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The geology of Antigua

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Abstract

Antigua is an island located on the volcanically extinct part of the lesser Antilles volcanic arc. The island contains a transition from volcanic, to volcaniclastic and pyroclastic and to carbonate rocks. Since the mapping of Martin-Kaye (1959) no research focusing on the whole island has been done. This study provides new data trough fieldwork and thin section investigating. We provide a complete stratigraphy of the island, providing a fence diagram showing lateral lithological differences. Next to this provide evidence for both extensional (e.g. normal faults, boudinage) and compressional deformation (reverse faults, folds) , of which we argue that first extension occurred, this was followed by compression, and this was followed by extension. Next to this we date the island from paleontological investigation of foraminifera the oldest carbonate rocks are deposited in P18-20, the youngest in the late Oligocene. We combine the lithological observations with structural measurements and ages to construct cross sections trough the island. These cross sections show that the island has been largely affected by series of tilted fault blocks, with normal faults separating them. We conclude with suggestions for future researches which can be done thanks to the generated data set.

Contents

Introduction

Introduction to Antigua

The eastern part of the Caribbean contains a large volcanic arc which can be linked to the westward subduction. In this region, the North and South American Plate subduct beneath the Caribbean plate. This volcanic arc, called the Lesser Antilles has been active since at least the Miocene, and still is. In the North of this arc, another series of islands is located, called the Limestone Caribbees. These islands are also formed due to volcanic activity, however have not been volcanically active since about 20 Ma (Bouysse and Westercamp, 1990).

The reason behind the divergence between the Limestone Caribbees and current volcanic arc is not completely clear. One of the causes could be a decreasing dip of the subduction slab, however, growing evidence supports an idea of deformation and rotation within the northern Caribbees, which can probably be linked to the strong curvature of the trench. For example on the island of st. Barthelomy evidence for uplift, compression, extension and rotation has been found (Legendre et al. 2018)

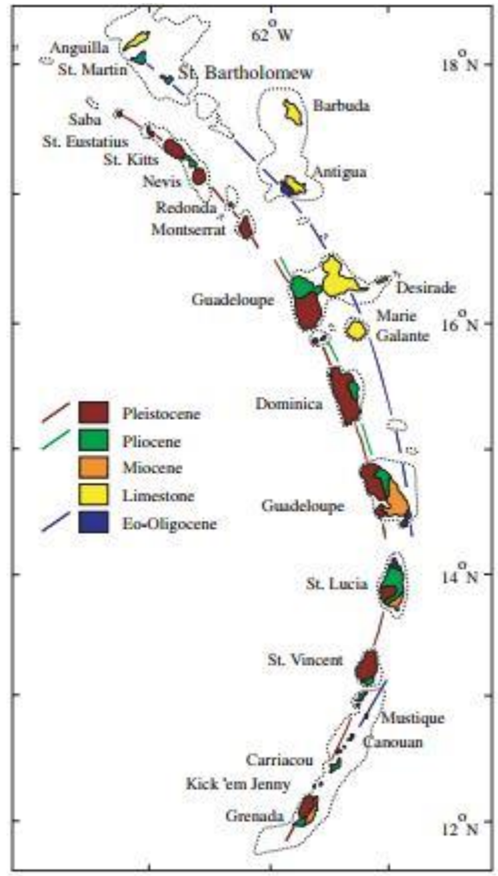

Figure 1 Map of the Lesser Antilles island arc, showing the ages of the exposed rocks and the positions of the volcanic front during the Eocene-Oligocene (ble line), Pliocene (green line), and Pleistocene (red line). The dashed line is the 200-m isobath (adapted from Fig. 9.3 of Wadge 1994).

The area of interest, Antigua, is one of these limestone Caribbees. The island is located south of st. Bartholomy and does contain Cenoczoic volcanic and sedimentairy rocks. The deformation and deposition history, along with the evolution of the volcanism on this island has not been studied recently. The island has a surface of about 281 km2. It's highest point is located in the southwest at Mount Obama (previously Boggy Peak). The south west of the island is a quite elevated area, with multiple of these higher peaks. This part of the island is dominated by igneous rocks, known as the Basal Volcanic Suite (BVS) (Martin-Kaye, 1959). The middle part of the island is characterized by a broad low plain trending SE to NW, which contains intercalated marine limestones and sedimentary rocks referred to as the Central Plain Group (CPG). The northeast of the island is also mostly flat but is elevated up to 70 m with respect to the middle plain. This part is dominated by limestones referred to as the Antigua Formation (AF) (Martin-Kaye, 1959, revised by Weiss, 1994)

The history of the island has been investigated during fieldwork by some geologists, starting in 1819 with Nugent. Nugents was the first person to describe the different lithologies on the island and divided it into 4 lithological formations. This lithological description was subsequently improved and modified by many (as will be discussed in "previous work") until Martin-Kaye published the first detailed geological map of the island in 1959. His lithological observations led to a map which is nowadays still the highest resolution scientifically published map of the island. Only Christmann (1973) proposed a slightly different map of the Basal Volcanic Suite and Weiss (1994) revised the location of formation boundaries. Recently, a map was created as containing an integrated lithology by G. Osborne of the Antigua's Marine Life association (2019, not scientifically published). This map and the map of Martin-Kaye (1959) will both be discussed in this study. The age of the Basal Volcanic Suite has been determined through whole rock K-AR dating at an age of 40 Ma (Nagle et al(1976), Briden et al(1979)). Other estimates concerning the age of the island were largely based on paleontological studies investigating samples containing foraminifera (e.g. Weiss (1994), Jackson (2013)) who dated the Antigua Formation as 25 to 26 MA or 24-27 Ma respectively. Sr isotope dating from Robinson et al (2017) determined the top of the Antigua Formation to be deposited between 26.55 Ma and 27.15 Ma.

The most recent work on geology was conducted by Mascle and Westercamp (1983). They describe the Central Plain Group as being the erosional products of the Basal Volcanic Suite and a gradual change towards the marine limestone depositioned Antigua Formation. Their cross sections and stratigraphic logs suggest some small normal faulting within the Central Plain Group and Antigua Formation.

Goal of the research

The goal of this research is to develop a lithostratigraphy for the island, date this through biostratigraphy, and isolate samples suitable for radiometric dating, and evaluate the structure and tectonic evolution of the island by constructing cross sections. From this, I will interpret a geological history of the island. This is done by conducting fieldwork on the island, sampling of rocks, and thin section investigation. The key questions answered are: How and when did the island form? Which geological events occurred during this formation? I will conclude with suggestions for future research to test our interpretations, and that can be done thanks to our data set.

Geological setting

The Caribbean subduction zone is a subduction zone between the mainland of Venezuela and the Dominican Republic. Along the strike of the subduction zone, the lesser Antilles formed. The subduction zone is relatively short, yet very curved. As a result, towards the north of the subduction zone obliquity of subduction is increasing, until the subduction zone turns into a complex transform fault along the northern margin of the Caribbean plate (Bouysse et al, 1990).

The strong curvature of the subduction arc may be explained through the entrance of the Bahamas bank in the Greater Antilles subduction zone during early Eocene. Since the bank was more buoyant than the surrounding oceanic plate, the subduction stopped. (Uchupi et al*., 1971;* Ladd and Sheridan, 1987; Pindell and Kennan*,* 2001, 2009]. Eastward movement of the Caribbean plate however continued, which is accommodated by the large sinistral strike slip faults in the north of the plate. During this period of seized subduction, the active volcanic arc moved eastward until the location of Antigua. During the middle Eocene to early Miocene, magmatism occurred on some of the islands of the lesser Antilles, among which Antigua. The corresponding basaltic lava's have been determined through K-AR dating on Antigua at 40 Ma [Nagle et al., 1976; Briden et al., 1979), although this dating needs further confirmation with modern techniques as of Antigua's volcanic rocks are very altered.

During the Oligocene, subduction continued in the east of the Caribbean plate which led to an episode of magmatism on the islands of Antigua, st. Martin and St. Barthelemy. In the late Oligocene/ early Miocene volcanism however stopped again. Bouysse and Westercamp [1990] argued that this cessation of volcanism may reflect arrest of subduction due to the entrance of a buoyant magmatic ridge on the subducting crust. McCann and Sykes (1984), on the other hand, suggested a change of subduction angle due to subduction of buoyant pieces of crust, and Westbrook and McCann(1984) suggested that the arc shift resulted from subduction erosion of the forearc. The hiatus of volcanic activity is estimated to be approximately 10 Myr. (Bouysse and Westercamp, 1990). During this interval, volcanic activity moved westwards to its present-day location of Saba, st. Eustatius, st. Kitts, etc.)

Geological architecture of Antigua

Only few researchers have actually conducted fieldwork on the island of Antigua. The first one to investigate the island was Nugent who published his findings in 1821. Since then it has been investigated by (a.o.) Hovey (1839), Purves (1885), Guppy (1911), Brown (1913), Trenchman (1949), Martin Kaye (1959), Christman (1972) and Mascle and Westercamp (1983).

Nugent is the first one to describe lithological formations on the island. He calls the formations with numbers 1 to 4 describing No. 1: trap and trap-breccia, no.2 Stratified conglomerate, no. 3 chert and no.4 marl or calcareous rock (the Antigua Formation). Hovey (1839) copied his formations. He recognized larger fossils within the Antigua Formation (echinoids, corals, molluscs). He also identified lacustrine limestones within the succession. Purves (1885) used the data of Nugent and Hovey and created a larger stratigraphy containing 8 different lithologies. He created a sketch in which he shows multiple faults, of which a large one transverses the island from half a mile south of Corbison Point (our stop 9.4) towards the small bay north of Standvast Point (our stop 1.2, appendix 2). This large fault would have sufficient offset to create a repetition of the lacustrine limestones in map view and to expose his volcanic sands (formation underneath the lacustrine limestone) next to the tuffs which form the formation above the lacustrine limestones. The fault is interpreted by Purves as being formed due to compression.

The first recognition of stratigraphically different limestones was done by Spencer (1901), who identified the "seaforth limestone" (figure 2) as being the oldest dateable location on the island. He suggested that the age of the limestone must be quite equal to the volcanic activity since the limestones is directly overlain by volcaniclastic deposits. These stratigraphical levels were further investigated by Brown (1913, 1914).

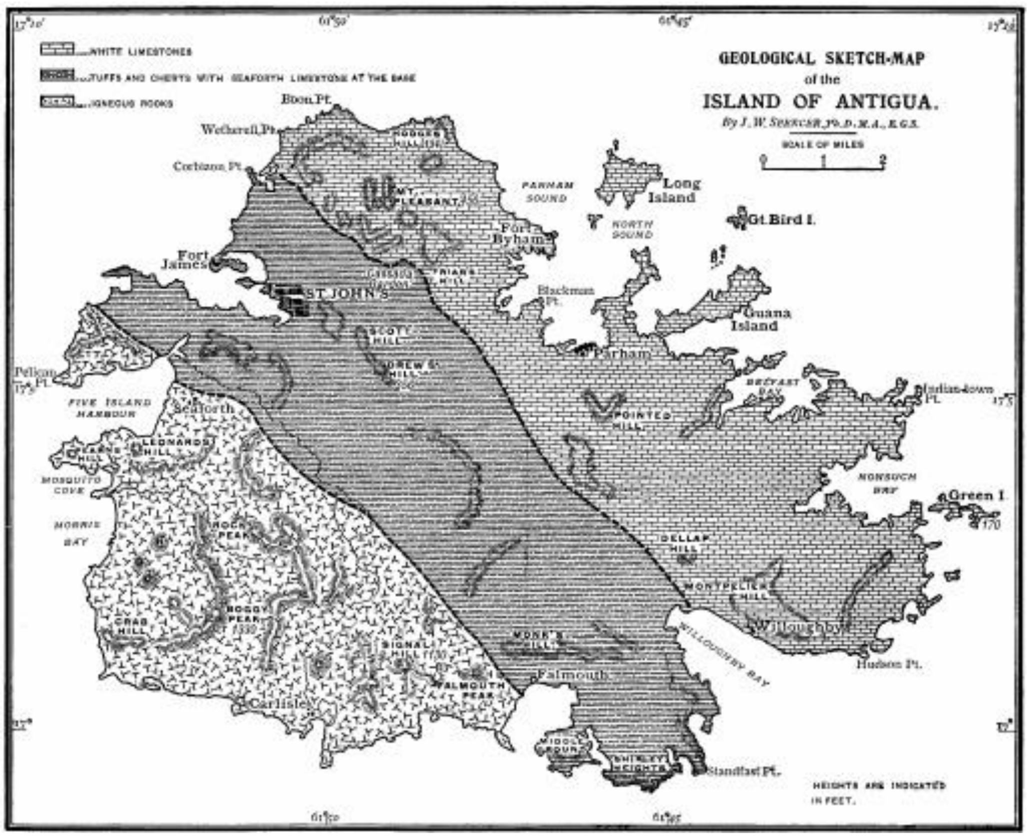

Figure 1:geological map by Spencer (1901) who divided the island into 3 main groups: ***igneous rocks, tuffs with cherts with seaforth limestone at base, white limestones (which he calls the Antigua Formation).***

Brown was the first one to actually use assign ages to the formation using fossils. He determined the age of the Antigua Formation as Oligocene. He also described a later stage of dikes cutting through both he Antigua Formation as the Basal Igneous rocks indicating a second phase of magmatic activity. He determined the age of the Seaforth limestone, an interbedded limestone at the base of the Central Plain, as containing Orbitoïdes. He argued that the whole Antigua Formation exists largely of Orbitoïde fossils. Also an unconformity in the northernmost part of the Antigua Formation is introduced by Spencer and discussed further by Brown. Brown noticed the angular dip, yet did not observe an erosional surface.

Guppy (1911) also reported signs for large-scale faulting. However, his idea was that the large Carribbean dislocation would run through Antigua. This is according to him a large fault cutting the island of Guadeloupe and Antigua in half. He states that the Antigua Formation is an older formation which was uplifted to the same elevation as the volcanics by movement along this fault. He ascribed the movement of this fault to the same event as the disappearance of Atlantis. The Central Plain is according to him a large fault zone filled with the erosional products of the Basal Igneous rocks. His cross section of the island thus contains a footwall syncline in the northern part of the Central Plain.

Brown (1913) stated that there is no sign for the occurrence of a large fault between the Antigua Formation and Central Plain since the fossils found at multiple stratigraphical levels in the cherts do show the same age of Oligocene but do not contain exactly the same species. This means that the Antigua Formation was deposited mostly on top of the Central Plain's rocks, and not as lateral equivalent.

Trenchmann (1949) revised the foraminifera viewed by Brown (1913, 1914) as being Lepidocyclina, He identified the age of the Seaforth limestone as being lower Oligocene. He stated that Drew's Hill, the ridge SE of St. Johns (Figure map) is a large andesitic laccolith, yet this was not confirmed on the map or in lithological descriptions of Martin-Kaye (1959). The information used by Trenchmann (1949) was collected by professor A. Holmes (non-published paper).

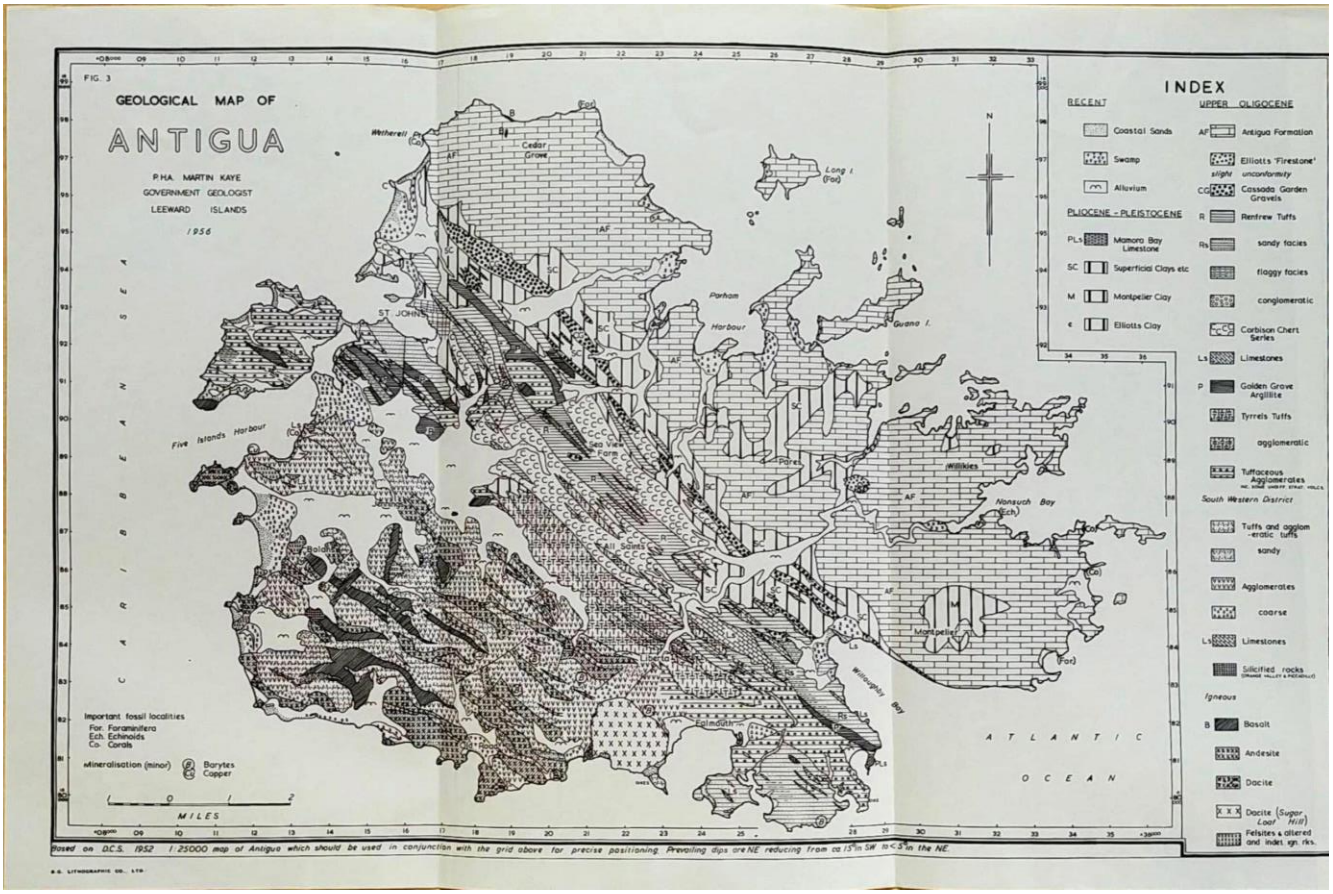

Figure 2the geological map constructed by Martin-Kaye(1959)

The scientifically published data with the highest detail so far was published by Martin-Kaye (1959). Martin-Kaye combined the information of earlier researches and confirmed it with own field data. Martin-Kaye used the same division into 3 "formations" as all papers before, yet with lightly different names (Basal Volcanic Suite (BVS), Central Plain Group (CPG) and Antigua Formation (AF)). The BVS is described it as a complex of basaltic or andesitic lava flows and pyroclastic flows intruded by volcanic pipes, domes, and dykes. The CPG exist mainly of pyroclastic material alternating with erosional products (conglomerates, sandstones) from the volcanic part. The group is described as containing some interbedded lava flows but also some interbedded limestone banks (Martin-Kaye, 1959) He also described the Antigua Formation as a 500 m thick sequence containing shallow to deep water limestones and marls with a lot of fossils, later the fossil assemblage was revised by (a.o.) Weiss (1994) and Donovan et al. (2015)) as containing a lot of corals, brachiopods, crinoids, and many foraminifera. Donovan et al. (2014; 2015) describe the AF as being a retrograde sequence. They do not identify any unconformity within the AF.

Martin-Kaye (1959) placed the boundary between the BVS and the CPG at the stratigraphical level of the youngest breccia, and placing the boundary between the AF and CPG at the base of the first elevated ridges northeast of the Central Plain. We will discuss the usefulness of these boundaries and names of the formations later in this paper. He recognized island-wide repetitions of stratigraphy in map view within the CPG. These repetitions he describes as the result of "strike faulting with downthrow" by which he means thrust faulting.

Christman (1972) revised the BVS of the island. He did however not modify the map much, but added data from bedding measurements in tuffs. We combined the lithologies and measurements of Martin-kaye (1959) and Christman (1972) to construct our cross section and stratigraphy through the volcanics, as will be explained in the results and discussion

Mascle and Westercamp (1984) estimated the thickness of the 3 groups, and ages of the foraminifera within the sequence. They state that the total thickness of the CPG is 500m. the thickness of the BVS is 2000 m and the AF is 500 m. The contact between the BVS and CPG is described as conformable, and the contact between the CPG and AF is described as gradually (Mascle and Westercamp, 1984). Mascle and Westercamp briefly address how they think Antigua was formed. They present the BVS as formed by lava flows and tuffs deposited on the flank of the volcanoe, which explains their similar dip. In a sketch of a cross section they try to explain one of the repetitions in map view through normal faulting which creates an omission. They also indicate small faults within their stratigraphical logs of the AF and parts of the CPG.

Several papers have tried to put age constraints on the different parts of the island, of which the age of the volcanics have been judged unreliable due to post-magmatism alteration (Jackson, 2013). The ages of the AF have been determined before by Weiss (1994), Jackson, 2013 and Robinson et al. (2017) based on formanifera. Robinson determined the age of the top AF in the west as being deposited in between 27.15 Ma and 26.55 Ma based on whole rock Sr isotope ratio's but admits that this data is unlikely and is probably altered due to marine fluids running through.

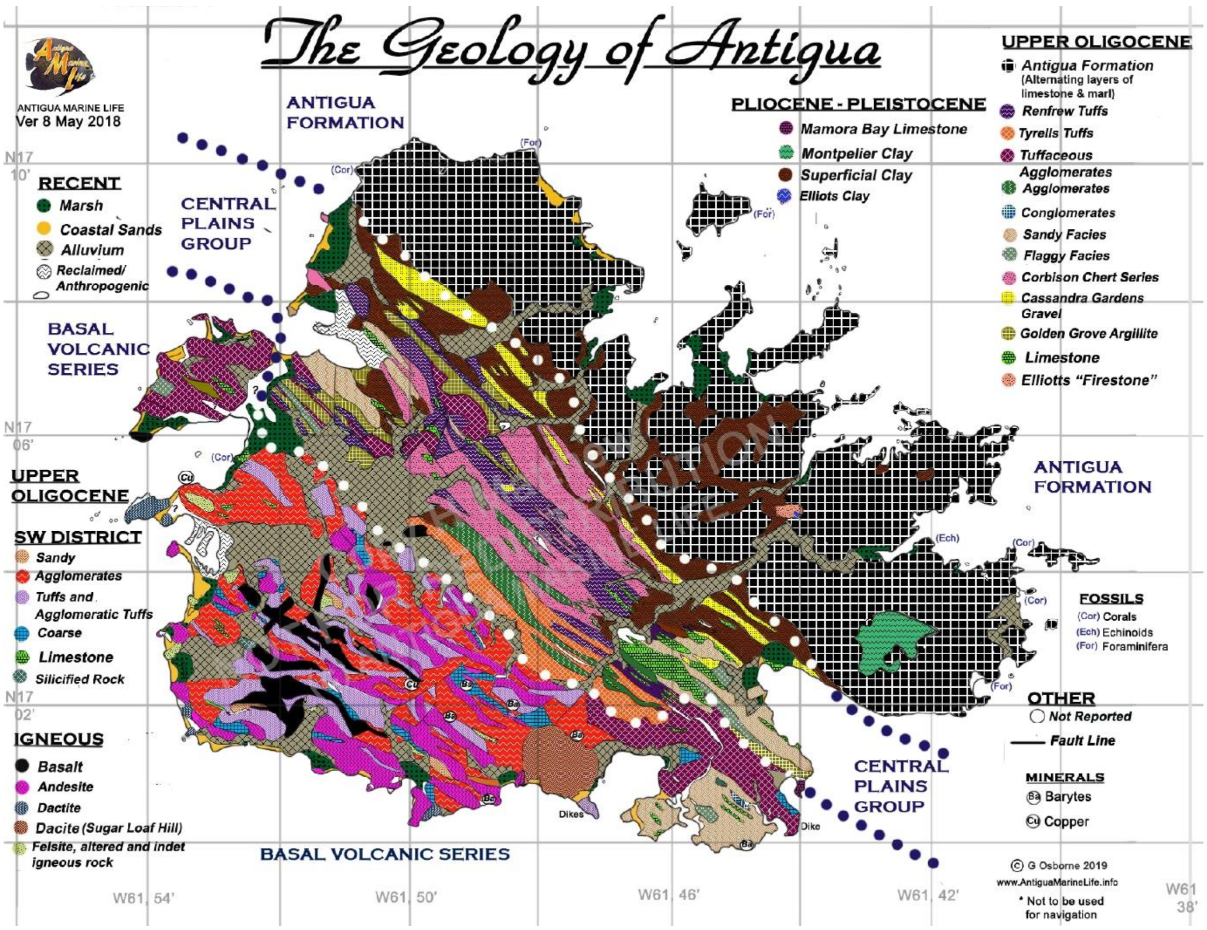

Figure 3the lithological map constructed by G. Osborne, 2019

G. Osborne (2019, not scientifically published) of the "Antigua's Marine Life Association" created an integrated lithological map of Antigua based on Martin Kaye (1959), Nagle (1976), Wadge (1986), Donovan (2014) and Dingwall (2015) amongst others. This is the most recent map created of the island. For the construction of the map, no fieldwork was done, however the map contains slightly more details than the map of Martin-Kaye (1959). We used this map as a base map for the processing of our data as will be discussed in "methods". Later in this paper I will also elaborate on the accuracy of the map.

Methods

Mapping

Prior to the fieldwork we prepared a first-order geological map based on satellite photo analysis. We used Google Earth and its tools for investigating the topography of the island. By increasing the vertical exaggeration of Google Earth, we approximated the dip of beds exposed in hill flanks. This, in combination with investigating the contour lines showed that several ridges in the middle and northeast of the island are along the same orientation striking 140/150 degrees. Also from this investigation followed that the NE side of these ridges was mostly shallowly dipping (10 to 20 degrees) while the SE flank of the ridges could be quite steep. Further subdivision of the map was done based on the color and structure of exposures visible through Google Earth or through Google Street View.

Another way of investigating in advance was through the geomorphology of the island. Overall orientation of rivers may indicate structural trends and the shape the coastline may also be geologically meaningful. On Antigua a large difference in coastal morphology was observed between the southwest, where the coasts are straight, and the north where the coastline may reveal a drowned topography. We hypothesized that this may either indicate way softer rock material in the north, that the island tilted, or that the southern coast was influenced by geological structures.

Through Google Earth investigation, in combination with the known literature, we construct an "expectations map". This map contains the main 3 lithological groups: the BVS, CPG and AF. Next to these main groups we identified the orientated ridges because of their divergence from the rest of the "flat" middle and northeast of the island. Also identified were regions described for further field evaluation which appeared geologically different from all the other regions. The expectations map was expanded by adding information from investigation of the morphology. This led to the identification of several structural trends which were already observed and formed a primary target for fieldwork.

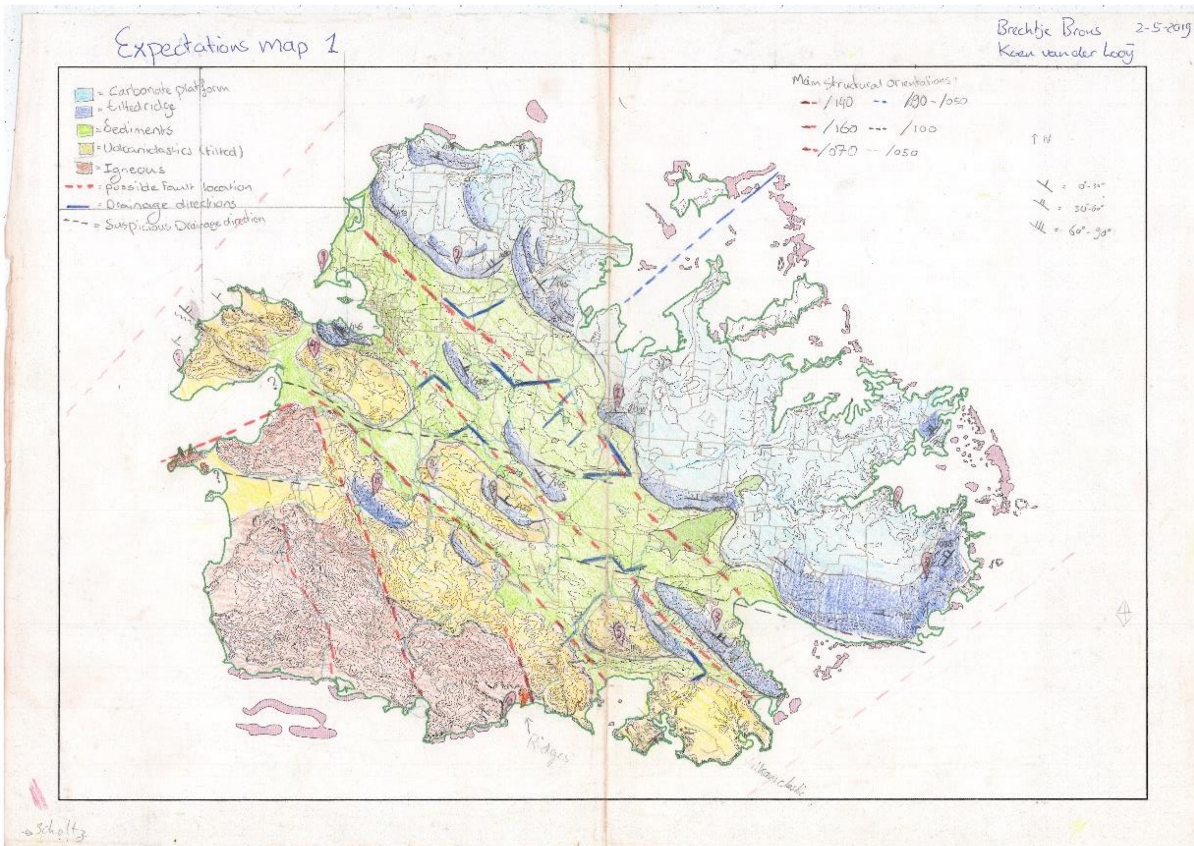

Figure 4 the “Expectations Map” created in advance of the fieldwork

In field methods

Lithology

Volcanic rocks were described on their mineralogy and colour. The rocks were determined from their mineralogic content according to a standard classification scheme of igneous rocks (Jerram and Petford, 2011 , p. 59). If the minerals are not visible, the determination is partly done on the colour of the rock or the hardness of the rocks. Through the classification scheme we were able to identify multiple mappable formations: intrusive rock, lava flows, hyaloclasticites, and basaltic, andesitic, or dacitic composition (or their coarser intrusive equivalents if present). The classification of the volcaniclastic rocks was based on grain size, angularity of the grains, and grain size of the matrix.

Interpretation of the depositional environment of the lithology led to the subdivision in breccias, tuffaceous sandstones (volcaniclastic sandstone with a tuffaceous matrix), tuffs, and fluviatile sandstones (sandstones, conglomerates or clays with a clay matrix). The classification of marine carbonate rocks was done in the field according to the Dunham classification scheme (Dunham, 1962), as modified by Embry and Ashton (1971). The final interpretative subdivision was made after thin section investigation after BouDaugher-Fadel (2018): mappable rock formations are: reef (high or low energetic) deposits, forereef deposits, slope deposits.

Apart from the main three groups (BVS, CPG and AF), two formations were mapped which have characteristics that do not exactly fit into one group. The "welded brecchia formation" and "lacustrine limestones formation". These were mapped individually. The welded brecchia formation contains polymict brecchia's of which the mesostase contains feldspar minerals large enough to see with a handlense.

Stratigraphy

The island does not contain sections along which the whole stratigraphy can be seen. The stratigraphy thus can be constructed together with the cross sections. For this, bedding orientation together with lithological observations is used to estimate the thickness of different formations. Structural data combined with lithological observations is used to construct a stratigraphy. For this construction, it was important to look for indicators of both relative age as absolute age formations. We described super/subposition, cross cutting relationships, erosional surfaces, unconformities and intrusive relationships. Absolute age is determined from paleontological investigation of gathered samples. Cross sections were constructed by combining literature data and field data with ages from lab data.

Deformation

Another important part of the research is to look for deformation indicators. We measured fracture planes, fault planes, dike orientations, and shear zones. On fault planes we measured striations to indicate the direction of movement We indicated where zones of more intense deformation were located (e.g. multiple parallel faults indicating the same direction of movement. Next to this we looked for signs of compressive or extensional deformation. These include conchoidal fracturing and folding. We measured fold limbs and fold planes where possible to identify the direction of compressive movement. An important potential deformation indicator were stylolites. Where present, we measured the stylolite planes, the dip direction of the peaks and the height of the peaks.

Sampling

Important was to find the absolute age of the rocks. For this we gathered samples around the island. Absolute age dating can be done through micropaleontology, e.g. using benthic and planktonic foraminifera. To obtain a good spreading of the locations with absolute age determination, we sampled along the line of the cross section, in different levels of the stratigraphy. For the basal volcanic formation it was also important to collect samples since these could lead to a better understanding of relative sequence of lava flows and intrusions and to a better determination of rocks.

Laboratory methods

After the fieldwork we conducted one week of laboratory work. During this week we made thin sections of the samples from the basal volcanic formation. We described all the different minerals and its characteristics (e.g. phenocryst size, cleavage planes, twinning, birefringence etc.) from thin sections. We looked for possible indicators of microdeformation and described, where possible, the relation between matrix and phenocrysts.

For the carbonate rock dating we used the samples from an earlier field excursion by collaborator Jean-Jacques Cornée. During this field excursion, samples were collected in the vicinity of our sample location. Since these were already processed into thin sections, it was decided to use these instead. From the thin sections we described the different samples following the Folk classification of carbonate rocks (Folk, 1959). This provided a first indication whether the sediments were been deposited in a high or low energetic environment, after which they became a rock upon compaction and cementation. After this, the different foraminifera in the rock were determined and photographed with assistance of J.J. Cornée. These photographs were sent to Marcella Boudaugher-Fadel (University College London, UK) for determination of the absolute age. After determination of the foraminifera, we classified the samples into paleoenvironments according to the classification from Boudaugher-Fadel (2018).

Data processing

The field data was plotted with the coordinates on a map trough Qgis. We plotted different shapefiles for the different formations, boundaries between formations, bedding, all different faults, fractures, folds, and stylolites. This was all projected on a map of contour lines extracted from a 30 strm DEM. At the background we projected the lithological map from Osborn, (2019). After this we plotted the four lines along which cross sections were constructed.

Cross sections were constructed by plotting the apparent dip of our bedding measurements on the cross section plane. The lithologies in the cross section were mainly taken from our own data but completed, where necessary, with the data from Martin-Kaye (1959). Faults within the stratigraphy were only plotted when the evidence from both the structural data as the stratigraphy supports the abundancy of it.

Finally we plotted all the different measured planes: bedding, fault, fracture, stylolite, fold axial plane in stereonets. These provide information on the different stress fields acting on the island and thus accompanying deformation phases. This is combined with the interpreted cross sections as basis for our interpretation of the geological history of the island. This evidence-based interpretation is described in the results section and evaluated in the following discussion section.

Results

Field data

Three main groups were described by us, each composed of multiple formation. Our evaluation revealed that the subdivision of Martin-Kaye (1959) is accurate and useful and we thus follow the same organization: the Basal Volcanic Group (BVG), Central Plain Group (CPG) and Antigua Group (AG). We changed the name for the Basal Volcanic Suite and Antigua Formation towards Basal Volcanic Group and Antigua Group respectively because this is the generally accepted terminology within stratigraphy for lithological units containing multiple formations without large genetical match. (as will be shown in "stratigraphy of Antigua"). Our evaluation also revealed that the lithological map from Osborn (2019) is largely accurate and thus can be used in the construction of the stratigraphy and cross sections. Our lithological mapping was done with different formations, which will be further described in the stratigraphy. The map we developed can be seen in appendix 2, the visited stops can also be seen on this map. The legend of the map is in appendix 1. For the construction of the stratigraphy and cross sections, we used our field data, and combined this with thin section data and structural data which are presented in the next section. As the "Results" and "discussion" section will contain many references to visited locations on Antigua (indicated as "stop…") it is recommended to keep the constructed map (appendix 2) close during reading.

Structural data

Main Faults

In the field we found some locations with many fault planes parallel to each other, these locations we first identified as schistosity planes. Thin section investigation of these regions however showed that the planes did not contain signs for ductile deformations, thus they should be named fault zones. These regions are however indicative for larger offset. We identified the direction of movement by measuring striations on fault planes, and in which direction along the striation movement occurred.

At the location of stop 1.4 (appendix 2) we found a faulted zone (up to 30 m thick). Striation on the fault planes indicated a normal fault direction, and we found displacements of up to 25 cm per fault. At this location, conjugate faults were also found, with steep dipping planes in both directions, indicating a vertical sigma 1 and horizontal sigma 3. The orientation of this fault zone is along the strike of about 130/140 degrees. At the location of stop 4.6 we found a quite similar faulted zone of 20m thick. This also contained conjugate faults indicating a vertical sigma 1 and horizontal sigma 3. The displacement could not be measured there, and the strike of this fault zone was about 80-90 degrees.

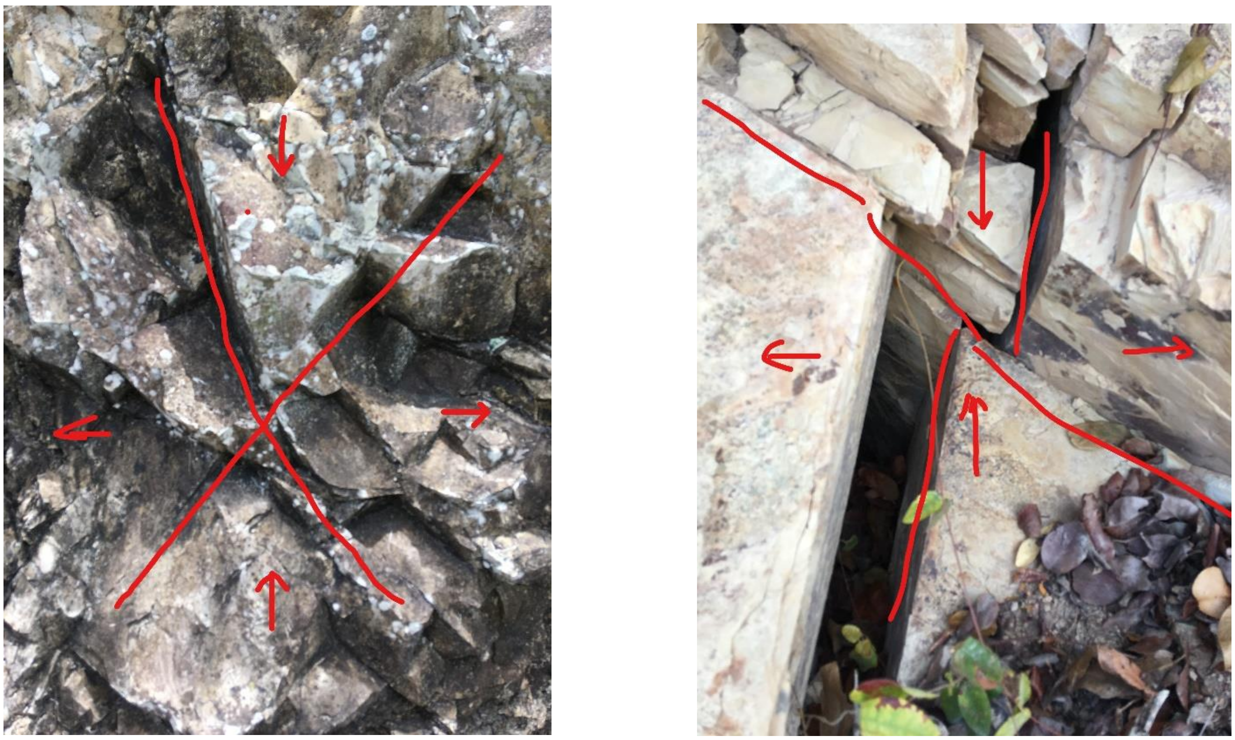

Figure 5: conjugate faults found at the location of stop 1.4 (appendix 2), arrows indicate the vertical sigma 1 and horizontal sigma 3. The left foto shows a part of a rock of about 50 cm. the right foto shows a part of a rock of about 1,5 m. the displacement along the fault in the right foto was about 25 cm.

Around English Harbour we found a few larger faults. At the location of stop 1.5 (appendix 2) we found a totally brecchiated and faulted zone of which we could not see the full thickness, but at least 20 m. the striations on fault planes indicated normal faulting here with a strike of 140 (striation’s dip direction of 10 degrees.) At a different location around English harbour we found multiple faults along a parallel strike of about 120-130 degrees forming a fanning pattern (stop 2.3, appendix 2).

Figure 6: "positive flowerstructure"at the location of stop 2.3 (appendix 2) the height of the outcrop is about 3 m. The photo is taken towards the West

Striations on the faultplane indicated that the direction of movement was partly sinistral, and compressive. We interpreted this as a positive flowerstructure formed due to transpression. The 2 observed faults can not have formed due to a single stress field, as will be discussed in “deformation phases”

At the locations of stop 12.5 and 15.5 we found a lot of faults of which the striation on the plane indicates normal/ sinistral faulting along planes with a strike of about 180 degrees which is about the same strike as the large dike which is located slightly to the south.

The location of stop 4.2 showed 2 different kinds of structures. We observed many parallel fault planes within a zone of 10 m (strike 120). Striations on the fault planes indicated normal faulting. within these fault planes, we found one boudinaged bed. The parallel fracture planes and boudinaged bed have been folded afterwards. Crosscutting through these folds we found a fault zone with fault gauch of 0,5 m of which striae indicated a normal shear sense (strike 150). This combination of fractures containing boudinaged structures, folds and faults could only have formed with at least 3 different stress fields, as will be discussed in “deformation phases”

Figure 7: outcrop at the location of stop 4.2. White lines indicate the parallel fault planes. The red area indicates the crosscutting fault. the folding can be seen left of where i am standing. within this fold, boudinaged structures were visible. Photo is taken towards the NW.

The location of stop 15.1 contained 2 different faulting patterns as well, with a fault zone containing fault gauch of about 0,5 m which has been folded, crosscut by a zone of parallel faults along a strike of 110 of two m thick. This combination of fault zones which have been folded and crosscut by faults can also only have formed with at least 3 different stress fields as will be discussed in “deformation phases

At only one location the total vertical displacement of a fault could be seen (stop 6.12- 6.15). this displacement indicated normal faulting with a sinistral component. The vertical displacement was about 30 m, the strike slip component could not be measured.

Figure 8: :image showing the faulted layer which has been folded at the location of stop 15.1(appendix 2) the white lines are drawn along folded beds (underneath the lower white line, the fault containing fault gauch is located.). the red lines are parallel faults cutting trough. The photo is taken towards the West, the outcrop is 4 m high.

Small faults

Next to these large faults/fault zones, we found a lot of individual fractures, or conjugate fractures. If striations on the fracture plane were present, the fractures were either indicated as normal, reverse, sinistral or dextral faults. When the direction of movement along the striation was not clear, they were indicated as “unidentified faults”. All the data from these smaller faults was combined and plotted in stereonets depending on their fault kinematics.

From this a main structural direction can be seen within the Normal faults (figure 1, top left) with an average strike of 130-140 dipping in both northern as southern direction which we interpreted as conjugate faults. These faults could have formed at the same time due to the same stress field. Within the reverse faults (figure 1, top right), the main structural direction is less evident, but one can see a combination of faults with an average strike of 100 dipping both in southern as northern direction which is interpreted as conjugate faults. Again, this could have formed within the same stress field, however not the same stress field as which formed the normal faults. The main structural direction within the sinistral faults (figure 1, bottom left) is even more divided, the average strike of most of these faults would be 160-170, again 2 pairs of conjugate faults are interpreted. The dextral faults (figure 1, bottom right) show an average structural direction comparable with the sinistral faults, about 160-170)

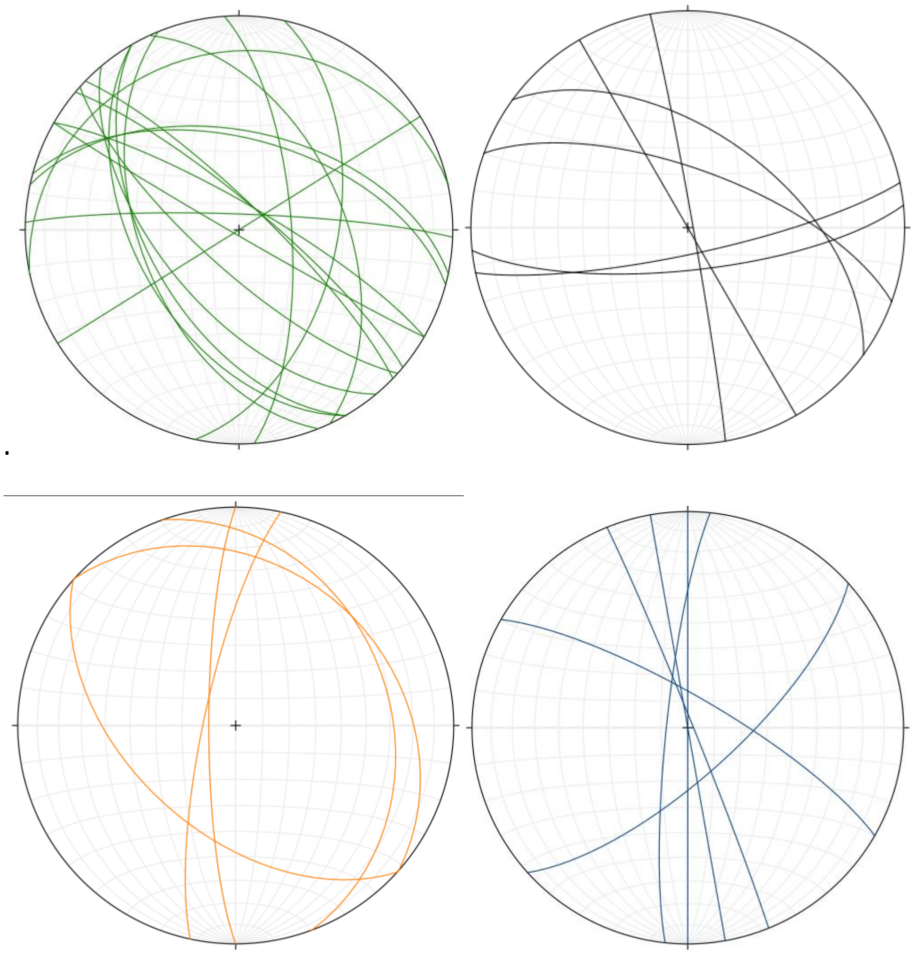

Figure 9: stereonet plots from our fault data. ***top-left: "****Normal faults".* ***Top right:*** *"reverse faults"*

Bottom left: *"sinistral faults".* ***Bottom right:*** *"dextral faults"*

Unidentified faults and joints

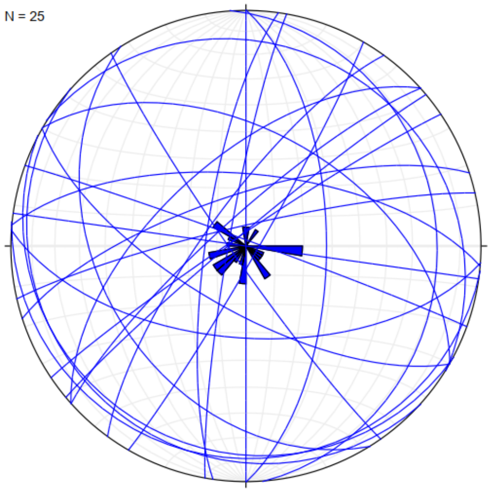

Figure 10: stereonet of all faults of which the movement direction was unclear. No preferred orientation visible.

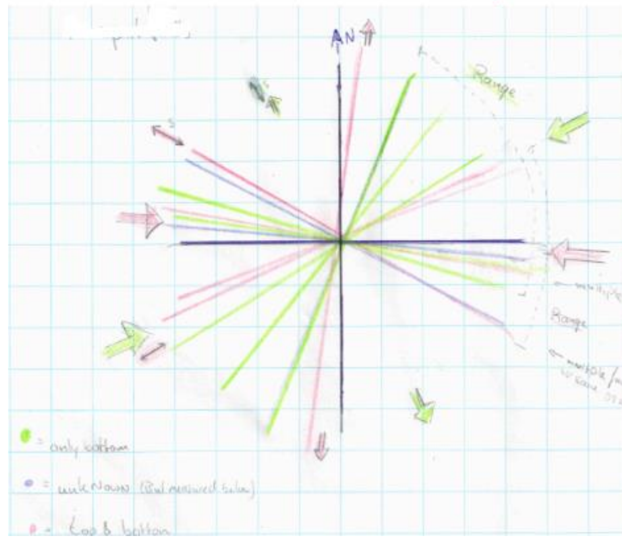

Figure 11: fractures measured in the burma quarry. Only the strike is plotted, not the dip (which was always near vertical). ***green;*** *"fractures only visible in the lower half of the quarry.* ***blue:*** *fractures which did occur in the lower half, but not sure if they do exist in the top half.* ***pink:*** *fractures existing in both the top as bottom half. Green and purple arrows pointing inwards are indicating the average strike of the colour. Arrows pointing outwards are perpendicular to the average strike of their colour*

We found many faults without a clear indicator of movement (e.g. striae were visible, but not visible what the direction of movement had been). When plotted within stereonets, the faults do not show any dominant directions. We also found a lot of joints with many different orientations which can have formed in all kinds of ways. (e.g. stresses on rock, cooling joints). When these joints are plotted within one stereonet, no dominant directions are seen. However, when the different joints are plotted for the Burma quarry (figure 3) (stop 14.3 – 14.5, appendix 2), we can see different joint patterns within the section. Figure 10 shows the contact at which half of the joints did not continue. Joints which are only present within the lower half of the quarry show a preferred orientation between 30 and 110. Joints which are both visible in the top half as the bottom half of the quarry, and thus formed in a later stage, show a preferred orientation between 60 and 130 degrees. As the joints are all near vertical, interpreted is that the different joint patterns have formed due to 2 different stress fields acting on the quarry at different times. These stress fields are the most likely to have a horizontal sigma 1 and sigma 3 and are either compressive or extensional. This interpretation should however be considered with caution as joints are able to form in many ways.

Figure 10: contact within the Burma Quarry at which many joints did not continue nor reappeared in the sequence above this contact. vertical white lines indicate the joints. horizontal white line indicates the contact. Height of the visible section is 8 m.

Folds

At four locations we were able to measure folded layers. These folds were all small-scale folds with wavelengths up to one meter and amplitudes of also max one meter. at the location of stops 4.2, 15.1 and 15.4 we found folds which we interpreted as being formed by compression. At the location of stop 9.1 we found a sheet fold, which showed a relative movement of the top of the beds towards the north. The axial planes of the folds

Figure 11: folded layer at the location of stop 15.1, compass for scale. the photo is taken towards the east.

were all aligned along a strike between 160 and 90. (see plot)

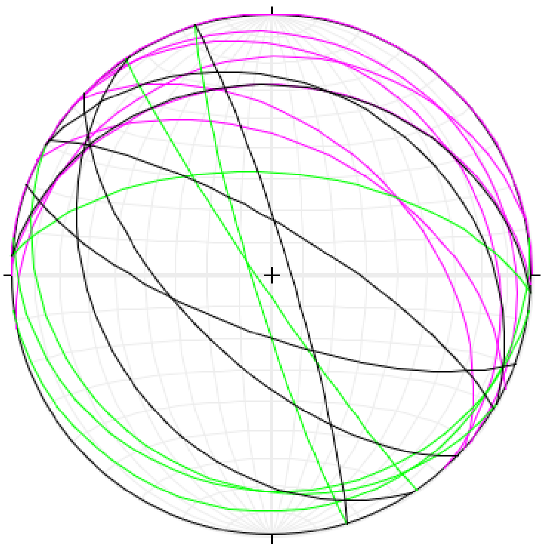

*Figure 14:**folds. Northern limbs:** purple of colour, all along a strike of 90-145. **Southern limbs:** green of colour, strike between 260 and 345. **Axial planes:** black of colour: strike between 90 and 165. Average strike about 130*

Stylolites

Stylolites are abundant in carbonate rocks in the north/northwest. We measured the stylolite peak direction, which was in all cases near vertical. We measured the stylolite planes, which are perpendicular to the peak direction and were in all cases near horizontal. And we measured peak length, which varied between 0,5 cm and 2 cm depending on the location. At 1 location in the Burma quarry we found two sets of stylolites with a slightly different dip crosscutting each other. Almost all stylolite planes were either horizontal, or subhorizontal suggesting vertical shortening

Figure 15: image containing 2 sets of stylolites within the Burma Quarry (stop 12.3, appendix 2) the green line indicates the stylolites with peaks of 1,5 cm. the blue lines indicate the stylolite set with peaks of 0,5 cm. photo is taken towards the SE. Pencill for scale.

Thin section data

The lithologies identified in the field were further studied with the thin sections. This allowed us to determine the different fossils. The most abundant ones were fossils of *lepidocyclina, heterostegina* and *globigerina,* benthic, benthic and planktonic foraminifera respectively. The complete data set from the carbonate thin sections and volcanic thin sections is given in the table of figures 16 and 17. From thin sections also a classification after Folk (1959) and a paleoenvironmental classification after Boudagher-Fadel (2018) was done, which is also shown in the figures 16 and 17 . in the thin sections concerning the BVG, at some locations, minerals from volcanic rocks were altered to chlorite or epidote, and showed reaction rims, which can are indicative for low-grade metamorphism. No signs for ductile deformation were found (e.g. sigma clasts, foliation, etc.). The data from volcanic rocks is used for determination of mineralogy and alteration, the data from carbonate rocks for determination of paleoenvironment and age.

Sample number and corresponding stop (appendix 2)	Lithology	Identified minerals	Alteration/weathering
3.10	Andesite, porphyritic, subsurface/shallow intrusive	Plagioclase Orthopyroxene Amphibole Oxides spherulitic aggregate	little
4.2	Dacite, porphyritic, extrusive	Feldspar Quartz Oxides Chalcedony (vein) Calcite (vein) Amphibole	little
4.5	Andesite, porphyritic, extrusive	Feldspar oxides	Quite weathered
4.7	Andesite, porphyritic, extrusive	Plagioclase Clinopyroxene Sericite (plagioclase inclusions) oxides	little
6.8	Dacite, porphyritic, contains basaltic xenoliths, intrusive	Feldspar Quartz Olivine(xenolith) Serpentine (xenolith Feldspar (xenolith) oxides	The olivine shows alteration to serpentine within the xenoliths.
7.12	Andesite, porphyritic Extrusive	Feldspar oxides	Feldspars have been weathered to clays
7.20	Andesite, porphyritic Extrusive	Feldspar Quartz Amphibole chlorite	Quite weathered and thin section was too thick
12.1	Dacite to rheolite, phaneritic to porphyritic intrusive	Feldspar Quartz Oxides	little
13.1	Andesite, porphyritic, extrusive	Plagioclase amphibole orthopyroxene oxides	little
13.6	Dacite to andesite, porphyritic	Feldspar Chlorite (inclusion)(vein) Quartz Calcite (vein) Oxides	Most porphyroblasts show alteration to chlorite.

		Amphibole?	
13.7	Andesite, porphyritic, extrusive	Feldspar Pyroxene (augite) Oxides	Feldspars very weathered to clay
DWB B	Dacite phaneritic to porphyritic, intrusive	Feldspar Quarts	Feldspars very weathered to clay

Figure 1612: table containing the data from thin section analysis of the volcanic rocks.

Sample nr and our corresponding stop (appendix 2)	Folk classification	Foraminifera (identified by us) Planctonic foraminifera are indicated with: “(p)”	other fossils	Foraminifera recognized by Marcelle Boudagher-Fadel from photographs	Paleoenvironment after Marcele-Boudagher-fadel (2018)	Age (or age zone)
ANT 27 Close to Stop 10.1	Poorly washed biosparite	Miliolidae Praerhapydionina Dendritina Lepidocyclina Peneroplidae Planktonics miogypsina	Red algae echinoid spine corals	Lepidocyclina (L.) pustulosa rodophyte	Reef wall/ talus	Oligocene p-21
ANT 24 A Stop 11.4	Unsorted biosparite	Lepidocyclina Heterostegina Miliolidae Dendritina Nummilite Operculina Miogypsina Bolivina?	Red algae Corals Algae	Heterostegina israelskyi Heterostegina panamensis Biarritzina sp., rodophyte spp.	Reef talus	Late oligocene
ANT 07 Lateral equivalent of stop 6.12	Unsorted biosparite	Lepidocyclina Nummelite Operculina Dendrita Miogypsina Praerhapydionina	Red algae	Eulepidina undosa Eulepidina sp. Amphistegina sp.	Patch reef/ fore reef detritus	Oligocene, P18-P20
ANT 21 Stop 2.8	Sparse biomicrite	Planctonics Miliolidae Globigeneridae(p) Turborotalia	Algae fragments	Catapsydrax dissimilis Dentoglobigerina sp.	Basin/ fore reef	Middle Eocene to early miocene

		Heterostegina		Globigerina praebulloides, Globigerina sp., Dentalina sp., small rotalids,		
ANT 22 Stop 2.7	Poorly washed biosparite	Dendritina Miliolidae Planktonic forams Globorotalia(p)	Echinoid spines	small rotalids Dentalina sp. Amphistegina sp., Textularia spp., Globigerina gortanii	Basin/fore reef	latest Eocene to Oligoce ne
ANT 23 a Stop 11.5	Packed biomicrite	Briozam Raniothalia Heterostegina Nummelite Discocyclina Miogypsina?	Red algae Corals Green algae worms		Reef/ back reef (forereef)	
ANT 23 b Stop 11.5	Packed biomicrite	Globogeneridae (p) Heterostegina Discocyclina Miogysina Miliolidae Globigerinatheka (p) Numellite	Red algae	Daviesina sp. Neorotalia sp. Heterostegina israelskyi Lepidocyclina (Lepidocyclina) yurnagunensis Lepidocyclina (Nephrolepidina) braziliana Lepidocyclina spp. Eorupertia sp. Paragloborotalia nana	Fore reef detritus/ fore reef basin	Late oligocen e
ANT 28 Stop 5.1	Packed biomicrite	Miogypsine Lepidocyclina Heterostegina Mililidae Nummelite Globorotalia (p) Dendrita Discocyclina		Heterostegina israelskyi Eulepidina spp. Eulepidina undosa Heterostegina panamensis Lepidocyclina (L.) pustulosa, Lepidocyclina (L.) rdouvillei	Reef talus	Rupelia n
Ant 32 Stop 5.2	Fossiliferous biomicrit to sparse biomicrite	Globogeneridae (p) Goborotaliidae (p) Nummelite		Paragloborotalia nana, Paragloborotalia opima, Globigerina spp.	Fore reef basin	Oligoce ne p-21

		Globigenerathek a (p)				
ANT 15 stop 1.4	Micrite	Ostracods			Lacustrine	
ANT 25 B Stop 2.7	Sparse biomicrite	Lepidocyclina Nummelite Globo… (p) Dentritina	Green algae		Fore reef detritus	
ANT 26 Stop 10.1	Fossiliferous biomicrite	Globigeneritheka (p) Globi ..(p) Heterostegina			Fore reef basin	

Figure 1713: table containing all the thin section data from the carbonate rocks

Description of stratigraphical groups

With our lithological observations, combined with structural data, thin section data (ages and mineralogy), we constructed the stratigraphy of Antigua. This has been graphically summarized in figure 5: "the Stratigraphy of Antigua". In the next section, the stratigraphy is elaborately explained.

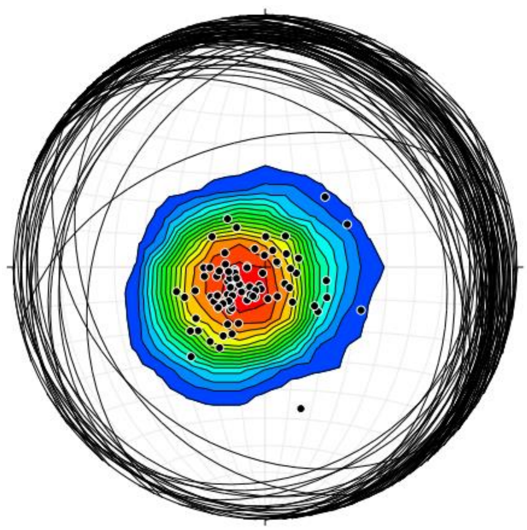

Figure 18: all bedding measurements. The black lines represent the bedding measurements, the black dots their poles. The colours show the density of poles at a location. Clearly visible is the general NE dip of the island of about 10-15 degrees, with some exceptions towards the W or S

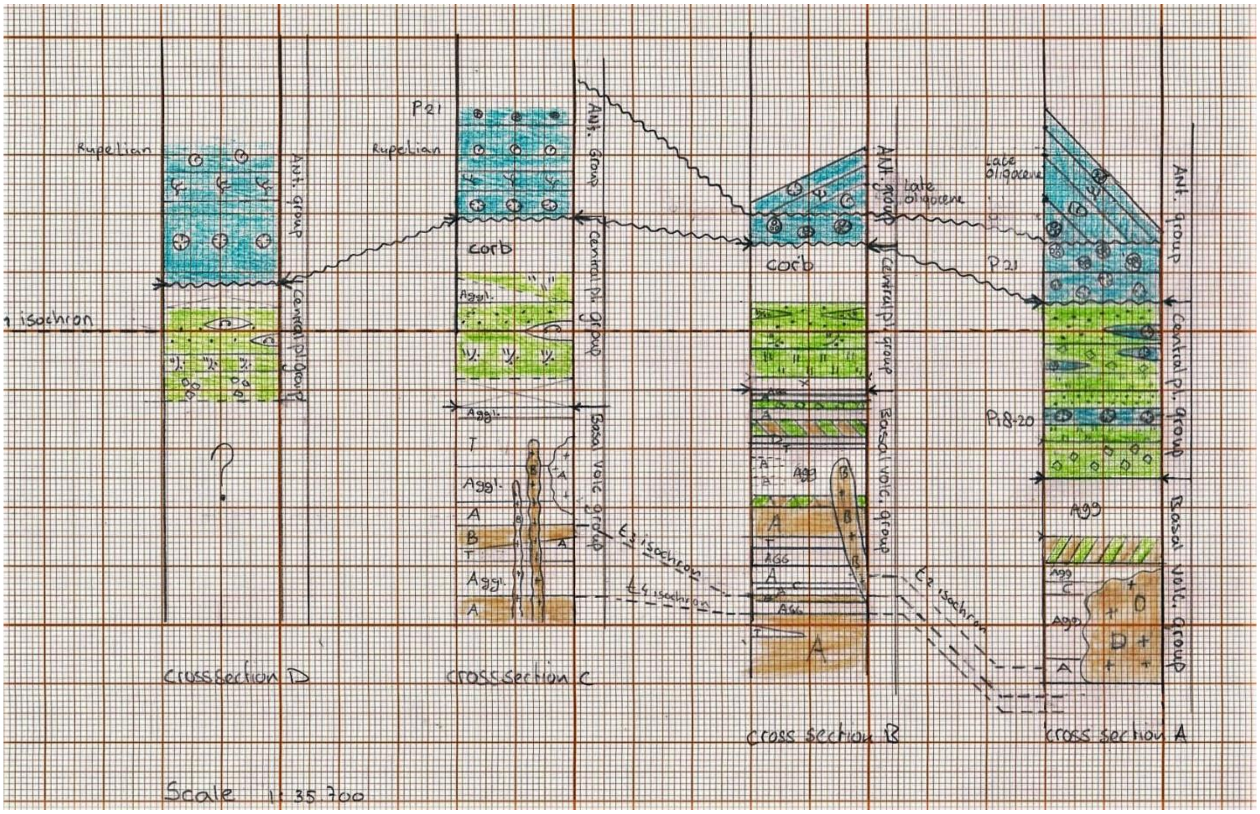

Figure 19: constructed stratigraphy of Antigua. figure showing the stratigraphy along the 4 different cross sections. The age from our paleontological studies is added. the stratigraphic columns are correlated trough isochrons and erosional surfaces. Our data is coloured within the stratigraphy, other data is copied from Martin-Kaye (1959). The Legend of the figure is in appendix 1.

Basal Volcanic Group formation

The Basal Volcanic Group (BVG) occupies the southwest of the island. It is a formation consisting of mainly lava flows and tuffs, or poorly sorted brecchia's interpreted as debris flows.

The lava flows range in mineralogic composition. We identified dacite, andesite and basalt. All the lava flows that we found can be identified as porphyritic, with larger white feldspar minerals in a finer matrix. The more basaltic lavas contained pyroxenes visible with the naked eye as well. Within some lava flows, we found evidence for flow structures, cleavage within the rocks indicating the direction of flow.

The tuffs and debris flows range from a clast size of millimeters up to car sized blocks in a finer matrix. the matrix (mesostase) of the debris flows either contains or does not contain feldspar minerals, depending on this they were indicated as "welded breccia" or "breccia" respectively. We identified mappable formations called: **Basalt, andesite, dacite, breccia, welded breccia**.

Next to these lithological formations, we identified a region in which the lava's contained glass shards, which is interpreted as being **hyaloclastides**. These have also been mapped.

Most of the formations within the group are outcropping with NW-SE striking bedding. Combining contour line data with lithology and the outcrop pattern indicates that most of the formation has a dip towards the NE. An exception are the hills north of Jennings (stop12.3, appendix 2) where the rocks are tilted towards the south.

The stratigraphically deepest rocks cropping out on the island are the andesitic lava flows in the Southwest of the island west of Urlings (stop 4.6, 13.3, 4.5) (appendix 2). The sequence might be continuing below water, but the deepest level of the stratigraphy is placed at these andesites. The youngest are the breccia's, welded breccia's and andesites west of Swetes along Fig Tree Drive (stop 7.9, appendix 2). We decided to place the boundary between the BVG and CPG at the stratigraphical height of the not outcropping valley which crosscuts the island in between Five Islands Bay and Fallmouth Bay. The sequence has a total thickness of 2000 m at it's thickest.

The stratigraphy changes laterally between the different cross sections which can be seen in the stratigraphic fence diagram (figure 19). The correlation between the different cross sections can be done through some andesite flows which extend over the area between the both cross sections, which are marked in the fence diagram as T2, T3 and T4 isochron.

Within this sequence of alternating lava flows and tuffs we also found some larger shallow intrusive bodies. Bendall's quarry (driving south on Bendall's main road) shows an intrusive andesite body (stop 4.7). The rocks also have a porphyritic texture indicating that it must have been a shallow intrusion. The largest intrusive body on the island is Sugar Loaf Hill, which we determined as a porphyritic dacite with large quartz and feldspar crystals in a finer matrix.

The BVG is crosscut by dikes on various scales, ranging from 1 to 200 meter width, and in various directions. The most prominent one is the large N-S trending dike SE of Jennings which can be seen from the road as a large vertical cliff (figure 20). Another important basaltic dike is the one cutting through the valley south of Bolans (stop 13.7) striking NW-SE. On a smaller scale we see vertical felsic dikes running through in multiple orientations (e.g. 150 north of Jennings (stop 12.3, 110 on southside of Mount Obama (stop 13.1), 50 south of Darkwood Beach (stop 4.6), Intrusions larger than 50 m were mapped (appendix 2).

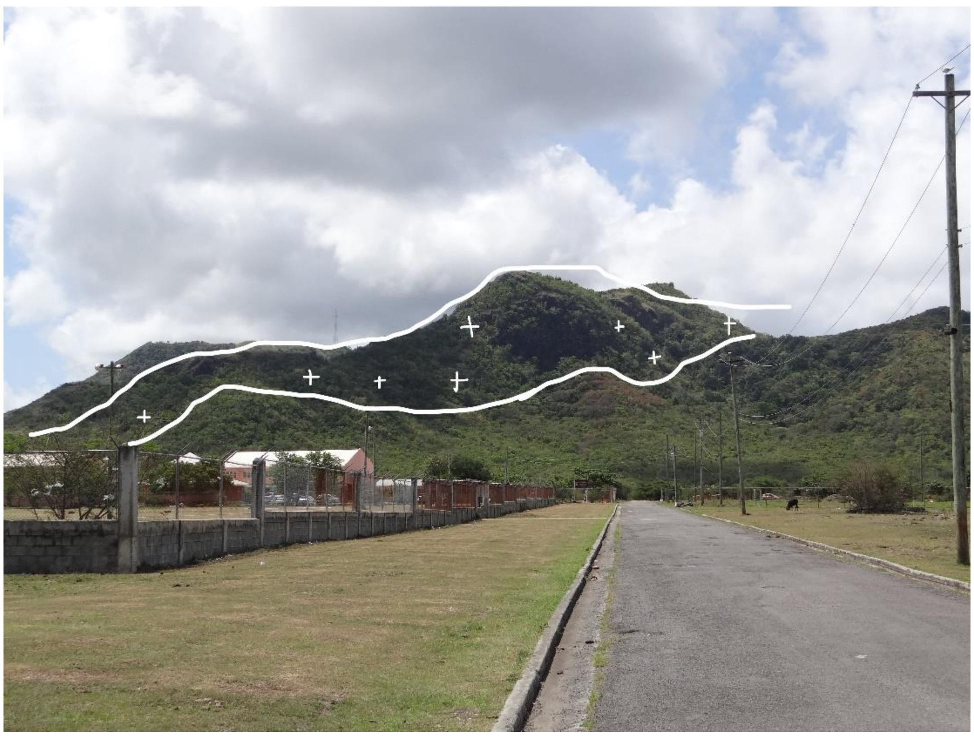

Figure 20: prominent dike SE of Jennings. White lines indicate the strike of the dike which was determined as being basaltic by Martin-Kaye (1959). Photo taken towards the SE from location of stop 15.4, height of the visible peak is 240 m

Some of the exposures showed a lot of alteration, with large plagioclases turning yellow or translucent and surrounding mesosases turning yellow or brown. This hydrothermal alteration was mainly located along the southern and southwestern border of the island, and mostly found in the dacitic or andesitic rocks. Most of the basalts showed less alteration.

Central Plain Group

The Central Plain Group (CPG) occupies the central part of the island (appendix 2). It consists mostly of the erosional products of the volcanic part of the island, or pyroclastic rocks.

The erosional products range from poorly sorted brechhia's interpreted as debris flows to fluvial sandstones and conglomerates, likely deposited in highly energetic braided river systems, intercalated with marls. We do not find deposits of large meandering river systems. The debris flows are mostly found close to the BVG and contain various lithoclasts among which are large andesite blocks, tuffaceous blocks in a fine tuffaceous matrix. The debris flows sometimes show a fining upwards sequence. The latter is well observed at Fort Berkeley in English Harbour, where the debris flows show a grain size decreasing from multiple meters to sand size (figure 21, stop 1.9-1.11).

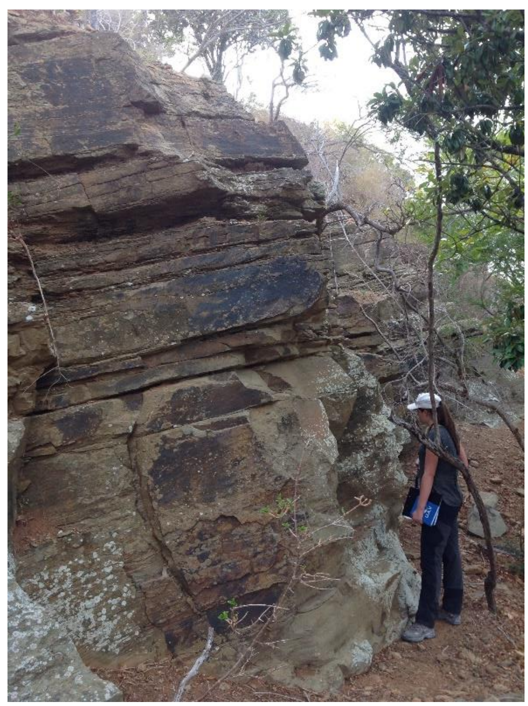

Figure 21: left image showing a polymict brecchia interpreted as debris flow. white lines indicate individual clasts up to 1,5 m, which contain smaller clasts inside of them. the right picture shows a stratified tuff/lapilli interpreted as ash fall deposit. the sequence gradually changes with a decrease in grain size upwards

Pyroclastic rocks range from tuffaceous sandstones with grains up to centimeters to very fine tuffs and lapilli. The tuffs consist of a very fine ash matrix with sometimes sand-size grains inside, this we interpreted as ash fall deposits. Beds are up to a few decimeters thick at most but can also be only centimeters when the clasts inside are smaller (silt size). Some tuffaceous sandstones show crossbedding in the form of dunes or antidunes. We identified **ash fall deposits**, **tuffaceous sandstones**, **brecchia's** and lithic arenites, clays and conglomerates without tuffaceous matrix interpreted as **fluvial deposits**.

Figure 2214: polymict conglomerate without tuffaceous matrix at the location of stop 2.4, interpreted as fluvial deposits. the outcrop shows crossbedding. picture taken towards the west.

The group often contains interbedded limestone banks, which show shallow-water **reef deposits**. At a few locations, we found **lacustrine limestones** containing freshwater gastropods (Scotss hill, Corbison point, e.g. stop 9.4 and 9.14, appendix 2). The formations of freshwater and marine limestones within the CPG are mapped separately. We determined the age of the oldest shallow water reef deposits within the CPG as being planktonic zone P18-20 (33.9-29.2 MA). We did not find any "chert" as described by Martin-Kaye (1959).

The CPG dips slightly towards the Northeast (strike of 130 to 160). At some locations the dip is turning more towards the east, e.g. at Scotts Hill (stop 9.11) (appendix 2). The youngest rocks are the breccia's located all along a NW-SE striking trend just north of the BVG andesites. The limestone bank at the bottom of the eastern stratigraphy has been dated planktonic zonation P18-P20 (33.9-29.2 MA). The top boundary of the CPG in the east is marked by a limestone that lies unconformable on top of a fluvial sandstone deposit (stop 10.12 and 2.6, appendix 2). We estimate the thickness of the group to be laterally variating between 850 and 1100 m.

The stratigraphy of the CPG changes laterally. We account for this by making three different stratigraphies. The eastern part (cross section a, figure 26) contains at the bottom the volcaniclastic deposits (brecchia's, tuffs) which are visible at the bottom of the ridge northwest of Falmouth Bay (stop 1.2, Appendix 2). Farther towards the NE and thus higher in the stratigraphy we find more fluvial sandstones/conglomerates with interbedded reef deposits. We explain the repetition of various parts along the cross section line as an omission created by normal faulting, which will be discussed further at structural interpretation.

The central part of the stratigraphy (cross section B, figure 26) differs from the east with respect to the amount of sandstones and limestones. The whole sequence exists of tuffs, sandy tuffs with sandstone lenses. The bottom of the sequence is again formed by breccia. The top of the central part of the CPG is not visible in outcrop anywhere.

The western part of the CPG is a mixture of both fluvial and pyroclastic deposits. The bottom is again marked by breccias. The top of the sequence is nowhere exposed, but we put it stratigraphically in between Corbison Point and Paradise View Hill (stop 9.4 and 9.5, respectively, appendix 2). Again, repetition along the cross section line is seen within this part of the sequence.

The central part of the island is mainly covered with Quarternary soils, however where the rocks crop out, it is mainly tuffs or tuffs containing sand size lithoclasts (sandy tuffs). The best exposures of the rocks are found along fresh cut roads, e.g. along the All Saints Road or Buckley's main road (e.g. stop 6.1 or 7.3, appendix 2). Closer to the AG, the rocks of the CPG are more sandy and less tuffaceous. We observed crossbedded sandstones interpreted as fluvial deposits along the road SW of Willoughby Bay (stop 2.4), north of Scotts Hill (stop 9.17) and south of Perry Bay (stop 3.1) (appendix 2).

Both in the Western as the Eastern part (cross section A and D, figure 26) we found lacustrine limestone deposits, and we managed to correlate the central part's tuffs to the same stratigraphic height. Assuming that the conditions on which these specific rocks formed were widespread and enclosed to a narrow time interval, we state that the lacustrine limestones can be seen as an isochron through the stratigraphy. This isochron is used to link the different cross sections to each other in the stratigraphic fence diagram (figure 19).

The tuffs often contain black/ brown elongated ash flakes. However, these weather easily, and in most exposures they are yellow or green. This green color dominates in many of the tuffs around the island, especially in the ones close to the volcanic suite around the villages Swetes and Liberta (stop 6.2), or in a sandy tuffaceous formation around Clarks Hill (stop 6.1) (appendix 2). Within the sequence of the CPG, some small (up to two meter) dikes were found, e.g.in the ridge south of Willoughby Bay (stop 1.3) , or in the tuffs around Buckleys (7.1) (appendix 2).

Antigua group

The Antigua Formation occupies the NE of the island. It contains marine carbonate rocks containing many fossils. The fossil assemblage is used in combination with the grain size of both bioclasts and lithoclasts to determine the paleoenviroment.

We found mudstones or marls, barely containing fossils or with planktonic foraminifera (e.g. *globigerina*), classified with the Folk classification as "packed biomicrite or Fossiliferous biomicrite" which we interpreted as deeper and lower energetic deposited. These were mapped as **slope (inner neretic).**

We found pack/grainstones with abundant larger benthic foraminifera (e.g. *Lepidocyclina* or *Heterostegina*) up to six cm in diameter, which we interpreted as either lagoonal or forereef deposits depending on their folk classification and abundancy of certain indicative foraminifera. These were mapped as **forereef**

We also find corals both in situ and transported. Corals ranged from species with branches with branch diameters up to five cm thick. Small branch diameters may indicate a lower energetic environments, mapped as **reef, low energetic** while the thicker branches could have withstood higher energetic environments, mapped as **reef high energetic**. We also found corals that we identified as "massive" that grew radially without specific branches, which we interpreted as the indicators of the highest energy environments, i.e. at a fringing reef's crest.

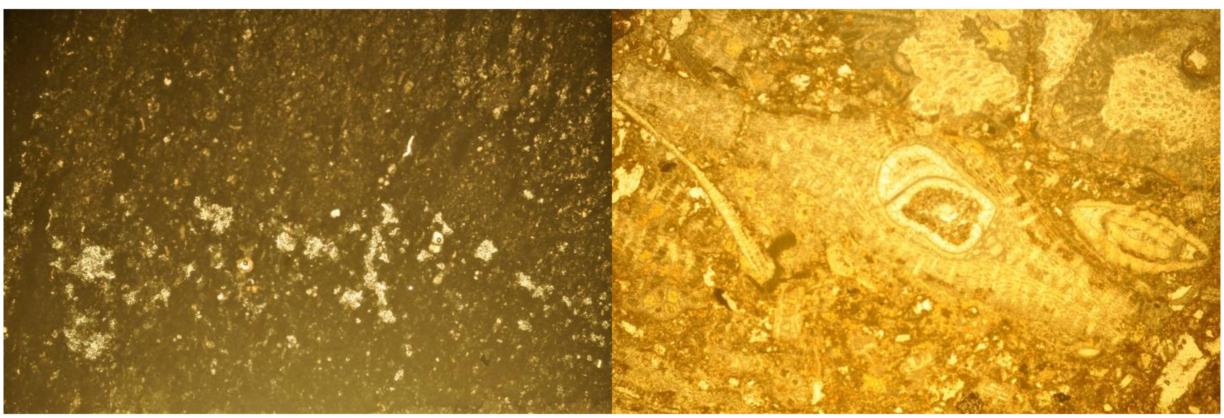

Figure 2315: thin section images of the Antigua Group. ***left:*** *sample nr 26, stop 10.1. planktonic foraminifera in a fossiliferous biomicrite, deposited in a slope/inner neretic environment. Right: sample nr. 07, lateral equivalent of stop 6.12: large benthic foraminifera(Lepidocyclina and Nummelite) in a unsorted biosparite, deposited in a patch-reef/ forereef detritus environment.*

*Figure 24 Images from: **left:** stop 2.6, high energetic reef deposits, coral branches up to 5 cm in diameter. **right:** stop 11.7: low energetic reef deposits, thinner coral branches max 2 cm in diameter.*

Most of the Antigua Formation NE of Saint Johns seems to be dipping in a similar way as the Central plain group towards the NE. The part of the group located NE of Saint Johns (between the Burma Quarry (stop 14.3) and Dickensons Bay towards the NE (stop 9.6) (Figure map) is completely dipping towards the NE with a dip of about 15

On the eastern side of the island, east of the Sir Richards cricket stadium (located near stop 16.2, appendix 2) this overall dip orientation changes. We find dip orientations towards the west in the middle of the Group. And horizontal or even southwest-dipping limestones in the northernmost part of the island (Crabs Peninsula (stop 11.2), Devils Bridge (stop 10.1) (appendix 2).

The stratigraphy of the Antigua Group can be divided in 2 parts, separated by an angular unconformity, which is visible in Half Moon Bay (stop 2.8) appendix 2, figure 25, left photo). The part below this angular unconformity is further described as the Lower Antigua Group (LAG), whereas part above the unconformity is described as the Higher Antigua Group (HAG).

Figure 2516:images of the unconformities at half moon bay, location of stop 2.9. ***left image:*** *white layers containing a lot of corals, interpreted as the oldest rocks exposed in half moon bay. Bottom of the sequence of the LAG. blue layers deposited unconformably on top of the white layers. The blue is interpreted as the top of the sequence of the HAC.* ***Right image:*** *a different unconformity within half moon bay. The white layers are the same as in the left picture. The Green layers contain benthic foraminifera interpreted as being deposited in high energetic forereef/ reef detritus. Within the stratigraphy, the green layers either belong to the LAC, or to the HAC, but have been placed on top of the white layers because of the unconformity.*

The LAG is exposed in the North/ Northwest of the island. The Burma quarry shows the lower part of the sequence of the LAG. The deposits show a gradually deepening upwards sequence throughout the LAG, with dip slightly decreasing towards the north. (appendix 2) (figure 26, C & D) We estimate a maximum thickness of the LAG sequence of 850 m here. The oldest outcropping rocks of the LAG are made of high energetic reef deposits (e.g. stop 9.5, 14.3 or 14.13, appendix 2). On top of the reef deposits, forereef deposits are found containing large benthic foraminifera, these are dated with an age constraint of Rupelian (33,9-28.1 Ma) The youngest outcropping layer of the LAG contains slope/inner neritic deposits containing mostly planktonic foraminifera. The age constraint of the top of the section is the planktonic biozone P21 (age 29.8-26.8 Ma) °.

The HAG mainly outcrops in the NE of the island. Dip measurements indicate that a large part of the succession here is slightly dipping to the SE or west or is about horizontal. (appendix 2, figure 26 A & B). We estimate the maximal thickness of the HAG sequence as being 800 m. Within the HAG, a shallowing upwards sequence can be found. The oldest rocks outcropping are slope/inner neretic deposits with an age constraint of planktonic biozone P21 (age 29.8-26.8 Ma)(e.g. stop 10.1, appendix 2). On top of this we find forereef deposits, containing large benthic foraminifera, these have been dated late Oligocene (28.1-24.0 ma) (e.g. 13.5, appendix 2). The top of the sequence contains both low as high energetic reef deposits.

Cross sections

Cross sections were made simultaneously with the stratigraphy. Important factors for the emplacement of faults were repetitive sections, change in dip direction and observed fault kinematics/ observed fault planes during stops. We present that the island is strongly affected by a system of tilted fault blocks. We infer that a large fault transverses the island, reaching from the west coast, creating repetition along the section between Corbison Point and Dry Hill, towards the East coast, creating repetition along the section in sandy layers with interbedded limestones and the large fault zone at the location of stop 1.4 (see appendix 2, figure 26A-D). A few other large faults along this strike are also creating repetitions within the section. Another important fault direction influencing the cross sections is along a strike of 170 forming sinistral strike slip faults as determined from striae on the fault plane. A few faults within the Basal Volcanic Group are associated with the large basaltic dikes running through the BVG intruding the faults. The final cross sections can be seen in figure 26

A-D. Our data is coloured in the cross section, locations where we did not have data are filled in with lithological data from the map from Martin-Kaye (1959) and Osborn (2019) and are not coloured.

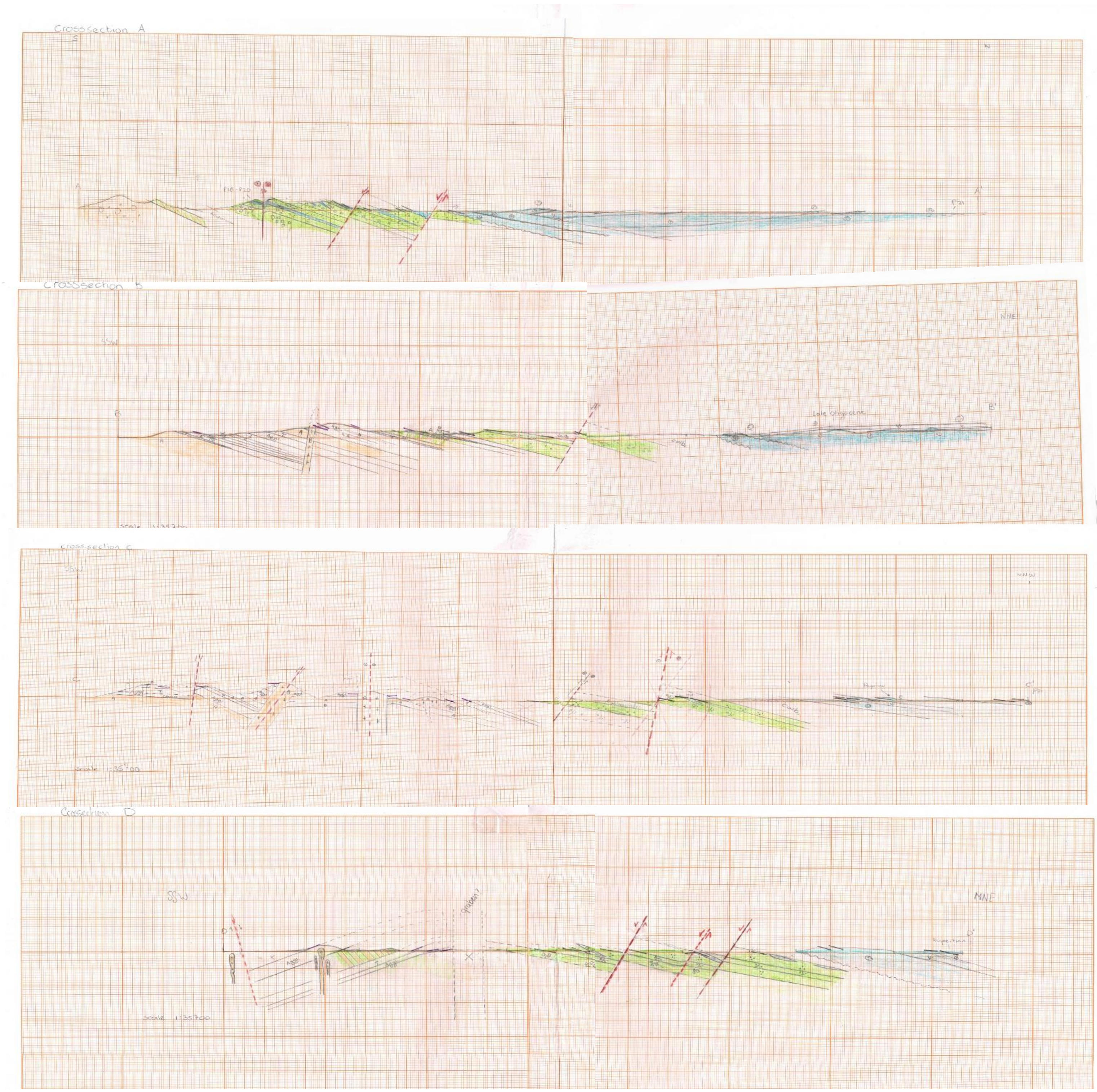

Figure 26: cross sections A, B, C, D from east to west respectively. Cross sections are drawn from SW to NE. Full size cross sections are in appendix 3. The legend of the figure is in appendix 1.

Discussion

Stratigraphical argumentation

Since no complete stratigraphy of the island has been published before, we cannot directly compare our results to other researches. We do however have the outcropping pattern of the different lithologies (Martin-Kaye, 1959, Osborn, 2019) and we know Martin-Kaye describes the stratigraphy as dipping slightly to the NE. We used our data and bedding measurements for the construction of the cross sections. Locations where we did not have data got filled up with data from the map of Martin-Kaye. Our data set does show some differences with Martin-Kaye's.

A difference between Martin-Kaye (1959) and us is the definition of the boundary between the Central Plain Group and Basal Volcanic Group. From English Harbour in the SE towards Five Islands Harbour in the West, there is a valley. We found evidence for normal faulting along-strike of this valley in English Harbour (appendix 2) but we do not see repetition along the section within all cross sections at the location of this valley. This means that rocks underlying the valley are nowhere exposed along our cross sections. We marked this "unexposed" interval as the lower boundary of the Central Plain Group. This boundary coincides with Martin-Kaye's for a large part in the center of the island but In the East, he placed the boundary above the highest exposed breccia, which means he there placed the boundary at a different stratigraphical level than in the center of the island. Another argument against his definition is that brecchia's from debris flows are quite local, and thus unlikely to be found at the same stratigraphic level along the whole lower boundary of the CPG.

Our boundary between the CPG and AG also differs slightly from Martin-Kaye's. His boundary is the base of the first elevated ridges NE of the lower central plain. We did however find a contact between the sandstones that we ascribe to the CPG, and the limestones that we ascribe to the AG slightly south of the ridges (stop 2.6 and 10.12, appendix 2). As this contact is angularly unconformable, we decided to place the lower boundary of the Antigua Group on top of this unconformity, which we consider a more logical place for a formation boundary than a geomorphological feature such as a ridge. Another reason for this boundary definition is the age of the elevated ridges. We interpret the top of the ridges in the NW as being younger than the top of the ridges in the NE (as described earlier). Mascle and Westercamp (1984) described the contact between the AG and CPG as gradually. We do not agree on this as we think that there is a slight angular unconformity between the two groups (as indicated in the stratigraphic fence diagram (figure 19)

Other choices made in the stratigraphy are the subdivisions of formations within the groups. We identified a total of 15 formations of which some do represent multiple lithologies (e.g. fluvial deposits represent clays, lithic (volcanic) arenites with clay matrix and conglomerates.), and some do not (e.g. tuffaceous sandstone). The division of these formations was based on whether all formations would be large enough to be seen on the map, lithological coherence of the formation and usefulness for future research. For example, a sandstone can either be deposited as surge deposit, fall deposit or fluviatile deposit. While all could be named sandstone, we decided to subdivide these into sandstones with tuffaceous matrix, tuff with sand size grains embedded and lithic arenite with clay matrix, which is usefull because of the different depositional settings.

Next to these differences in definitions of formations and boundaries, we also described rocks differently at some locations, for example where we identified dacites instead of andesites. (e.g. stop 7.20, 7.21, 7.22, appendix 2)

Cross section argumentation

For the construction of the final cross sections, we used our own lithological measurements, bedding measurements and fault measurements to construct the first cross sections. These data were combined with the lithological map from Martin-Kaye(1959), at locations along the section where our map was incomplete, and dip measurements in tuffs from Christman (1973). Correlating lithologies was not always straightforward, because the lithological classification of rocks used by Martin-Kaye was slightly different. The interpretation of combination of the data led to the cross sections and stratigraphy we have now.

Inferred faults

Large fault displacements or offsets were barely visible on the island. The CPG shows several repetitions along the cross sections, these can be solved through faulting, or just repetitions within the sedimentary sequence. We argue large normal faulting, based on:

1) evidence for large scale normal faulting at stops 1.4, 1.5, 3.8, where brittle fault planes indicated fault zones of 10s of meters thick, Scholz (1989) indicates that brittle fault zones of this thickness are capable accommodate displacement on this scale.

2) repetitions along our line of section within the sequence even at lithological horizons that we interpret as the same stratigraphic horizon (e.g. the lacustrine limestones exposed at Corbison Point and Dry Hill (stop 9.3 and 9.4, appendix 2). Also other repetitions within the sequence that look suspiciously similar (mineralogy, alteration), or even repetition of an unconformity (stop 2.6 and 10.12, appendix 2).

3) evidence for multiple stages of deformation from fracturing and unconformities, of which the final one was larger and extensional (discussed later in fault and fracture patterns or deformation phases)
4) subdivision of all fault patterns within 2 stress fields show that the extensional component must have been relatively large (discussed at fault and fracture patterns).

5) some localities showing a vertical downward shortening direction, forming conjugate faults, indicating a horizontal extensional sigma 3 (stop1.4, 1.9, 2.4, 4.5, 16.5).

Stress fields

When combining the structural data of larger faults, smaller individual faults and joints, we see that all of these could not have formed in a single stress field during one deformation phase. We propose that there have been three different stress fields which have acted on the island. Some of the larger faults on the island could all have formed due to a stress field compressive in the NE-SW direction(sigma 1), and extensional in the NW-SE direction(sigma 3), as shown in figure 27 A whereas the rest of the larger faults of the island could only have formed through a stress field extensional in the NE-SW direction (sigma 1), and compressional in the NW-SE direction(sigma 3) as shown in figure 27 B

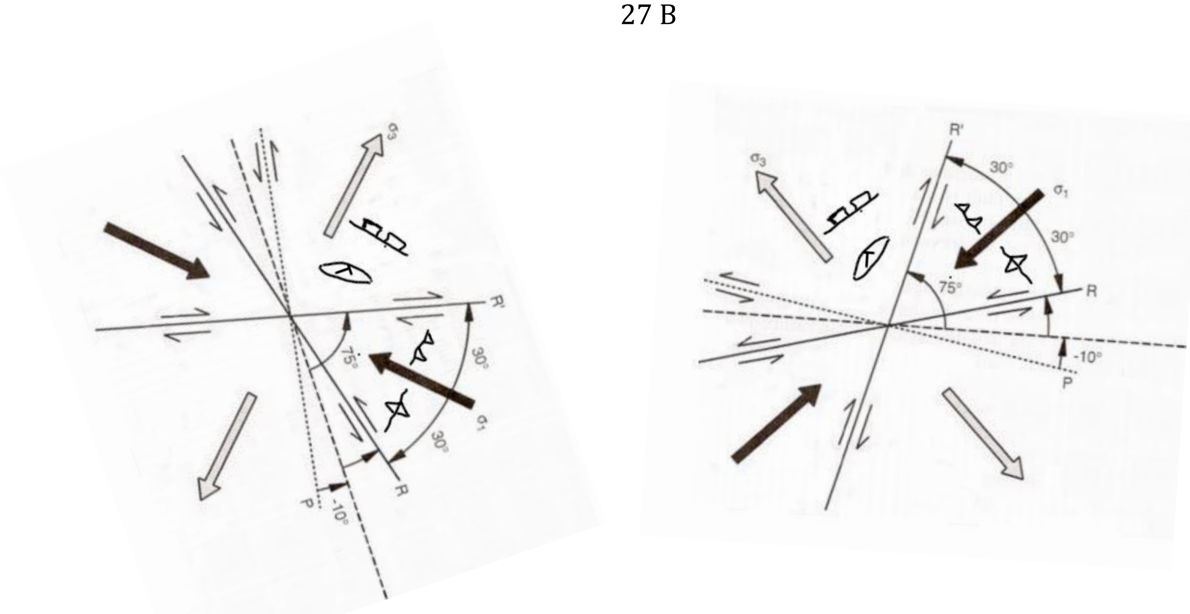

Figure 2717: interpreted stress fields diagrams containing orientations of Riedel faults, folds, reverse faulting, normal faulting and tension gashes. ***left:*** *whit arrows indicate sigma 1, black arrows indicate sigma 3. Normal faults are oriented along a strike of 130. Sinistral strike slip faults are oriented along a strike of 170.* ***Right:*** *black arrows indicate sigma 1, white arrows indicate the sigma 3. Sinistral strike slip is found along a strike of 110-120 (like a large part of the flower structure, stop 2.3)*

The same can be said for the smaller/individual faults, where one stress field could explain the strike of the average normal faults and part of the sinistral faults, and one stress field could explain the strike of the average reverse faults part of the dextral faults.

Relative ages of the different stress fields can be seen at the locations of stops 4.2 and 15.1 (appendix 2) which both show fault planes, which have been folded, and have been crosscut by a second set of normal fault planes after the folding. This indicates on both locations that there must have been three different stress fields acting on the rocks, of which the first and last were extensional, and the second was compressional. The absolute age of the final two deformation phases can be derived from the joint patterns in the Burma quarry

Deformation phases

The oldest deformation phase, was due to an extensional stress field. We have only found evidence for this deformation phase at the locations of 4.2 and 15.1. The stress field was most likely extensional in the N-S direction, and compressional in the E-W direction.

We infer that the second phase must have been compressional, and is responsible for 1) the positive flower structure near English Harbour, 2) the folded layers in the west of the island, and 3) faults which can only be explained by a N-S compression like at the location of stop 7.12(appendix 2). 4) the lower pattern within the Burma quarry can also have formed with this stress field as the average fracture pattern is along the same strike as the average reverse fault strike. The age of this deformation phase is the same age as the deposition of the bottom set of the Burma quarry: early Oligocene.

The largest and final phase we infer as extensional, 1)creating the large normal faulting crossing the central plain group, 2) accommodating enough space for basalt intrusions, 3) creating large sinistral faulting in the West of the island and 4) tilting the whole succession 10 to 15 degrees towards the NE through a system of rotating fault blocks. Evidence comes from large zones of normal faulting in the east (stop 1.4). The tilting has also created the unconformity between the LAG and HAG. Balancing of the faults within the stratigraphy from the cross section (calculating the horizontal heave along the cross section line from the dip of the fault and the displacement of layers along the fault plane as measured from the cross section) shows that the extension was larger on the west side of the island (190m, 250 m, 280 m and 300 m on cross sections A to D respectively). This should be considered with caution however since we did not take in account any strike slip component.

Geological reconstruction

First the Basal Volcanic Group formed as an alternation of tuff's and lava flows deposited on the flank of a volcano. As we found hyaloclasts we know that some of the volcanic activity happened in shallow water. The age of this group is determined as 40-36 Ma (Nagle et al, 1976 and Briden et al, 1979).

After this the deposition of the Central Plain Group occurred. Age dating from the oldest interbedded limestones determines an age of planktonic zone P18-20 (33.9-29.2 MA). We find both continental deposits as shallow marine limestones as well as volcanic ashes/tuffs within the Central Plain Group. Slightly unconformable on top of the CPG, the lower part of the Antigua Group was deposited during the Rupelian to planktonic zone P21 (older than 28.1 Ma). The LAG shows a deepening upwards sequence, like the one described by Donovan et al. (2014, 2015). We saw evidence for compression in the BVG (folding and thrusting), CPG (folding and transpression), and AG (thrusting). The compressive event thus must have been after Planktonic zone p20 (29.2 Ma) but before P22 (26.8Ma).

After the compression, an extensional phase has occurred. This caused: 1) tilting the section, 2) creating the angular unconformity between the LAG and HAG 3) creating repetitions along the cross sections. The extension could also be the cause of accommodation space for large basalt intrusions however we know that the basalts do contain some fault planes indicating deformation after their deposition. Whether this is a later stage of deformation should be examined from age dating within the basalt. We know that the HAG has been deposited in the late Oligocene with the lowest part being planktonic zone P21. This creates the same age constraint for the extensional as the compressive deformation event (29.2-26.8 MA). The HAG is deposited as a shallowing upwards sequence. Within the HAG, dykes cut through the sequence (Brown1914, Trenchmann, 1949). The age of these dykes and magmatic event is younger than the deposition of the top of the HAG, making the age of the dykes younger than 28.1 Ma.

Future research

Diverging dips of Jennings

According to the dip measurements of Christman (1972), the hills north of Jennings are dipping towards the SW / W. Christman described the whole hill as fine grained volcanic rocks. We have only one measurement which confirms this dip direction (stop12.3). The area however does also contain the Seaforth Limestone, a locality which we could not visit but has been described before as being dipping towards the North (Brown 1913). The area is difficult to link stratigraphically to the beds towards the north or east, but if the measured dips of Christman are correct, this could be a key point to confirming the extension on Antigua. We have measured fault planes indicating normal faulting slightly farther towards the SW (stop 4.2, Figure map). One hypothesis could be that these normal faults dipping to the north accommodated the change of dip within this part of the island, which would lead to the unexposed part east of Five Islands Bay being a horst, with grabens tilted towards the NE on the NE side, and a graben tilted towards the SW on the south side. This hypothesis can either be confirmed or falsified by investigating the actual dip and age of the Seaforth limestone.

Stylolites

We have found stylolites in multiple locations in the North and NW of the island. These stylolites were all sub-horizontal, with a small angle to the tilted bedding. The stylolites were located at multiple stratigraphical levels. Interpreted is that the stylolites formed from pressure due to burial. The fact that the stylolite planes have lower dips than the bedding in which they formed tells that the bedding was tilted before it was buried. Within the classification of Park and Schot (1969) we identified the stylolites as “sharp-peak type horizontal stylolites”. Measured was the direction, of the peaks and the height of the peaks.

Stylolites are formed through pressure-solution when stress is put on limestones (Toussaint et al. 2018 and references therein). From modelling of stylolites it was shown that not the peak length, but the roughness of the stylolite can indicate the paleostress and depth at which it formed (Toussaint et al. 2018, Rolland et al. 2012). This roughness can be determined through scanning the stylolite plane with lasers. The actual paleodepth can then be calculated trough mathematical derivations. We did not investigate the stylolites of Antigua in detail, since we had no laser scanning equipment to our availability. Future research would be interesting to investigate the burial depth of the different stylolites. One opportunity is to conduct this future research on one of our already sampled limestones containing some stylolites.

Absolute ages

More future research should be done on the different sampled rocks within the sequence. We have sampled different volcanic rocks in and dikes of different material in greater amount (basalt, andesite, dacite and one sample looking nearly rhyolitic). These samples might provide an age trough isotope dating with a smaller constraint than the current guess of "Eocene to oligocene". We sampled the oldest volcanic rocks in the SW (andesites) and the youngest within the stratigraphy further towards the north. When a proper age dating of this is combined with age dating of the different sorts of intrusions, our geological reconstruction can be confirmed or falsified. This could also provide a more exact dating of when the Bahama's bank entered the subduction zone. Considering the age of the Antigua Group, we mostly looked at rocks sampled by an earlier field excursion on the island. During the fieldwork, we collected more rocks from the Antigua Group, this could create a narrower timespan for the different parts of the Antigua Group and if possible with less overlap of biozone ages. The youngest rocks of the island are the dikes which cut through the HAG (brown, 1914 trenchmann, 1949) interesting would be to properly date these dykes to find the age of the latest magmatic event on the island.

Figure 27: image taken at stop 6.2, the rock is determined as tuffaceous sandstone. The eock show the green colour of the chlorite.

Alteration/metamorphism

As described before, many locations of the island show rocks which have been chemically altered. Recrystrallization occurred within many tuffs and andesites. This recrystallization shows sometimes low-grade metamorphism, for example many Quartz and Feldspar minerals contain reaction rims, and minerals which have been chemically altered to chlorite. Within the tuffs, this green colour is also found in a lot of locations (Martin-Kaye 1959, hristman, 1972, Jackson and Donovan, 2013). We did not further investigate this alteration, but Jackson and Donovan (2013) suggested that the tuff's are comparable in mineralogy to the Dacitic Sugar Loaf Hill intrusion (appendix 2). They also describe that most of the "chloritized" tuff's can be found in the vicinity of the intrusion. Our data do not agree with this, since we found it at multiple locations (stop 7.1, 6.2, 6.14) and even at different stratigraphical levels (stop 11.8) (appendix 2). No explanation has been given so far. But the fact that we see this alteration within sequences located at multiple stratigraphical levels suggests a common origin. Contact metamorphism is excluded from possible explanations, as the heat would destroy all the fossils in surrounding rocks. A possible explanation is that the metamorphism occurred due to burial, this should however be further investigated from the produced thin sections of the Basal Volcanic Suite.

Paleomagnetism

Our fieldwork provides the reader with a lithological map containing lavas and intrusions of different age. Paleomagnetism can be used to indicate the paleomagnetic field which was present during the cooling of the lava, or lithification of sediments. This magnetic field orients the magnetic minerals within the matrix along a certain direction. As this can be combined with age dating, one can see directly whether the rocks have undergone any rotation or tilting after deposition. The same cored samples can be used for paleointensity, which focuses on the mineralogy, cooling speed/temperature and alteration of igneous rocks. For the paleomagnetic measurements, it is important to know where the most altered rocks or least altered rocks can be found. The most altered rocks are the different andesites of the island. the small dome South of Galleon Bay (stop 16.5, appendix 2). Also the oldest andesites of the Southwest and south do show much alteration. Within the sedimentary rocks in the CPG, the rocks which have been altered to chlorite (as described in the past section) are the most altered rocks. Better preserved rocks are the basalts and basaltic intrusions in the central part of the

BVG (stop 7.12, 13.1 or 13.7). A particulary well-preserved andesite is located in a fresh cut quarry between the much altered andesites along Old Road (stop 4.5).

Paleontology

Most of the deposition of the Central Plain Group happened either in shallow marine or on continental setting. This provides a research opportunity for researches interested in possible land bridges along the extinct northern part of the Lesser Antilles arc. Previous work on this has proved that with a lowered sea level during the Eocene-Oligocene boundary many islands of the lesser Antilles and Aves Ridge might have been emergent for 1 or 2 Myr, the GAARlandia land bridge hypothesis (Ali, 2012 and references therein). Fossils from plants or land animals within the continental succession could lead to new observations which might confirm or deny parts of the hypothesis. If this land bridge existed, it did either during or slightly prior the formation of Antigua. Fossils thus could place another clear age constraint on the formation of the BVS. Important locations for this research are in the SE, where a thick succession of fluvial sandstones were deposited (stop 2.4, 6.15, 6.13). Another location containing fluvial sandstones are SW of St. Johns (stop 3.1) (appendix 2).

Conclusions

-The oldest stratigraphical formations of the island are located in the SW, these consist of lavas and tuffs deposited near a volcano. These are topped by the Central Plain Group, which is a mixture of deposits from the volcano, fluvial deposits, lacustrine deposits and marine deposits. This is topped by the Antigua formation, which is deposited in marine setting with a deepening upwards sequence in the LAC and a shallowing upwards sequence in the HAC.

-the oldest rocks of the Central Plain Group are deposited in between 33.9 and 29.2 MA. The top of the Antigua Group was deposited in the late Oligocene (28.1-23.0 MA)

-the Central Plain Group contains multiple repetitions in the stratigraphy of the same formation. This is accommodated by normal faults transversing the island.

--multiple deformation features are found on the island, of which some indicate a compression (folds, positive flower structure, thrusting) and some indicate extension (normal faulting).

-the Antigua Group contains at least 2 unconformities, of which one marks the bottom of the group. The Antigua Group is built from a deepening upwards sequence at the bottom to a shallowing sequence at the top, which are divided by the second unconformity.

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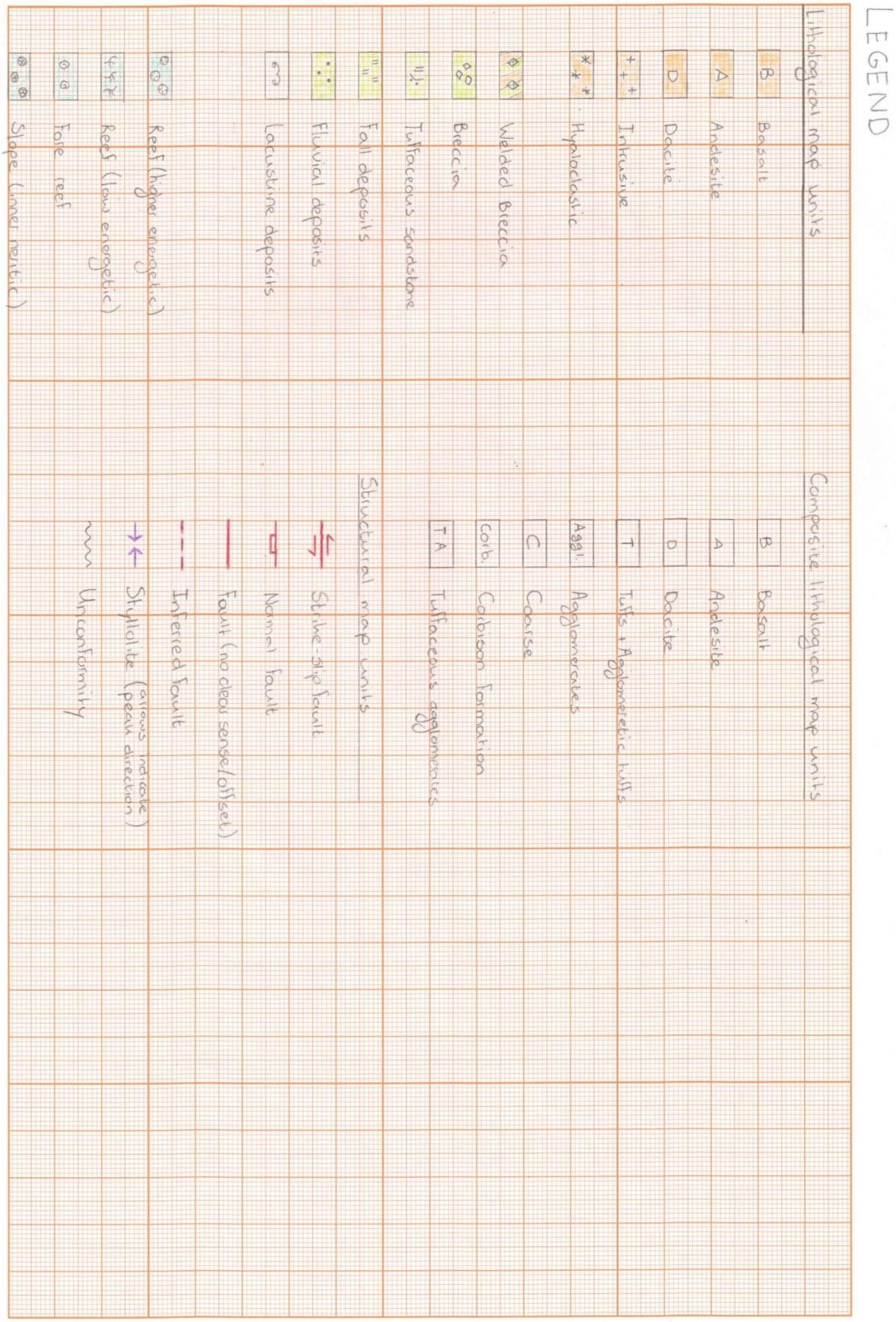
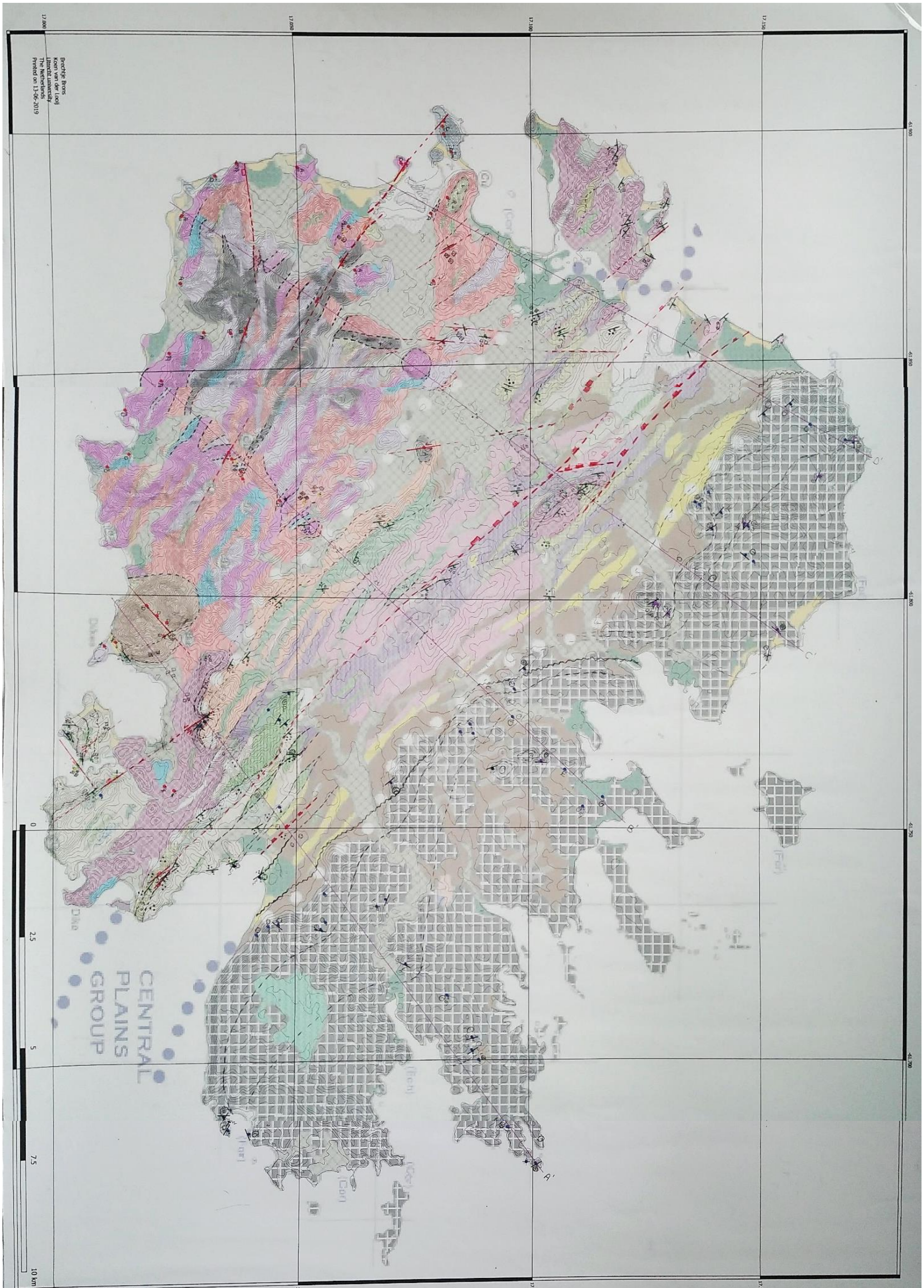
Appendices

1) Legend of map , stratigraphy and cross sections
2) Map of Antigua
3) Cross sections A,B,C,D

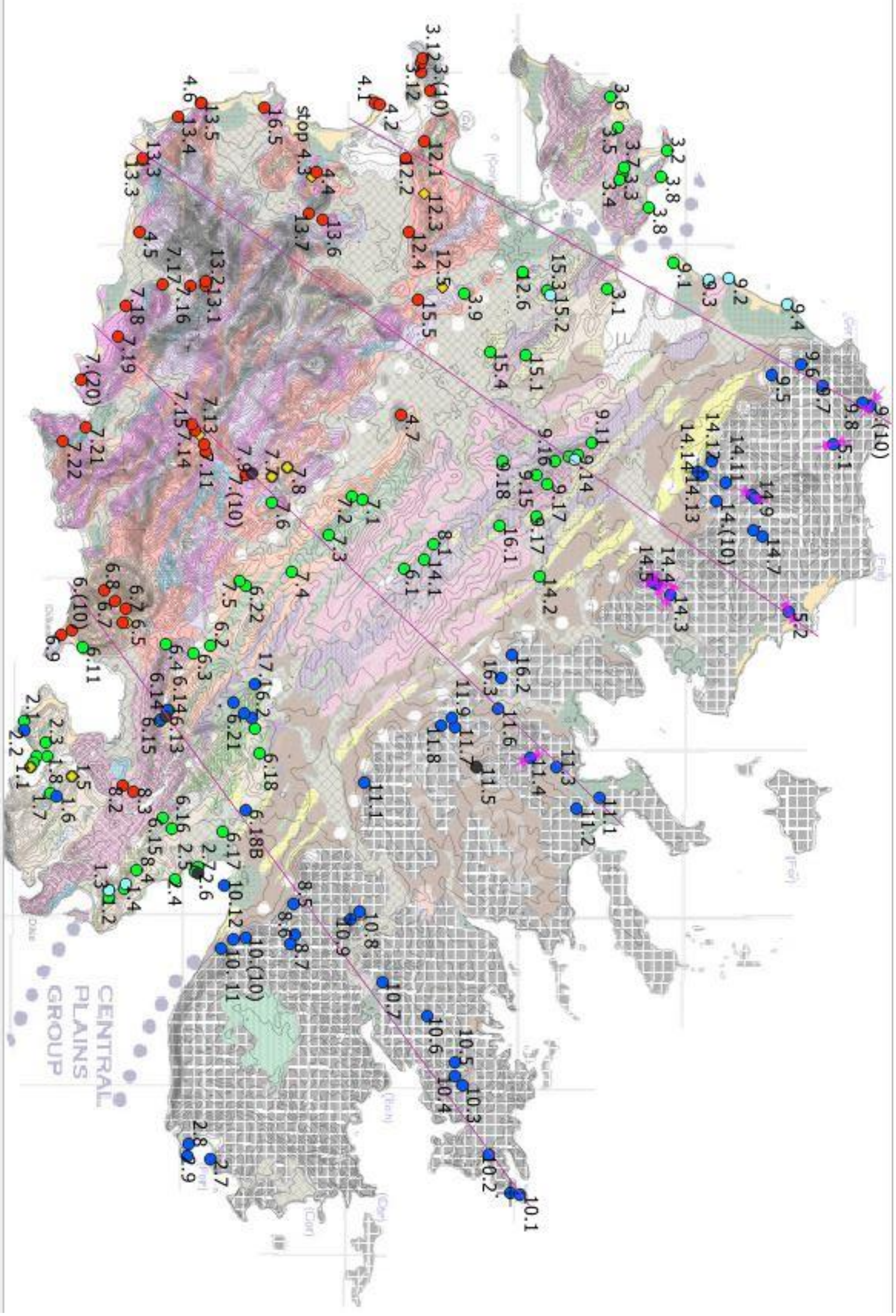
1.legend


LEGEND
Lithological map units
B
Basalt
A
Andesite
D
Dacite
Intrusive
Hyaloclastic
Welded Breccia
Breccia
Tuffaceous sandstone
Fall deposits
Fluvial deposits
Lacustrine deposits
Reef (higher energetic)
Reef (low energetic)
Fore reef
Slope (inner neritic)
Composite lithological map units
B
Basalt
A
Andesite
D
Dacite
T
Tuffs + Agglomeratic tuffs
Aggl.
Agglomerates
C
Coarse
Corb.
Corbison formation
TA
Tuffaceous agglomerates
Structural map units
Strike-slip fault
Normal fault
Fault (no clear sense/offset)
Inferred fault
Stylolite (arrows indicate peak direction)
Unconformity

2. Map of Antigua + map containing all stops

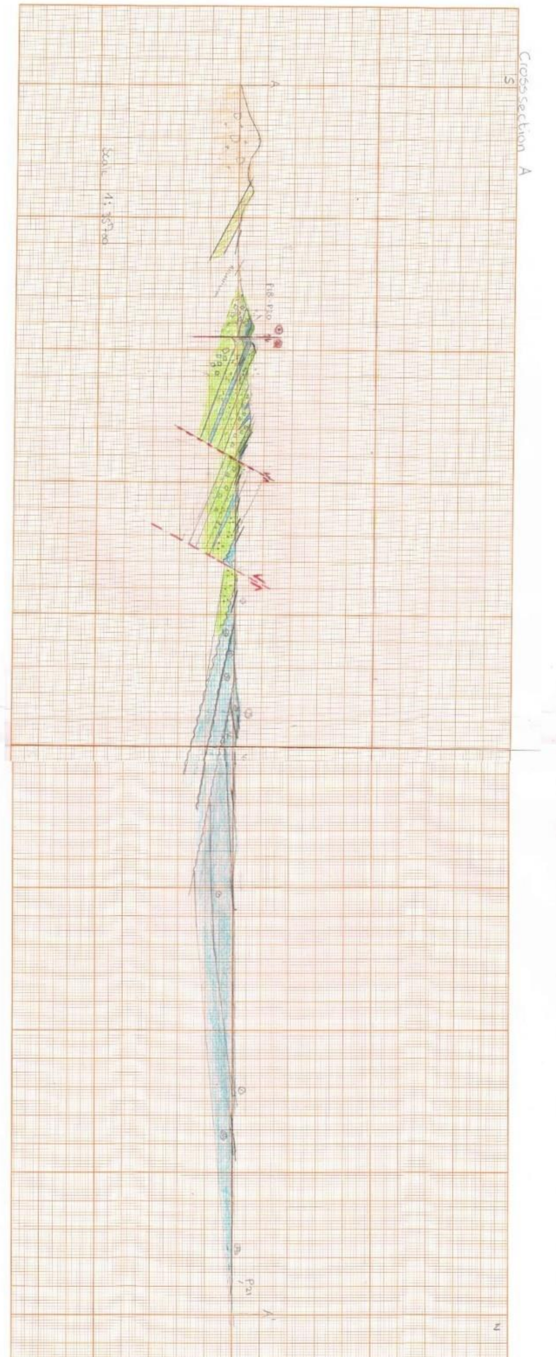


Revised geological map of Antigua showing data locations, faults and cross section lines.

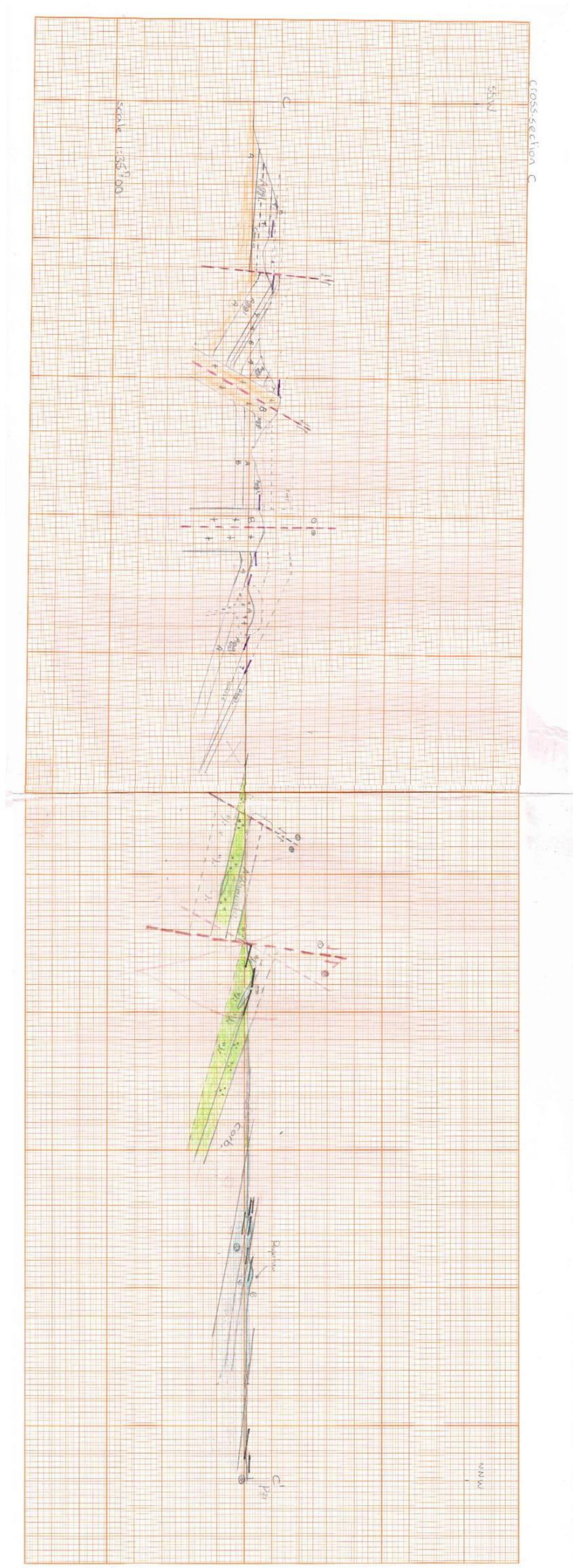

CENTRAL
PLAINS
GROUP

3. cross sections.

Cross section A

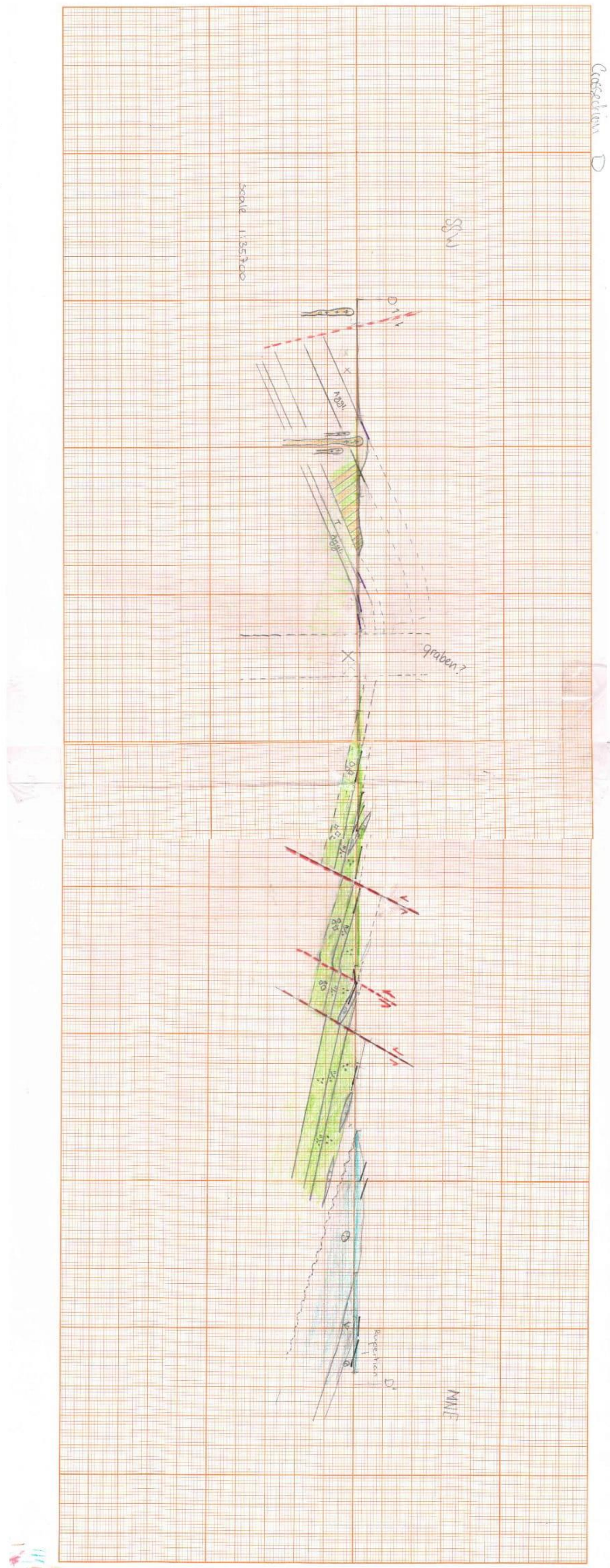


Cross section C



5.

Cross section D



6.

Cross section B