. Remnants of Middle Terrace I dominate the landscape; the Lower Terrace has a width of about 700 m.

Excursion point 5: Montagne - Ceru Largo

The Seroe Domi Formation is capped by eolianites. From an elevation of 123 m. above sealevel one has a beautiful view over south Bonaire. In the foreground the denudational plain in Washikemba Formation, from which the more resistent dacites protrude in relatively low hills. In the background the low and flat Middle Terrace region, the Lac with its mangrove vegetation, the shallow lagoon, and the coral reef that separates the Lac from the open sea. In the far distance the salt lakes of south Bonaire are visible.

Outcrops of the Soebi Blanco Formation occur along the east flank of Ceru Largo. Best outcrop is along the main road Rincon - Kralendijk near Soebi Blanco, where a northward dipping sequence of little consolidated conglomerates, sandstones and clays can be seen. The latter rocks have dark red and green colours, and contain irregular limestone concretions, considered by us to be caliche nodules. Exotic pebbles and cobbles, in particular those of leucocratic gneisses and granulite-like rocks, are numerous.

In the outcrop along the touristic road from Ceru Largo to Kralendijk, the Soebi Blanco is overlain by a thin strip of Eocene limestones which, in turn, are covered by Quaternary limestones.

FIELD TRIP TO THE SALIÑAS OF BONAIRE

C.G. van der Meer Mohr

General advice

During this fieldtrip the participants will be almost continuously exposed to sunshine. Therefore wear longsleeved shirts, long pants, a hat or a cap and sunglasses. The use of a polaroidfilter on your camera might improve your pictures. Those who plan to visit the Cueva di Watapana should use thick soled footwear and carry along an electric torch. Brinesamples are best collected in polyethylene bottles.

The area

The area to be visited (figs. 26) includes about 2200 hectares covered by the solar salt works of the Antilles International Salt Company Ltd. (AISCO), constructed on Recent carbonates and Pleistocene limestones; the Lac, a lagoon on the eastern side of Bonaire and a system of five abandoned saltpans, the saliñas di Cai.

Geological setting

The following major geological units can be distinguished.

1) Pleistocene limestones exposed in the central part of the area. They consist mainly of limestones of the lower terrace (Laagterras) and the middle terrace (Middenterras), wich surround the core of the island. In S. Bonaire the Laagterras is partly covered by Recent carbonates and gypsum. where the terrace limestones outcrop they lie about 1-5 m. above sea level. The older Middenterras lies in the northern part of the fieldtrip area, near the airport. Its elevation varies between 5-8 m. The surface of the limestone terraces is karsted, cut by fissures and contains several sinkholes and caves, e.q. Cueva di Watapana and Pos Calbas (Wagenaar Hummelinck, 1943; Murray, 1969; van der Meer Mohr, 1977).

2) A coral rubble ridge surrounding the southwestern part of the inland which once isolated a lagoon from the Caribbean Sea.

3) An area of Recent, mainly unconsolidated, sometimes dolomitized carbonates and gypsum (Deffeyes et al, 1962; Lucia, 1968). From base to top occurs a sequence of marine carbonate sand, probably deposited in a lagoon, to gypsum. A carbon-14 determination of a mangrovepeat, occurring in the sequence, yielded an age of 3405 $\pm$ 35 years B.P.

4) A formerly, i.e. before the construction of the AISCO-works, hypersaline lake, the Pekelmeer. Prior to its incorporation in the present solar salt works, the level of this lake was slightly below sea level. Effluent seepage of sea water via

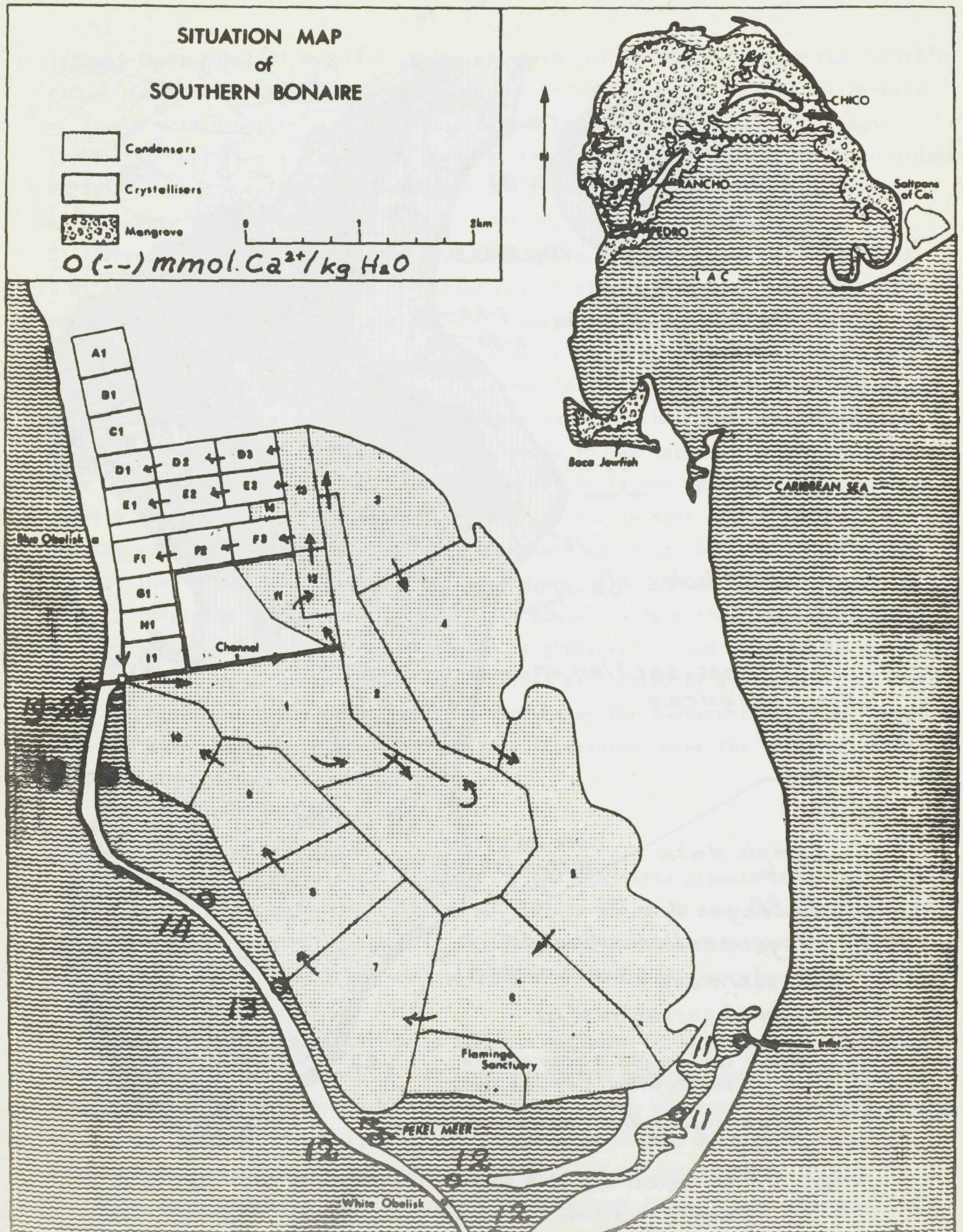


fig.26 **Situation map of Southern Bonaire showing the extensive complex of saltpans now in use, the Lac and its immediate surroundings.**

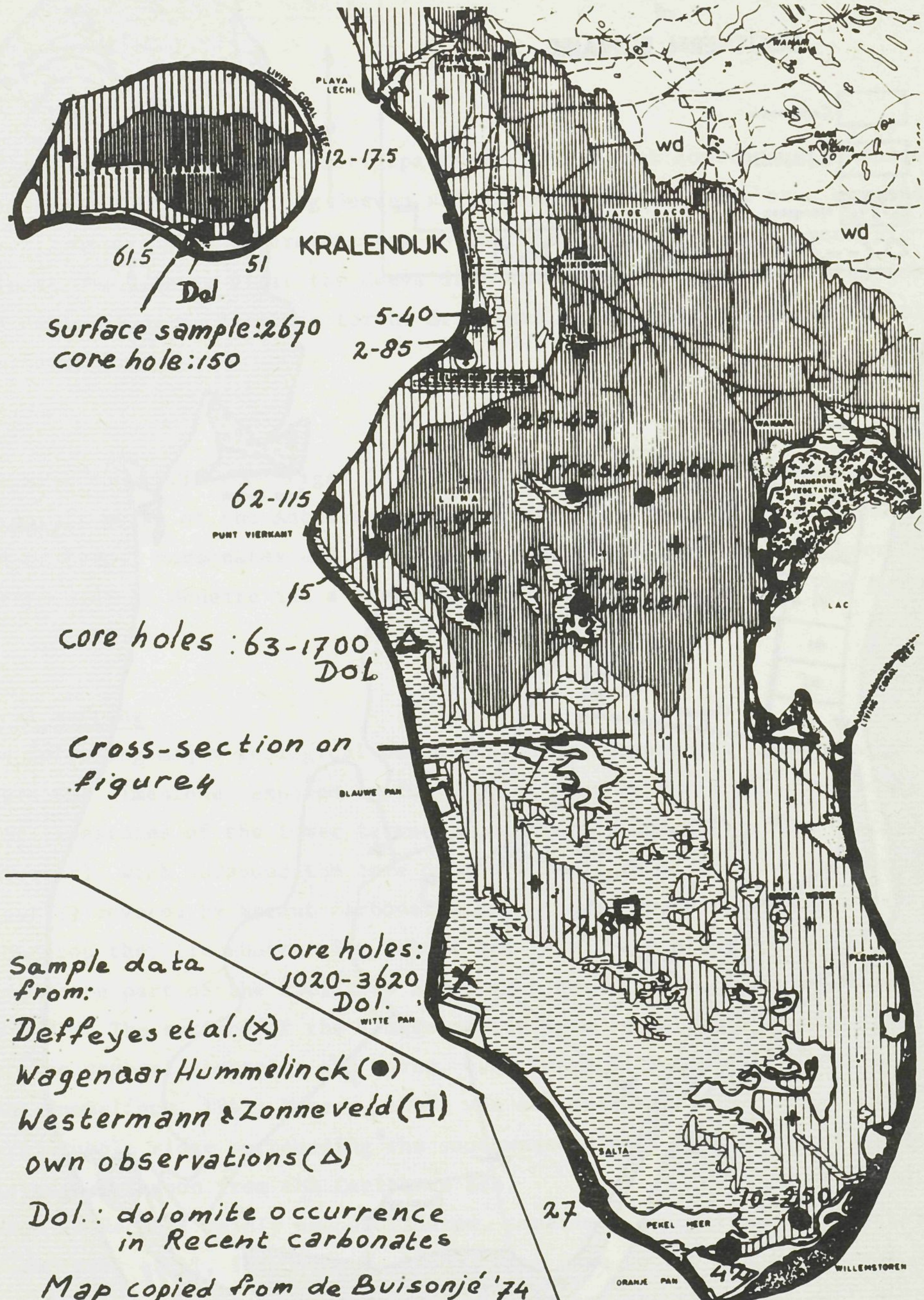


fig. 27 . Geological map of S.Bonaire (de Buisonjé,1974) with water sample locations by various investigators. Numerical values give the clorine contents of water in mmol Cl^-/kg H_2O (Caribbean seawater contains about 600 mmol Cl^-/kg H_2O).

springs (seepageholes) supplied saline water to the Pekelmeer. Due to the island's climatic conditions hypersaline brine formed in the lake and significant amounts of gypsum were deposited on the lake's bottom together with carbonates. Lucia (1968) reported from the southern shore of the Pekelmeer lithified carbonate crusts. These encrusted outcropping Pleistocene and formed polygonal ridges containing considerable amounts of gypsum (Lucia, 1968, p. 852 and fig. 16).

5) A lagoon, the Lac which has an open connection to the sea. It has a depth of 3 m. in its center and 8 m. in its inlet and is rimmed by mangrove forests and a few sandflats. The bottom of the lagoon is covered by sea grass, green algae and coralline algae. Natives find it an excellent place for catching Strombus gigas. The carbonate sand flats near Cai and Sorobon (fig.26) contain numerous Calianassa-mounds. Algal mats cover the slightly higher parts of the flats (Scytonema-mats) while algal biscuits (Schizothrix) can be found in the subtidal-intertidal area of Boca Jewfish. The sand formed on the bottom of the lagoon (predominantly Halimeda-debris) is swept up by currents forming four little islands (Pedro, Rancho, Fogon and Chico) and the sandspit Awa Blancu. The saliñas di Cai form part of the Lac-region. They became isolated from the Lac by a sandbar and gradually changed into a small evaporite basin. Cores taken in the saliñas showed that the uppermost part of the sediment in the saliñas is gypsum or gypsiferous sand followed by mangrove-peat (fig.28). The western side of the saliñas is covered by gypsum precipitated from a hyper-saline spray blown onto the surface by the eastern trade wind. Algal mats and carbonate crusts with thrombolitic structures cover the bottom of some of the saltpans.

Climate and precipitation

The deposition of evaporites is due to the semi-arid climate on Bonaire. Annual rainfall varies between 340-680 mm. and is greatest from September-January. The main diurnal temperature is 27°C (Westermann & Zonneveld, 1956). The island is exposed to an eastern trade wind blowing with an average velocity of 3.9-4.9 m. per second.

There are few surface waters on Bonaire and none in S.Bonaire. All rainwater disappears into the limestone or the unconsolidated sediments adding to an underground reservoir of fresh-brackish groundwater. During the rainy season large parts of southern Bonaire become flooded due to the lack of good surface drainage (it forms a continuous problem for the AISCO). Analysis of watersamples (fig.27) collected from pools and caves by Wagenaar Hummelinck (1940, 1943) show that the chlorine concentrations vary between 2-250 mmol Cl-/1 (Caribbean seawater: + 600 mmol Cl-/1). Fluctuations on a single locality are mainly due to sampling

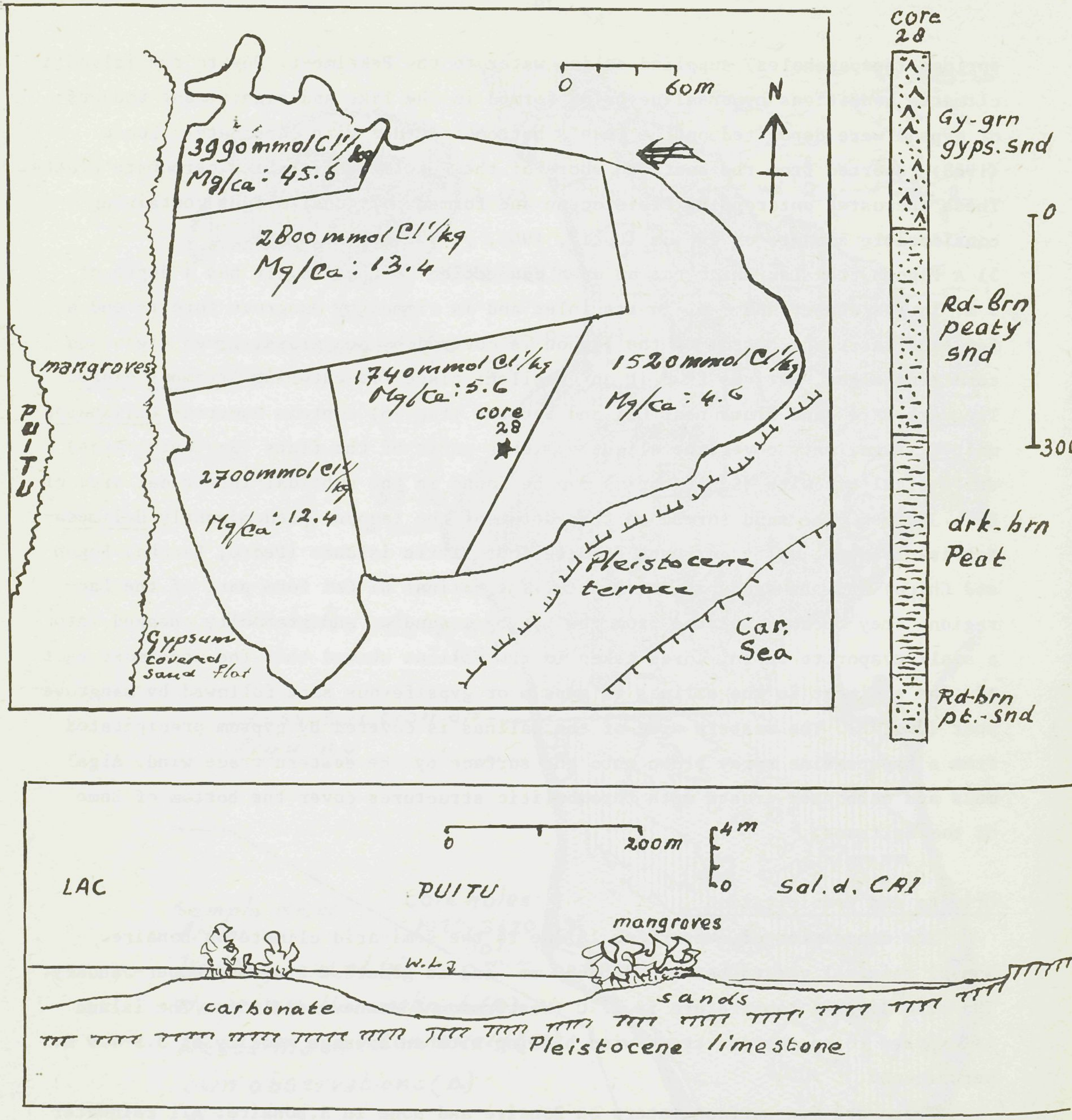


fig.28 . Sketch map and cross-section of the salinas di Cai with generalized lithology of 1 m long core taken from the area.

at different times of the year. Hypersaline brines occurred in the Pekelmeer.

Analysis of intersticial groundwater in the sediment cored from the central part of the Pekelmeer (Lucia, 1968) showed that the salinities decreased from ± 200% (± 3420 mmol Cl-/l) at the surface to ± 50% (± 850 mmol Cl-/l) at 200 cm. below the surface. Groundwater samples from shallow (1 m.) coreholes collected by Van der Meer Mohr in 1970, near Trans World Radio, had Cl- concentrations varying between 645 mmol Cl-/l and 1750 mmol Cl-/l with Mg/Ca-ratios varying from 1.8 to 5.4 (in the most saline sample) (fig.27).These samples were bulk samples of the water that flowed into the corehole after extraction of the core. No hydrological studies have been made so far to determine the exact nature of the underground fresh water, brackish water or saline water reservoirs, their contacts and the possible migration of the contacts during periods of dryness or excessive precipitation. Wagenaar Hummelinck (1943) observed that the water level in a pool near Pos Calbas, more than 1 km. inland fluctuates with the tide. The pool water is brackish, 25-43 mmol Cl-/l (Wagenaar Hummelinck, 1940). The cross-section in fig.29 shows the assumed relationship between ground water reservoirs of fresh, brackish and saline composition during the dry and the rainy season.

Reflux, evaporative pumping or mixing?

The hydrology of S. Bonaire is important to the study of the diagenesis of carbonate sediments and particularly the dolomite problem. Deffeyes et al (1962) suggested a mechanism of refluxing, magnesium-enriched brine to explain the presence of dolomite in the Recent carbonates and in Pleistocene terrace limestones. Hsü and Siegenthaler (1969) suggested that an opposite mechanism "evaporative-pumping" takes place. Hanshaw et al (1971), Land (1973 a and b), Badiozamani (1973) and Folk and Land (1975) adhere the theory that dolomitization takes place in the mixing zone between a fresh water lens and underlying saline water. All these theories hinge on the problem that a hydrological study has to be made in a certain area over a sufficiently long span of time to determine what mechanism or combination of mechanisms is conclusive. Other factors, equally or perhaps even more important lie beyond the field of geologists and hydrologists and belong purely to chemistry. It is one thing to unravel the environmental conditions but another to understand the process which is a chemical and crystallographic problem.

The solar salt works of the Antilles International Salt Cy. Ltd.

Since the late sixties the Antilles International Salt Cy. has altered the scenery in S. Bonaire. Most of the area, covered by Recent carbonates has now become an extensive complex of saltpans (fig.26). Sea water is being driven into

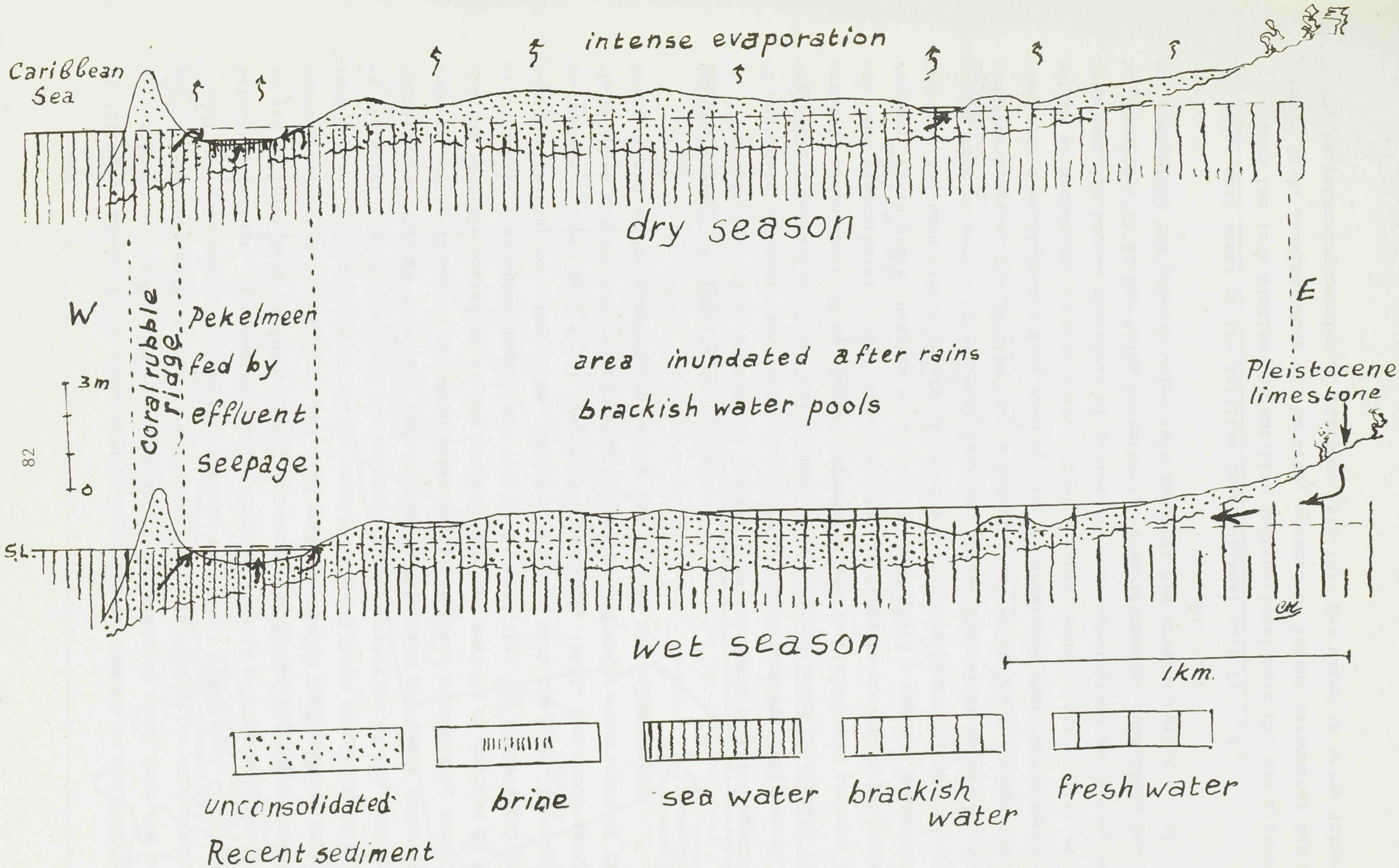


fig. 29. General cross-section through the northernpart of the Pekelmeer area with a hydrological interpretation (see also fig. 27)

the system by the trade wind through an eastern inlet cut in the coral rubble ridge. It circulates through ten condensors until it reaches a specific gravity of ± 1.151 and is then brought into three saturating ponds where the brine stays until it reaches the saturation point of sodiumchloride. Then it is led into a system of crystallizers where the sodiumchloride can precipitate. the rest of the brine is disposed of through a channel into the Caribbean Sea before bitterns can precipitate in the crystallizers. The bottom of the condensors is held as impermeable as possible by a layer of bluegreen algae. *Cerithium* lives in the Pekelmeer and in the first four condensors (Rooth, 1974). Brine shrimps, *Artemia salina*, and brine flies, *Ephydra cinera*, feed on the algae and serve in term as food for the flamingo's and other birds. Bird droppings supply nutrients to the algae, a neatly closed biological system. After the brine has passed through the first four condensors, gypsum precipitates from it forming thick crusts with compressional ridge structures.

The following can be reported on the composition of the brines (figs.30 & 31).

1) The pH, measured during the daytime hours varies between 7.4 and 8.9. The Caribbean sea water near the inlet has a pH of 8.3, a pH of 8.9 was measured in condensor 6 (increase due to photosynthesis?) and the crystallizers have a pH around 7.5. The decrease in the crystallizers is probably due to acid hydrolysis of hydrated magnesium ions (Van der Meer Mohr & Stephan, in preparation). Similar pH-drops were reported by Amit & Bentor (1971) from the Dead Sea (pH of 6.1 - 6.7).

2) A plot of the magnesium, calcium, strontium, sulphate, total CO_2 and oxygen concentrations against the chlorine concentration gives the following results:

a) The Mg-concentration shows a perfect linear increase: no precipitation of magnesium compounds.

b) The Ca-concentrations increase in the Pekelmeer due to the dissolution of gypsum, occurring on the bottom, in the sea water. (Sea water is undersaturated with regard to Ca SO_4). Calciumcarbonate starts to precipitate in condensor 3 and gypsum precipitates in condensor 5 and onward. The brines in the crystallizers contain very little Ca.

c) The Sr-concentrations show a similar picture as with Ca. This is due to the slight amounts of Sr (± 0,002 mol Sr/kg) present in the gypsum.

d) The SO_4-concentrations show the same anomaly.

e) The total CO_2-concentrations decrease slightly up to condensor 4. From condensor 5 onward there is a linear increase. A total CO_2 versus Mg plot shows a linear relationship from condensor 5 onward probably caused by the formation of poly-nuclear carbonate complexes.

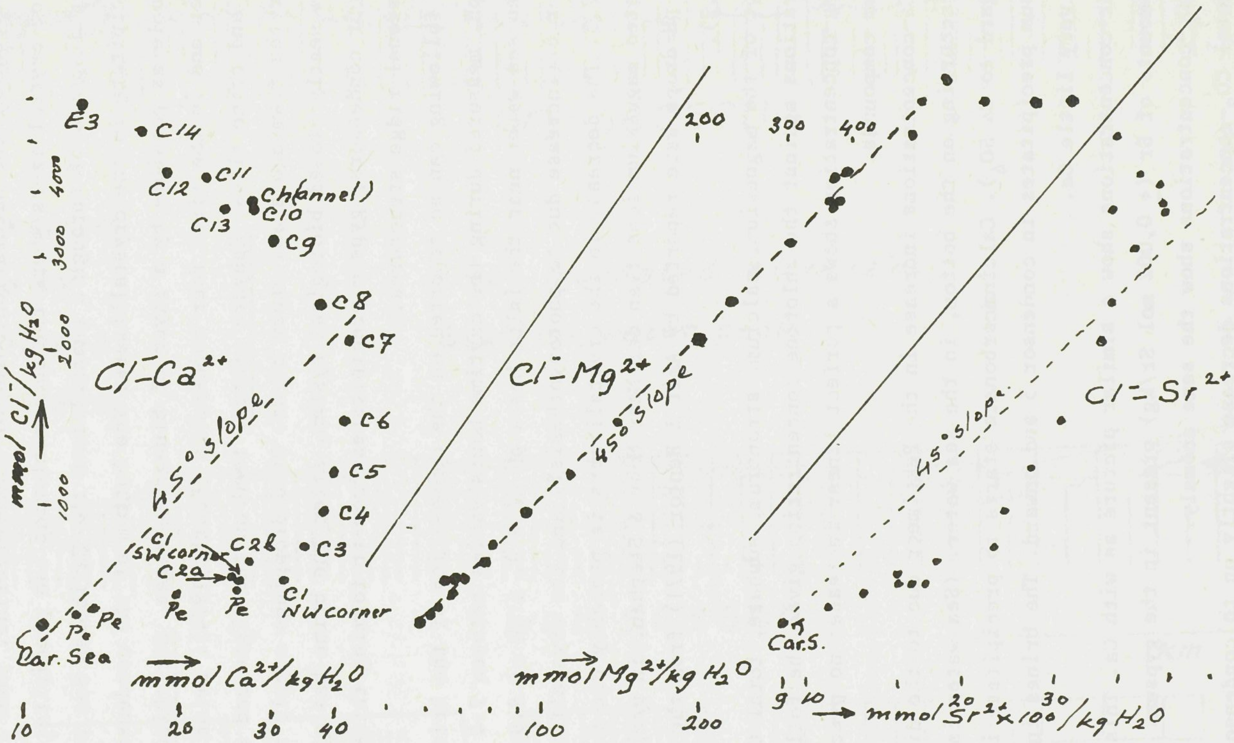


fig. 30 . Calcium, magnesium and strontium concentrations in the AISCO-solar salt works plotted against the chlorine concentration.

f) The oxygen-concentrations fall into two groups. The first includes the measurements taken up to condensor 7. The other group consists of the rest.

Locations to be visited

En route to stop 1 notice the coral rubble ridge to the right and remnant of the supratidal carbonate/gypsum flat to the left as well as the Pleistocene limestone terrace.

Stop 1. Pumping station AISCO. General explanation; view of Pekelmeer, condensor 10, channel and crystallizers (notice colour-differences due to algae & bacteria); discussion dissolution old gypsum deposits into present-day brine in the Pekelmeer (undersaturated with regard to $CaCO_4.2H_2O$). Leaving stop 1 we drive past an area covered by low underbrush. This is slightly higher lying Pleistocene limestone of the Laagterras.

Stop 2. Condensors 2/3/4. Here we are at the junction of dikes separating 3 condensors. Fauna & flora still relatively abundant (Cerithium etc.) $CaCo_3$ precipitation, retarded in condensors 1 and 2 takes place in condensors 3 and 4.

Stop 3. Condensor 5. First precipitation of $CaSO_4.2H_2O$ (see Ca^{++}-Cl^-diagram, fig)

Stop 4. Flamingo-sanctuary. Touriststop to show flamingonests. This stop might be by-passed if it would upset the birds.

Stop 5. Condensors 7 and 8; compressional ridges in gypsum deposits.

Stop 6. Crystallizer 11: Salthoppers and saltooids. Discussion formation of salthoppers (Dellwig 1955) and saltooids.

Stop 7. Washing plant: auxiliary stop. Here we leave the AISCO-works.

Stop 8. Slavehuts near White Obelisk. Touriststop. History of saltexploration on Bonaire (Focke 1974). Drive to Sorobon along E-side of the island, pass the "inlet". Notice limestone cliff.

Stop 9. Sorobon, Pintu and Boca Jewfish. Dunes. Walk along the coral rubble ridge to Awa Blancu (view of Lac). At the rim of the mangrovebush: flat-pebbles of detached algal mats. Subtidal mats. In Boca Jewfish algal biscuits, Acetabularia and young Melongena. Drive to the saliñas di Cai. En route notice the green and lush mangrove forests along that part of the Lac which still has normal marine conditions. Dead mangroves behind the four sand islands (Pedro, Rancho, Fogon and Chico).

Stop 10. Saliñas di Cai, (fig.28). Gypsum covered rim on W. side. Soft jelly-like masses of algae and hard lithified crusts (thrombolites: Aitken, 1967; Horodowsky and von der Haar, 1975; Van der Meer Mohr, 1977).

Stop 11. Fishing huts of Cai: Sandflat with Calianassa-mounds; Strombus gigas-hills. From here the party can return to Kralendijk to relax in the Flamingo Beach Hotel,

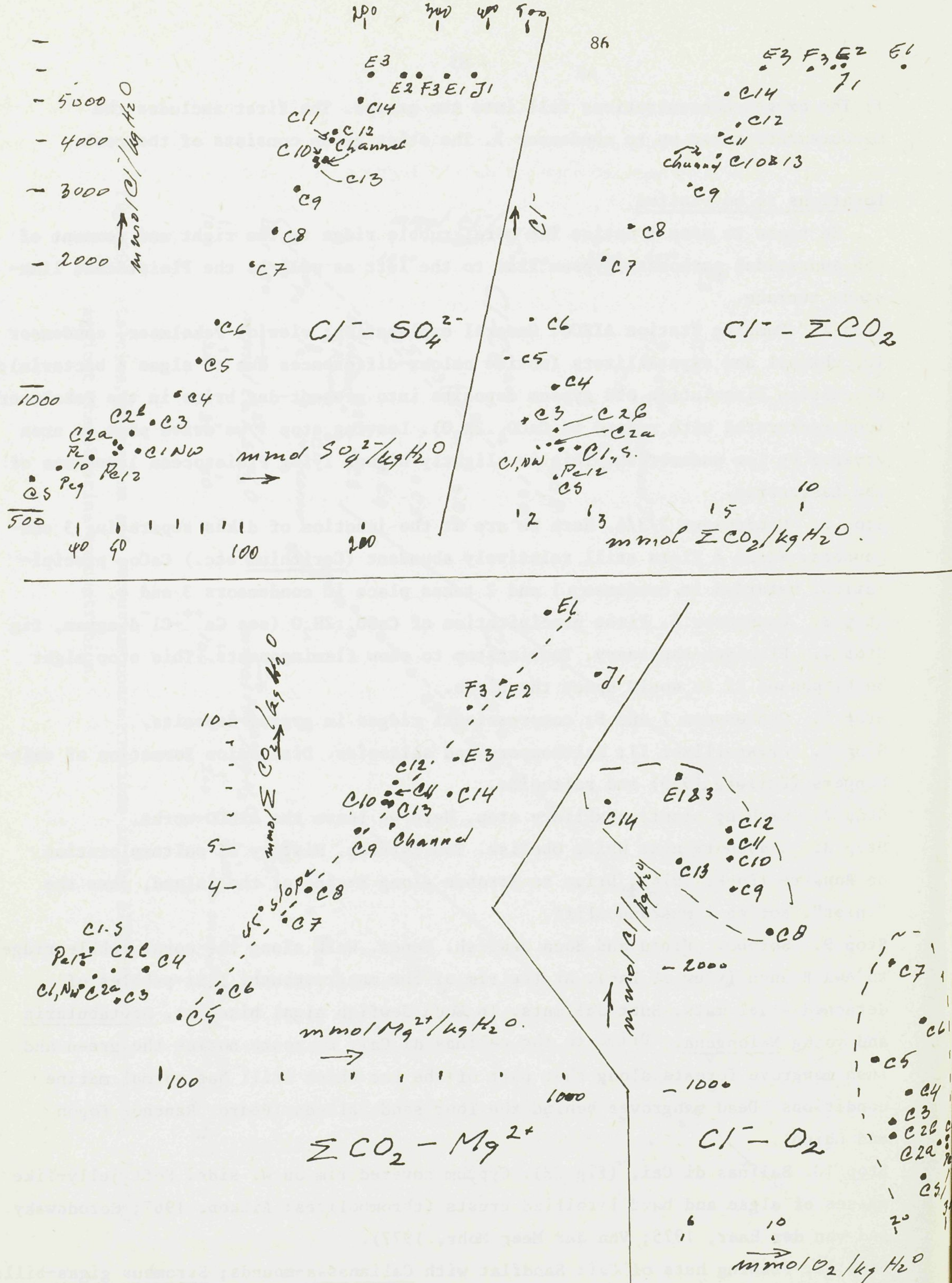


fig. 31. Total CO_2, sulphate and oxygen concentrations versus the chlorine concentration and a total CO_2 - magnesium diagram from the brines in the AISCO-solar salt works

or drive to a point south of the airport for a visit to the Cueva di Watapana. The participants should realize that there is no electric light in the cave.

Stop 12. Cueva di Watapana: cave in Middle Terrace. Brackish water pools at the end of the cave, (Low Mg)-Calcite precipitates as calcite-ice (floating calcite scales) at water surface. Aragonite precipitates next to calcite. Influence underground sea water lens (Van der Meer Mohr, 1977).

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FIELD TRIP OF A GENERAL NATURE TO ARUBA (C = M)

From airport by way of Oranjestad to the northern point of the island. The road leads over limestones of the Lower Terrace or recent beach deposits.

Excursion point 1: Hudishibana and California

The lighthouse of N. Aruba is constructed upon a terrace-like platform consisting of eolianites. These eolianites obviously have been deposited as dune sands blown up from a beach in Lower Terrace time. They show a steep foreset lamination, dipping in a westward direction. They contain a few percents of non-calcareous material (mainly quartz grains). The retreating terrace walls exposed the surface of the basement rocks, consisting here of quartz diorite. As in other parts of Aruba the main masses of quartz diorite are strongly weathered in the Hudishibana area. A relatively great number of corestones, however, escaped weathering. Recent sheetwash, adjusted to the surface of the Lower Terrace (here situated at an elevation of less than 5 m.) or the recent sealevel as base level, transports the fine weathering products downwards, the resulting denudational plain is dotted with corestones exposed in this way.

North of Hudishibana a dune field has developed (fig. 32). It consists of a multitude of steep and elongated dunes. The presence of a vegetation of Suriana maritima plays an important role in the evolution of this dune type. The sand originates from the narrow beach at the windward coast where some huge diorite boulders are washed by the surf. At a short distance from the coast, however, a living coral reef is present; the sands of the beach (and therefore also the dunes) are supplied by that reef. Again only a few percents of the grains are calcareous. As observed by De Buisonjé (1974), the dunesand, at a distance of about 10 m. from the beach, not only shows a sorting that is characteristic for eolian material, but also the degree of roundness is suddenly much higher than in the beach sands. From here on sorting and roundness remain constant towards the west and are therefore considered to be the result of eolian selection which occurred during the deflation from the beach.

The dunes overlie an outcrop area of the tonalite batholith with basic clots, schlieren of layered trondjemite, small pegmatite veins, a thin semi-lamprophyric dike and numerous late, hydrothermal alteration veins.

From California over tonalite with characteristic corestone landscape to Altovista.

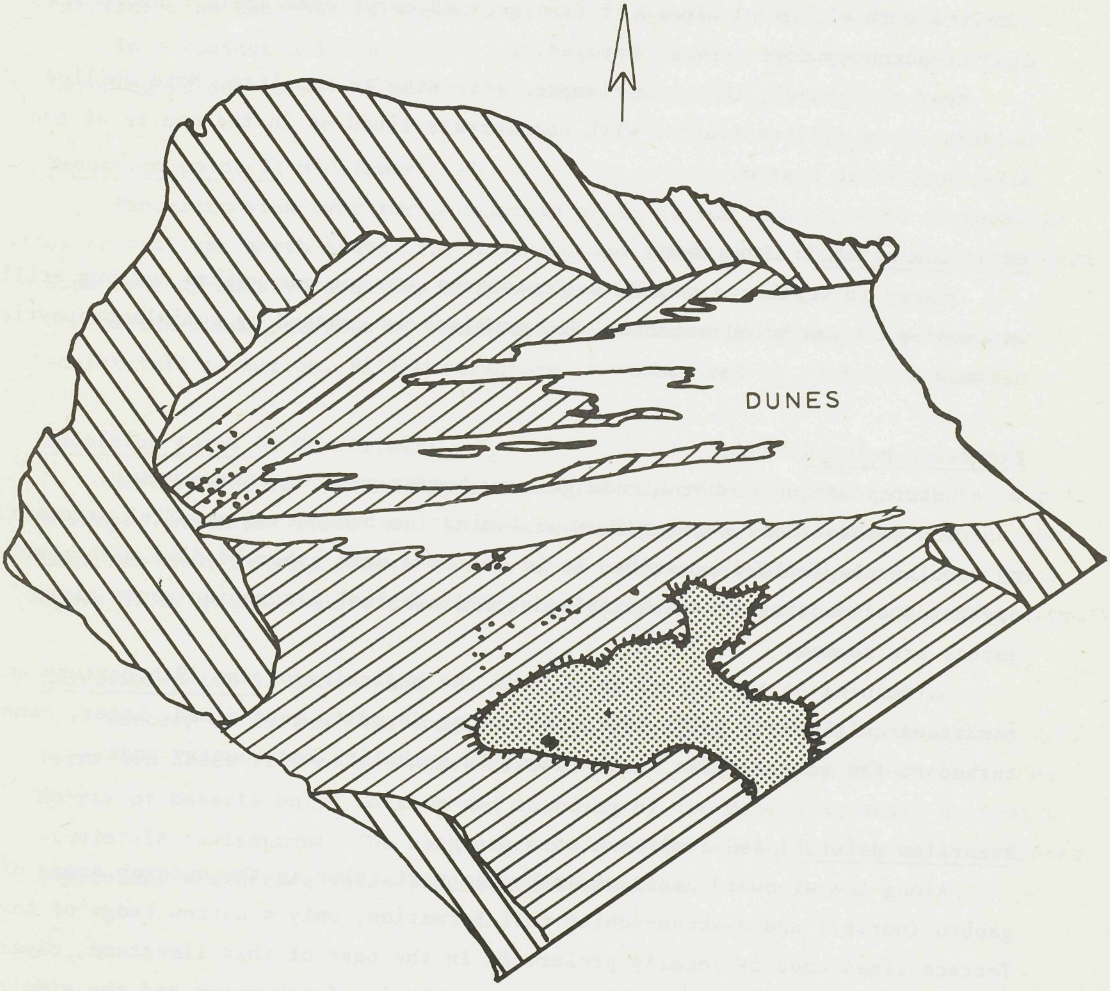
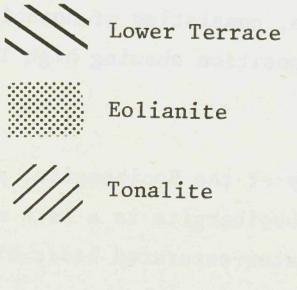


Fig. 32. Sketch map of Califorinia with recent dunes
(approximately 1 : 16.000).



Excursion point 2: Altovista

Three hundred meters before reaching the chapel a magmatic breccia of tonalite with elongated blocks of fine grained hornblende gneis, gabbro and diorite-porphyry dike rock is exposed.

Near the chapel, thin semi-lamprophyric dike in tonalite. Note chilled borders, flow differentiation with phenocrysts lined up in the centre of the dike, and joint system.

Excursion point 3: Jaburibari

Quarry in weathered tonalite. Corestones are not yet washed out but still in an envelop of weathered material. The tonalite is crossed by semi-lamprophyric dikes.

Excursion point 4: Budui

Outcrop of quartz-hornblende gabbro. Former gold smelting-works.

The gabbro shows a faint igneous lamination because of parallel orientation of tabular plagioclase crystals. It is cut by a dark gabbroid dike with phenocrysts of clinopyroxene and hornblende. Hydrothermal alteration zones along joints are common.

Goldmining on the island dates from the beginning of the 19th century and continued until about 1920. Initially placer deposits were mined. Later, miners turned to the quartz veins in the tonalite batholith and country rock.

Excursion point 5: Andicouri

Along the windward coast of Aruba, in particular in the outcrop areas of gabbro (norite) and diabase-schist-tuff formation, only a narrow ledge of Lower Terrace limestones is locally preserved. In the base of this limestone, caves and natural bridges were formed because of percolating fresh water and the simultaneous attack by coastal processes. Steps in slope of Matividiri correspond to marine denudational terraces.

At Andicouri the norite is exposed, showing faint igneous lamination. It is cut by dark semi-lamprophyric dikes, consisting of hornblende and plagioclase, and a felsic dike of tonalitic composition showing high T. hydrothermal alteration.

Excursion point 6: Hooiberg

This hill is the type-locality of the Hooibergite, a basic rock characterized by large hornblende crystals. The hooibergite is a late member of the igneous series and interpreted as either water-saturated basic clots, or the intruded products of partially melted country rock fragments.

The Hooiberg is the largest outcrop of this rock-type. Hooiberg means haystack. The lens-shaped hooibergite body is surrounded by sheared tonalite.

In a roadcut near this hill, outcrops of layered trondjemite occur. Layering is due to variation in the amount of biotite.

Excursion point 7: Miralamar

Panoramic view over the denudation plain of the outcrop area of tonalite of central and north Aruba. The Hooiberg and other hills stand out as inselbergs. Some tors of massive tonalite boulders are visible.

Aside road, outcrops of metamorphosed pillowed basalts of the diabase-schist-tuff formation. Pillow structure is emphasized by vesicular rims.

Excursion point 8: Quadirikiri

Cave in Middle Terrace limestones. The top of the Terrace consists of a strongly indurated limestone. It covers highly porous eolianites in which the cave has been formed, probably under more humid conditions. In the cave two types of dripstone occur: flowstones, and dripstone in stalactites and stalagmites

Excursion point 9: Boca Prins

Outcrop of metamorphic conglomerates, belonging to the diabase-schist-tuff formation about 1250 m. southeast of Boca Prins. The conglomerates consist of debris of basalts only. Sorting and rounding of the debris strongly suggest a fluviatile environment. The conglomerates overlie a diabase with well-developed spheroidal weathering which predates metamorphism.

FIELD TRIP D,H, TO THE EOCENE OF THE CER'I CUEBA

H.J. Mac Gillavry

The Seroe di Cueba, or Cer'i Cueba in modern spelling, is a table mountain, flat topped and bounded on all sides by steep cliffs or scree slopes 1). The mountain is surrounded on all sides by topographically lower exposures of older rocks.

The flat top is an erosional extension of the Higher Terrace. This surface recurs to the northwest as the erosional top of the Ceru Bomba Bua (Late Senonian Seroe Teintje limestone) and as the top of the depositional Higher Terrace limestone further north. These three remnants of the Higher Terrace are separated by deep erosional valleys (Figs. 43 & 33).

The cliffs are clearly erosional. The original extent of Eocene deposition can therefore not be ascertained. It is likely that the extent of the outcrop was bounded on the north- and northwest sides by post-Middle-Eocene faults and that it did not extend on that side much beyond the position of the present cliffs after this faulting. On the south side the outcrop may have extended further southward beyond the present cliff; this southern cliff is marked by young faults which are nearly parallel to the cliff face; some subsided blocks or masses are found in front of it. Tafonic weathering is developed on this leeward side. The south cliff is interrupted in the middle by an erosional embayment.

The Eocene is gently folded into two shallow synclines separated by a saddle. The structure is well shown on the top surface in air photographs (Fig.34). The base of the formation unconformably and transgressively overlies the Sint Christoffel Formation, the lowermost unit of the Late Senonian Knip Group. Actual exposures of this base are not found. To the east of the embayment in the south cliff the basal plane can be followed as a line of large pebbles of older rocks and is seen to rise up eastward at a low angle until at the east point of the mountain it must be just below the top; here, however, it is covered by scree.

The Eocene is typically in carbonate facies, except for some conglomerate layers near the base. A lithologic description of a section across the southwest point is given by Schaub (1948) which section is considered as type section by Jung (1974). A detailed sedimentological description is lacking.

1) For the derivation of the name see note in the text for the Eocene.

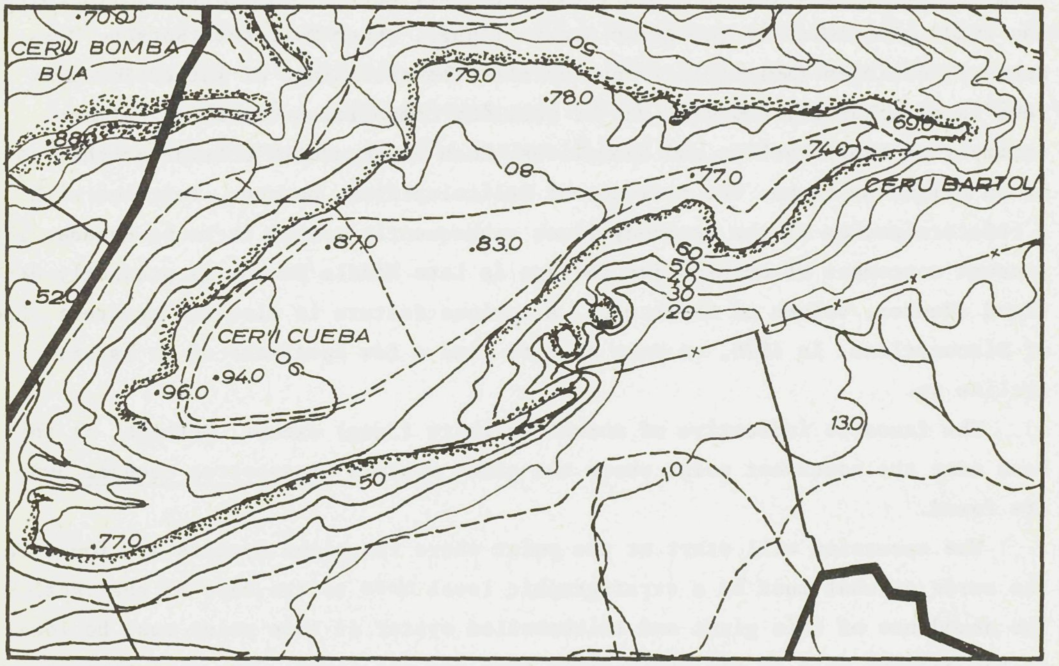


Fig. 33. Topographic map of the Cer 'I Cueba on scale 1 : 20.000.

Fig. 34. Aerial photograph interpretation of Cer 'I Cueba.

The formation is well known because of its rich and abundant fauna of larger Foraminifera (Koch, L.M.R., Rutten, M.G., Rutten & Vermunt); furthermore one finds nautiloids of the genus Aturia (Jung), other Molluscs (Rutsch, Jung, Hunter), echinids (Molengraaff) and corals. The assemblage of larger Foraminifera is particularly abundant but of peculiar composition consisting almost entirely of Lepidocyclina and Nummulites. Koch consequently considered this to be an Oligocene fauna. The presence of Helicolepidina, however, together with a redetermination of the Lepidocyclines subsequently proved it to be Eocene. The present concensus of opinion for the age is Late Middle Eocene as presently defined (Hunter, volume of abstracts). A curious feature is also the apparent absence of Discocyclina. In 1976, we were able to find a few specimens of an Asterocyclina sp.

The fauna is indicative of normal salinity (Jung) except, perhaps, at the base near the southwest point where the giant oysters Crassostrea cuebana Jung are found.

The excursion will start at the point where the giant oysters are found in the scree at what must be a stratigraphic level close to the base of the section. The abundance of this giant and thickshelled oyster at this point must be local: in the eastern half of the south cliff they are not found. Jung discusses the habitat of these oysters, whether they lived on hard substrate or on a soft muddy bottom. We were able to observe on several specimens that their plane of attachment, which is rather large, shows the imprint of the inner shell surface of oysters of the same kind and in one specimen the imprint of a Turritella. Accordingly they grew upon the empty shells of dead Molluscs to which, however, they are no longer attached.

From here the trip goes to the southwest point where a good exposure is found of beds close to the base of the formation (fig. 35). Here there are a number of layers of conglomerate with well developed foreset-bedding. Some pebbles are still found higher up in the section where carbonate dominates. Next follows an alternation of intervals with bioturbation of two different intensities and mode. This part of the section suggests rather quiet water. Here also one encounters an occasional internal mould of a large bivalve in position of growth.

Higher up in the section some of the beds with concentration of larger Foraminifera suggest more pronounced water movement.

The excursion will follow the section to the centre of the westernmost syncline. If time permits we can descend to the other side to look at the Cretaceous of the Ceru Bomba Bua.

Selected references:

Koch, R., 1928, Eclogae geol. Helv., 22,1,51; Rutten, L.M.R., 1928, Proc. Kon. Ned. Akad. Wet. 31,10,1061; Schaub, H.P., 1948, Bull. Am. Assoc. Petr. Geo., 32, 7, 1275; Rutsch, R., 1939, Eclogae geol. Helv., 32, 2, 231; Jung, P., 1974, Verh. Naturf. Ges. Basel, 84, 1, 483; Hunter, V.F., 1977, vol. abstracts.

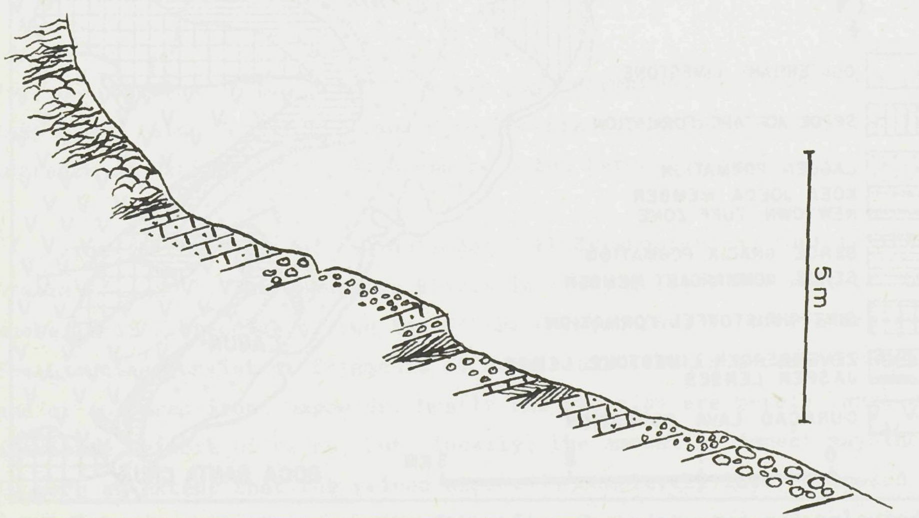


Fig. 35. Section at SW point of Cer 'I Cueba close to base of formation.

FIELD TRIP TO LATE SENONIAN KNIP GROUP, ZEVENBERGEN, NORTHWEST CURAÇAO.

(E and J)

D.J. Beets

By touringcar along mainroad Willemstad - Westpunt (plate 1) to Hyronimus, about 8 km southeast of Westpunt. From there by truck over an unpaved road to the National Park Zevenbergen, about 4 km west of Hyronimus. The road leads through the large outcrop area of the Curaçao Lava Formation in the core of the northwestern anticlinorium. En route, good views on the 218 m high table mountain Hyronimus with a horizontal cap of Quaternary eolianites, and on the highest hill of the island, the Sint Christoffelberg (375 m), consisting of a steeply dipping succession of silica-rich sediments of the lower unit of the Knip Group, the Christoffel Formation (fig. 36).

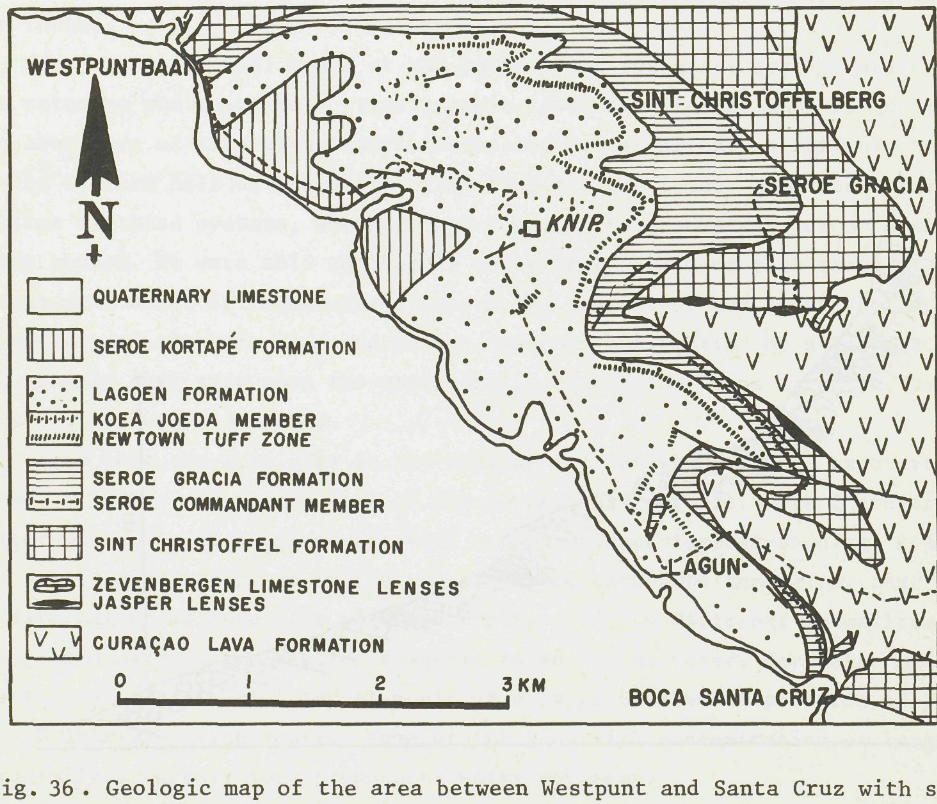


Fig. 36. Geologic map of the area between Westpunt and Santa Cruz with subdivisions of the Knip Group. Field trips E and J follow small road from Zevenbergen limestone lens to the Seroe Gracia (hatched line, centrum right of map). During field trip G a stop will be made in the Lagoen Formation near the country house Knip.

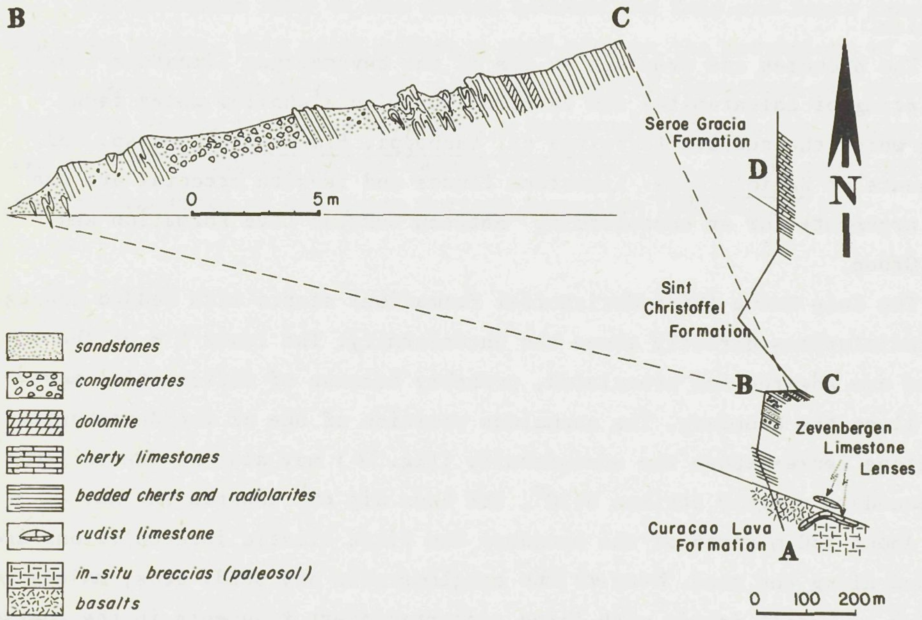


Fig. 37. Section of top of the Curaçao Lava Formation and lower half of the Knip Group (Sint Christoffel and Seroe Gracia Formations) along road from entrance of National Park Zevenbergen to the Seroe Gracia.

From the entrance of the National Park Zevenbergen on foot to the Seroe Gracia (fig. 37). The excursion starts in a dry gully 100 m east of the road where in-situ breccias of the top of the Curaçao Lava Formation are exposed. The breccias consist of fragments of basalt embedded in a cement of carbonate and/or coloured iron compounds. Mostly the breccias are merely lavas with an intricate network of veins, but, locally, the amount of cement may increase to such an extent that the veined aspect is completely lost. Downward the breccias grade into non-brecciated basalts. Carbonate and red coloured iron compounds are thought to be weathering residues of a (semi-)arid and a more humid tropical climate, respectively. Fragmentation of the basalts may be due to weathering only, but the orderly pattern of the veins in some of the outcrops are reminiscent of joint patterns. Impregnation of the basalt fragments by red iron compounds and replacement of plagioclase and pyroxene by carbonate and chlorite is common. Nevertheless, at present the breccias are more resistant to weathering than the majority of the basalts of the Curaçao Lava Formation. Probably, this is due to early Tertiary low-grade metamorphism.

The breccias are overlain by one of the Zevenbergen limestone lenses, consisting of calcarenites and calcirudites with a shallow water fauna among which the rudists Torreites cf. tschoppi, Plachiopthychus sp. and fragments of Radiolitidae. Limestone lenses and in-situ breccias are the main arguments for an unconformity between Curaçao Lava Formation and Knip Group.

The Knip Group (Sint Christoffel Formation) starts with bedded cherts and radiolarites directly above the unconformity. The lower 5 m of the cherts are sheared and brecciated, probably because of differential movement along the boundary. The anomalous position of one of the Zevenbergen limestone lenses above the unconformity (fig. 37) may also be due to faulting. The boundary roughly strikes N120°, the beds dip 60° towards the NE.

About 130 m north of the boundary the first clastic intercalations are exposed along the road. These are fine conglomeratic and sandy beds, mainly consisting of basalt debris with large contorted chert fragments in the coarser beds. Graded bedding is ill-developed, and probably most of the clastics are grain flows and debris flows. The intercalated intervals of bedded cherts and radiolarites show slump overfolds. Radiolaria sands of a few cm. thickness with sharp bases have been found in the intervals. A few dolomitic beds occur in the section near C. These dolomites are typical for the Sint Christoffel Formation in this region, but are not very well exposed in the section. The dolomites are hard, compact and fine-grained rocks with a bluish colour, weathering to grey and orange. The dolomite has been formed at the expense of fine grained volcanic debris (sand and small pebbles of basalt mainly) probably because of low-grade metamorphism (zeolite facies) under high P_{CO2}. Grain boundaries of the original detritus has often been preserved as ghost structures.

Although not exposed, the next 350 m consists mainly of dolomitic rocks and silica-rich sediments, with an increase of the latter rocks upward. The upper part of the section (near D, fig. 37) shows the gradual transition from bedded cherts and radiolarites of the top of the Sint Christoffel Formation to cherty limestones of the Seroe Gracia Formation. Characteristic feature of the latter rocks are early diagenetic black silica concretions.

Cherts, radiolarites and cherty limestones show minor folding with vertical to steeply dipping axial planes; axial plane separation is in the order of several tenth of metres.

The excursion ends at the divide between the Knip and Santa Cruz drainage basins. This point offers a good view on the morphology of the higher units of the Knip Group: a ridge of cherty limestones and cherts of the Seroe Gracia Formation bordering a topographic depression in the outer fan turbidite sequence of the Lagoen Formation with, in the west, hills of cherty limestones of the Seroe Kortapê Formation (see fig. 36).

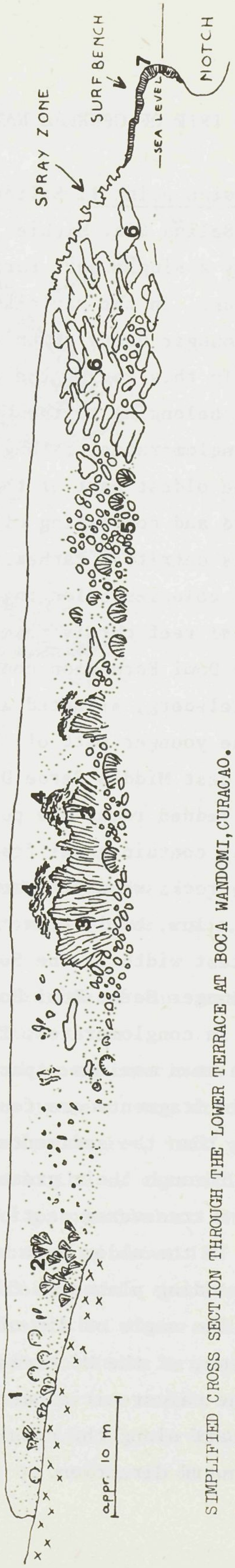
FIELD TRIP TO BOCA WANDOMI, CURAÇAO.

J.W. Focke

Boca Wandomi shows a section through the Late Pleistocene Lower Terrace, which in this area is only a few hundred meters wide. The section is perpendicular to the reef trend and shows a well developed barrier reef at the seaward margin. This barrier is a regular feature along the entire windward coast of Curaçao and consists of an interlocking Acropora palmata/coralline algal (predominantly Porolithon pachydermum) framework. Locally Diploria sp. is an important framebuilder in the barrier. The barrier at this locality enclosed a more or less protected lagoon only in the final stages of its development. The lower part of the outcropping back-barrier deposits bear witness of open oceanic, relatively turbulent conditions, with large Acropora palmata and Montastrea annularis colonies, head corals and coralline algal caps and pavements. Particularly the coralline alga Lithophyllum congestum is very abundant as framebuilder as well as debris. The upper parts of the back-barrier deposits contain calcareous sands with bivalves and gastropods (notably Strombus gigas), finely branched Acropora cervicornis in growth position, beachrocks and eolianites (the latter three are not exposed in Boca Wandomi). The Pleistocene terrace, comprising a vertical interval of at least 15 meter, presumably represents the last period of (decreasing) sea level rise, still stand, and sea level lowering. The still stand is also witnessed by a well developed notch in higher cliffs at approximately 10 m above present mean sea level. Tentative results from growth ring studies on Montastrea annularis colonies indicate that the exposed part of the lower terrace (the upper ten meters) have been deposited in a time span in the order of only one thousand years (representing an accumulation rate of approximately 10m/1000y).

The present coastal cliff at the north eastern- and the north western side of Curaçao, including the cliffs near Boca Wandomi, show a complex morphology with a rugged spray zone (zone of 'lapies' or 'karren'), a horizontal seaward protruding surf bench ('ledge', 'platform', 'trottoir', 'cornice') and a sub-tidal notch. The cliff as a whole is characterized by intensive bio-erosion. The surf bench results from the presence of thick (up to 50 cm) accretions built in the surf zone by the vermetid gastropod Spiroglyphus irregularis (= Dendropoma irregulare) and the coralline algae Porolithon pachydermum and Lithophyllum congestum. The accretions show fabrics known from algal/vermetid reefs ("ridges") from other Caribbean islands and from Bermuda. Void space is filled with cavity dwellers (notably Homotrema rubrum) and sediment. Below the living surface the accretions are well lithified by aragonite and magnesian calcite cements. Some alteration of the original framework results from repetitive boring, infill and cementation. The horizontal upper face of the bench is determined by the upper limit at which the vermetids are able to build accretions. The accretions retard the erosion of the cliff, the width of the bench (up to 10 meters) represents the time lag. Once created, the presence of the bench is believed to retard similarly the erosion rates in the adjacent parts of the cliff, resulting presumably in an equilibrium in which the profile will not notably change as the cliff recedes landward.

Fig. 38



SIMPLIFIED CROSS SECTION THROUGH THE LOWER TERRACE AT BOCA WANDOMI, CURACAO.

1 sands with Strombus gigas and rhodolites 3 Montastrea annularis 5 Acropora palmata debris 6 Acropora palmata/Porolithon pachydermum interlocking framework

2 Siderastrea siderea 4 Lithophyllum congestum 7 recent organic accretions

FIELD TRIP OF GENERAL NATURE TO SOUTHEAST CURACAO

Excursion point 1: Saliña Sint Michiel

Saliña Sint Michiel is a lobate bay that has been separated from the open sea by a single bar. Part of the bay has been used for the construction of saltpans. In the vicinity of the bay the Seroe Domi Formation, c.q. the Middle and Younger Units of this formation are exposed.

In this region the rocks may be divided into three kinds: the two oldest parts belonging to the Middle Seroe Domi Formation, and a younger part, rich in conglomerates, belonging to the Younger Seroe Domi Formation.

a. The oldest part of the Middle Seroe Domi Formation. Situated farthest land-inward and consisting of calcareous and dolomitized rocks. It is poor in terrigenous detritus, rather thick-bedded and of a massive development. It contains coral colonies belonging to the genera Siderastrea and Montastrea, whereas typical reef corals such as Diploria are absent. This oldest part of the Middle Seroe Domi Formation constitutes the high tops of the Seroe Spreit and the Michielsberg, situated at the north and south sides of the salinja respectively.

b. The younger part of the Middle Seroe Domi Formation. In a seaward direction of oldest Middle Seroe Domi Formation. These stratigraphically higher, more thin-bedded rocks are poor in terrigenous detritus, coarsely calcarenitic and rarely contain coral fragments. They are rich in fossil molluscs and echinids. These rocks weather more rapidly than those situated more landinward, and form here a low, hilly area, in which the salinja with the saltpans reaches its greatest width in the Seroe Domi rocks. (Fig. 39)

c. Younger Seroe Domi Formation. The Younger Seroe Domi Formation is extremely rich in conglomerates. The dimensions of the well-rounded diabase pebbles are 10 cm at a maximum. Apart from these conglomerates, branch-like Acropora cervicornis fragments are found. The conglomerates are more resistant against weathering than the sediments of the Younger Middle Seroe Domi Formation.

Through their greater resistance here the salinja is narrowest. Over the entire transverse section the dip of the layers remains directed towards the sea. In the older part of the deposit variation in direction of the strike of the bedding planes is to be observed.

The angle of dip of the bedding is not constant over the entire cross-section; at the Michielsberg it amounts to about 25^{o} in a seaward direction, in the calcarenitic part the angle of dip decreases to about 18^{o}, whereas in the part along the coast, it increases again to about 30^{o} at a maximum: all in a seaward direction.

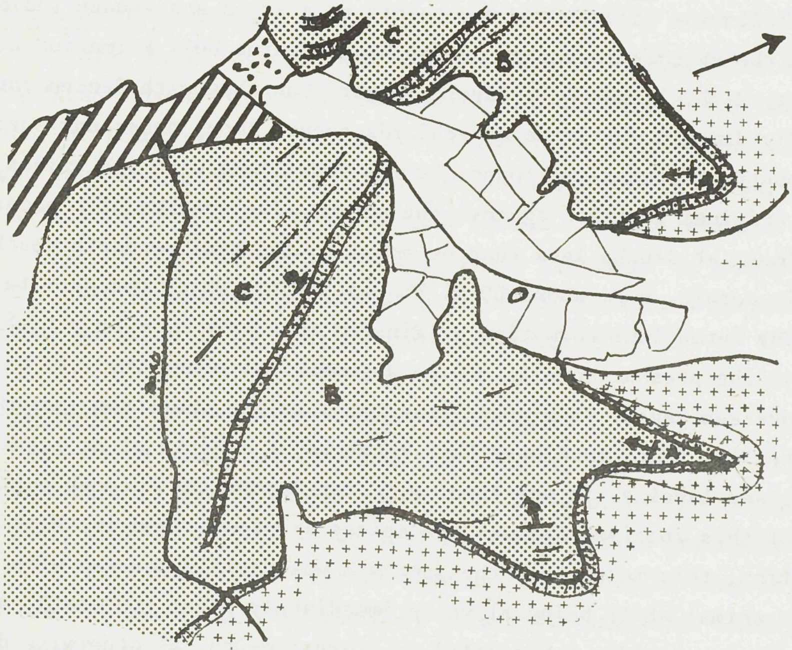


Fig. 39. Sketch map of Salina Sint Michiel. Seroe Domi Formation: grey; Lower Terrace limestone: hatched; Curaçao Lava Formation: plus signs.

Special mention must be made of the mode of fossilization of the various macro-fossils, occurring in the coarsely calcarenitic part.

In one of the calcarenitic layers, some meters thick, many specimens of Pecten raveneli are found. Nearly always both valves are present: the strongly convex right valve completely adjoins the flat, or faintly concave, left valve. The closed specimens appear to be distributed at random in the calcarenitic sediment, they do not even seem to have any preference e.g. parallel to the top level and basal plane of this calcarenitic layer, that dips about 18^{o} towards the sea. It is known, however, that during its lifetime this species lies with its convex valve lowermost. The closed valves indicate that these shells must have arrived alive in the sediment, but in a completely random arrangement. This observation is an argument that the Seroe Domi Formation was mainly deposited as a result of slumping of offshore sediments, consisting of detrital fragments of lime-secreting organisms that originally lived on reefs, mixed with pelagic organisms and terrigenous detritus. Apparently the living Pecten became embedded in the moving mass of sand, suffocated and were deposited at random in a rather thick calcarenite comples on a lower level.

The following observation too points to a rapid and sudden sedimentation. In the calcarenitic part of the Middle Seroe Domi Formation near Salinja St. Michiel, but in a layer younger than that with Pecten raveneli, many hardly damaged specimens of echinids occur. Among these one specimen of Echinometra lucunter was found. It was fossilized with the spines still in their original position against the corona. The species also occurs in recent times: at depths less than or equal to the maximum depth reached by hermatypic corals, e.g. about 50 m. The reefs from which the detrital material of the Seroe Domi Formation originated must have been at a higher level than the present summits of the asymmetrical mountains i.e. more than 190 m above sea level. This means that the locality where the specimen of E. lucunter was found must have been situated at a depth of at least 240 m below the sea level as it was then, e.g. far beyond the deepest part of the habitat of this species. Because the spines are fossilized in their original position, this means that the specimen was rapidly covered with sediment, the animal still being alive or immediately after its death, and that moreover it was rapidly transported to a great depth, as otherwise during the transport the spines would have become loosened. Here the same conclusion is drawn: slumping of a mass of calcareous sand from an offshore position.

Excursion point 2: Bullenbaai

View in northwestern direction on Seroe Domi Limestones along the shore of Bullenbaai. Higher and Middle Terrace formed as marine denudational terraces in the forereef deposits of the Seroe Domi Formation; Lower Terrace as an accumulation terrace. Strike of the Seroe Domi limestones follow present outlines of Bullenbaai. This is considered to be an important argument in favour of a primary dip of the limestone. In the narrow central part of the island, northeast of Bullenbaai, Highest Terrace deposits are present. They are the first indication for Quaternary eustatic sealevel movement.

Excursion point 3: Schottegat

Section through limestones of the Middle Seroe Domi Formation (see excursion point 1). See De Buisonjé (1974, p. 149) for description. Outcrops are difficult to reach, and therefore the point can not be visited with a large group.

Excursion point 4: Phoenixweg

View over Schottegat Harbour and the interior of southeastern Curaçao. The landscape shows distinctly the effects of different base levels of erosion: a. Schottegat is the result of incisions into the basalts of the Curaçao Lava Formation during lower sea levels. b. Hills in the surrounding are planated on at least three distinct levels. The correlation of these levels with the coastal terraces still gives problems. In general, it can be stated that in the non-calcareous part of the island, a greater number of planation surfaces occur than in the coastal terraces.

Excursion point 5: Technical School, Cas Coraweg

The Curaçao Lava Formation has its greatest outcrop area in southeast Curaçao, where it covers almost all of the interior of the island. The outcrop which will be visited shows well-developed pillow structure in the LKT basalts of this formation. Pillows have up to 5 cm thick rims of glass and glass breccia now largely replaced by palagonite and other chlorite minerals. Basalt has variolitic and intersertal texture. Note absence of vesicles, which suggests eruption in deeper water. In a faulted zone on the westside of the outcrop fine grained hyaloclastites occur. Hyaloclastites are the only sediments found in the Curaçao Lava Formation. Absence of pelagic sediments could be due to rapid piling up of basalts.

Excursion point 6: Caracasbaai

The Caracasbaai is the result of a huge slide. Here over an area of about $\frac{1}{4}$ km^2 the Seroe Domi Deposits, and part of underlying basalt slid down into the adjacent sea. Some remnants of the basalt sediments of the Seroe Domi Formation are visible in a small quarry NE of the bay. A study of the hydrographic map and the situation in the surroundings of Fort Beekenburg gives rise to the opinion that the sliding block split up in at least three parts. One large block (I, fig. 39) went down into the head of a submarine valley. It left a very prominent scar in the form of an elongated depression. Seismic reflection profiling suggests that remnants of this fragment now occur at a depth of 800 m in a submarine canyon (De Buisonjé & Zonneveld, 1976). The relatively shallow SE part of the bay seems to indicate that a

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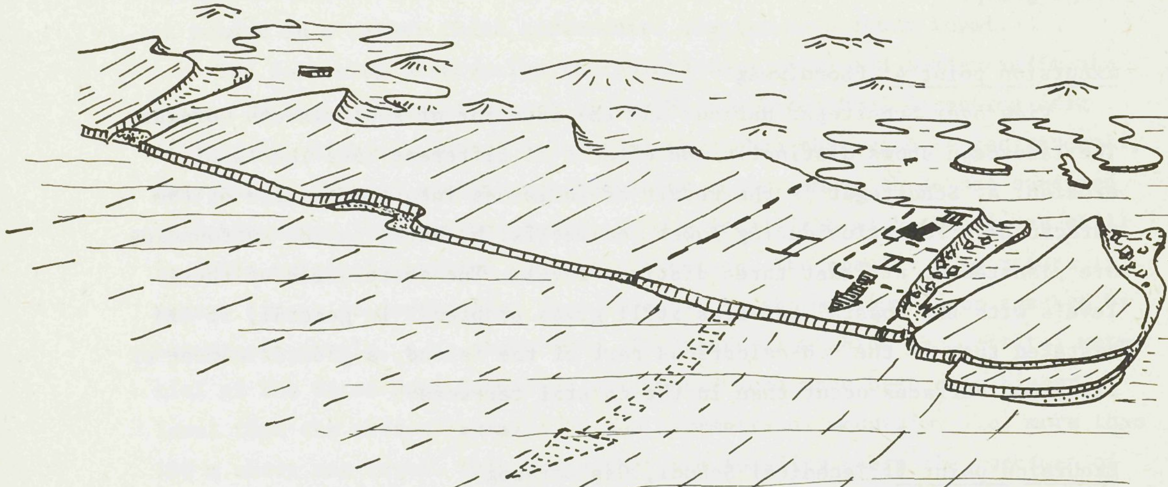

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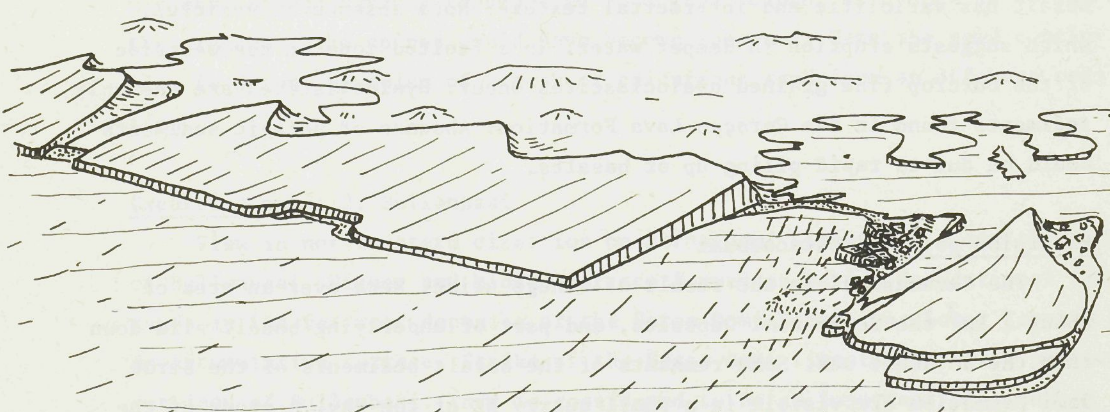


Fig. 40. Birds-eye view of Caracasbaai.

second block (II) was stuck there after moving a short distance. A third block (III) was rotated and fragmented. Its remnants can be observed along the eastern shore of the bay. They consist of broken slabs of Seroe Domi limestones, dipping in different direction. Some of the now vertical walls of the loose blocks show karst phenomena that must have originated on a horizontal or only slightly dipping surface. The slide took place after the formation of the Lower Terrace, as neither Lower Terrace limestone nor solution notches from this time are found in the bay. It is assumed that the slide went down quite recently, probably not more than 5 or 10000 yrs ago.

From Caracasbaai via Midden Seinpost to Klein Sint Joris. Along road outcrops of pillow basalt of the Curaçao Lava Formation. Midden Seinpost is one of the higher hills (104 m) in the otherwise strongly planated south-eastern part of the island. It has stepped slopes. It is assumed that the steps are formed by climatic changes and/or variation in rate of sealevel movement during formation of the Higher Terrace, as the steps are a regular feature on slopes of all higher hills on the island. The relief of the greater part of southeast Curaçao is lower than 50 m. Three important plan-ation surfaces can be distinguished in this lower area. Each of these re-present prolonged periods of relatively constant sealevel. Small steps in the slopes of river valleys incised in these planation surfaces bear witness of more complicated sealevel movement.

From Klein Sint Joris, one of the old typical Curaçaoan plantation houses, along Sint Jorisbaai to the northeast coast of the island. Just be-fore reaching the Lower Terrace limestones, a small hill on the south side of the road, capped by Middle Terrace limestone, shows an outcrop of con-glomerates, sandstones and marls of middle Eocene age (Seroe Mainsji).

As can be seen on plates 1 and 2, the Middle and higher terraces along the north coast of the island are preferentially resting on clastic rocks of Midden-Curaçao Formation and Eocene. Assuming that the extension of these terraces originally was much greater (thus also covering large parts of the Curaçao Lava Formation), the question suggests itself that the present distribution is related to type of basement, and their respective reaction to weathering processes.

Excursion point 7: Sint Jorisbaai

Lower Terrace is here covered by ill-sorted clastic debris, which indicates that base level of erosion is defined by the terrace.

The coast near Sint Joris has a morphology characteristic for the windward side of the island: wide notch, benches formed by algae just above mean sealevel, steep cliff, lapies (karst) zone, and hurricane-built ridge of large, often imbricated limestone blocks, torn loose from the cliff.

FIELD TRIP OF A GENERAL NATURE TO NORTHWEST CURAÇAO (G)

From Holiday Inn towards the north along Schottegat to Gasparitu.

Excursion point 8: Gasparitu

Quarry in pillow basalts of Curaçao Lava Formation. In outcrops of this size, bedding and facing can be inferred from the shape of the pillows. The basalt is heavily jointed. It is quarried for road-building purposes. See also excursion point 3.

From Gasparitu along main road towards the northwestern part of the island. Before reaching the narrow, central part of the island (plates 1 and 2), the northward dipping boundary between the Curaçao Lava Formation and overlying Midden Curaçao Formation is passed. Note that Knip Group is thin or absent in this area. About 3 km. north of this boundary the road climbs to the level of Higher Terrace, with on the left hand limestone caps of the Highest Terrace. Approximately 9 kms. more to the north a small road to San Pedro is taken.

Excursion point 9: San Pedro

In the San Pedro area the flight of marine terrace steps is practically complete. West of the main road to Westpunt, the Highest Terrace is represented in the form of a slightly eastward dipping plateau with a maximum elevation of 150 m. and a minimum height of about 90 m. The deposits of this Highest Terrace consist of coral detritus with some coral colonies in growing position. The higher part consists mainly of eolianites. It is assumed that the terrace originated during a gradual lowering of the sea level; it has a regressive nature.

The "Higher Terrace" (level 80-50 m.), is situated east of the road. According to De Buisonjé (1974) this terrace was formed during a regressive phase subsequent to a period of a relative standstill of the sealevel (at 85 m.). Over the entire width of the terrace, colonies of Acropora palmata and Diploria sp. have been found; species which prefer a very turbulent, surf swept environment.

The Middle Terrace consists of two parts: Middle Terrace II dipping from about 45 m. to approximately 25 m., and Middle Terrace I between 25 m. and 15 m.. De Buisonjé (1974) has shown that both are depositional terraces. At first, Middle Terrace I developed as a lagoonal area with a Montastrea zone at the seaward side and a Siderastrea zone at the landward side. Subsequently, during a relatively rapid rise of the sealevel, the Middle Terrace II sediments have been formed upon

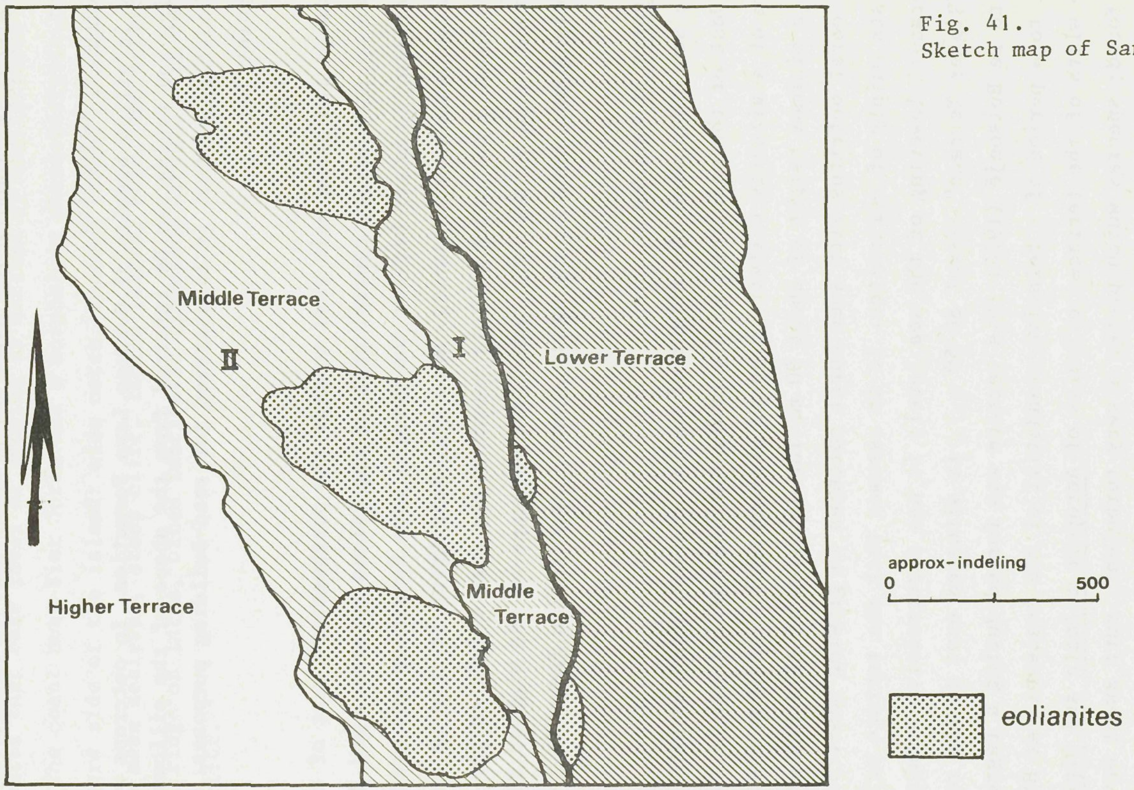


Fig. 41.
Sketch map of San Pedro.

the lagoonal deposits of Middle Terrace I. In Middle Terrace II no zonation has been found. Apparently, no barrier reef and lagoon existed; nor have coral colonies in growing position been found. In general, the deposits are calcirudites.

On top of the Middle Terrace eolianites occur with westward dipping slipface lamination. Not only the bedding, but also the elongated shape of these dunes, point to transport by the easterly trade winds. The dunes must have been formed during the final phase of the evolution of the Lower Terrace.

The Lower Terrace has a width of nearly 800 m.. It possesses all the qualities that have been mentioned on page 66 of this excursionguide, including the shingle ridge near the coastline and the fossil solution notch at the landward side. Locally this notch and part of the cliff between the Lower and the Middle Terrace are covered by fossil calcareous dunesand.

About 1 km NNW of the cross-road to San Pedro, the main road leaves the Higher Terrace level and comes in the large outcrop area of the Curaçao Lava Formation in the core of the northwestern anticlinorium. Where road descends sharply (Ceru Kloof) tilted sandy sediments of Eocene age outcrop below limestone caps of Higher (east of road) and Highest (west of road) Terrace.

The basalt landscape in this part of the island is hilly and strongly dissected, in contrast to that of the southeastern part of Curaçao. The difference in type of morphology in apparently similar rocks is still not understood.

En rout, views on limestone cap of the Tafelberg Sint Hyronimus and the higher hills in the northwest, formed by cherty sediments of the Knip Group.

Two kilometers before reaching excursion point 10 a view on the Cer 'I Cueba, the largest outcrop of Eocene limestones on the island.

Excursion point 10: Ceru Treinchi (former name: Seroe Teintje)

In the Sint Christoffel Formation, the lower unit of the Knip Group of northwestern Curaçao, large boulders and blocks of a shallow water limestone are intercalated in a chaotic succession of boulderbeds, slump breccias, pebbly mudstones, grain flow deposits, turbidites and silica-rich sediments (fig. 42).

In this roadcut the type-locality of these Seroe Teintje limestone lenses is exposed, intercalated between turbidites, grainflow deposits and silica-rich sediments. Slump phenomena are numerous. The strike of the beds varies between N100 and N140, the dip is 50-70^{o} towards the north; position is normal. The base of the limestone lens is not exposed. Near the base large boulders of this limestone occur interbedded between silica-rich sediments. A massive recrystallized limestone forms the bulk of the lens. Fossil-rich, well-bedded calcarenites occur about 40 m above the base. Remains of rudists, corals, stromatoporoids, algae, gastropods other pelecypods and echinids occur. Very common are fragments of Durania curasavica.

In this area the Zevenbergen Formation forms a syncline or synclinorium separated by a steep dipping fault from the outcrop area of Curaçao Lava Formation in the extreme norhtwestern part of the island (fig. 43). This fault expresses itself distinctly in the landscape near Ceru di Rooi Salga (fig. 43), where cherts of the Seroe Gracia Formation (Knip Group are faulted against basalts of the Curaçao Lava Formation.

Excursion point 11: Boca Wandomi
(Quartz-)dioritic plugs intrusive into basalts of the Curaçao Lava Formation

More than 25 small plugs are found in the extreme northwestern part of the island near to the village Westpunt. The intrusions have irregular, but more of less equidimensional cross-sections and vary in diameter from a few meters to about 50 m. The rocks are holocrystalline and orfter porphyritic with plagioclase (oscillatory zoned; 60 -20% An) and amphibole as phenocrysts. Plagioclase is often largely replaced by albite and epidote, the amphibole by chlorite. The country rock, basalts of the Curaçao Lava Formation, has been uralitized along the borders of the intrusions.

Age: K-Ar (whole rock), 72 $\pm$ 7 m.y.

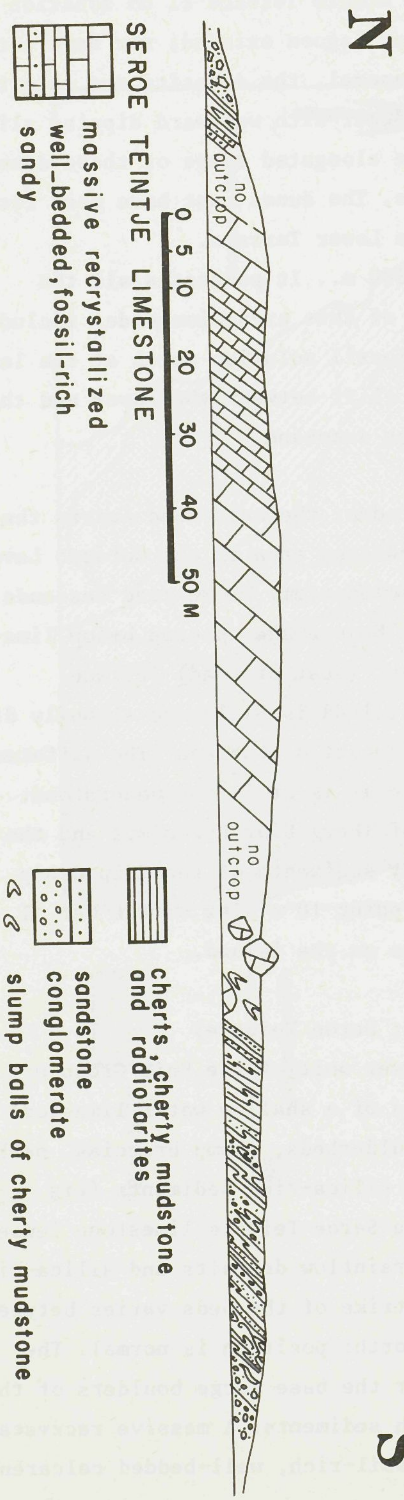


Fig. 42. Sketch of outcrop in road-cut at Ceru Treinchi.

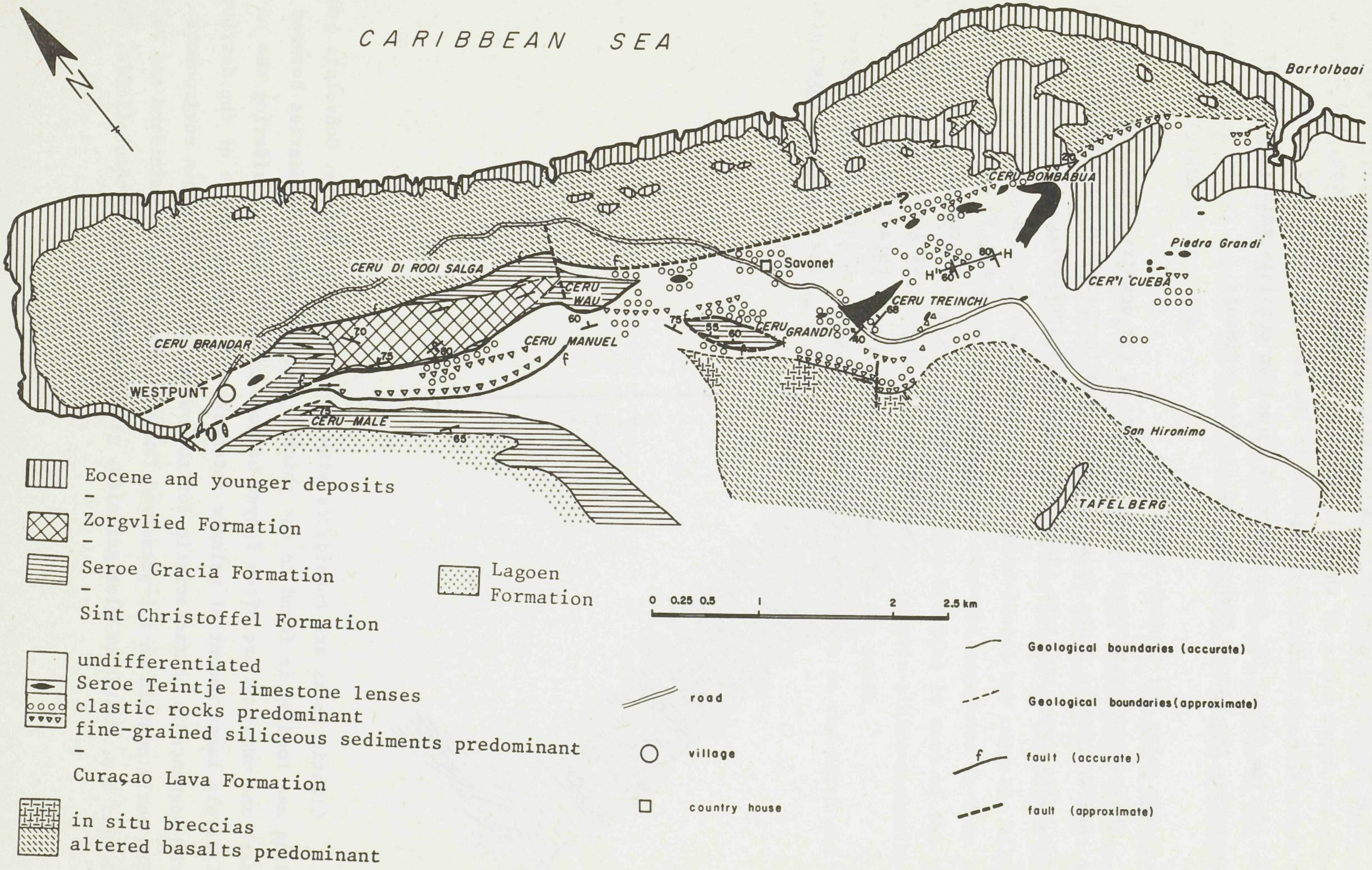


Fig. 43. Simplified geologic map of Westpunt-Savonet area.

From Westpunt southward to the country house Knip. Road passes outcrops of the two upper units of the Knip Group of northwestern Curaçao, the Lagoen and Seroe Kortapê Formations, exposed in the core of a westward plunging synclinorium (fig. 36). Seroe Kortapê Formation consists mainly of cherty limestones, the Lagoen Formation of clastic sediments.

<u>Excursion point 12</u>: Country house Knip

The outcrop is situated about 50 m SW of the country house Knip along the road Westpunt - Santa Cruz. It shows an alternation of thin bedded sandstone, siltstone, mudstone (dark grey) and marl (yellow).

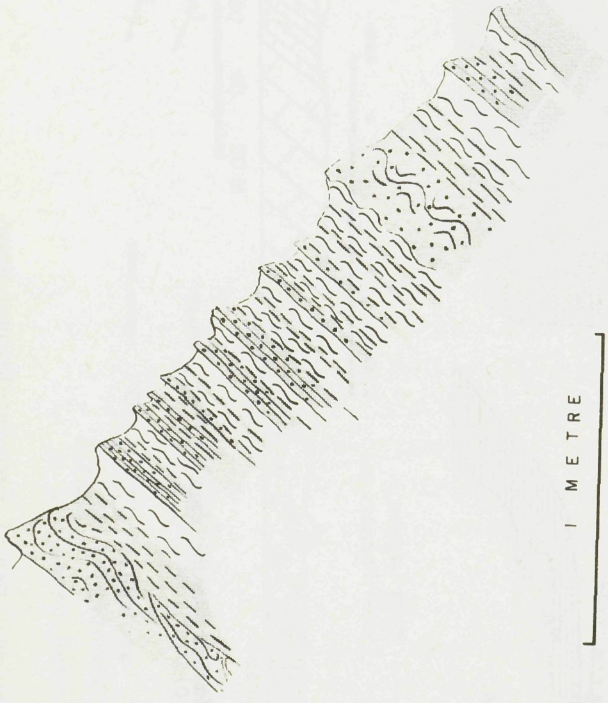


Fig. 44 .
Sketch of the outcrop of rocks of the Lagoen Formation at stop 11. Clastic intervals are grey; pelagic intervals white.

Clastic rocks are turbidites with Td-c intervals, mainly. Convolute bedding and loading is found in the thicker sandstone beds. Boundaries between marl and mudstone are often frayed because of burrowing. Considering the relatively large amount of pelagic intervals and fine grainsize of the detritus, the sequence is characteristic for the outer fan - basin plain environment. The marls contain an ill-preserved fauna of planktonic foraminifera and radiolaria: a.o. moulds of globigerinids, globotruncanids and heterohelicids. The detritus consists mainly of quartz, plagioclase and muscovite and comes from a sialic source.

Back to Westpunt and via Sint Hyronimus, Santa Cruz and Soto to the central part of the island, the outcrop area of the Danian Midden-Curaçao Formation (plate 1, fig. 7).

Excursion stop 13: Salinja's of Sint Willebrordus with outcrops of the outer fan facies of the Midden-Curaçao Formation (central-Curaçao).

A strongly folded succession of turbidites and shales of the Midden-Curaçao Formation is exposed along the borders of the hand-shaped bay near the village Sint Willebrordus. Most of the turbidites show base-cut sequences Tb-d or Tc-d. Good developed pelagic intervals are lacking. The detritus in most of the turbidites is similar to that of the Lagoen Formation (quartz-albite-muscovite association) and derives from a source somewhere to the south.

Good views on the excarpments of the Highest Terrace in the north and the Seroe Domi Formation in the south.

FIELD TRIP TO WASHIKEMBA FORMATION OF BONAIRE (L).

Warning: Roads which are followed are unpaved and bumpy. Near Slagbaai participants have to leave bus in order to take a steep climb.

From airport by bus to northwestern Bonaire along touristic road on leeward side of the island (plate 3). Road is constructed on Quaternary limestones of lower and middle terrace (see excursion A, excursion points 1 and 2),. Concrete road is left at inlet of Goto, and an unpaved road along southcoast is followed (fig. 8). On westbank of Goto-inlet the tanks of Bonaire oil terminal. From Goto to Saliña Tam the road follows Neogene and Quaternary coastward-dipping forereef limestones of the Seroe Domi Formation.

Excursion point 6. Saliña Tam; deepest part of Washikemba Formation.

The Washikemba Formation is a continuous northeastward-dipping sequence of ?Albian-Coniacian age. The excursion is planned in such a way that the entire section will be crossed from base to top. Its oldest part is exposed in this area (actually, the ?Albian ammonites occur slightly higher in the section, Figs 8 and 9). It consists of about 250 m. of andesitic-dacitic flows, ?sills and pyroclastics. Along Saliña Tam outcrops of agglomerates, lapillituffs and a ?sill occur. The agglomerate consists of up to 1 m. large, angular lava fragments.

From Saliña Tam the road continues along the coast for 3 km. more. At first heading west, around the foot of the Wecua, a 160 m. high hill largely made up of intermediate flows, and subsequently heading north along Neogene and Quaternary limestones of Seroe Domi Formation. After turn towards east we come in an area of basalts and diabases. The rocks stratigraphically overlie the intermediate volcanites near Saliña Tam. Towards the southeast they pass laterally into a succession of lapillituffs and intermediate flows near Goto (see excursion A). As discussed in the introduction we think that intermediate volcanites (andesitic and dacitic flows, sills and pyroclastics) built volcanic cones and that basalt eruption is largely confined to the basins between the cones. Near A (fig. 8) ammonites have been collected from pelagic chert intercalations in this sequence.

Excursion point 7: Saliña Slagbaai

Shallow intrusive sheets of basalt (diabase) alternate with sequences of pyroclastics (fig.45). The sheets may attain a thickness of over 50 m. The sediments on top of the sheets are often strongly folded and crumpled, which suggests intrusion slightly below sediment top. The sheets show faint layering. The layers

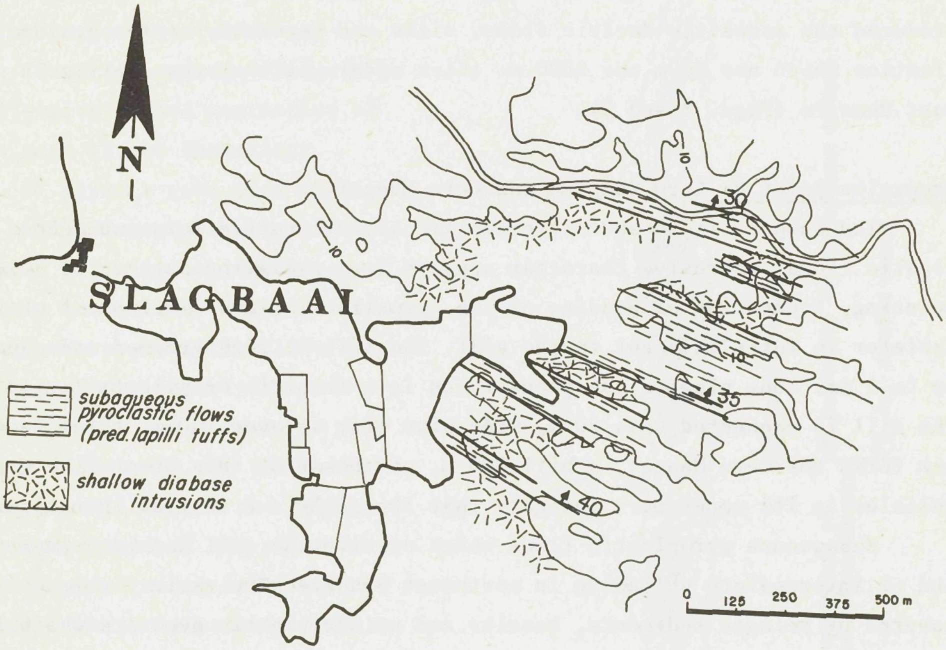


Fig. 45. Simplified map of Saliña Slagbaai.

are 5-25 cm. thick, and have a dark coloured basal part and a lighter top part. The latter often with small carbonate-or zeolite-filled vesicles. Dark colour of basal part is due to a concentration of small, irregular glass lumps in a coarser crystalline intersertal-intergranular intergrowth of plagioclase and clinopyroxene. By want of better explanation we assume at present that layering is due to multiple intrusion.

Pyroclastics in the Washikemba Formation are all subaqueous debris flows or turbidites. Good examples of the subaqueous pyroclastic debris flows can be seen in this outcrop. Monomict character of lava fragments, and high amount of pumice and glass shards suggests eruption from a submarine vent.

Where basalts intrude into fine grained tuffs, the latter are metamorphosed to fleckschiefer.

From Saliña Slagbaai the road curves westwards around the Brandaris, the highest hill of the island. The Brandaris is a large neck of andesitic-dacitic composition, and could represent the central pipe conduit of a volcano which produced the andesitic-dacitic flows, sills and generally coarse grained pyroclastics which now form the 2000 m. thick middle part of the section in northwest Bonaire (Figs. 8 and 9).

Excursion point 8: Ceru Sumpiña and Ceru Mangel

The Sumpiña is an andesitic-dacitic sill intrusive into subaqueous pyroclastic flows. Intrusive character appears from radiating pattern of columnar jointing, truncation of bedding of the pyroclastics, and development of fleckschiefer in tuffs adjacent to the sill. The sill is fine grained and consists of up to 5 mm. long plagioclase phenocrysts in a felsitic or pilotaxitic groundmass. The sill is connected by a 20 m. wide pipe with an over 100 m. thick lava which now forms the Ceru Mangel, a hill 500 m. northeast of this stop. Fine grain and vesicles in its upper part indicate that the sill is a shallow intrusion.

Subaqueous pyroclastic flows which overlie the sill and lava represent the end of intermediate volcanism in northwest Bonaire. The extinct volcano is covered by pelagic sediments, basalts and volcaniclastic deposits which form the highest part of the formation in this area.

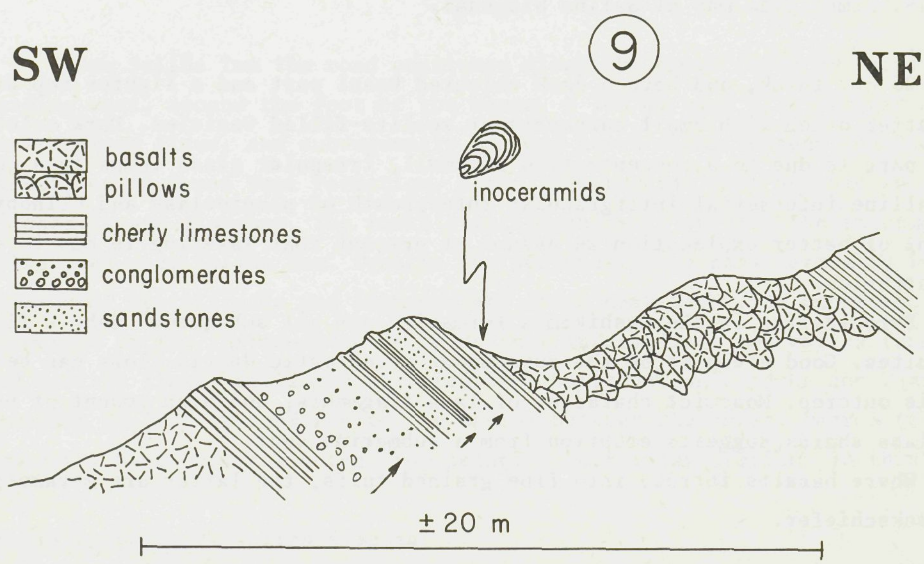


Fig. 46 Detail of fig. 47

<u>Excursion point 9:</u> Saliña Matijs; upper 1000 m. of Washikemba Formation in northwest Bonaire.

Outcrops around Saliña Matijs give a good impression of this part of the formation. Fig. 47 gives a good view over the saliña towards the northwest. Rounded hills in the south are diabase laccoliths intrusive into subaqueous pyroclastic flows of the top of the underlying andesitic-dacitic sequence or in cherty limestones. We think that these laccoliths are the hypabyssal equivalents of the pillowed basalts which occur interbedded between cherty limestones and volcaniclastics. The latter rocks have various outcrops along the saliña. They range in grainsize from boulderbeds to sandstones. Almost all detritus in these rocks is volcanic debris, both basaltic and andesitic-dacitic, although the latter predominate. In addition to these, gabbro and fossiliferous limestone fragments have been found. Most of the debris is strongly impregnated by red cloured iron compounds. In contrast to the pyroclastics pumice fragments are scarce and only occur in the finer grained fraction. Coarse grained boulderbeds and conglomerates are thick bedded, and probably deposited as debris flow. Sandy volcaniclastics are turbidites.

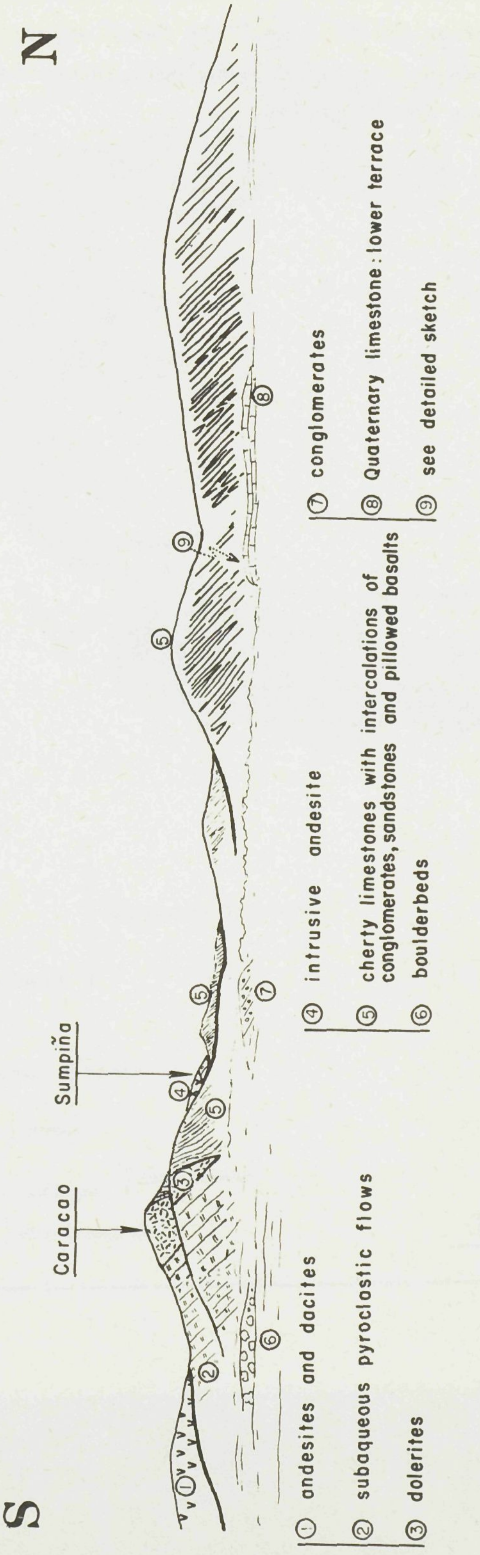
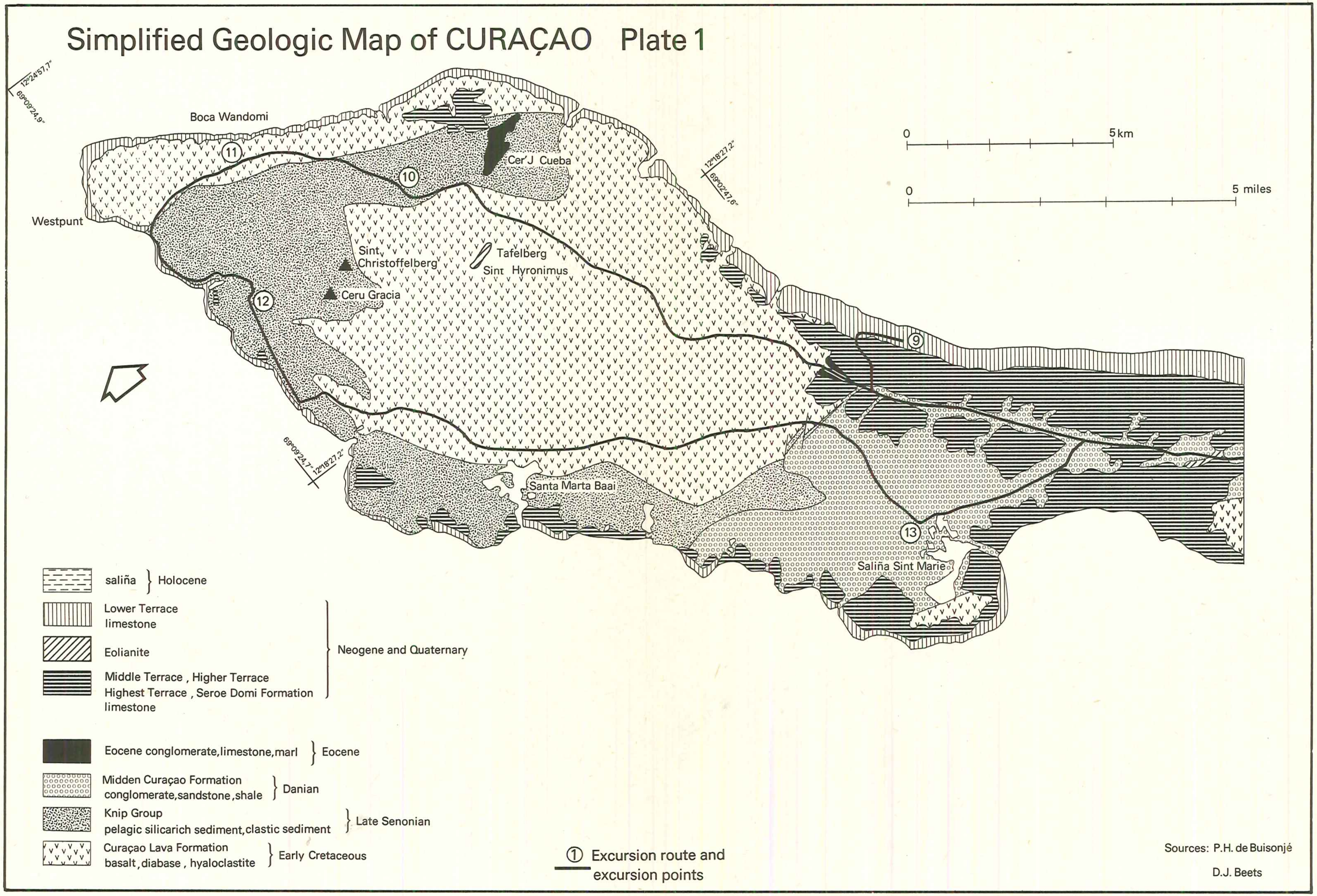


Fig. 47, View over Salina Matijs towards the northeast

The cherty limestones yielded a rich fauna of inoceramids. According to Dr. Kaufman (pers. comm.) the fauna suggests a Turonian-Coniacian age. Figure 46 gives a simplified lithologic succession of one of the inoceramid occurrences along Saliña Matijs.



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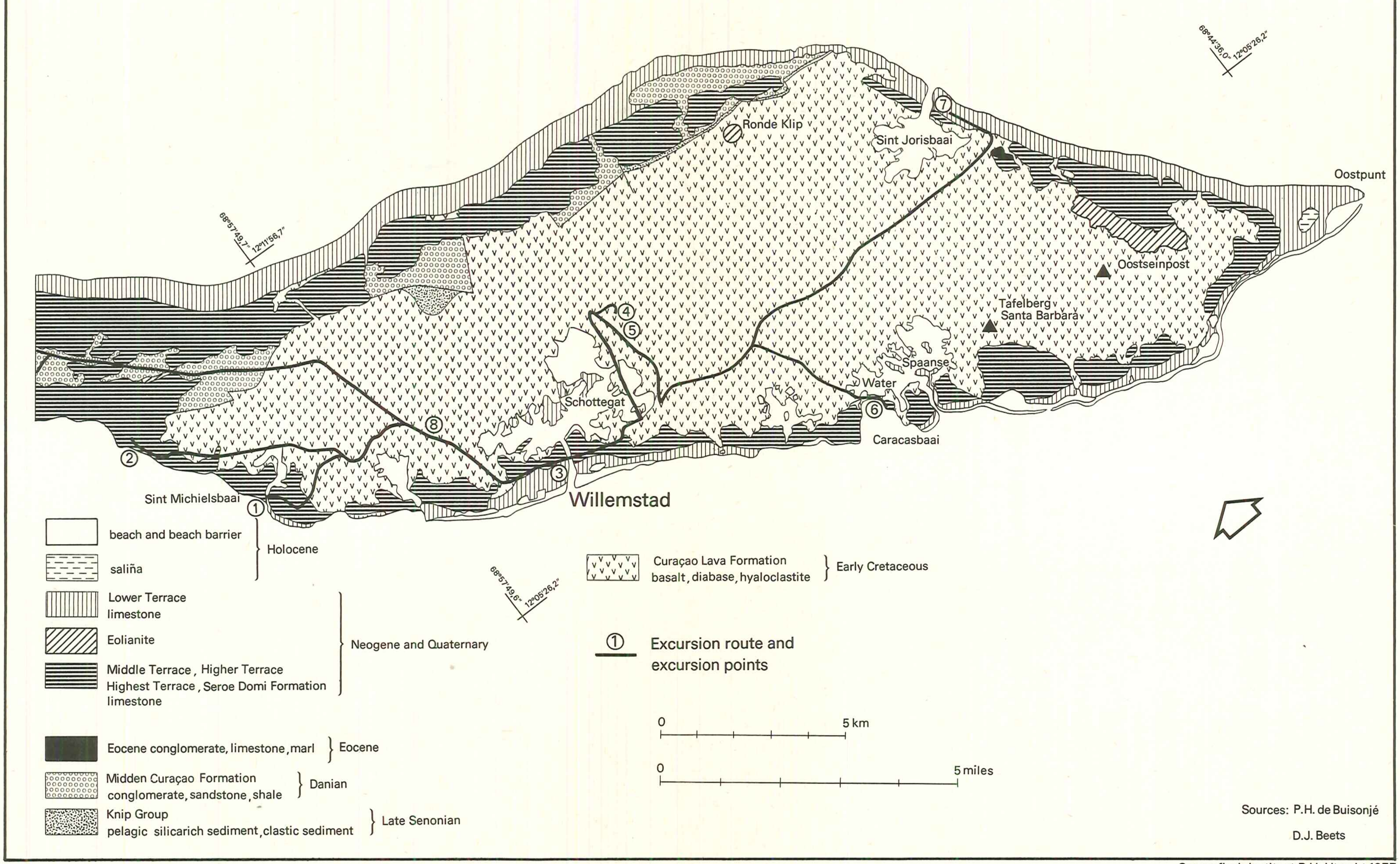
Simplified Geologic Map of CURAÇAO Plate 2



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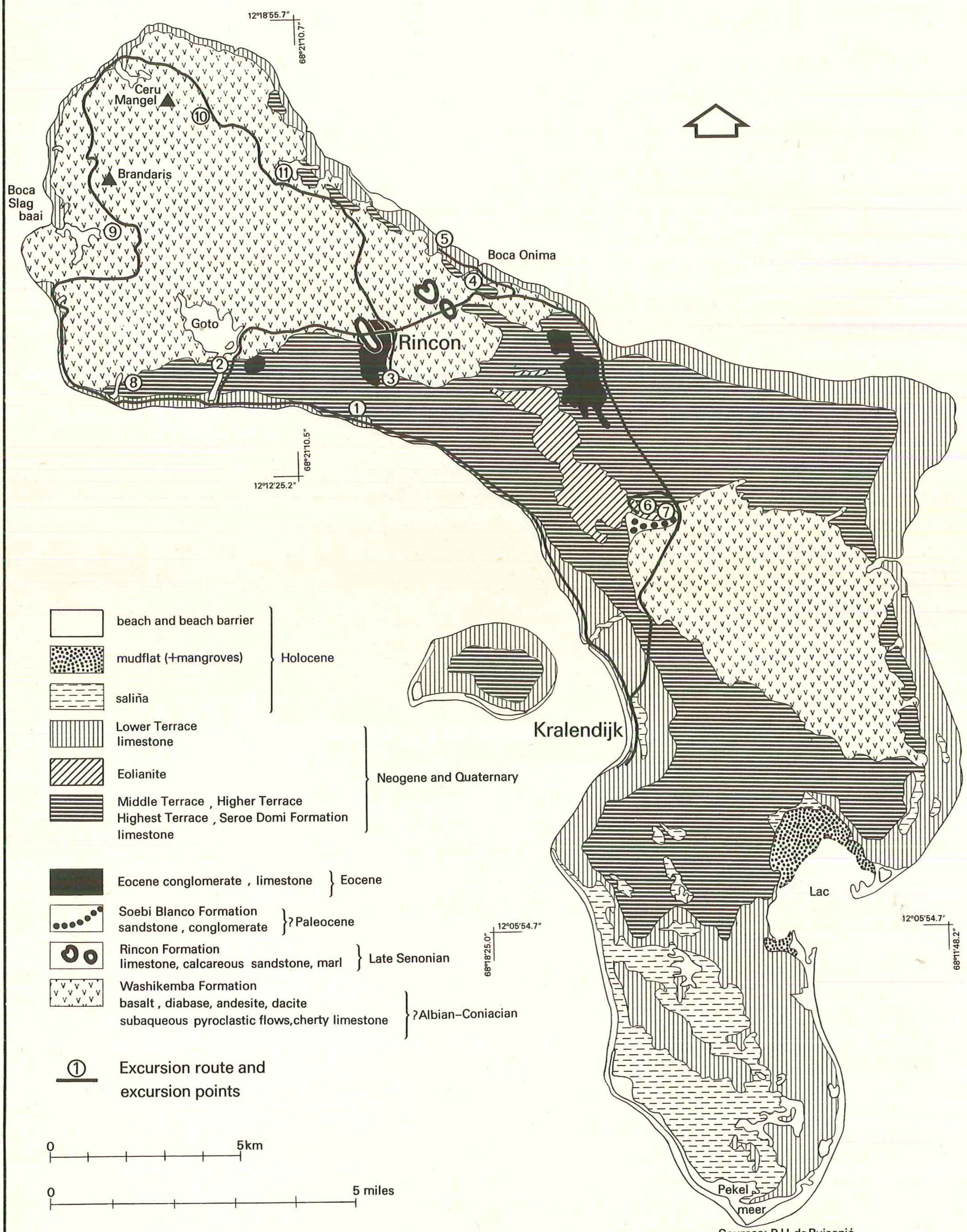
Simplified Geologic Map of BONAIRE Plate 3



Sources: P.H. de Buisonjé

J.I.S. Zonneveld en J.H. Westermann

P.J. Pijpers

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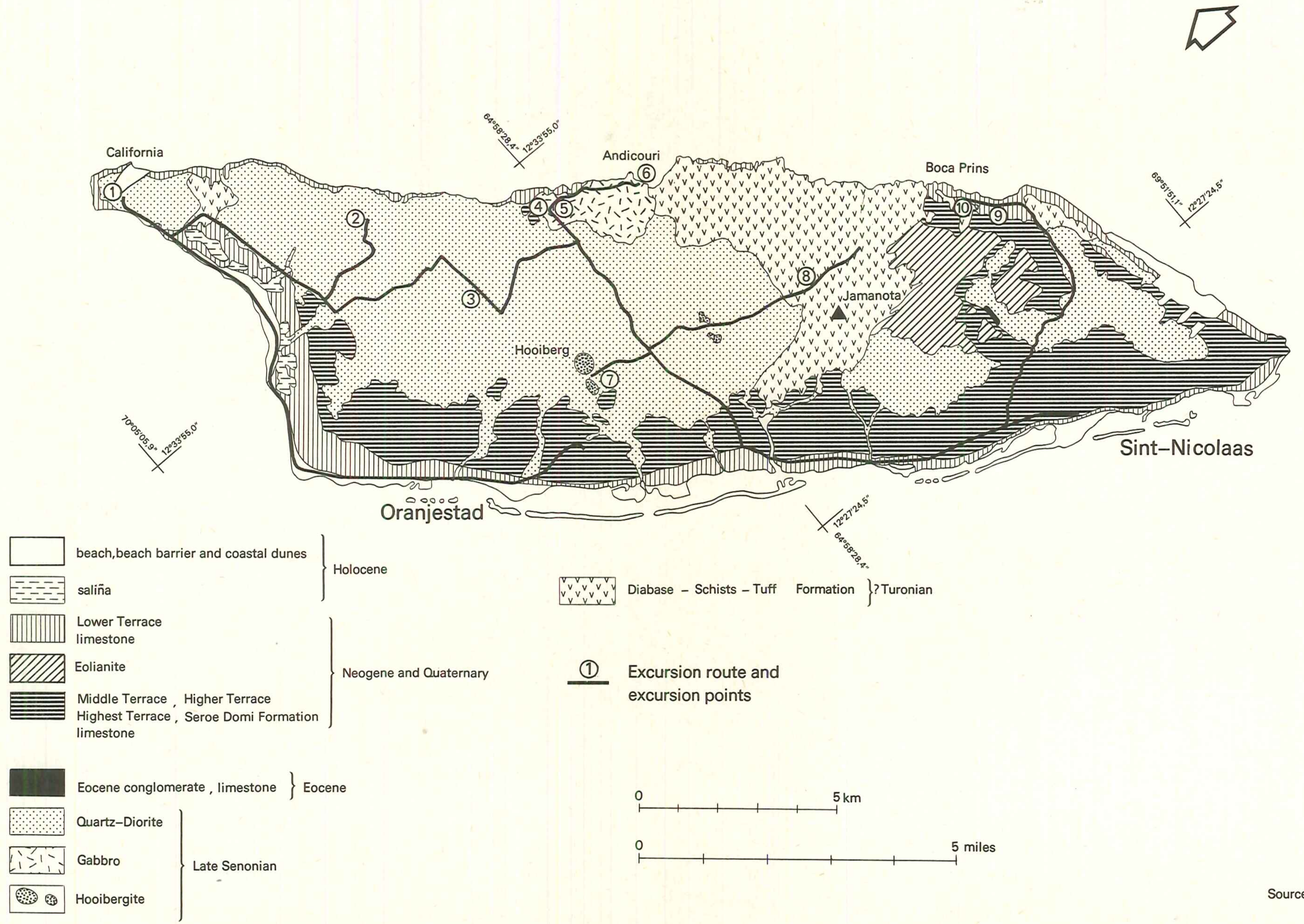
Simplified Geologic Map of ARUBA Plate 4



Sources: P.H. de Buisonjé
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