Biosis: Biological Systems (2021) 2(1), 1-173
https://doi.org/10.37819/biosis.002.01.0095

ORIGINAL RESEARCH

Stratigraphic Lexicon: The Onshore Cenozoic Sedimentary Formations of The Republic of Panama

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ABSTRACT

The stratigraphic knowledge of Panama was, until now, spread over hundreds of scientific/geologic publications written during the past 120 years. The construction of the Panama Canal during the early twentieth century helped galvanizing the engineering and geological disciplines to understand the tectonic, sedimentation and biodiversity of the Cenozoic Era in this part of the world. Later, few petroleum companies arrived on the scene and contributed to our knowledge of the sub-surface. The past thirty years saw a surge of studies by many institutions in areas away from the Canal, such as in Darien, Azuero Peninsula, Bocas del Toro, and the Burica Peninsula near the Costa Rica Border. Our most recent knowledge came from the widening of the Panama Canal between 2007 and 2016. It is from all these older and recent studies that the present Lexicon draws its content. It provides the historical background of all described geological units in Panama and summarizes the lithological and paleontological knowledge of each units in an easy-to-search format.

ARTICLE HISTORY

Received: 11-12-2020
Revised: 9-02-2021
Accepted: 17-02-2021

KEYWORDS

Panama
Geology
Paleontology
Stratigraphy
Lexicon
Cenozoic

1 Introduction

In early 2020, I was planning to retire in Panama from a life spent working overseas as a Petroleum/Mining Geologist and Oil & Gas Data Management Specialist. While in retirement in Panama, my plan was to investigate in the field the geological and paleontological treasures of the Republic in the same way that I had done in other countries (Qatar, Libya, Niger, Colombia, Canada, etc..). In preparation for this, and while still based in the Middle East, a large amount of publicly available publications was gathered about the surface geology of Panama. These would have been the basis for many interesting geological outings and investigations.

Unfortunately, the health restrictions imposed by the authorities in Panama due to the pandemic of Covid-19 stopped short my ambitions since the country closed its door to all foreigners over the period that I was to retire. I was left with no other choice but to return to Canada, where this first Lexicon of Geologic Names dedicated only to Panama saw the light. Other Lexicons do exist, such as Wilmarth (1938), Wilson et al. (1957), Hoffstetter et al. (1960) and Keroher (1966), but they are very old and, for the most part, their scope is greater than just Panama. So much has happened since they were written.

Therefore, using the mountain of knowledge in the geological publications that were previously gathered, I extracted all the pertinent material to make up the present Lexicon. It contains 145 Geologic Names (Appendix C) that cover the entire Cenozoic sedimentary Basins of the country. The system of rock unit terminology described herein has evolved since at least the turn of the 19th century. Some terms appeared in the nomenclature and disappeared almost immediately for various reasons, while others have endured since the early days or have been reassigned a thicker or smaller sequence within the Stratigraphic Column. Although most Group/Formation/Member names in this Lexicon concern units which are considered as having legitimate geologic values, some obsolete (indicated with *) and little-known names are also included. In some cases, recommendation is made to abandon some geologic names in favor of others or to completely disregard them. The Lexicon also mentions few igneous units that have a close affinity to the sedimentary formations occurring in the Cenozoic Basins.

The Lexicon discusses all the geological Basins in Panama; however, it must be stressed that the terminology within the Chiriqui Basin (Chiriqui Province) could gain from an access to stratigraphical studies not immediately available to the public. Should such studies become available to me, an attempt to update the Lexicon could be made. Also, Dr. Laurel Collins, of the Florida International University, invited me to scan all her non-digital collection of geological/paleontological articles on Panama, however due to the currently closed borders between Canada and the United States because of Covid-19 this offer could not be acted upon. When these circumstances change the offer will certainly be be revisited.

An updated geological map (and corresponding stratigraphic column) does not accompany this new Lexicon, however the maps of Ministerio de Comercio e Industrias (1991) (App-B3; App-B4) and Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) (App-B1; App-B2) are often referred to within the text and are to be used only to understand the evolution of the geologic names of Panama. For a lack of better maps, these two maps are extremely popular in the geological community, professional or amateur alike; however, while they look remarkably similar when compared with each other's, their stratigraphic columns on the other hand display striking differences in their details without discussing what brought about the differences. Only when one takes the time to read all the geological literature available on the subject between 1991 and 2020, that many recommendations for improvement can be made. For instance, some of the notable differences between the two maps are listed below:

- The Santiago Formation is listed as younger than the Gatún Formation in 1991, but older in 1996.
- The Caimito Formation is younger than the Panamá Formation in 1991 and older in 1996.
- The Culebra Formation is listed as older than Alajuela Formation in 1991 but younger in 1996.
- La Boca Formation is listed as younger than Alajuela in 1991 but older in 1996.
- The map of 1991 includes the formation names of Tuira, Boca de Chucara, Pucro, but are not mentioned on the 1996 map. There is no reason given for these discrepancies.
- The two 1991-1996 maps use the formation names of Gatún-Uscari Formation (Miocene) and Sinosri-Uscari Formation (Oligocene), especially over the Burica Peninsula area. These terms are misleading and should be abandoned and replaced by the names identified in the present Lexicon.
- There are also several misspellings of Formation/Member names, such as: Topaliza" instead of "Tapaliza"; "Chuqunaque" instead of "Chucunaque"; "Arusa" instead of "Aruza"; "Senosri" or "Sensori" instead of "Sinosri"; etc.
- In the two 1991-1996 maps, the Charco Azul Group is shown as a "Formation". It still has not been differentiated into "La Peñita", "Burica" and "Armuelles" Formations.
- The most recent formation names now identified in the "Bocas del Toro" area still have not been properly mapped and recorded.
- Etc..

Considering the above, it is recommended that future cartographers provide individual stratigraphic columns of each geological Basin in Panama rather than one general column encompassing the whole country. It will be easier to understand the position of each formation in relation to each other's.

It is hoped that the present work, the most up-to-date description of the Panama rock units, will foster discussions within the geoscience community of Panama and help their current and future geological projects.

2 Understanding the Lexicon

Section 6 of this document is the Lexicon proper. The description of all units (Group, Formation, Member, etc..) has been included within a similar format as the one shown below. If all the information exists regarding the Unit, the format will look exactly like the template on this page; however, if some information is not known, the title line concerned will have been removed completely. The text in italic within the below template explains the purpose of each line.

Unit: ***NAME of GROUP / FORMATION / MEMBER*** *stated in bold capitalized letters. When an asterix (*) precedes it, the name is obsolete, or recommended to be made obsolete.*
Epoch/Age/Author: *The Geological Epoch, and sometimes the Stage. The author(s) who has defined the Age of the Unit is also mentioned.*
Original Author and/or Origin of the Name: *This is the first author who named and formally or informally described the unit in some way or another. The origin of the name is mentioned when ever possible. This can be the name of a town, river, creek, hill, etc..*
Relevant documents discussing the Unit: *Other than the original author, this is the list of all pertinent references discussing the unit. The list is presented chronologically.*
Synonymy: *A Unit, or part of a unit, can be known under many other names for various reasons. Sometimes it involves a misspelling that was wrongly carried over for many years in the literature.*
Location of the type section / Stratotype / Reference Section / Other localities: *See definition of these terms under section "Definition of some terms" below.*
Lithology: *Description of the type of sediments/rocks that compose the Unit.*
Thickness: *The total thickness of the Unit discussed.*
Macro Fossils: *The fossil types that can be seen with the naked eye.*
Overlying Unit: *The name of the geological Group / Formation / Member immediately above it.*
Underlying Unit: *The name of the geological Group / Formation / Member immediately below it.*
Remarks: *Any pertinent comments*
Maps, Cross-Sections & Pictures: *Any images that can help understanding the written description above.*

3 Definition of some terms

Atlantic Meridional Overturning Circulation (AMOC)

The zonally-integrated component of surface and deep currents in the Atlantic Ocean. It is characterized by a northward flow of warm, salty water in the upper layers of the Atlantic, and a southward flow of colder, deep waters that are part of the thermohaline circulation. These "limbs" are linked by regions of overturning in the Nordic and Labrador Seas and the Southern Ocean. The AMOC is an important component of the Earth's climate system, and is a result of both atmospheric and thermohaline drivers.

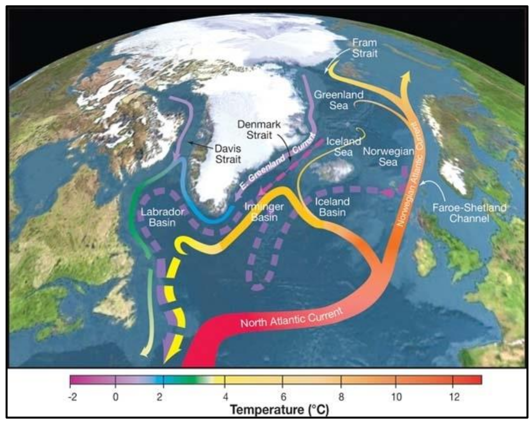


Figure 001. AMOC (Source: https://en.wikipedia.org/)

Atrato Seaway (or "Central American Seaway", CAS)

The deep oceanic seaway along the tectonic boundary of the South American plate and the Panama microplate which closed 10 Ma ago (Figure 007) and interrupted the exchange of deep waters between the Caribbean and the Pacific. It also generated most of the landscape across the Isthmus (exchange of shallow waters continued until 3.5Ma, albeit intermittently). Jaramillo (2018).

Barro Colorado Island

Located in the man-made Gatún Lake in the middle of the Panama Canal. The island was formed when the waters of the Chagres River were dammed to form the lake in 1913.

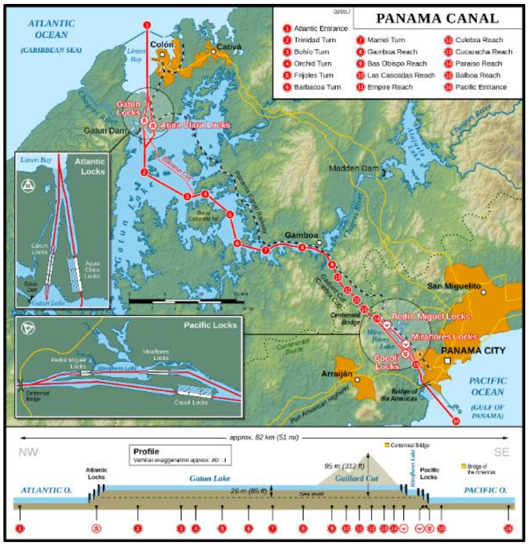


Figure 002. A schematic of the Panama Canal, showing Barro Colorado Island, Alajuela Lake, Gatún Lake, Gamboa, Panama City, Colon and all the locks along the Canal. (Source: https://en.wikipedia.org/)

Caribbean large igneous province (CLIP)

CLIP formed as a large igneous province and now forms a thickened zone of oceanic crust between the North American and South American Plates. In some places the oceanic crust is 2–3 times as thick as normal oceanic crust; 15–20 km vs 7 km. CLIP consists of a major flood basalt, which created this large igneous province (LIP). It is the source of the current large eastern Pacific oceanic plateau, of which the Caribbean-Colombian oceanic plateau is the tectonized remnant. The deeper levels of the plateau have been exposed on its margins at the North and South American plates. The volcanism took place between 139 and 69 million years ago, with the majority of activity appearing to lie between 95 and 88 Ma. The plateau volume has been estimated as on the order of 4 x 106 km³.

Centenario Fauna

One of the most productive zones for the discovery of terrestrial vertebrate fossils comes from a 115m stratigraphic interval that includes the uppermost part of the Culebra Formation and the overlying Cucaracha Formation (see description of each individual formation) in the Panama Canal Basin. The fossils from this interval have been referred to as the Centenario Fauna (MacFadden et al. (2010)), which takes its name from the Centenario Bridge that spans the Culebra Cut along the southern reaches of the Panama Canal north of the Pedro Miguel locks. The paleobiogeography of the mammals from the Centenario indicates entirely North American affinities and thus a significant expansion of the North American Land Mammal Age (NALMA) biochronology (APP-A) into the low latitudes of the ancient North American tropics was applied to this assemblage. MacFadden (2014) conducted several $^{40}Ar/^{39}Ar$ and U-Pb zircon age tests within the Centenario fauna interval and conluded that the Centenario Fauna spanned an interval of 0.27Ma between 18.78 and 19.05Ma; thus placing it completely within the Lower Miocene (Burdigalian). The Miocene was an important time in mammalian evolution and biogeography in the Americas. It was the time of the Middle Miocene Climatic Optimum, the spread of grasslands, and the beginnings of the Great American Biotic Interchange, to name a few of the important events (Woodburne (2010)). Since the designation of the Centenario Fauna, new additions have included descriptions of plants (Herrera et al. (2010)), crocodilians (Hastings et al. (2013)), turtles (Cadena et al. (2012)), and boid snakes (Headet al. (2012)).

Culebra Cut (formerly called "Gaillard Cut") (Figure 002 and Figure 003**)**

The Culebra Cut, formerly called Gaillard Cut, is an artificial valley that cuts through the Continental Divide in Panama. The cut forms part of the Panama Canal, linking Gatún Lake, and thereby the Atlantic Ocean, to the Gulf of Panama and hence the Pacific Ocean. It is 7.8 miles (12.6 kms) from the Pedro Miguel lock on the Pacific side to the Chagres River arm of Lake Gatún, with a water level 85 feet (26 m) above sea level.

"Culebra" is the name for the mountain ridge it cuts through and was also originally applied to the cut itself. From 1915 to 2000 the cut was named Gaillard Cut after US Major David du Bose Gaillard, who had led the excavation. After the canal handover to Panama in 2000, the name was changed back to Culebra. In Spanish, the cut is known as the Corte Culebra and is also called the Snake Cut.

Las Cascadas: 9°4' 52.1394″N, 79°40' 42.5994″W;
Lirio Norte: 9°3' 22.327″ N, 79°39' 35,8″W;
Lirio Este: 9° 3' 4.6434″N, 79°38' 58.1784″W;
Hodges: 9°2' 51.7014″N, 79° 39' 13.7298″W;
Cartagena: 9° 10' 14.412″N, 79°37' 12.61″W.

Pimiento's et al. (2013b)

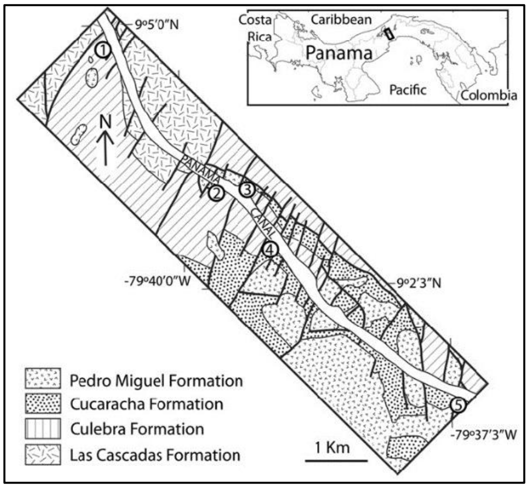


Figure 003. Some sites along the Culebra Cut.

Emperador Limestone (Formerly named "Empire Limestone")

Early in the Culebra Formation stratigraphic sequence there exist limestone and patchy coral reefs that are collectively referred to as the Emperador Limestone, the middle Member of the Culebra Formation composed of 5 facies. (See the description of the "Culebra Formation" and "Emperador Limestone" for more details)

Endocarp

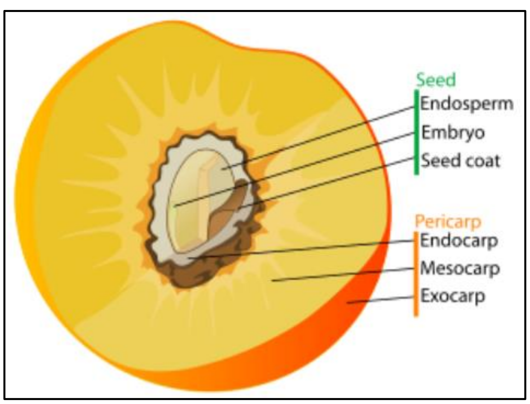


Figure 004. The innermost layer of the pericarp which surrounds a seed in a fruit. It may be membranous (as in apples) or woody (as in the stone of a peach or cherry). (Source: Fruit anatomy - Wikipedia)

Humiriaceae

A family of evergreen flowering plants. It comprises 8 genera and 56 known species. The family is exclusively Neotropical, except one species found in tropical West Africa.

Lahar

A destructive mudflow on the slopes of a volcano.

Las Cascadas Fauna Assemblage, or Lirio Norte Local Fauna

The late Arikareean (~21 Ma) "Lirio Norte Local Fauna", known also as "Las Cascadas Fauna Assemblage" represents terrestrial mammalian communities from the uppermost part of the Las Cascadas Formation (Figure 093). This interval includes discrete fossiliferous sequences of subaerial volcanic products deposited in sporadic fluvial settings. Rincon (2016)

Madden Reservoir Basin, Madden hydrological Basin, Madden Lake (Figure 002)

Now called Alajuela Reservoir Basin and Alajuela hydrological Basin respectively

NALMA (APP-A)

The North American land mammal ages (NALMA) establishes a geologic timescale for North American fauna beginning during the Late Cretaceous and continuing through to the present. These periods are referred to as ages or intervals (or stages when referring to the rock strata of that age) and were established using geographic place names where fossil materials were obtained

Reference Section

The designated exposure of a named layered stratigraphic unit or of a stratigraphic boundary that serves as the standard of reference.

A surface exposure of rock or a rock volume penetrated by a well in which lithologic characteristics of a particular rock unit are well illustrated. The well in question is called "Reference Well"

SALMA (APP-A)

The South American land mammal ages (SALMA) establish a geologic timescale for prehistoric South American fauna beginning 64.5 Ma during the Paleocene and continuing through to the Late Pleistocene (0.011 Ma). These periods are referred to as ages, stages, or intervals and were established using geographic place names where fossil materials where obtained.

Sedimentary Basin

The term “Basin” has different meanings depending on its location and containment. Groundwater Basin is for aquifers; drainage Basin delineates a river system; oceanic Basin refers to the abyss; and sedimentary Basin is a depression in the earth’s crust filled with sediments. Sedimentary Basins are on the scale of tens to hundreds of kilometers in length and width, and thousands of meters in depth. As such they are usually tectonic Basins formed by plate tectonic processes. Basins may also be described in terms of depositional environment (fluvial, eolian, deltaic, lacustrine, continental, marine, reefal, abyssal) or sedimentary fill (clastic, carbonate, evaporate, turbidite) or what economic resource they contain (petroleum, natural gas or coal). Only a tectonic classification explains the origin and evolution of sedimentary Basins and their sediment fill. More details can be found in Sorkhabi (2019).

Stratotype

See “Type Locality”

Type Locality

Also called type area, or type section, is the locality where a particular rock type, stratigraphic unit, fossil species or mineral is first identified. If the stratigraphic unit in a locality is layered, it is called a stratotype, whereas the standard of reference for unlayered rocks is the type locality.

4 Brief geological background of Panama

The Republic of Panama is a transcontinental country in Central America and South America, bordered by Costa Rica to the west, Colombia to the southeast, the Caribbean Sea to the north, and the Pacific Ocean to the south. It covers an area of 75,417 km^2 (29,119 sq mi); its population is about 4,177,000 inhabitants and its capital is Panama City. (www.wikipedia.org)

The geology of Panama has been described initially by Hill R.T. (1898), Bertrand and Zürcher (1899), Olsson (1922, 1942), Terry (1956), Woodring (1957) and Weyl (1980). The geology of the Caribbean Basin was described by Dengo and Case (1990). The Pacific Plate margin of Panama (and Costa Rica) was described in Mann (1995). The most recent tectonic research on the Caribbean Plate and Northern Andes was performed by James et al. (2009). Arc magmatism in Panama from the Late Cretaceous to present was described by Lissinna (2005), Wegner et al. (2011), Montes et al. (2012a, 2012b) and Farris et al. (2011, 2017). The geology of the Eastern Region was described by Redwood (2019). Many other authors mentioned in reference have described more localized geology but always keeping in mind the bigger picture and the work of all those who preceded them. Paleocene and early Eocene sedimentary rocks have not been recognized in the Isthmus of Panama, with a possible exception with the uppermost part of the Ocú Formation. The oldest recognized Cenozoic sedimentary rocks comprise the Darien (East Panama) and Gatuncillo, Tonosí and Covachón Formations (Azuero Peninsula).

The Changuinola group, of the Mesozoic Period, is sub-divided in the Changuinola, Ocú and Piriatí Formations, with the first two formations standing out as they are the ones with the highest percentage of sedimentary composition. Another older group from this Period is the Paraguito, which contains the Paraguito, Tiurti and C. Sardina Formations. The sequence culminates with the oldest Cuango Formation below the Paraguito Group. These Mesozoic formations are not described in the present Lexicon (Appendix B).

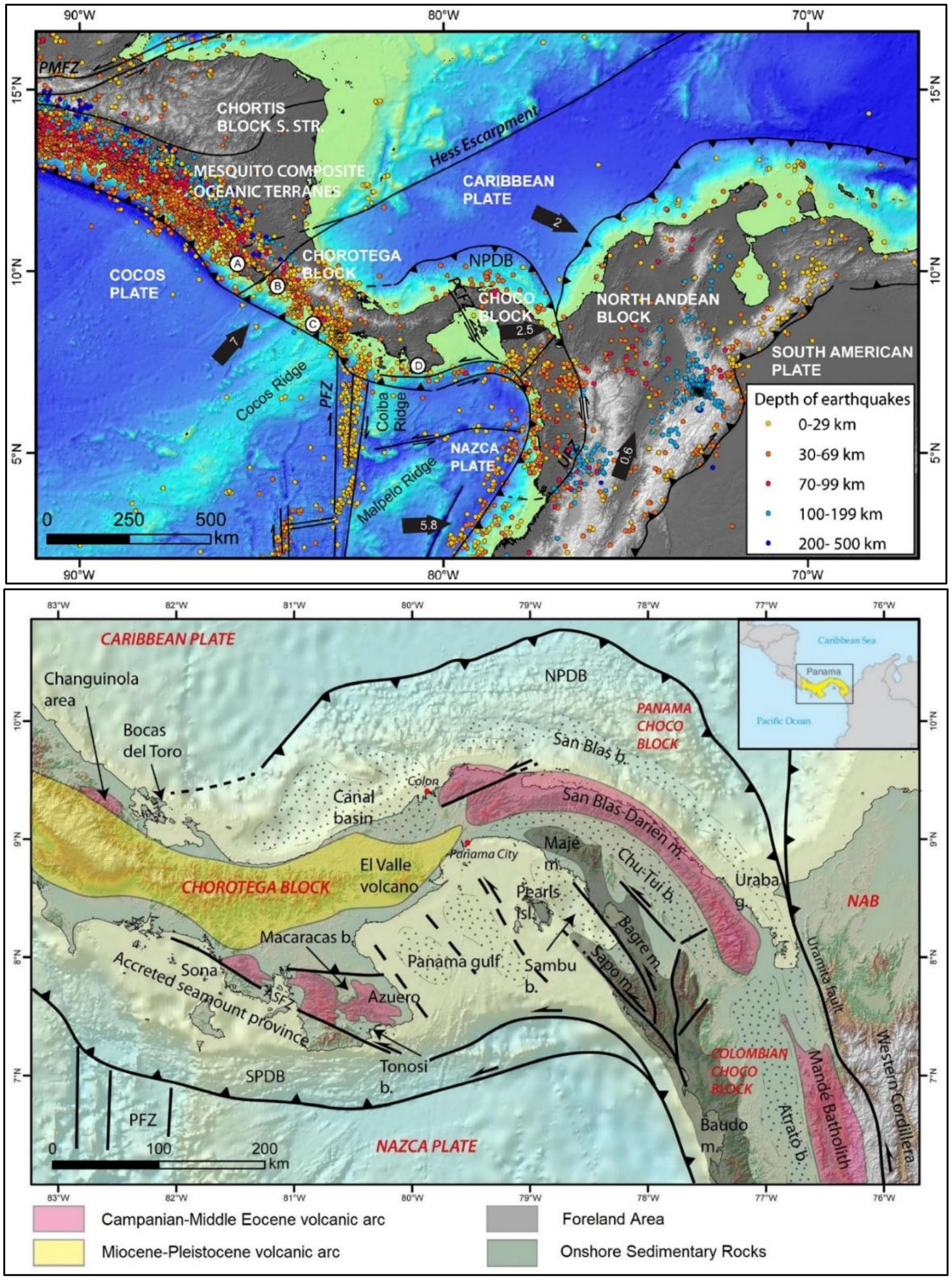


Figure 005. Above - Tectonic and geological context of Central America. The seismicity was taken from the USGS catalog (2002–2009) and the Engdhal catalog (1900–2002). Black arrows show present day GPS relative velocities of major tectonic plates and blocks (white velocities in cm/yr) relative to stable South America (Trenkamp et al. (2002)). Letters A to D represent accreted geological complexes: (A) Nicoya; (B) Herradura; (C) OSA peninsula; and (D) Azuero peninsula. Below - Simplified tectonic map of Panama: ASFZ : Azuero-Sona Fault Zone, PFZ : Panama Fault Zone, NPDB : North Panama Deformed Belt, SPDB : South Panama Deformed Belt, NAB : North Andean Block. (Modified from Barat (2013)).

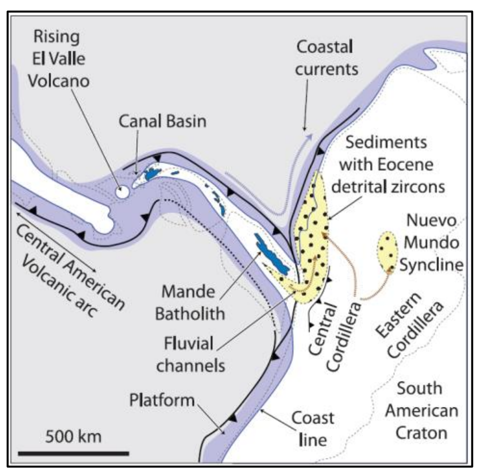
The Isthmus of Panama is located on a tectonic macroplate called the Panama Plate (a southwestern extension of the Caribbean Plate). This macroplate is seismically active, due to the collision of four large tectonic plates: the Caribbean Plate (extending to the north), the

Nazca Plate (to the south), the Cocos Plate (to the southwest) and the South American Plate (to the east) (Figure 005). Panama displays at least one impact structure[1] (Tornabene (2001); Heckadon-Moreno (2013)) and a recent seismotectonic history of the Cenozoic involving the South America and North America Collision, a time when the structures that are currently known emerged.

During the early–middle Eocene (50–43 Ma), a large exhumation pulse occurred, which was probably the result of the accretion of intraplate Pacific volcanoes to the southern boundary of the Caribbean plate. This accretion generated the first terrestrial land in Panama during the late Eocene (Figure 007): a large island that extended from the present-day Azuero Peninsula to central Panama (Jaramillo (2018)). A second major build-up of the terrestrial landscape occurred during the early Miocene (~21Ma). By 19-20 Ma, Panama would have been a peninsula connected to North America, with an oceanic pathway (CAS) (Figure 007 & Section 3: Definition of some terms) between Panama and South America connecting the Pacific and Atlantic Oceans (Jaramillo (2018)). Bathyal sediments in the upper Member of the Culebra Formation suggest that a short-lived strait may have existed across the Panama Canal Basin between 21 and 20 Ma (Figure 028) (Kirby et al. (2008)). A third occurred during the late Miocene (~12–10 Ma) (Figure 007). There was an extensive exhumation pulse during the late–middle Miocene to the late Miocene (15–10 Ma) (Jaramillo (2018)). This pulse was produced by the collision of the Panamanian Volcanic Arc with South America, which resulted in the closure of the CAS (Montes et al. (2015)) by 10 Ma, ending the exchange of deep and intermediate waters between the Caribbean and the Pacific (Jaramillo (2018)). From 10.0 to 3.5 Ma, there were intermittent Caribbean–Pacific connections through pathways other than the CAS, allowing the migration of chondrichthyans between Basins (Carillo-Briceno (2015)). At 3.5 Ma, there was a complete closure of the Isthmus (Figure 007). Jaramillo (2018)

Numerous paleoclimatic and paleoceanographic studies have addressed the implications of the rise of the Isthmus, from both modeling and empirical perspectives. Although models differ in the assumed width and depth of the CAS, almost all of them produce similar results. Once the CAS is closed, the salinity of the Atlantic Ocean increases, and Atlantic Meridional Overturning Circulation (AMOC) (Figure 001) is greatly enhanced. Sepulchre et al. (2014) found that the CAS depth is critical for paleoceanographic purposes. Once the flow of deep and intermediate waters (>200 − 500 m depth) of the Pacific Ocean into the Caribbean is interrupted, AMOC is enhanced. Additional reduction of shallow water flow across the Isthmus does not greatly affect Atlantic Ocean circulation. Empirical evidence indicates that AMOC is much older than 3.5 Ma, and that it has become significantly stronger since the late Miocene, 12–10 Ma. This new geological evidence allows for the reconciliation of the empirical evidence of the link between AMOC and the closure of the CAS, as most modeling exercises have predicted – not at 3.5 Ma, as has been traditionally accepted, but rather at 12–10 Ma. Jaramillo (2018)

The above also agrees with Montes et al. (2012b & 2015) who studied ancient river deposits found in northern Colombia. Through a combination of geochronological analysis and geological mapping, they determined the age, origin, and pathway of this river. They show that the river system began to flow about 15 to 13 million years ago and could not have originated in any other place than the volcanic arc of Panama. This means that a terrestrial connection must have existed between northern Colombia and the river's source area at this time (Figure 006).



[1] The Gatún Structure (N 09º 05' 58.1", W 79º 47' 21.8", situated in the triple-canopy rainforest 10 km to the WSW of the Gamboa and about 2 km south.

Figure 006. Paleogeographic reconstruction of the Panama arc and northwestern South America during middle Miocene times (13 to 15 Ma) according to Montes et al. (2015).The first detrital loads from Panama arrived in one of two, or both, paths to the Basins of northwestern South America: (i) along coastal currents transporting detritus product of the erosion of exposed plutonic rocks along the northern coast of the Panama arc and/or (ii) along fluvial channels draining emerging ranges parallel to the length of the Isthmus.

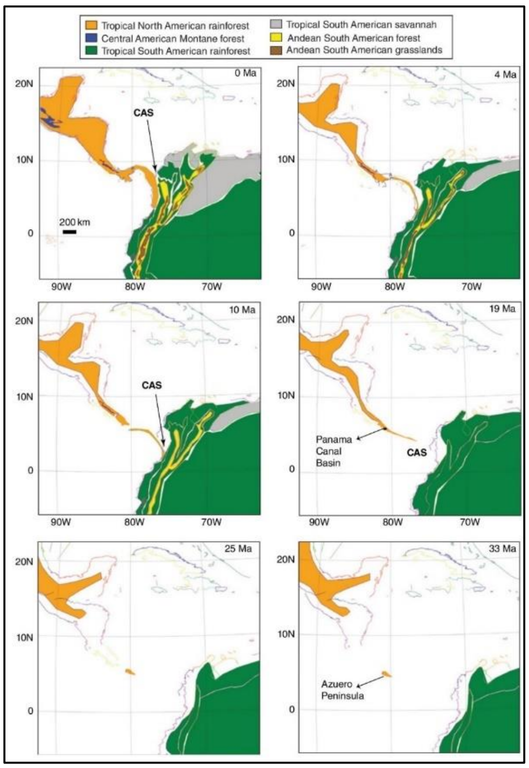


Figure 007. Paleogeographic reconstructions of Central America as per Jaramillo (2018). Terrestrial biome reconstruction for the past 36 My of the Isthmus of Panama. The reconstruction is an orthographic projection based on the plate tectonic model of GPlates 1.5.0, using the plate reconstruction of Seton et al. (2012). Terrestrial biomes include the tropical rainforest from South America, the tropical rainforest of North America (corresponding to the Central American rainforest), the Central American montane forests (forest >2000 m elevation), the Andean South American forest (forest >2000 m elevation) and the Andean South American grasslands (grasslands above the tree line in the Andes of South America).

Other relevant studies confirming the above scenario (Figure 007) include Kirby & MacFadden (2005) who tested the paleogeographic models by comparing the size of teeth (as a proxy for body size) of middle Miocene land mammals from the Cucaracha Formation in Panama with their conspecifics in North America. They concluded that the land mammals from Panama had ready gene flow with populations in North America across a continuous peninsula during the middle Miocene. Bacon et al (2013) tested the geological models of evolution of the Isthmus of Panama in a phylogenetic framework by studying several species of palm trees. Their results supported recent geological and palaeobiological data that suggest an early Oligocene to early Miocene model of evolution of the Isthmus of Panama. Lastly, over 2000 publications (compiled in Bacon et al. 2015) have cited an age of 4.2–3.5 Ma for the rise of the Isthmus. Jaramillo (2018)

In addition, during the last 20 years of paleontological expeditions in different sedimentary Basins of Brazil, Colombia, Costa Rica, Ecuador, Jamaica, Trinidad, Panama, the Dominican Republic and Venezuela, teleost otoliths have been found along the tropical western central Atlantic (TWCA) and the tropical eastern central Pacific (TECP); these otoliths relate to the amphi-American distribution of fishes and the paleoceanographic and paleoenvironmental changes in the region during the Cenozoic. This investigation lead Gonzalez-Castillo et al. (2020) to adjust/refine the correlation of the exposed formations involved in Panama (Figure 008).

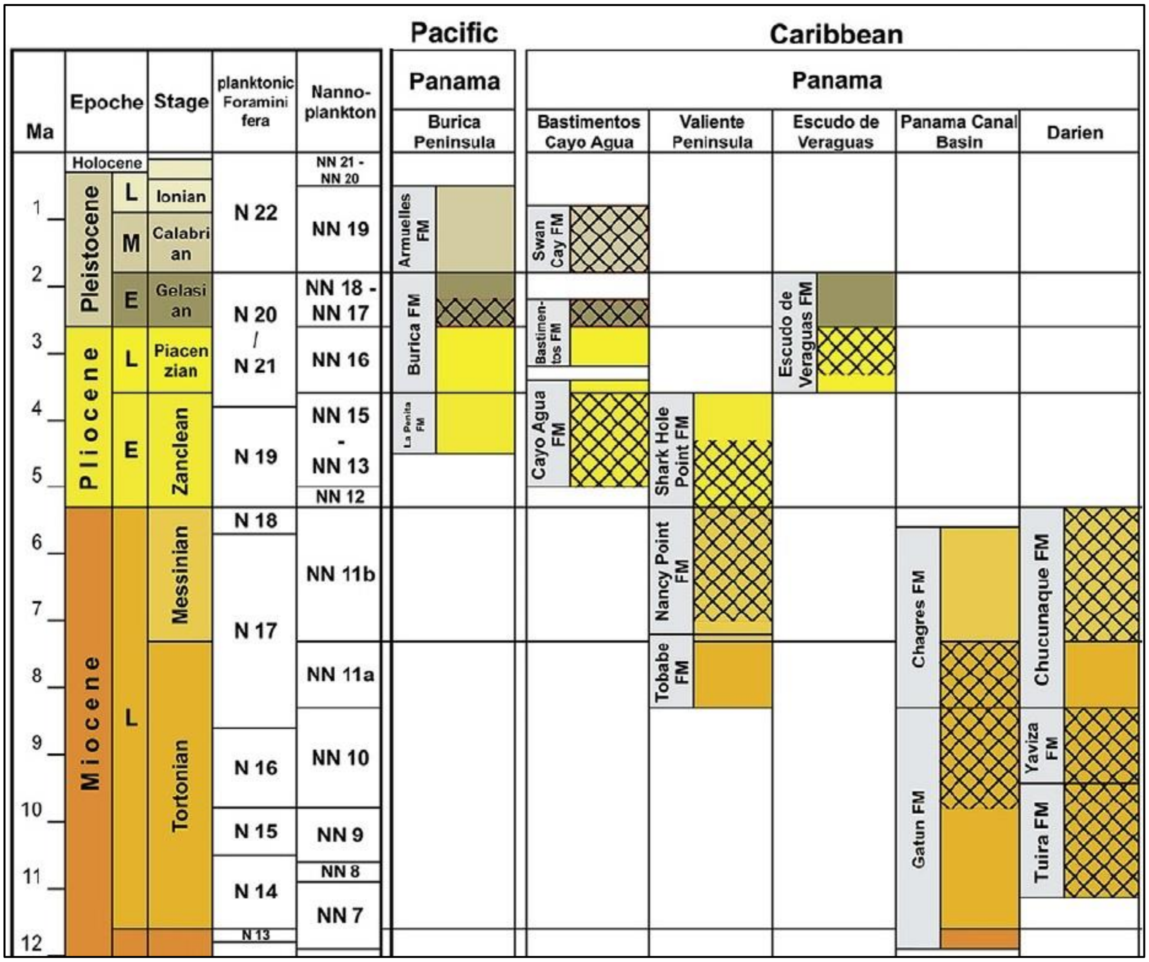


Figure 008. Stratigraphic correlation chart depicting stratigraphic positions of otoliths obtained from Panama. (Gonzalez-Castillo et al. (2020))

The importance of the formation of the Isthmus of Panama cannot be denied. It was important because it allowed the mixing of terrestrial faunas between the two continents (Figure 009), as well as physically separating a once continuous marine province into separate and distinct Pacific and Caribbean communities. Older studies (Kirby et al. (2008)) believes that the formation of the Isthmus of Panama also ultimately led to profound changes in global climate by strengthening the Gulf Stream and thermohaline downwelling in the North Atlantic. However, more recent studies (Sepulchre et al. (2014) & Brierley and Fedorov (2016)) shed some doubts by showing that models do not support any influence of the Panama Isthmus on climate during the Pliocene.

During the Cenozoic, and especially during the Miocene, the volcanism was of the Continental type, very explosive, and created the main mountain range that can be observed today in the country. In addition to the volcanic rocks, marine sediments were deposited in the various geological Basins of the country during calmer time intervals of the Eocene to the current period.

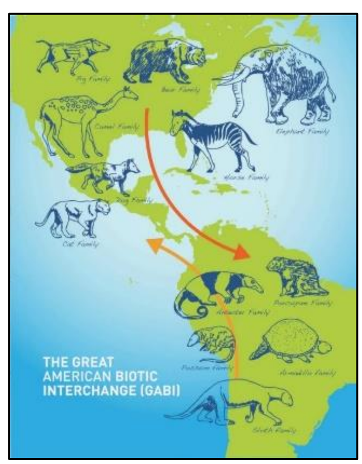


Figure 009. Migration of terrestrial animals between the Americas after the formation of the Isthmus of Panama. Roberti (2015).

5 The Cenozoic sedimentary basins of Panama

One main offshore Cenozoic sedimentary Basin (Gulf of Panama) and eigth onshore Cenozoic sedimentary Basins are present in Panama. These are shown in Figure 010 and described individually in the pages that follow. Two additional, less important, offshore Basins (Cebaco & Montuosa) exist west of the Azuero Peninsula but will not be discussed in the present document. The "Gulf of Panama" Basin has been included in the description due to the Pearl Islands located near its centre.

For the purpose of this description, the country has been divided into two Regions: the **Eastern Region** (Section 5.1**)** (including Río Bayano Basin, the Sambu Basin, the Chucunaque – Tuira Basin, and the Gulf of Panama Basin), and **Western Region** (Section 5.2) (including the Panama Canal Basin, the Tonosí/Azuero Basin, the Bocas del Toro Basin and the Burica Basin). The sedimentary formations within the Chiriqui Basin (Chiriqui Province) are mentioned in the Lexicon but the Basin itself is not described below due to the lack of public information about it.

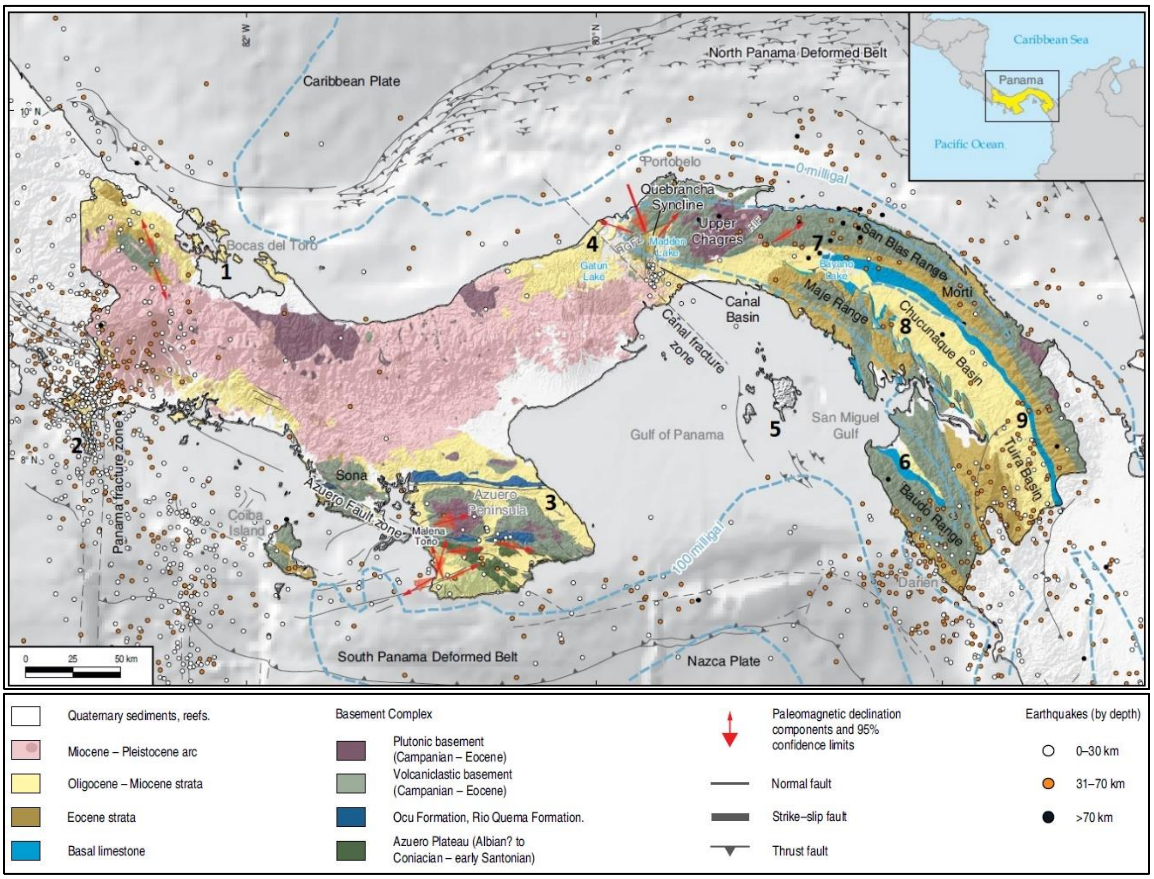


Figure 010. Simplified Geologic map of the Isthmus of Panama (modified from ©Montes & Hoyos (2020); see "Open Access Statement" in the reference section). Topography and earthquakes from Amante & Eakins (2009), U.S. Geological Survey (2010, 2017). (RGFZ) Río Gatún Fault zone; (RIF) Río Indio Fault. The nine sedimentary Basins included in this lexicon are represented by numbers 1 to 9 as follows: **1)** Bocas del Toro Basin; **2)** Burica Basin; **3)** Tonosí/Azuero Basin; **4)** Panama Canal Basin; **5)** Gulf of Panama Basin (offshore); **6)** Sambu Basin (onshore/offshore); **7)** Río Bayano Basin; **8)** Chucunaque Basin; **9)** Tuira Basin. See also Figure 005.

5.1 The Eastern Region

The Darién Isthmus of eastern Panama is bounded by a northwest-trending set of rugged mountains along both its Caribbean and Pacific coasts. These include the San Blas and Darién ranges along the Caribbean coast, and the Majé, Bagre, and Sapo ranges along the Pacific side. These coastal highlands flank an elongate lowland Basin centered along the broad valleys of the Bayano, Chucunaque, and Tuira rivers. On the Pacific coast, the Gulf of San Miguel forms a deep bight into the coastal mountains where the Tuira river estuary drains from the central lowland into the ocean. Much of the humid and rugged landscape of the Darién Isthmus remains cloaked in dense tropical vegetation, contributing to its reputation as one of Central America's most remote regions. Marshall (2007).

The coastal massifs of the Darién Isthmus expose a Cretaceous-Eocene crystalline basement complex comprised predominantly of highly deformed mafic igneous rocks. These rocks belong to the Chocó block, an allocthonous oceanic basement terrane that lies beneath eastern Panama and western Colombia. The Chocó block is separated from the Chorotega block to the west, across Cenozoic basement faults of the Panama Canal Discontinuity. Marshall (2007).

The basement rocks of the Darién region are overlain along the flanks of the coastal mountains by Eocene-Miocene pillow basalts and deep marine sediments deposited prior to Panama's collision with South America. These rocks are inturn buried by a thick, post-collisional sequence of Neogene siliciclastic sediments within the core of a complex synclinorium centered along the Bayano-Chucunaque Basin. Marshall (2007).

Within Panama and southern Costa Rica, the Chocó and Chorotega basement terranes together form the modern Panama block, a semi-rigid microplate that is caught between the Caribbean, Cocos, Nazca, and South American plates. Fold and thrust belts offshore of both the northern and southern Darién isthmus (North and South Panama deformed belts) accommodate active convergence with the Caribbean and Nazca plates. Active collision between the Panama block and the South American craton to the east occurs across thrust faults of the Atrato-Urubá suture zone in western Colombia. Marshall (2007).

The earliest geological studies of the eastern region were carried out in the mid- to late nineteenth century to explore possible routes for a trans-isthmian canal in eastern Panama and the Atrato Basin in Colombia (Wyse (1877)) and again in the mid-twentieth century to explore for sea-level canal routes (Governor of the Panama Canal (1947a, 1947b, 1949); Schmidt et al. (1947); Interoceanic Canal Study Commission (1968); MacDonald (1969)). The sedimentary Basins were explored for oil by geological mapping along rivers, seismic surveys and limited drilling in the twentieth century and are generally better studied than the oceanic and arc rocks of the mountain belts. Mineral reconnaissance programmes were carried out in the mountain belts of eastern Panama by the United Nations Development Programme (UNDP) in the late 1960s to early 1970s, which added greatly to the geological knowledge of these areas. The structural geology of the Eastern Region is shown in Figure 012; the the stratigraphy detailed in Figure 011 and the location of five cross-sections (Figure 015; Figure 016; Figure 018; Figure 019) is seen in Figure 013. The basement San Blas Complex of Coates et al. (2004) outcrops in the mountains of San Blas, Majé, Bagre, Sapo, Jaque, the Gulf of San Miguel, the Pearl Islands and the Portobello Peninsula. It comprises basement of oceanic crust including pillow and massive basaltic lavas with red radiolarites and cherts (Case et al. (1971); Case (1974)). The Pearl Islands correspond to a large anticline which could represent the continuity of the Sapo Massif, an onshore anticline with matching characteristics (Barat (2013)). The Sapo basalts were dated to the Turonian at 88 Ma, (Lissinna 2005), and the oceanic crust is dated at Coniacian to Lower Campanian. The oceanic crust is interpreted to have formed at the Caribbean Large Igneous Province (CLIP) oceanic plateau (Kerr et al. (1997)).

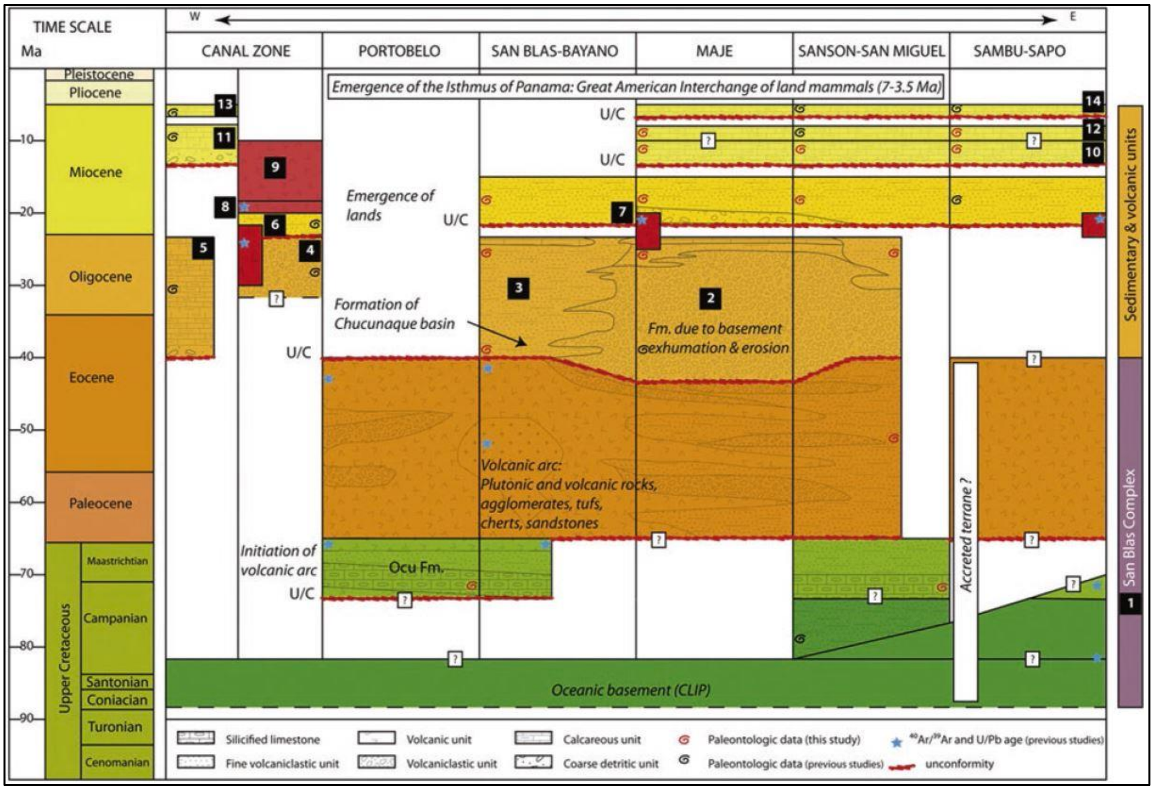


Figure 011. Synthetic chronostratigraphic chart of the different areas of study. The Canal Zone area shows a comparison with the eastern Panama data. Colors are identical to the associated cross sections (Figure 016; Figure 018; Figure 019) (Barat (2013) and Barat et al. (2014)). **1)** San Blas Complex; **2)** Darien Formation; **3)** Porcona Formation; **4)** Bas Obispo Formation; **5)** Gatuncillo Formation; **6)** Las Cascadas Formation, La Culebra Formation and Cucaracha Formation; **7)** Clarita Formation; **8)** Pedro Miguel Formation; **9)** Late Basalts Formation; **10)** Tapaliza Formation; **11)** Gatún Formation; **12)** Tuira Formation; **13)** Chagres Formation; **14)** Chucunaque Formation.

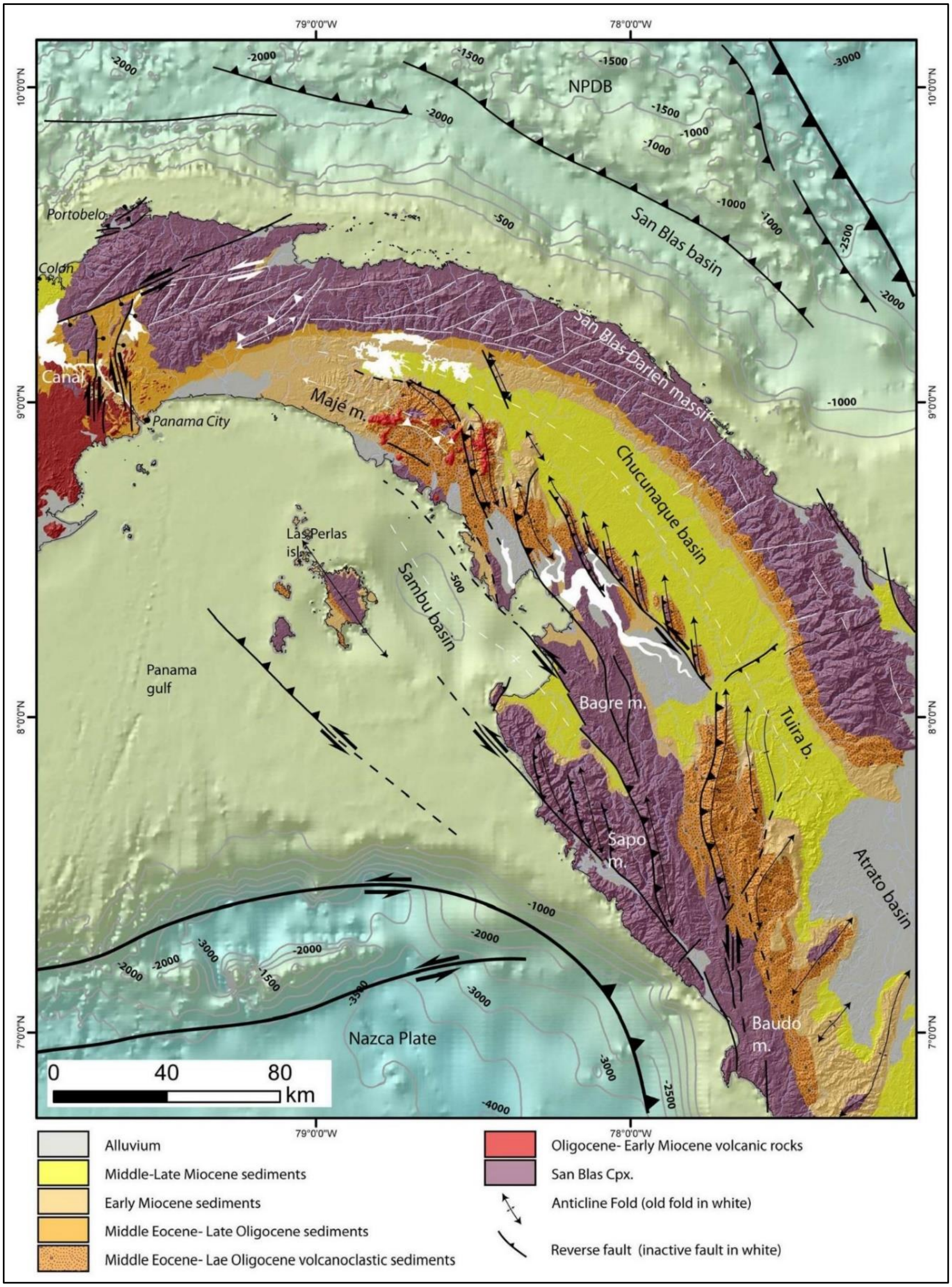


Figure 012. Simplified structural map of the Eastern/Darien Region of Panama. Barat (2013)

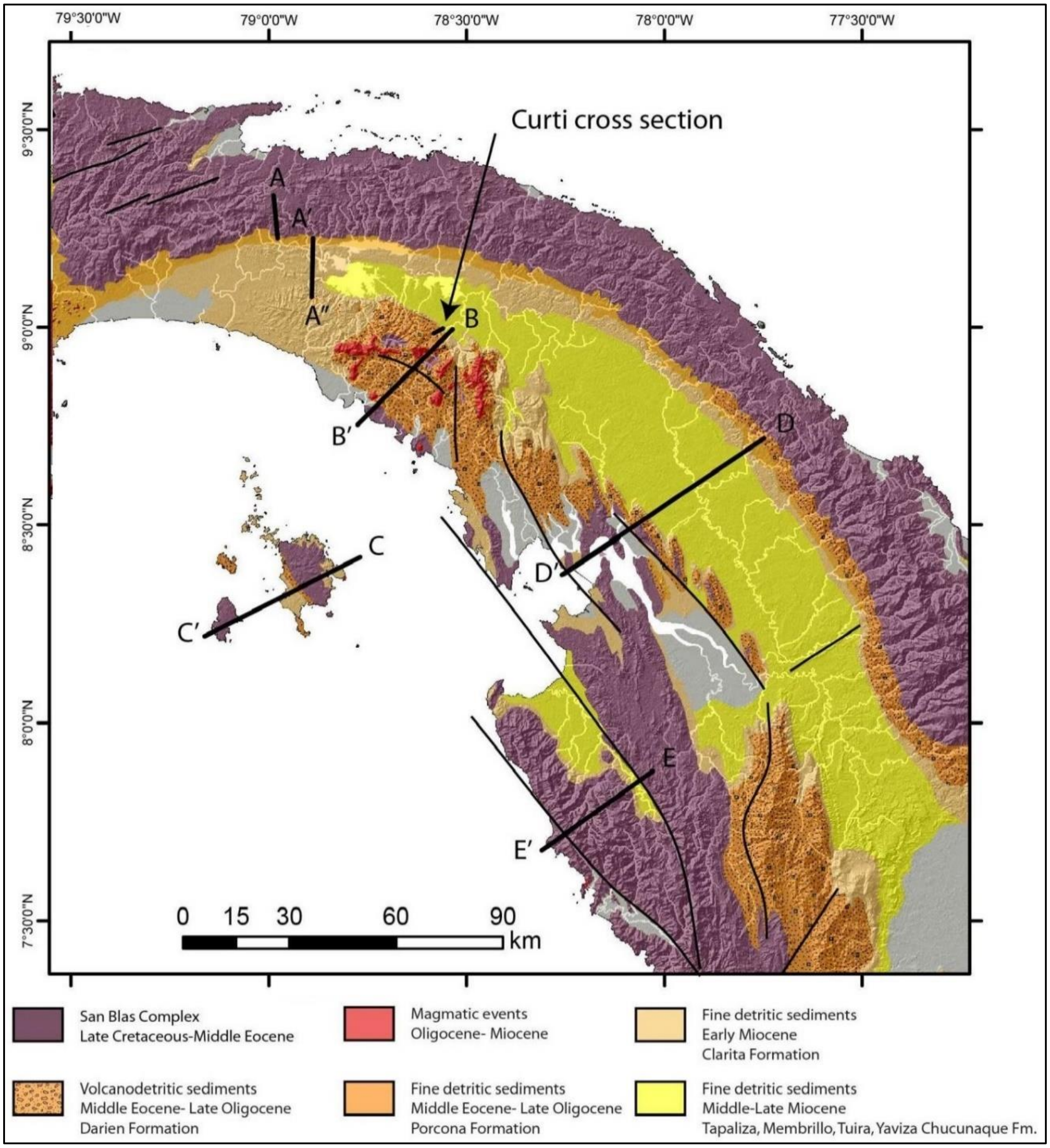


Figure 013. Simplified geological map of the Eastern/Darien Region of Panama. Cross-Sections **A** to **E** are represented in Figure 015; Figure 016; Figure 018; Figure 019. Modified from Barat (2013)

5.1.1 - THE RÍO BAYANO BASIN (Figure 014; Figure 015)

5.1.1.1 – Regional Geological studies

In the period between November 1969 and 1972, the Government of Panama, in conjunction with UNDP, carried out a regional geological survey of the Azuero Mining Project. This study included the Majé and San Blas-Darién Regions, within which the Bayano River Basin is located. In 1966, Robert Stewart produced the geological report "The Río Bayano Basin", related to the study of the interoceanic canal, for the Panama Canal Company. In 1970-1971, the Esso Exploration Company and Production (1970, 1971a, 1971b), with the interest of carrying out oil exploration to the east of the Province of Panama and in the Province of Darién, made several stratigraphic sections and a preliminary geological map. From 1970 to 1972 the IRHE carried out geological studies in the middle course of the River Bayano, in order to build the Bayano Hydroelectric. Gobierno Nacional, Republica de Panama (2017).

5.1.1.2 – Geology of the Bayano Basin (Gobierno Nacional, Republica de Panama (2017)).

The Cordillera de San Blas is made up of undifferentiated volcanic cretaceous rocks (Kv) that include andesitic and basaltic lavas, volcanoclastic as agglomerate variety and tuffs; as well as intrusive rocks (Ki) granodiorites, quartzodiorites, tonalite, diorites, syenite and granite. More recent studies, such as that of Lissinna in 2005, establish new ages for this igneous rock complex, between 49 and 62 Ma, locating them in the Paleocene to the lower Eocene.

The Maje Cordillera is made up of Paleogene to Oligocene and Miocene volcanic rocks, which include andesitic and basaltic lava and volcanoclastic, as well as undefined Paleogene sedimentary rocks to Oligocene and Lower Miocene sedimentary rocks. Lissinna's 2005 report indicates that the Maje Cordillera is 18 to 32 Ma in age, thus locating them as part of the Oligocene to Lower Miocene volcanic arc.

The lower course of the Bayano River extends over sedimentary rocks from the Oligocene to the lower Miocene Tapaliza Formation

In a general sense, the succession in the Lago Bayano area consists of Cretaceous volcanic intrusives (Darien Formation), Oligocene–early Miocene agglomerates (Porcona Formation), early–middle Miocene limestone (Clarita Formation), turbiditic sandstone and claystone (Membrillo Formation), overlain by late Miocene fossiliferous and conglomeratic sandstone and siltstone (Chucunaque Formation) (Perez et al. (2017))

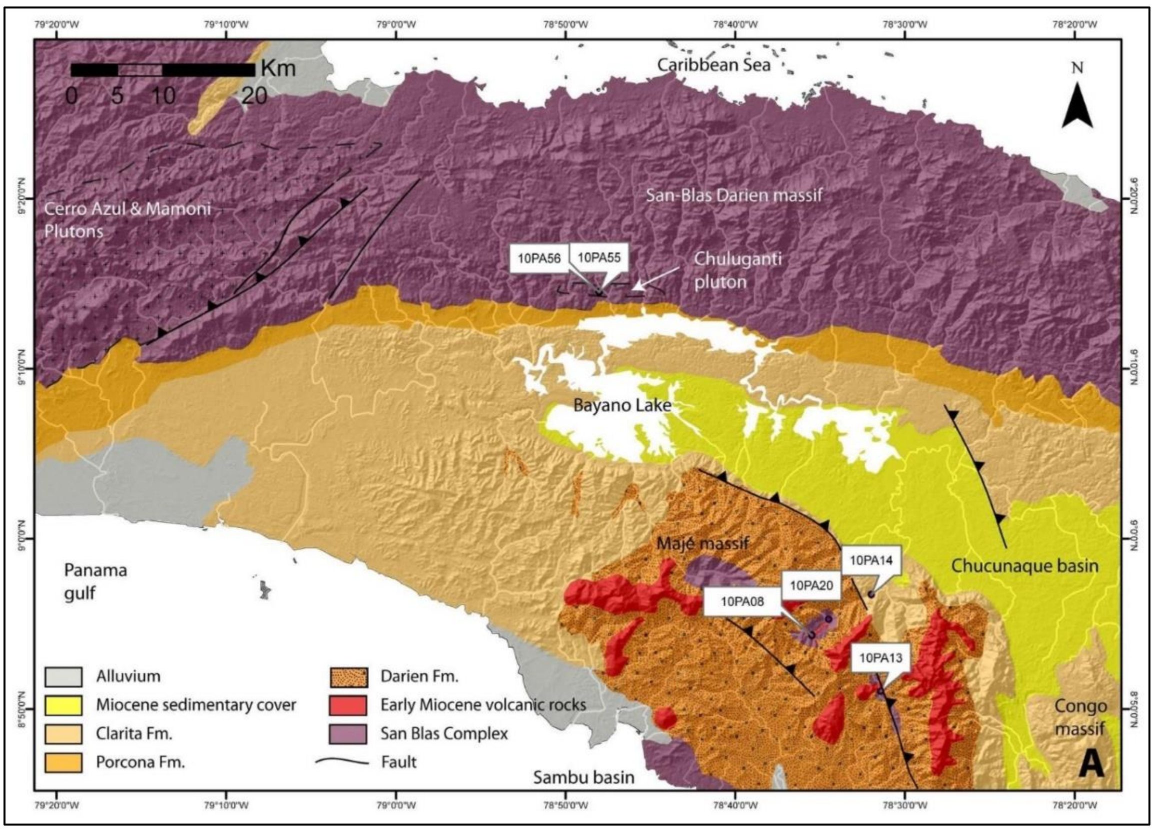


Figure 014. Geological map of the Bayano Basin. See Figure 012 for a wider view. Barat (2013)

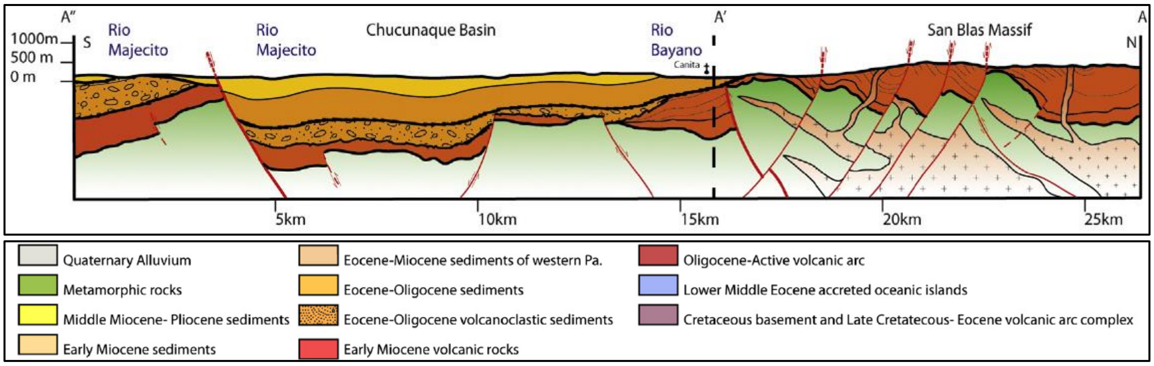


Figure 015. North-South Cross-sections A-A" through the Río Bayano Basin. Its location is seen in Figure 013. Barat (2013) and Barat *et al*. (2014)

5.1.2 - CHUCUNAQUE – TUIRA BASIN

This Basin was created in a large syncline formed in response to the bending and strike-slip deformation of the Isthmus of Panama following its collision with the South America margin (Mann and Kolarsky (1995)).

The stratigraphy of the Chucunaque-Tuira (and Sambu) Basins was described by Coates et al. (2004) (Figure 017) and Barat et al. (2014) based on field mapping along rivers, previous surveys for interoceanic canal routes and oil exploration and radar imagery mapping (MacDonald (1969)). This sedimentary sequence passes into the Río Bayano Basin to the northwest and the Atrato Basin (in Colombia) going south.

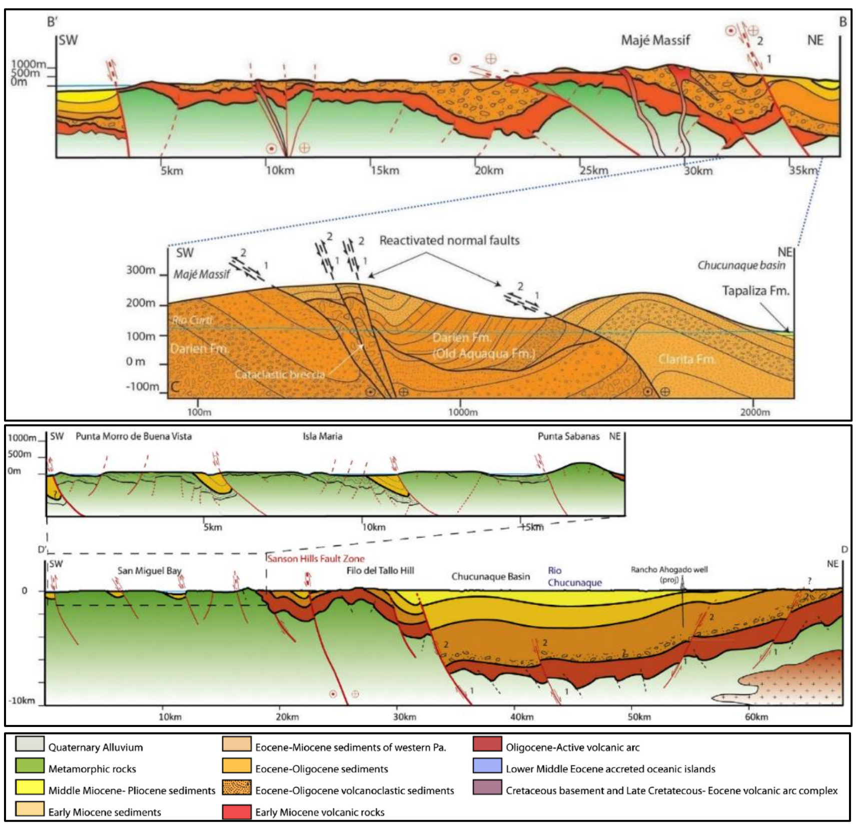


Figure 016. Cross-sections B-B' & D-D' through the Chucunaque-Tuira Basin. The position of each cross-section is shown in Figure 013 (Barat (2013) and Barat et al. (2014)).

The initiation of the volcanic arc is marked at Portobello by the Late Campanian Ocú Formation of volcanic breccia with andesite basalt clasts overlain by limestone (with Late Campanian foraminifera) and siliceous tuffs cut by basaltic andesite dikes (Barat et al. (2014)). This is overlain by a poorly known Paleocene to Eocene volcanic arc which forms the San Blas Mountains.

The Upper Cretaceous to Eocene basement crystalline rocks of the San Blas Complex of the mountains on both coasts are overlain by 4000 m of arc-related volcanic and sedimentary rocks of Eocene to Lower Miocene age. They consist of the Eocene-Oligocene Darien Formation of tuffs, agglomerate, radiolarian chert and basalt in the lower part, overlain by calcareous and siliceous mudstone, micritic calcarenite and volcaniclastic rocks in the upper part; the Oligocene Porcona Formation of calcareous, foraminiferal shale, limestone and tuff with radiolarians and resedimented blocks of glauconitic sandstone; and the Lower-Middle Miocene Clarita Formation of thick-bedded, crystalline limestone with sandy, shaly and tuffaceous mudstone units.

These are overlain unconformably by a 3000 m thick sequence of deposits which are coarse- to fine-grained siliciclastic sedimentary rocks and turbiditic sandstone of upper middle to latest Miocene age (Coates et al. (2004)). This sequence comprises the upper middle Miocene Tapaliza Formation of foraminiferal mudstone and siltstone, volcanic sandstone, black shale and turbidites; the lower upper Miocene Tuira Formation of greywacke, sandstone, siltstone and claystone, and Membrillo Formation of shelly mudstone; the middle upper Miocene Yaviza Formation of shelly sandstone overlain by coquinoid limestone; and the middle to upper Miocene Chucunaque Formation of silty claystone and siltstone. The sequence was deformed into a synclinorium in the Chucunaque-Tuira Basin. There is a shallowing of the sedimentary package in the Middle Miocene at 12.8–7.1 Ma which is interpreted as synchronous with the approach of the Panama-Chocó Arc with the Northern Andes.

The so-called pre-collisional open marine strata of Late Cretaceous to Middle Miocene age are separated from the overlying post-collisional sequence of Middle to Late Miocene age by a regional unconformity at 14.8–12.8 Ma. This unconformity was interpreted to be related to the initial collision between the Panama-Chocó Arc with South America (Coates et al. (2004)).

The Bayano-Chucunaque-Tuira syncline was formed after the Chucunaque Formation (5.6 Ma) by shortening within the Panama Microplate, together with the NW-trending Jaque River Fault and the Sambu and Majé Faults. Continued deformation produced en echelon, doubly plunging and truncated folds along the southern side of the syncline. These were subsequently truncated by the left-lateral strike-slip Sanson Hills Fault. These are, in turn, cut by the NE-trending Pirre Fault, an east-dipping high-angle reverse fault. The left-lateral, strike-slip fault movement in the Darien indicates that internal deformation of the Panama Microplate was accompanied by northwestward "escape" of fault-bounded blocks (Coates et al. (2004)). Undeformed late Pliocene-Pleistocene sediments bury deformed older Neogene sediments in the east Panama deformed belt and the western Gulf of Panama and Pearl Islands Basins (Mann and Kolarsky (1995)).

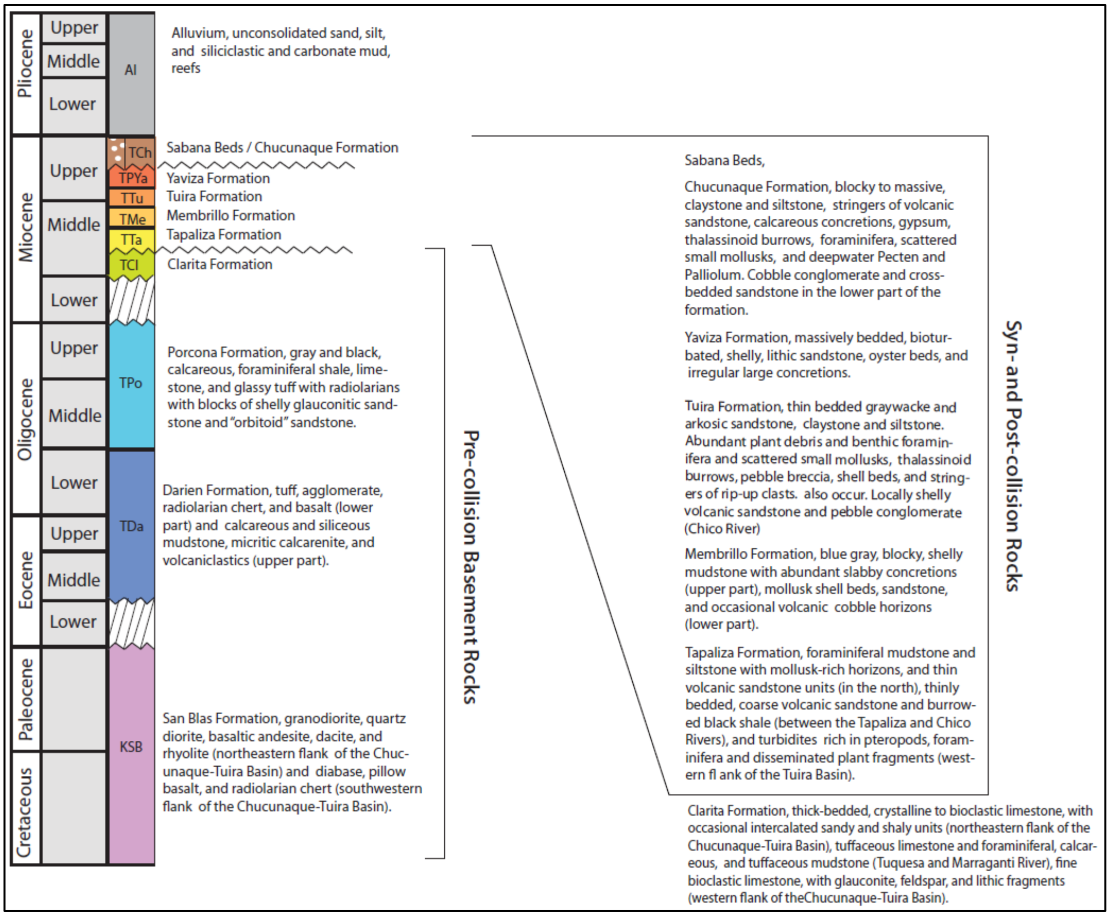


Figure 017. Overlay of bedrock geology and stratigraphic column of Eastern Panama (Farris, D.W., O'Dea, A. et al. (in prep); modified after Coates et al. (2004))

These are overlain unconformably by a 3000 m thick sequence of deposits which are coarse- to fine-grained siliciclastic sedimentary rocks and turbiditic sandstone of upper middle to latest Miocene age (Coates et al. (2004)). This sequence comprises the upper middle Miocene Tapaliza Formation of foraminiferal mudstone and siltstone, volcanic sandstone, black shale and turbidites; the lower upper Miocene Tuira Formation of greywacke, sandstone, siltstone and claystone, and Membrillo Formation of shelly mudstone; the middle upper Miocene Yaviza Formation of shelly sandstone overlain by coquinoid limestone; and the middle to upper Miocene Chucunaque Formation of silty claystone and siltstone. The sequence was deformed into a synclinorium in the Chucunaque-Tuira Basin. There is a shallowing of the sedimentary package in the Middle Miocene at 12.8–7.1 Ma which is interpreted as synchronous with the approach of the Panama-Chocó Arc with the Northern Andes.

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5.1.3 The Gulf of Panama basin and the Sambu basin

The crustal structure of the Gulf of Panama Basin, also called Pearl Islands Basin, was described by Briceno-Guarupe (1979) while its geology was studied by Kolarsky (1992), Mann and Kolarsky (1995) and Derksen et al. (2003) based on 2D seismic surveys and oil wells. The Gulf of Panamá covers an area of about 25,000 km^2 on the Pacific side of the Isthmus of Panamá; the Pearl Islands are slightly east of its center. It is essentially an offshore Basin but is included in this lexicon due to the Pearl Islands located approximately at its centre and also because of the discovery of Pleistocene fossil mammals just offshore these islands (Figure 027). The geology of the Pearl Islands suggests that the islands are the exposed axis of a hanging-wall anticline associated with an east-dipping reverse fault zone (Mann and Kolarsky (1995)).

The eastern Gulf and adjoining mainland are geologically distinct from the western part of the Gulf. The eastern Gulf contains a thick Cretaceous to Recent sedimentary section. The Miocene to Oligocene is the most prospective part for oil of this section, (Figure 021) but it is missing in the western Gulf, where Pliocene sediments rest directly on Eocene or older rocks. The Middle Miocene-Pleistocene Gulf of Panama Basin formed as a small foreland Basin in front of east-dipping reverse faults of the East Panama deformed belt. Coates et al. (2004) correlated the stratigraphy of the Pearl Islands with that of the Chucunaque-Tuira Basin, showing the San Blas Complex, Darien and Clarita Formations. The two Basins are separated by the basement highs and Neogene magmatic arcs of the Majé and Bagre mountains. The Sambu Basin (Figure 012; Figure 018; Figure 025) of the eastern gulf, which extends onshore, is a left-lateral pull-apart Basin controlled by the NW-trending Sambu Fault and is separated from the Plaris offshore sub-Basin of the southern gulf by a deformed anticlinal belt exposed in the Pearl Islands (Derksen et al. (2003)). It has recently been interpreted as evidence of an extensive regime during the Upper Oligocene, producing structures in horst and graben (Montes et al., 2012b; Coates et al., 2004). There is a thick sedimentary sequence of Eocene to Pleistocene age beneath the Gulf of Panama (Figure 022), with Neogene depocentres west of the Pearl Islands (Figure 019), and in the Sambu Basin (18,000') and Plaris (12,000') sub-Basin (Mann and Kolarsky 1995; Derksen et al. (2003)). In the eastern half of the gulf (Figure 023 and Figure 024), these are deformed by east-dipping, west-verging reverse faults, which may have a left-slip component, of Middle Miocene to Plio-Pleistocene age which form a largely buried, 90-km-wide thrust belt which is part of the East Panama Deformed Belt (Mann and Kolarsky (1995)). Several thousand feet of Eocene interbedded volcanic and sedimentary rocks overlie the Cretaceous. This is followed by more than 13,000 feet of organic shale, clastic sediments, and carbonates of Oligocene to Pliocene age. Volcaniclastic sediments and ash-flow tuffs occur throughout the section. Cenozoic strata are involved in complex stratigraphic relationships involving facies changes, offlaps, onlaps, and unconformities. Much of the section was deposited in deep water. The stratigraphic nomenclature used by Derksen et al. (2003) is shown in Figure 020.

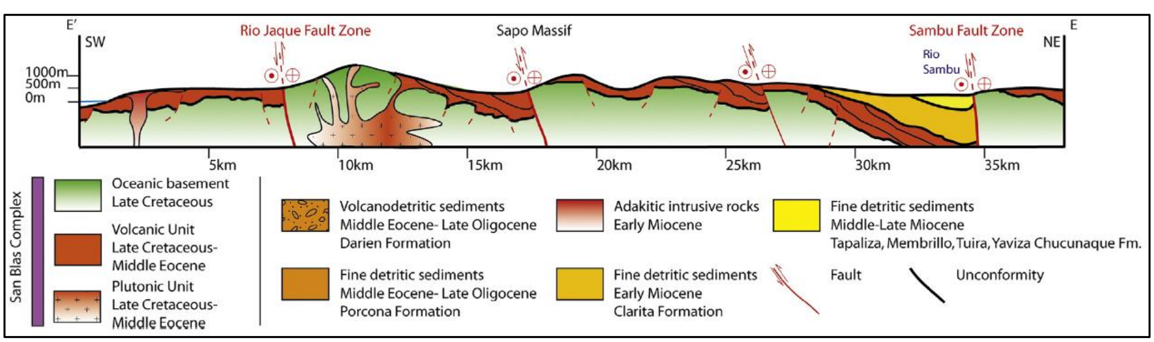

Figure 018. Cross-sections through the Sambu Basin, together with the legend for Figure 019. The position of the cross-section is shown in Figure 013. Barat (2013) and Barat *et al*. (2014)

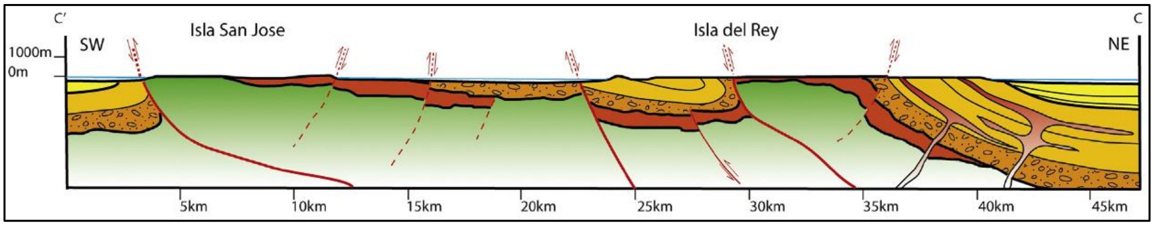

Figure 019. Cross-section through the Pearl Islands in the Gulf of Panama Basin. The position of the cross-section is shown in Figure 013 (Barat (2013) and Barat et al. (2014)). See Figure 018 for the legend.

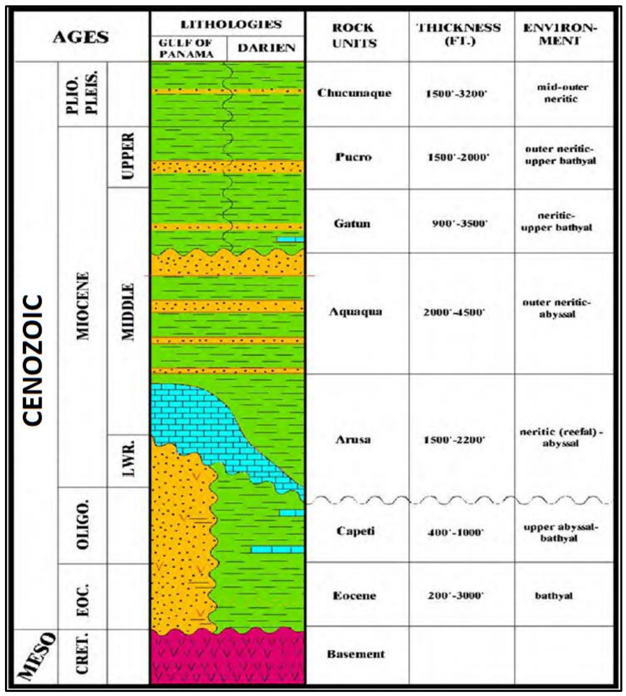

Figure 020. Generalized sub-surface stratigraphic column for the eastern Gulf of Panama (Derksen et al. (2003)). **Note from the author:** The reader must consider it doubtful that the names of the sub-surface formations in the above column represent the equivalent of those onshore formations with the same names in other geological Basins of Panama. It is highly recommended to abandon the use of those names in the sub-surface of the eastern Gulf of Panama as they only bring confusion.

Figure 021. Oil seep at the Garachiné-2 well location, drilled in 1926 in the onshore Sambu sub-Basin. Derksen *et al*. (2003)

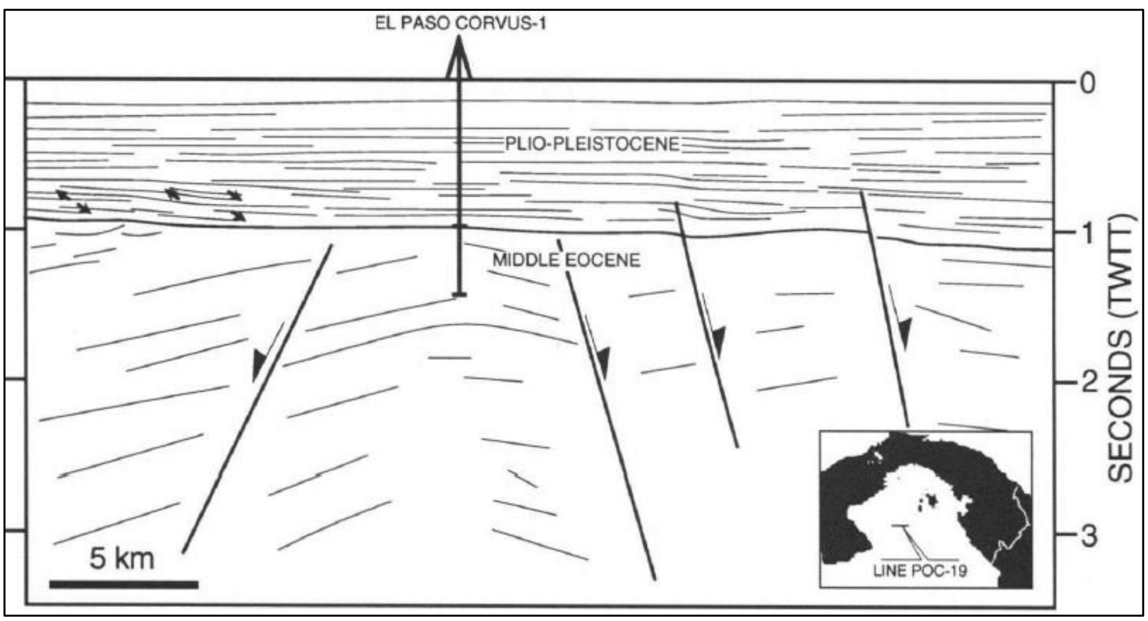

Figure 022. Interpretation of a segment of the unmigrated Mobil 24-fold seismic line POC-19 from the East Panama deformed belt in the west-central Gulf of Panama. Note that the line is tied to the El Paso Corvus-l well. It shows block-faulted and truncated Middle Eocene sedimentary sequence overlain unconformably by a flat-lying Plio-Pleistocene sedimentary section. Mann and Kolarsky (1995)

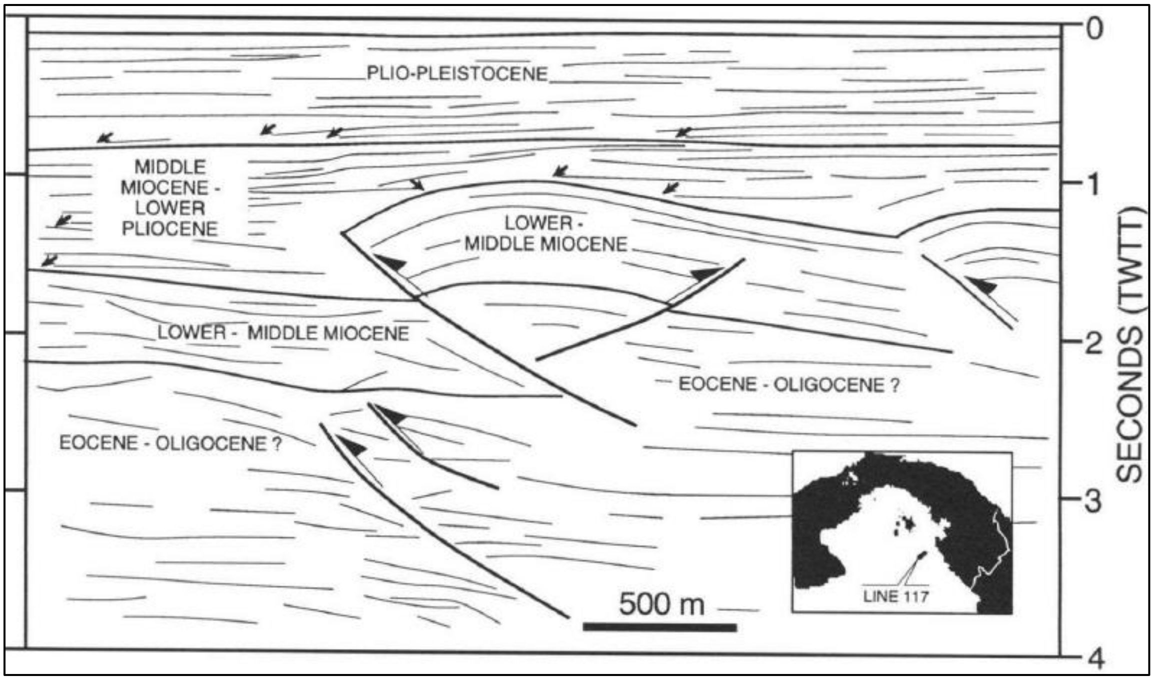

Figure 023. Interpretation of a segment of the migrated Mobil 24-fold seismic line 117 from the East Panama deformed belt in the eastern Gulf of Panama. It shows folded and thrusted Paleogene-middle Miocene sedimentary sequence onlapped and unconformably overlain by a less deformed Plio-Pleistocene section. Mann and Kolarsky (1995).

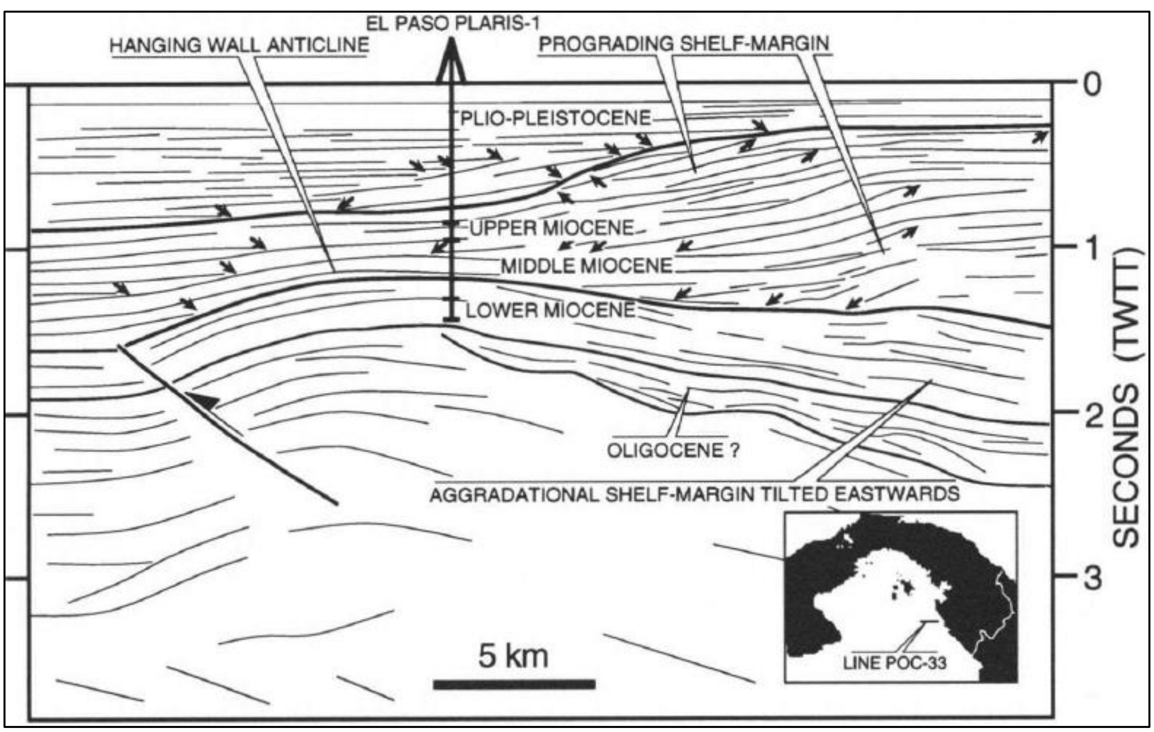

Figure 024. Interpretation of a segment of the migrated Mobil 24-fold seismic line POC-33 from the East Panama deformed belt in the eastern Gulf of Panama. It shows an Oligocene?-Lower Miocene aggradational shelf margin that is tilted eastward in the hanging wall of an east-dipping thrust fault and middle Miocene-Pliocene progradational shelf margin. Mann and Kolarsky (1995).

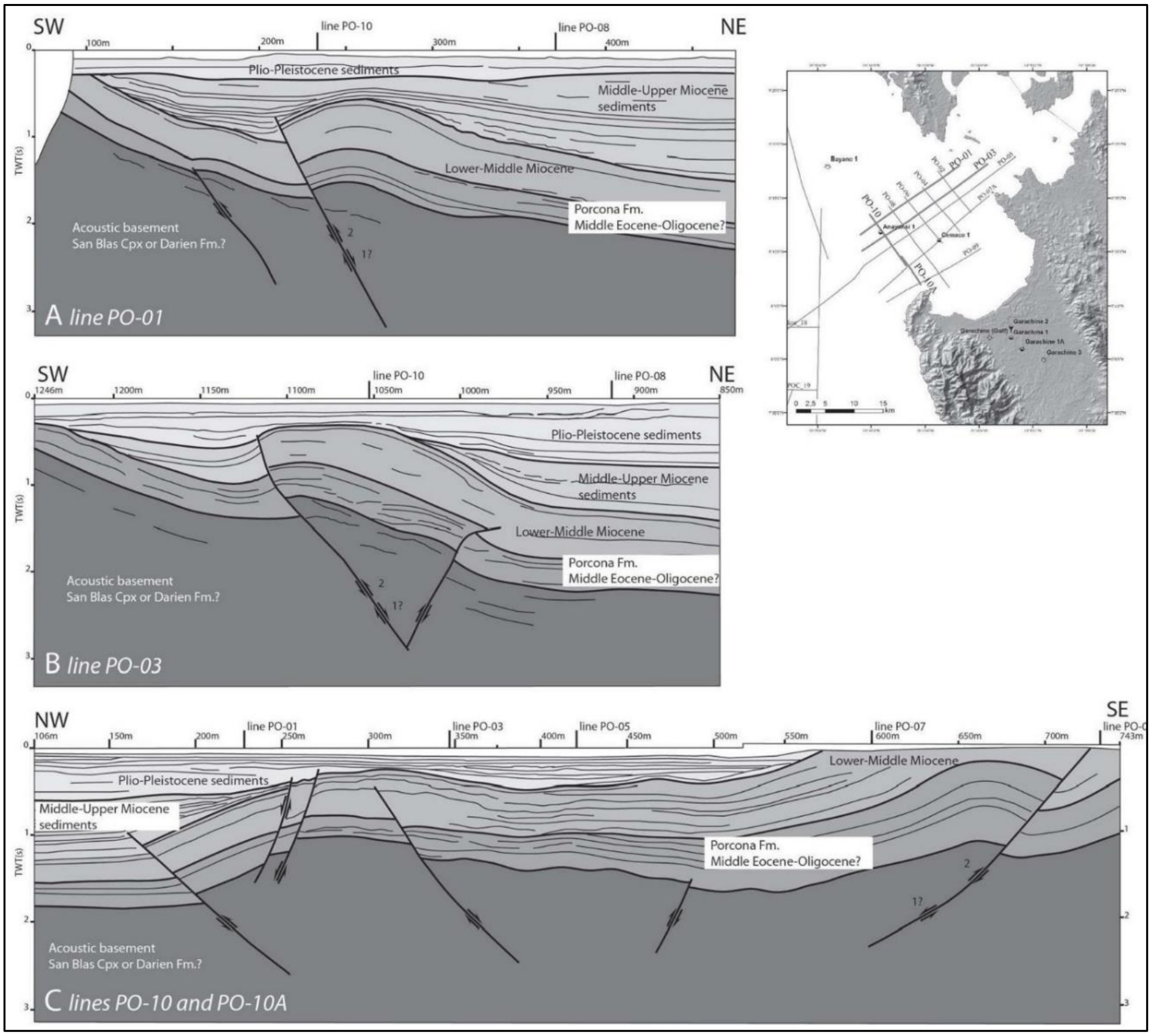

Figure 025. Extracts of migrated seismic lines from the Sambu Basin, taken from the Oxoco and Aracca (1983) report, reinterpreted by Barat (2013) according to current geological formations.

At the last glacial maximum (21,000 years ago), sea level was about 120 to 130 m below present and the entire Gulf of Panama was dry land from Punta Mala, on the southeast point of the Azuero Peninsula, to the Colombian border. The plain was probably a dry and open habitat or grassland as the late Pleistocene climate was drier and cooler, based on pollen records from lake sediments at Lake Gatún. Sea-level rose by 125 m (from -130 to -5 m) in about 14,000 years between 21 ka and 7 ka, at an average rate of about 9 mm per year, and it traversed 150 km horizontally almost to the present-day shore in this time, a horizontal rate of 10.7 m per year. Redwood (2020).

The Pearl Islands archipelago was part of the mainland at 21 ka and became, firstly, a peninsula and then a single big island, separated by a channel from the Darien mainland to the east by the time sea level reached about -37 m between about 10.2 and 10.0 ka. Pedro González Island (P.G.) and San José Island on the west side of the archipelago were separated from the other islands by the North and South Channels by the time sea level reached -18 m at about 8.8 to 8.3 ka. The two islands were probably joined initially. Redwood (2020).

The Gulf of San Miguel forms the estuary of the River Tuira and is a major flooded valley, 50 km long by up to 25 km wide, formed by the late Pleistocene to Holocene sea level rise. The submarine river channel can be clearly seen on the bathymetric maps. Submarine valleys in the Gulf of Panama were first described from bathymetric data by Terry (1940) and are clear on the palaeogeographic maps (Figure 026). These formed by river erosion during times of low sea levels. There was a central palaeo-Bayano river valley beginning near the mouth of the River Bayano and running along the west side of the Pearl Islands, which are bounded by a fault. Redwood (2020).

Four Pleistocene proboscidean teeth (~1.6 Ma-10ka) were recovered by fishermen from the continental shelf in the vicinity of the Pearl Islands, about 50-80 km offshore from the southern coast of Panama (Figure 027). They were identified as coming from the gomphothere *Cuvieronius hyodon*. All four teeth were found in a marine environment, and the two specimens with the most complete data were recovered in shrimp nets from a depth of approximately 50 fathoms (~300 feet or ~90 m). All four teeth were in excellent condition, although lacking roots, suggesting that they were not transported a long distance and were probably buried for a considerable period of time and not subjected to movement by tides or currents. Two of the teeth have attached specimens of modern epiphytic marine invertebrates, indicating that the specimens rested on the sea floor for at least a short period of time, although not long enough to have suffered much damage. If the teeth were not transported a long distance from where they were recovered on the sea floor in the Gulf of Panama, then the depth at which they were found (~90 m) should give a good indication of sea level at the time the fossils were deposited, considering that the continental shelf must have been dry land for the gomphotheres to have survived there. Morgan et al. (2015). Other than the above Pleistocene proboscidean fossils, 6,000 years old fossils of dolphins (Holocene) were found at a preceramic site in the Pearl Island archipelago (Cooke, et al. (2015)) indicating possible human interference.

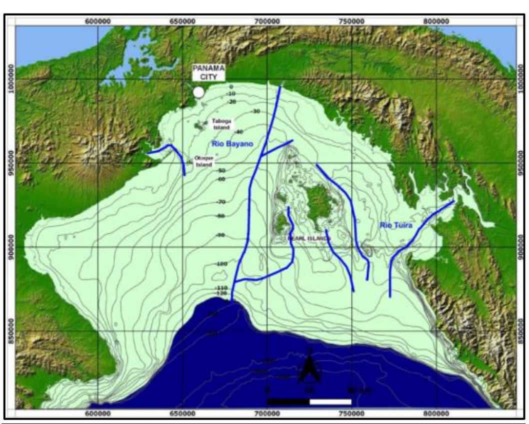

Figure 026: Map of interpreted submarine valleys of the Gulf of Panama and Sambu Basins. The sea level is at -130 m; 21,000 years ago (Redwood (2020)).

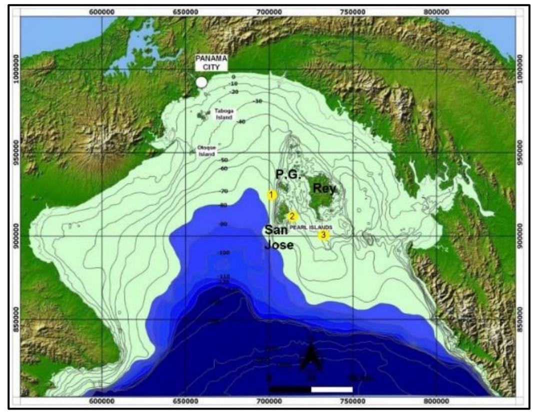

Figure 027. Map of the Gulf of Panama showing the location of late Pleistocene sites (1, 2 and 3) containing the gomphothere *Cuvieronius hyodon* (Morgan et al. (2015)). The sea level is at -80 m; 14,000 years ago (Redwood (2020)). P.G.= Pedro González Island.

5.2 The Western Region

5.2.1 The Panama Canal basin

The Panama Canal Zone (Figure 028) occupies a region of relatively low topography between the Central Volcanic Cordillera of western Panama and the mountainous Darien isthmus to the east. This lowland encompasses a network of lowgradient river valleys that drain surrounding hills with peak elevations of less than 1200 m. The Pacific-Caribbean drainage divide descends to one of its lowest elevations in Central America (<200 m) in the low saddle of the Culebra Cut along the Panama Canal. The most pronounced expression of low topography in this region is the once-extensive swamp within the broad valley of the Chagres river, now covered by the Panama Canal's Gatún lake. (Marshall (2007))

The stratigraphy of the Canal Zone Lowlands includes a Cretaceous volcanic basement that is overlain unconformably by a thick sequence of Eocene-Miocene shallow marine and terrestrial sediments. These rocks are moderately folded and were affected by late Neogene faulting and uplift that produced localized bedrock highs within fault-bounded blocks. Within adjacent topographic lows, these sedimentary rocks are buried unconformably by a horizontal valley-fill sequence of Pleistocene-Holocene estuarine and swamp deposits referred to as the Atlantic Muck. The low topography of the Canal Zone has been attributed to pervasive faulting and fracturing that extends across the Panamanian isthmus within an 80-km wide zone referred to as the Canal Discontinuity or the Gatún Fracture Zone. This major crustal discontinuity has been interpreted as a Neogene-age basement fault that divides the Chorotega block to the west from the Chocó block of eastern Panama and western South America. (Marshall (2007))

The Panama Canal Basin has been extensively studied for more than a century for engineering geology for canal construction (Bertrand and Zürcher (1899); Howe (1907a, 1907b, 1907c); MacDonald (1915); Reeves and Ross (1930); Governor of the Panama Canal (1947b); Jones S.M. (1950) and palaeontology (Woodring (1957, 1982)), with maps by Stewart et al. (1980) and Woodring (1982). Detailed recent studies of stratigraphy (Escalante (1990); Kirby and MacFadden (2005); Kirby et al. (2008); Montes et al. (2011, 2012b)), paleontology (MacFadden (2006, 2010, 2014)), volcanic rocks (Rooney et al. (2011); Farris et al. (2011, 2017)), neotectonics and paleoseismicity (Rockwell et al. (2010a, 2010b)) were carried out in the second decade of this century during the canal expansion.

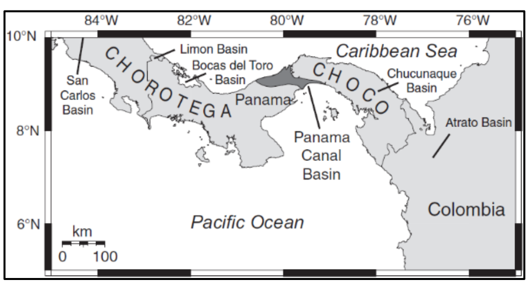

Figure 028. Location of the Panama Canal Basin and other depositional Basins in southern Central America. Kirby *et al.* (2008).

The Panama Canal Basin is a Cenozoic structural and depositional Basin at the boundary between the Chorotega and Choco terranes of the Panama microplate that formed in response to the convergent tectonics of the eastern Pacific subduction zone and associated arc volcanism (Figure 028) during the Cretaceous and Cenozoic. The tectonic nature of this Basin most likely represents an active rift Basin or a forearc Basin (Mann (1995) and Johnson & Kirby (2006)). The basement of the sedimentary succession is formed by Cretaceous volcanics which occupy large parts of the region.

The geology of Central Panama consists of a pre-Upper Eocene volcanic basement overlain by Upper Eocene to Pliocene marine to terrestrial sedimentary deposits interbedded with volcanic and volcaniclastic rocks. Upper Eocene sedimentary deposits include shallow-marine limestones and tuffaceous mudstone-sandstone (Gatuncillo and Caimito Formations) that rest unconformably on top of an uplifted volcanic basement and mark a regional marine transgression. Along the Culebra Cut of the Panama Canal (southern Central Panama) (Figure 029, Figure 030, Figure 031, Figure 032, Figure 033, Figure 034, Figure 035, Figure 036, Figure 037, Figure 038), this Late Eocene transgression was followed by deposition of sediments and volcanic/volcaniclastic products in:

i) a terrestrial environment (Bas Obispo and Las Cascadas Formations, Oligocene to Early Miocene);
ii) shallow-marine to bathyal environments (Culebra Formation, Early Miocene);
iii) a terrestrial environment (Cucaracha and Pedro Miguel Formations, Early Miocene).

These sequences are followed by the deposition of younger marine sediments in northern Central Panama in the Late Miocene to Pleistocene (Alajuela, Gatún and Chagres Formations). Finally, a more recent marine regression possibly accompanied the first complete emergence of the Panama Isthmus. Therefore, the geological record in Central Panama preserves at least 3 main cycles of marine transgression and regression since the Late Eocene (Buchs et al. (2019)).

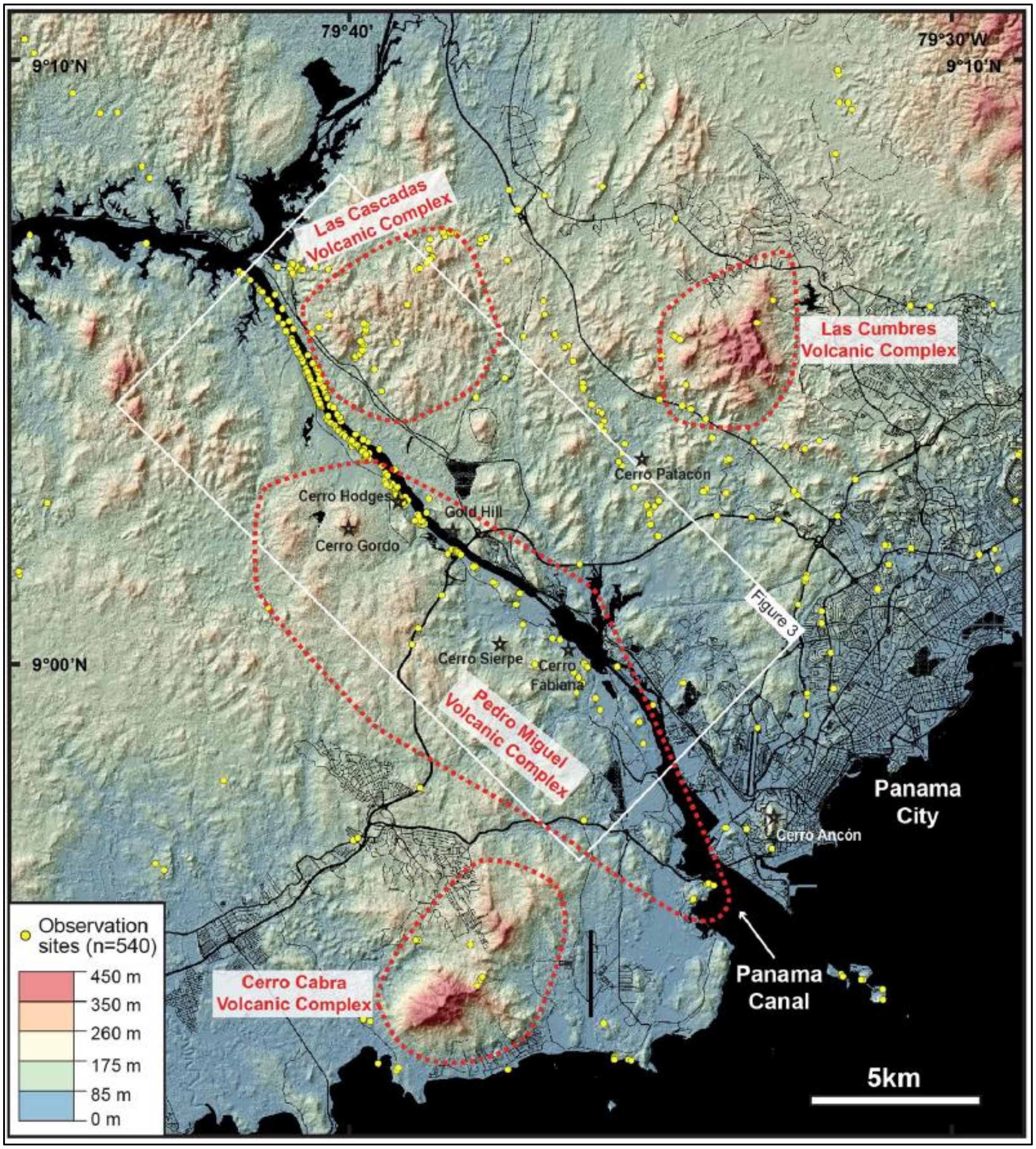

Figure 029. Topography of the Central Panama in the southern Panama Canal area and its main volcanic complexes (Buchs et al. (2019)). Digital topography model based on Lidar survey by the Panama Canal Authority. The geological details of the area within the white rectangle (figure 3 of Buchs et al. (2019)) can be seen in Figure 030.

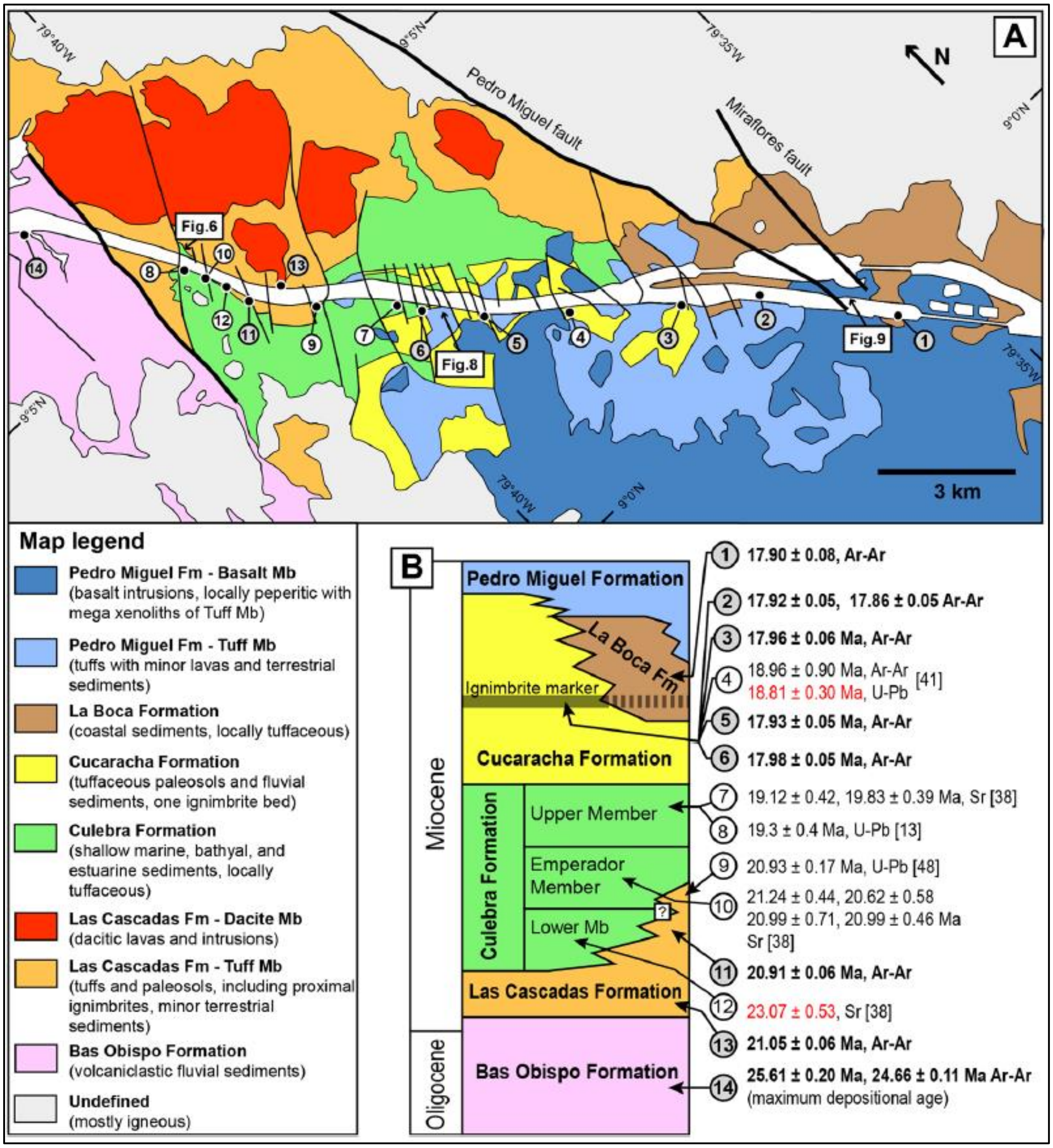

Figure 030. Geology of the southern part of the Panama Canal (Culebra Cut and new Pacific locks area). **(A)** Revised geological map. **(B)** Revised chronostratigraphic chart with previous and new geochronological constraints (new data in dark circles and bold text) (Buchs et al. (2019)). See location of the area in Figure 029.

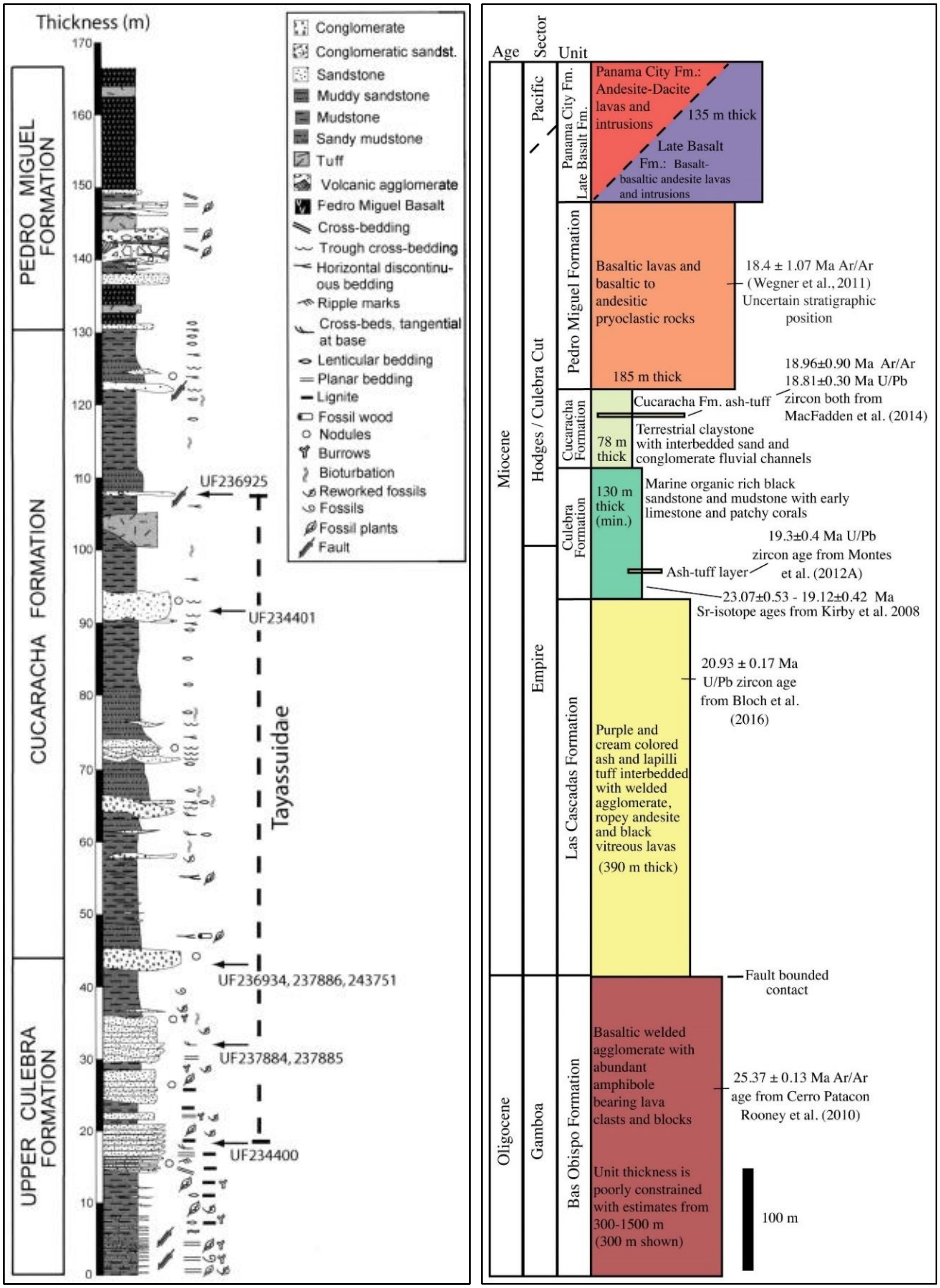

Figure 031. **Left:** Stratigraphic section of the Centenario Fauna interval based on the Hodges Hill locality (Figure 032) (Kirby et al. (2008)). **Right**: Stratigraphic column of volcanic and sedimentary rocks exposed along the southern Panama Canal. Depicted total thickness of section is 1218 m. Section from Farris et al. (2017).

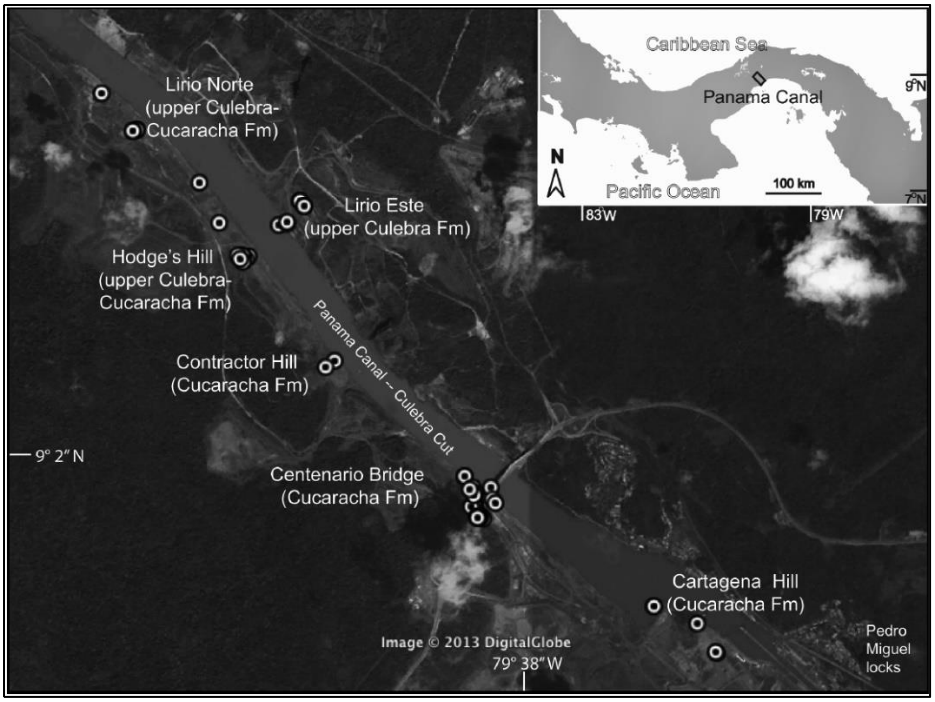

Figure 032. Google Earth image of the southern part of Panama Canal in the region of Centenario Bridge, showing all Centenario Fauna locations and specific collecting sites studied by MacFadden *et al*. (2014).

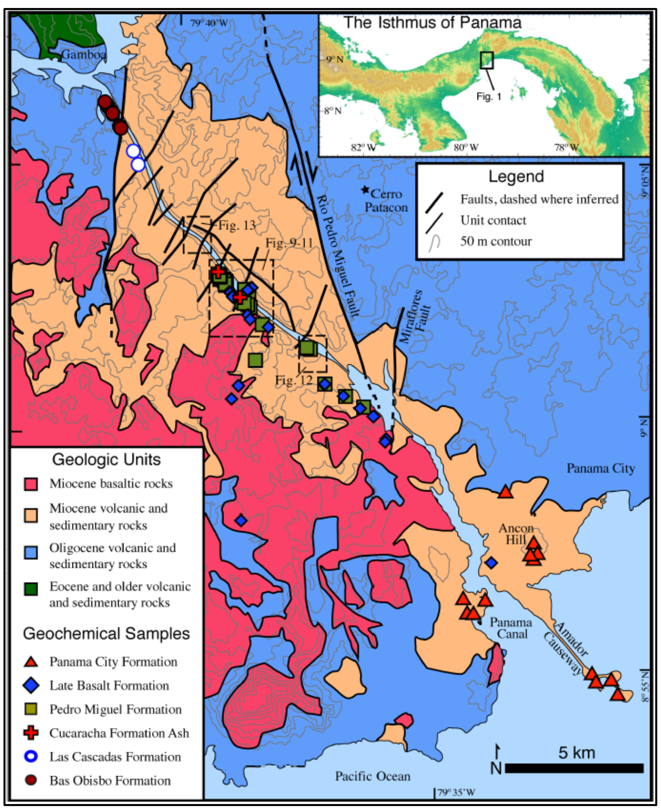

Figure 033. **Geologic map of the southern Panama Canal Basin** adapted from Stewart and Stewart. Symbols indicate the location of geochemical samples. Boxes denote the location of high-resolution mapping areas. Map from Farris *et al*. (2017).

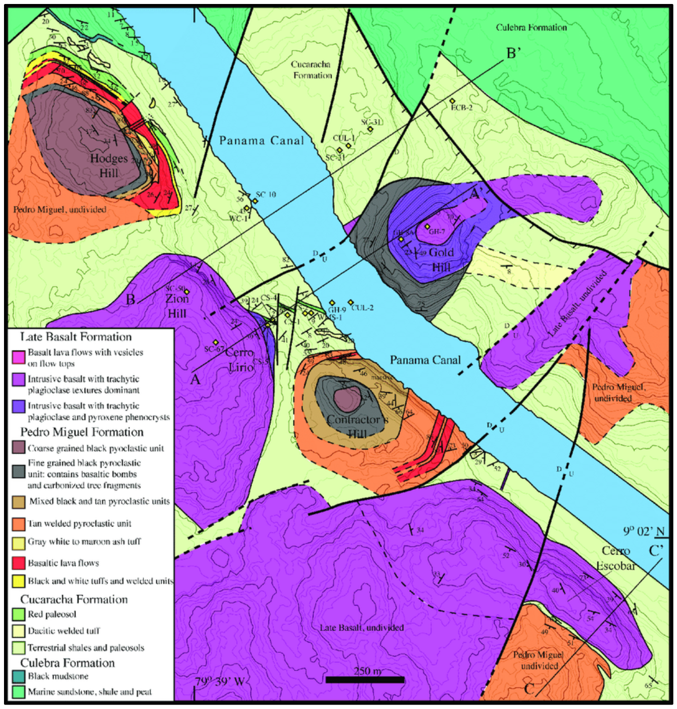

Figure 034. **Geologic map of the Culebra Cut** along the Panama Canal. The map depicts Miocene pyroclastic pipes of the Pedro Miguel Formation, and large basaltic sills and flows of the Late Basalt Formation both of which intrude and are deposited atop the sedimentary Cucaracha Formation. See Figure 033 for map location. Map from Farris *et al.* (2017).

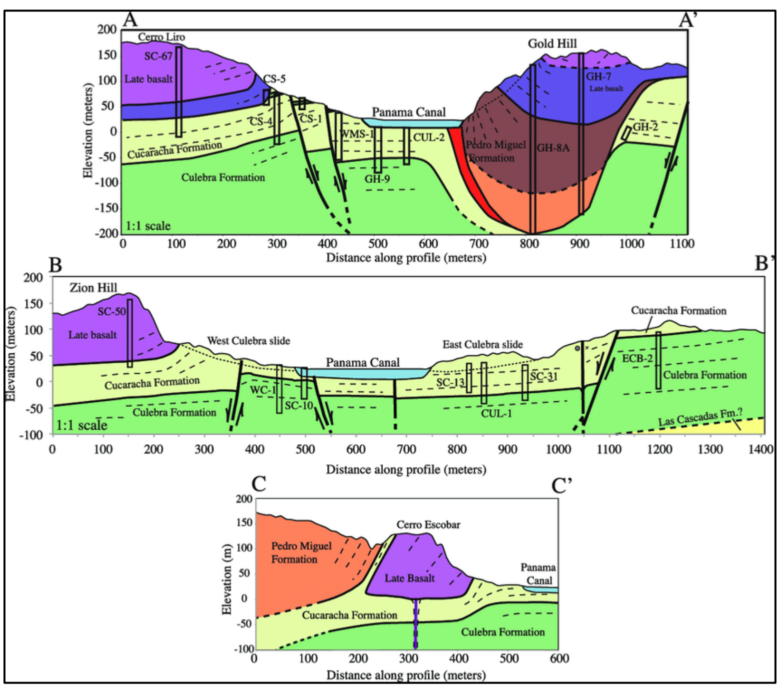

Figure 035. **Geologic cross-sections A-A', B-B', and C-C' across the Culebra Cut**. See Figure 034 for line locations. Cross-sections are derived from structural field observations and constrained by drill core data from Lutton and Banks (1970). These cross-sections clearly show the subsurface thickness of basaltic sills and pyroclastic bodies and provide vertical offset constraints for normal faults. The cross-sections indicate that the Panama Canal is roughly centered on a small structural graben. See Figure 033 for location. Cross-Section from Farris et al. (2017)

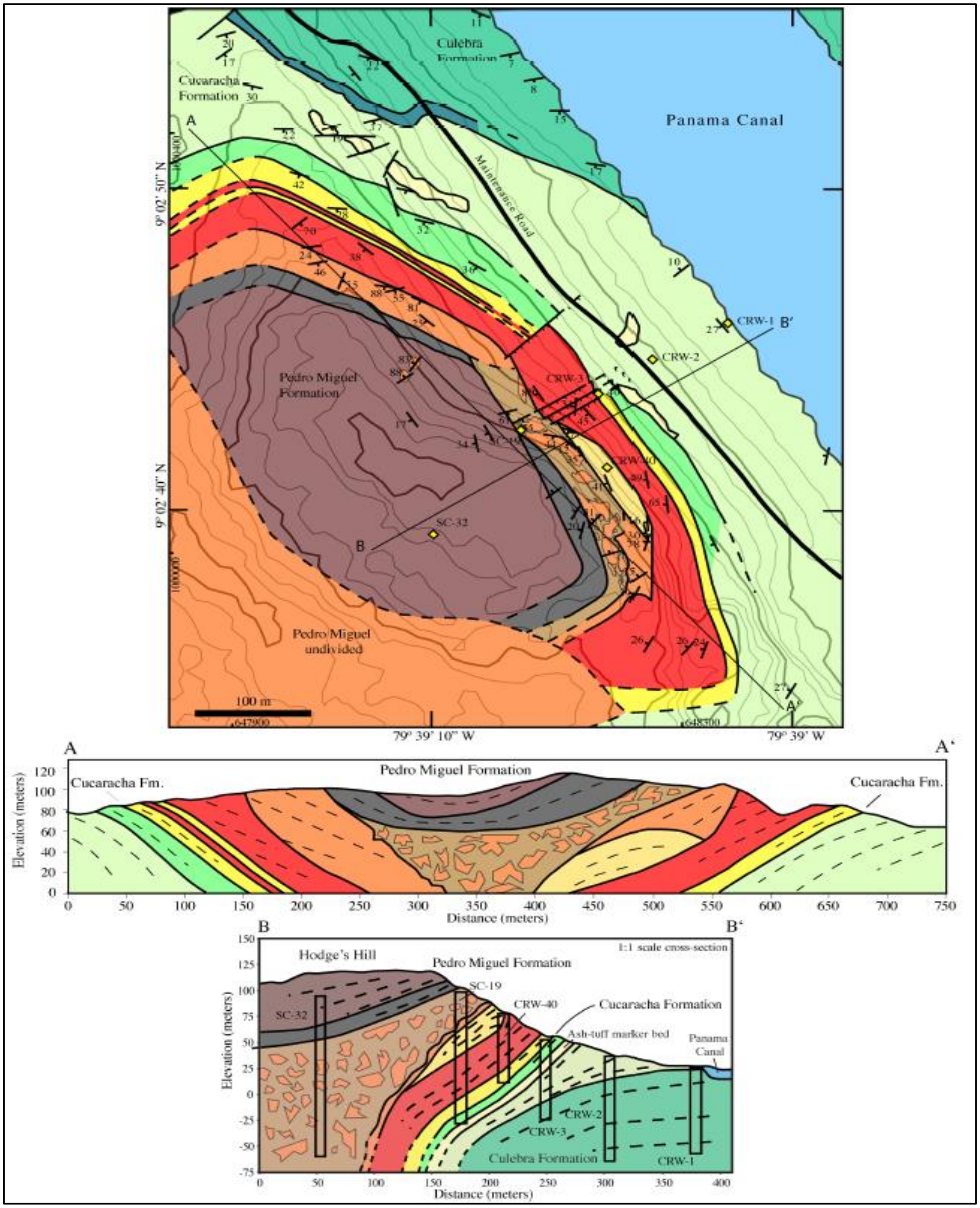

Figure 036. **Geologic map and cross-section of Hodges Hill**. Hodges Hill is the "type" Pedro Miguel Formation locality. It is composed of inward dipping pyroclastic deposits and lava flows deposited over multiple episodes of explosive eruptions. The 3-D internal geometry as shown in cross-sections A-A' and B-B' are derived from structural measurements and Lutton and Banks (1970) drill core data. See Figure 034 for unit key. See Figure 033 for location. Map and Cross-Sections from Farris *et al*. (2017).

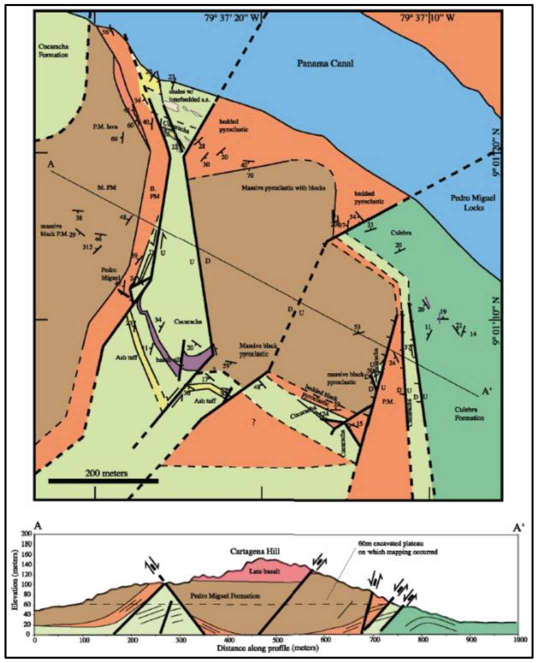

Figure 037. **Cartagena Hill geologic map and cross-section**. At this locality, inward dipping Pedro Miguel Formation pyroclastic strata are observed, but the volcanic edifice is partially dismembered by subsequent normal and strike slip faulting. Cross-section A-A' shows pre-excavation topography. The horizontal dashed line on the cross-section indicates the excavation level on which geologic mapping was conducted. See Figure 033 for location. Map and Cross-Section from Farris *et al*. (2017).

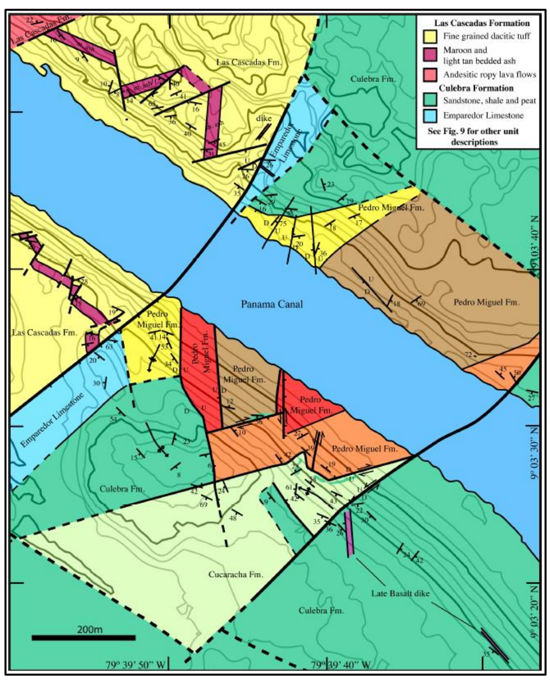

Figure 038. Empire reach (also known as Lirio Norte) geologic map. This map contains the northernmost exposure of the Pedro Miguel Formation along the Panama Canal. At this location, the Pedro Miguel volcanic edifice has been crushed by faulting to a degree that it is not stratigraphically coherent. A large normal fault separates the Pedro Miguel and underlying Cucaracha and Culebra Formations from the Las Cascadas Formation to the northwest. A large left-lateral strike-slip fault also bounds the Pedro Miguel body to the southeast. See Figure 033 for location. Map from Farris *et al*. (2017).

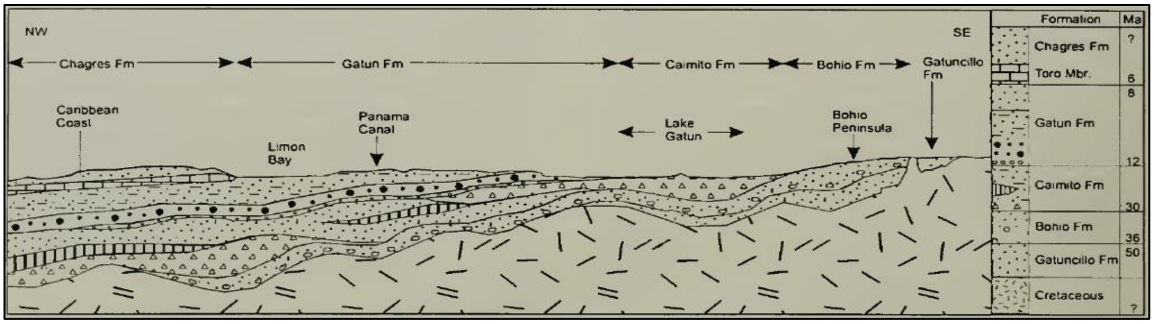

Figure 039. Schematic geologic cross section of the Panama Canal Basin from the Bohío Peninsula to the Caribbean coast west of Toro Point. Coates (1999). (Reproduced with permission of the Paleontological Research Institution, Ithaca, New York).

Late Miocene, shallow marine sediments of the Gatún Formation occur in the NW part of the Basin at Lake Gatún and on the Caribbean coast around Colón and are overlain by the Pliocene Chagres Sandstone, with the basal coquina Toro Limestone or Toro Point Member. Coates et al. (1992). Figure 040; Figure 039.

Some unconsolidated deposits of Quaternary age also occur in the Panama Canal area. The "Pacific Muck" is located in the southern area and the "Atlantic Muck" (Thompson (1943) and Jones (1950)) is located in the northern area. Both deposits are discordantly spread over older Neogene rock units, specifically, the Culebra Formation in the south, and the Gatún Formation in the north (Figure 040). Black organic muck is the most widely distributed type of deposit (Woodring (1957)). Much of the black muck represents swamp deposits and is a mixture of silt, very fine-grained organic debris, and partly carbonized wood, stems, and leaves (Woodring (1957)). There are also marine fossils in these deposits. During the construction of the Panama Canal, oysters, other mollusks and plant material were found locally (Dall (1912); Brown and Pilsbry (1913)). Woodring (1957) suggests a Pleistocene age but in Woodring (1970) he changes his statement by writing "*According to radiocarbon dates, the informally named Atlantic and Pacific muck, formerly assigned a Pleistocene age, were deposited during the post-glacial rise of sea level*", which is confirmed by additional tests performed by the USGS in 1996; they record the ages of the mucks between 6,000 and 10,000 years. (Kirby (2006)). More recent radiocarbon ages for the Atlantic muck from geotechnical boreholes beneath the Gatún Dam are conformable and range from about cal 7,055 to 5,805 BP at elevations of -35.5 to -41.1 m, to cal 4,700 to 3,945 BP at elevations of 9.6 to 10.0 m (Pratt et al. (2003)). The elevations of up to +10 m of the Atlantic muck are higher than the Holocene high stand of about +2 m which may indicate that the high stand is due to regional tectonic uplift rather than a eustatic sea level high. The only radiocarbon dates of Pacific muck are those from Mitchell et al. (1975) which gave ages of cal 9,291 – 7,934 BP and cal 8,172 – 6,960 BP at depths of -9.8 to -10.2 m and -5 m, respectively. Redwood (2020).

The volcanic rocks record a change from hydrous basaltic pyroclastic deposits, typical of mantle wedge-derived subduction zone magmas, to hot, dry, bimodal tholeiitic volcanism at the Oligocene-Miocene boundary (21–25 Ma; Farris et al. (2017)). This transition is synchronous with formation of the Canal Basin and extensional faulting in a radial rift Basin, which is the cause of the change in magma chemistry (Farris et al. (2011, 2017)). The Basin is a graben with the main normal faults parallel to the axis and normal to the arc. Extension ceased at about 3–6 Ma and changed to the modern strike-slip fault regime (Rockwell et al. (2010b)). Collins et al. (1996) provided strong evidence to suggest that the southern Central American archipelago was an almost complete ecological barrier between the Pacific and the Caribbean, at the time of the deposition of the Gatún Formation (Late Miocene, about 8 Ma). The elongated outcrop pattern, parallel to the isthmus, and the shallow marine depositional environment (20-40 m, Collins et al. (1999a & 1999b)) indicates that the Gatún Formation sediments formed as an apron of volcaniclastics flanking the isthmian arc with no marine connection to the Pacific side. However, Collins et al. (1996) also show that the Panama Canal Basin became temporarily a marine strait again, at about 6 Ma, during the time of deposition of the Chagres Formation, because it contains abundant bathyal benthic foraminifera of dominantly Pacific affinity. Fossils from the Panama Canal area indicate that by the early Miocene much of Panama was part of a peninsula connected to North America, but the flora was already dominated by primarily South American tropical plants (Jaramillo et al. (2014); Jud et al. (2017a)). According to Escalante (1990), the entire Cenozoic succession of the Panama Canal Basin amounts to at least 2900 m.

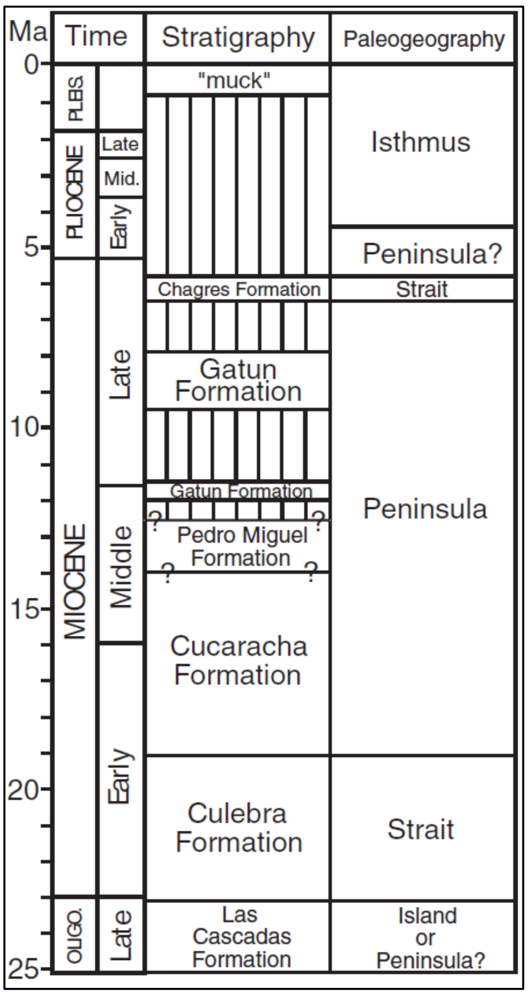

Figure 040. Geologic history of the Panama Canal Basin, showing geologic time, stratigraphy and paleogeography at the Culebra Cut. Kirby *et al*. (2008).

5.2.2 Bocas del Toro basin

At Bocas del Toro in northwestern Panama, an extensive low-relief coastal embayment (70 km wide) lies inboard of an emergent string of cliff-lined islands and promontories. To the east of Bocas del Toro, the Chorotega back arc extends along the Gulf of Mosquitoes where a series of river deltas form localized bulges in the coastline. (Marshall (2007))

The rugged geomorphology of the Limón region (in Costa Rica) and Bocas del Toro region (Panama) is controlled by active crustal shortening within the North Panama deformed belt along the Caribbean margin of the Panama block. Rapid uplift above northeast-verging thrust faults has led to the emergence of Quaternary coral terraces along the southern Limón coastline. Active subsidence has also produced a low-relief trough inboard of the emergent islands of the Bocas del Toro archipelago. During the 1991 M7.6 Valle de la Estrella earthquake, coseismic uplift of 0.5-1.5 m affected the southern Limón coast, while subsidence of 0.5-0.7 m resulted in inundation of peat swamps along the Bocas del Toro embayment. Toward the northwest, the zone of active coastal deformation ends abruptly at the Limón headland, where thrust faulting within the North Panama deformed belt gives way to oblique slip along steeply-dipping faults of the Central Costa Rica deformed belt. (Marshall (2007))

Uplift along the Limón-Bocas del Toro coast has exposed a Neogene sequence of marine to terrestrial sediments and volcanic rocks along coastal cliffs and islands. These deposits are correlative with similar units mapped in the Canal Zone and Darién regions of Panama. As a whole, this rock sequence provides a detailed record of Neogene emergence along the Panama isthmus, resulting in closure of the oceanic strait between the Atlantic and Pacific Ocean Basins. (Marshall (2007))

An extensive series of exposures of upper Neogene sediments can be observed in the coastal region of Bocas del Toro in Panama where they form an extensive archipelago (Figure 041). Mapping has revealed a Miocene basement of widely distributed basalt lava, flow breccia, and coarse, pyroclastic and volcaniclastic sediments. The Bocas del Toro Group lies nonconformably on the underlying volcanics of the Valiente Formation.

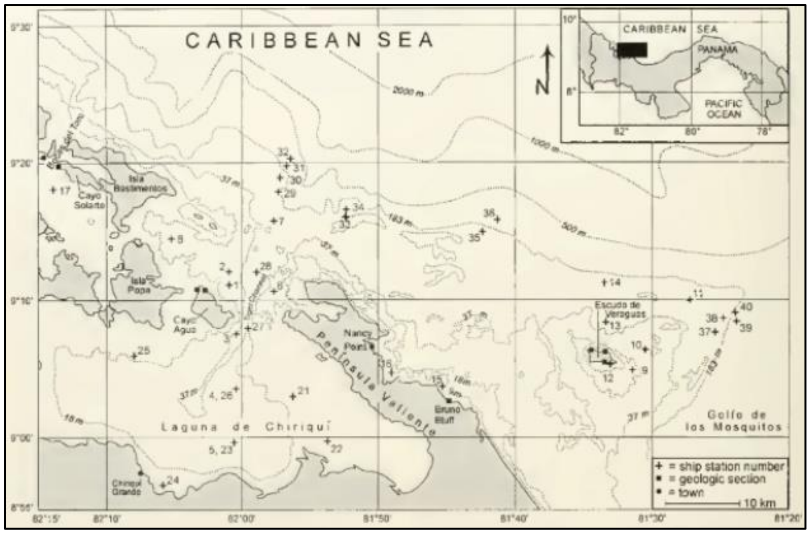

Figure 041: Bocas del Toro archipelago, NW Panama. Map of the eastern portion (Collins L. (1999b). (Reproduced with permission of the Paleontological Research Institution, Ithaca, New York)

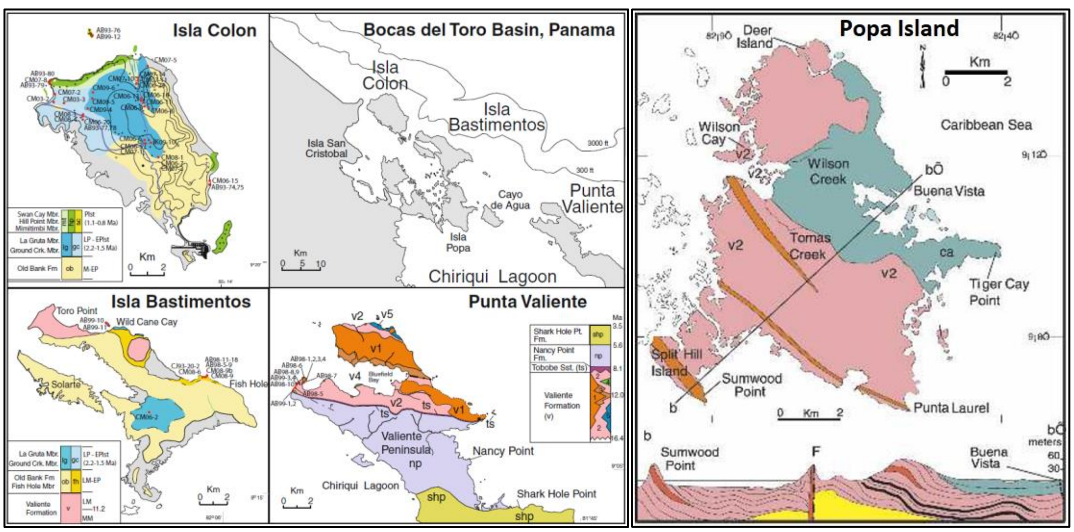

Figure 042. Bocas del Toro archipelago, NW Panama with map of the western & central portion together with the geological maps of Isla Colon, Isla Bastimentos, Punta Valiente (Klaus et al. (2012)) and Popa Island (Coates et al. (2005)). Section (b-b') over Popa Island shows the Valiente Formation where it is unconformably overlain by the Pliocene Cayo Agua Formation. On Popa Island, only the v1 basalt flow facies and the v2 coarse volcaniclastic facies (see Figure 043) (not associated with reef lenses) are present, with thin layers of low rank coal, an example of which is exposed along the coast immediately north of Punta Laurel. A prominent basalt dike is exposed at the tip of the Punta Laurel where it cuts the Valiente Formation.

Eigth main formations are represented in the Southern Region (which comprises the islands of Popa (Figure 042), Deer, Cayo Agua, and Escudo de Veraguas, and the Valiente Peninsula (Figure 043; Figure 042)), namely (from youngest to oldest): Cayo Agua, Escudo de Veraguas, Shark Hole Point, Nancy Point, Tobabe Sandstone, Bocas del Toro, Valiente and Punta Alegre Formations for which the stratigraphic relations are shown in Figure 043, Figure 044, Figure 045. The contact is well exposed in the Plantain Cays and on the coast south and west of Tobabe Point, where the volcanics form prominent bluffs of columnar basalt. Extinction, cooling, and subsidence of the volcanic arc locally in the region of the Bocas del Toro archipelago engendered a marine transgression represented by the Bocas del Toro Group. Outcrops of the Bocas del Toro Group on the Valiente Peninsula (Figure 043; Figure 042) and the islands of Cayo Agua and Escudo de Veraguas reflect paleoenvironments that were: 1) muddy bathyal in latest Miocene; 2) inner to middle neritic, carbonate shoal or reef in early to middle Pliocene; and 3) carbonate-influenced, muddy outer neritic in middle to latest Pliocene (Collins (1993)).

Always in the Southern Region, the basal Member of the Bocas del Toro Group is the Tobabe Sandstone, named by Collins (1993). Messinian (7.2-5.3 Ma) in age, it represents a basal, transgressive, near-shore marine facies that gradually gives way to the upper bathyal facies of the overlying Nancy Point Formation (Figure 043). Continued regional elevation of the isthmus initiated, about 5 Ma, a shallowing upward sequence represented by the Shark Hole Point, Cayo Agua, and Escudo de Veraguas Formations. This culminated in extensive, shallow marine, mixed volcaniclastic and coral reef deposits, about 2 Ma, many of which are exposed in on Bastimentos and Colon islands (Figure 042). Also included is the early Pleistocene Swan Cay Formation, a deep fore-reef deposit exposed only on Swan Cay, a small island immediately north of Colon Island. The new Tobabe sandstone and Swan Cay Formations were added to the Nancy Point, Shark Hole Point, Cayo Agua, and Escudo de Veraguas Formations by Coates et al. (1992) to form the expanded Bocas del Toro Group. The Caribbean Bocas del Toro Basin has about 1000 m of sediments, ranging from 8.5 to about 1.5 Ma.

The islands in the northern region of the Bocas del Toro archipelago (which comprises Swan Cay, Colon, Pastora, San Cristobal, Carinero, and Bastimentos islands, and the Zapatillo Cays) have a different geologic history than the southern region. At least four formations are present (from youngest to oldest): Swan Cay (Coates et al. (1999)), Isla Colon (with Members Ground Creek and La Gruta; Klaus et al. (2012)), Old Bank and Valiente Formations (Coates et al. (2005)). Volcanic arc columnar basalts of the Valiente Formation form the basement that underlies the marine late Neogene succession, as in the southern region. While no radiometric dates for these basalts are available, it can be presumed they are part of the same volcanic arc that went extinct and cooled after the middle Miocene (∼12 Ma). In all the Northern Region, the sediments unconformably overlying the Valiente Formation basalt are Plio-Pleistocene in age. The upper Miocene succession of Tobabe Sandstone, Nancy Point, and Shark Hole Formations are absent. Furthermore, the northern units are characterized by a major component of coral reef limestone. In general, the geological sequence on the Colon and Bastimentos islands (Figure 042) is younger than the section to the south with the exception of the Escudo de Veraguas Formation. The oldest units on Colon and Bastimentos islands may overlap in time with the top of the Cayo Agua and Shark Hole Point sequences at ∼3.5 Ma. (Coates et al. (2005)).

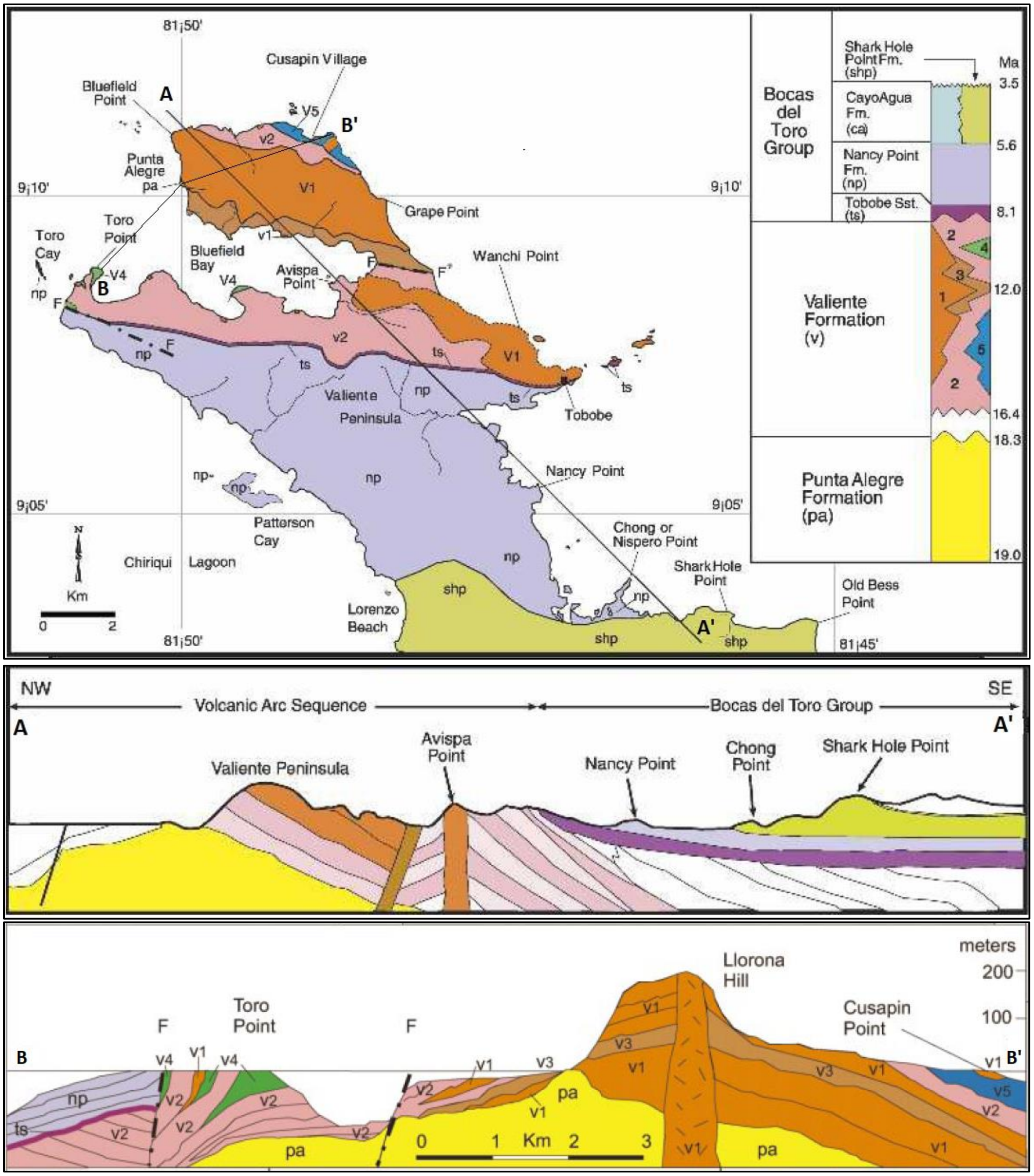

Figure 043. Coates et al. (2003 & 2005)'s description of the geological map and cross sections (A-A' and B-B') of the Valiente Peninsula (Punta Valiente) showing the distribution of the Punta Alegre and Valiente Formations and the Bocas del Toro Group. The five lithofacies of the Valiente Formation are indicated by separate colors and numbers on the key (upper right) as follows; v1) basalt lava and flow breccia facies; v2) coarse volcaniclastic facies; v3) pyroclastic facies; v4) coral reef facies; v5) marine debris flow and turbidite facies.

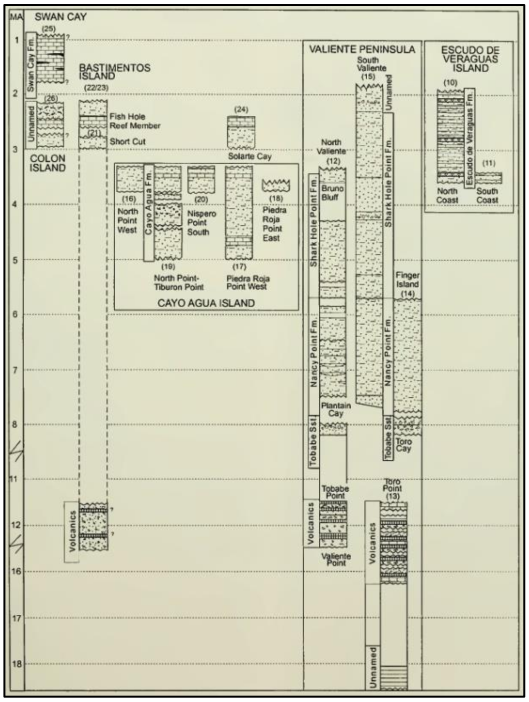

Figure 044. Correlation of measured sections in the Bocas del Toro Basin. Coates (1999). (Reproduced with permission of the Paleontological Research Institution, Ithaca, New York)

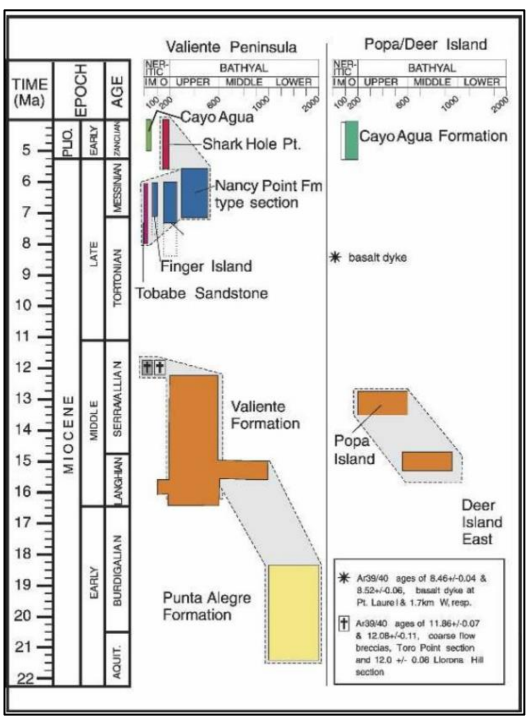

Figure 045. Chronological chart showing bathymetric ranges of various formations from the Valiente Peninsula (Figure 043; Figure 042), Popa Island (Figure 042), Deer Island and Cayo Agua. Dashed lines enclose the same geologic section. Dotted lines show the biochronologic ranges of sections that are placed according to physical stratigraphy. Coates *et al*. (2005).

5.2.3 Burica basin

The Burica Peninsula, on the border between Costa Rica and Panama in the Pacific coast of the Central American Isthmus (Figure 046), is a fore-arc Basin (Corrigan et al. (1990); Coates et al. (1992)) with more than 4000 m of sediments, ranging from about 3.5 to < 1 .7 Ma (Coates A.G. (1999)). Corrigan (1986) (Figure 048) & Corrigan et al. (1990) were the first to study the Neogene sequences and the recent structure of the Burica Peninsula while Obando (1986)'s unpublished thesis is the first report on the Paleogene sequences (Di Marco (1995)). The peninsula originates geologically from an unsubsided underwater mountain range of volcanic origin (Schlegel (1996); Coates and Obando (1996)). The basement underlying the Burica Peninsula consists mainly of massive pillow basalts that can contain minor gabbros, radiolarian cherts and basaltic breccias (Morell et al. (2011)). Above the volcanic sediments is a complex series of three sedimentary formations that overlap sequentially. The oldest is the La Peñita Formation (> 3.5Ma), followed by the Burica Formation (~ 3Ma). The youngest is the Armuelles Formation (1.9-1.7Ma) (Coates et al. (1992), O'Dea et al. (2012)) (Figure 046 & Figure 047). The general tendency of these formations is to dip in a northerly direction, so that as one advances along the peninsula in a southerly direction, older sediments are found (Olsson (1942a)). These three formations have been grouped under the Charco Azul Group. Also, mapping and precise differential GPS (DGPS) surveying by Morell et al. (2011) throughout the Burica Peninsula along ~20 transects indicate the presence of as many as eight laterally extensive late Pleistocene to Holocene marine terraces (Figure 046, RIGHT) which they named the Monte Verde Formation (Figure 113).

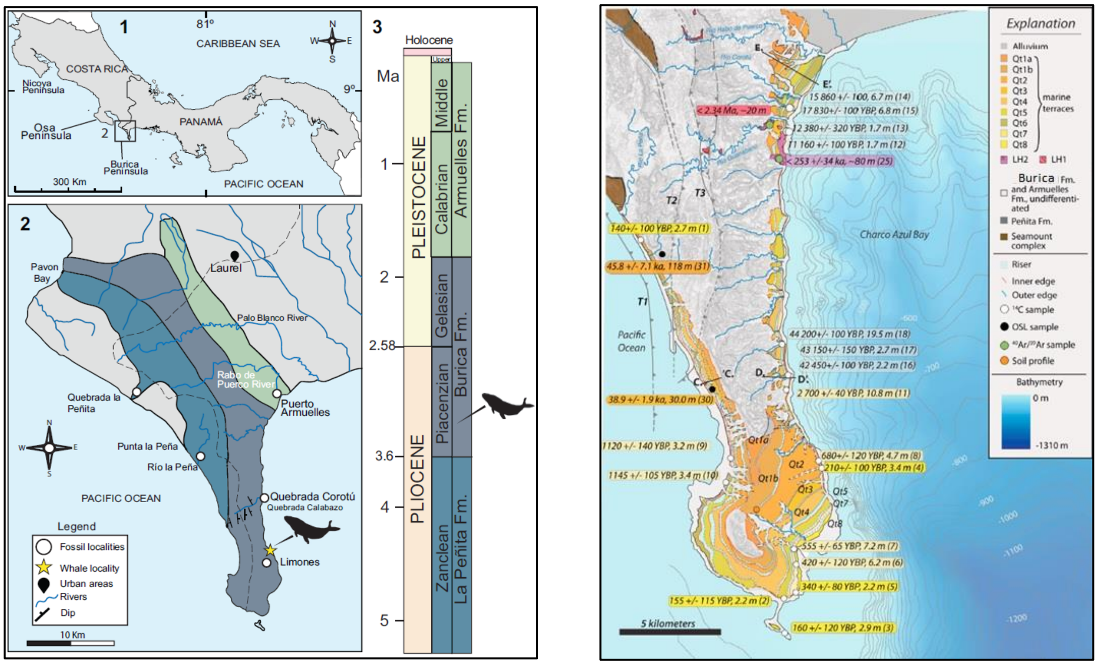

Figure 046. Left - Geological map of the Burica Peninsula showing the location of a Pliocene fossil whale found in the Burica Formation (Cortés et al. (2019)). Note also the dash line delineating the border between Costa Rica and Panama Right - Geologic and geomorphic map of the ESE Burica Peninsula draped on slope map and displaying the Quaternary marine terraces. LH1 and LH2 correspond to the lahar sequences described below. Also, Qt1 to Qt8 represent the Monte Verde Formation. Modified from Morell et al. (2011)

Morell et al. (2011) also identify at least two volcanic lahar deposits (LH1 & LH2) on the Burica Peninsula located south of the town of Puerto Armuelles, located at ~20 m and ~80 m elevation, respectively (Figure 046, RIGHT). The first (LH1), exposed along the Guanábano River at ~20 m elevation, is likely older than the second in that it is buried by at least ~20 m of gently dipping marine sediment of the Armuelles Formation. This deposit is a poorly sorted lahar or debris flow, with abundant meter to decimeter-sized clasts contained in a fine-grained mud matrix. Clasts are commonly well-rounded andesite or dacite cobbles, but large (~0.5 m), angular mudstone fragments or andesitic boulders are also present. Shell fragments within the matrix of this unit imply coastal or submarine deposition.

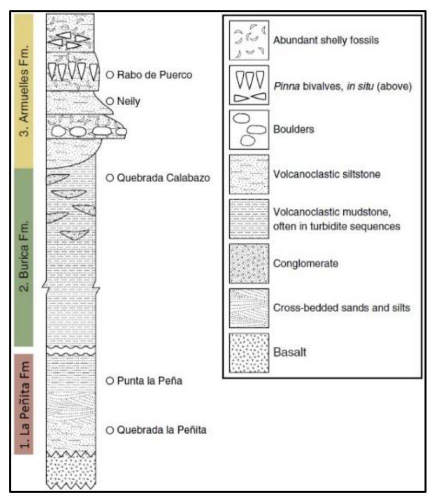

Figure 047. Stratigraphic section with location of fossil sites. Modified from O'Dea et al. (2012)

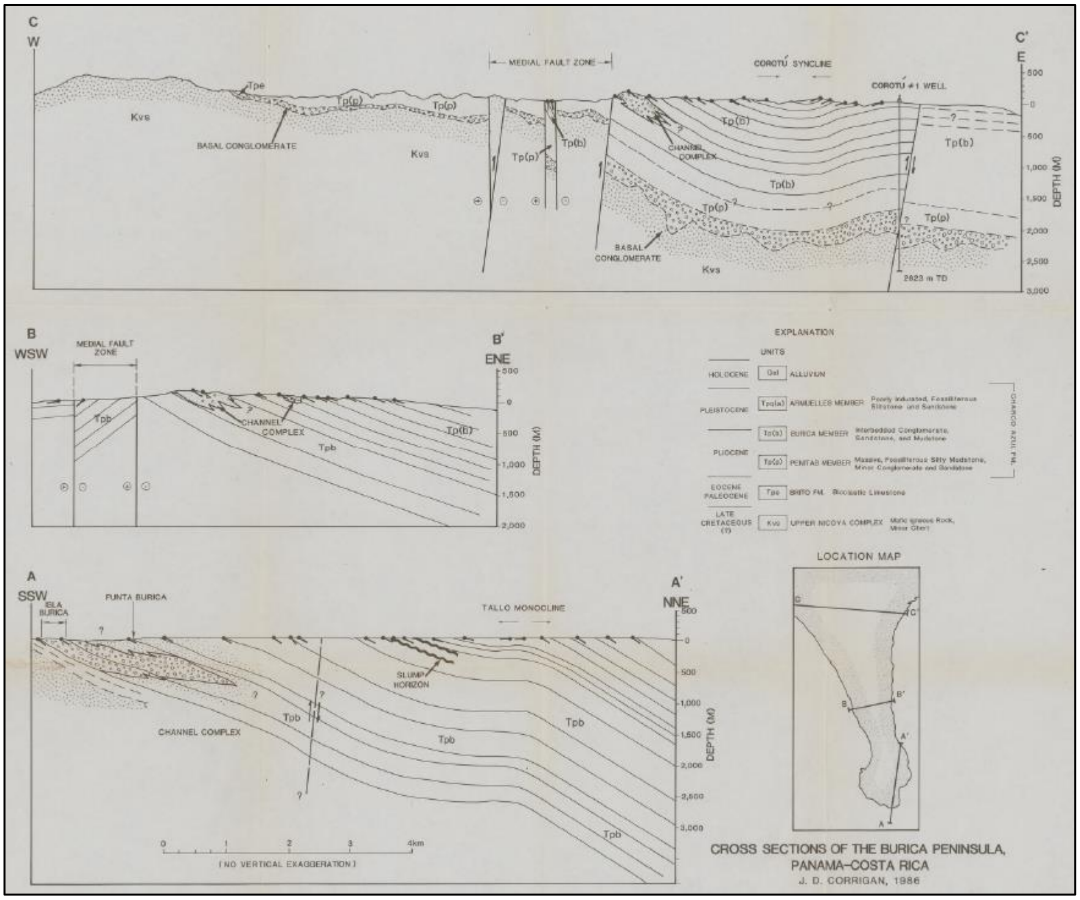

Figure 048. Cross-Sections of the Burica Peninsula, Panama-Costa Rica. Corrigan (1986).

5.2.4 Tonosí basin (or azuero basin)

The Soná and Azuero peninsulas (Figure 050; Figure 052) of western Panama together form a major forearc promontory (>10,000 km2) that extends over 100 km southward into the Pacific Ocean from the Panamanian isthmus. This prominent coastal landmass forms the eastern edge of the Gulf of Chiriquí and the western shore of the Gulf of Panama. Both peninsulas feature central mountain ranges (>500 m elevation) that are separated from the volcanic cordillera to the north by east-west trending lowlands. The two peninsulas are separated from each other by the narrow north-trending Gulf of Montijo. Offshore to the southwest of the Soná peninsula, lies Coiba Island within the Gulf of Chiriquí. (Marshall (2007))

The mountains of the Soná and Azuero peninsulas are both cut by the northwest-trending Soná-Azuero fault. This major left-lateral strike-slip fault forms a prominent lineament that cuts across the peninsulas along a series of aligned river valleys. Deformation along the Soná-Azuero fault affects a 40-km-wide zone marked by steep fault scarps and prominent linear valleys. This fault separates two distinct suites of basement rocks common to both peninsulas. South of the fault, the basement is comprised of homogenous Cretaceous seafloor basalts, while to the north it consists of a heterogeneous late Cretaceous-Eocene volcanic arc complex of basalts and intrusive rocks overlain by intermediate lavas. Offshore to the southwest, the Coiba fault zone runs parallel to the Soná-Azuero fault, resulting in uplift at Coiba Island. (Marshall (2007))

The Azuero Peninsula is composed of a series of igneous provinces unconformably overlain by a multiple forearc sedimentary sequences. The most recent tectonostratigraphic subdivision of the Southern Azuero Peninsula by Buchs et al. (2011) separated these units into four distinct sequences (Figure 050):

5.2.4.1 The Azuero Marginal Complex (Kedenburg (2016))

The Azuero Marginal complex consists of a series of Early Cretaceous to Middle Paleogene oceanic plateau basalts, pelagic and hemipelagic limestone, arc-related volcanic and plutonic rocks, and a sequence of undifferentiated metamorphic rocks (Buchs et al. (2011)). The oceanic plateau basalts occur in the southern Azuero Peninsula and yield late Turonian to Santonian ages. It is interpreted to represent autochthonous basement for this area. Pelagic and hemipelagic limestones of the Cretaceous Ocú Formation form a series of late Campanian units overlying the Azuero Plateau, and range in composition from detrital greenish-gray tuffaceous to gray micritic limestones.

The Proto-Arc Group is Late Campanian in age, and is interpreted as a primitive island arc sequence, while the Arc Group is Late Campanian to Eocene in age and is comprised of arc-related volcanic sequences. Undifferentiated metamorphic rocks have a minimum Campanian-Maastrichtian age based on overlying sedimentary deposits, and are interpreted as a relic of early deformation in the South American arc and later accretion events

5.2.4.2 The Azuero Mélange (Kedenburg (2016))

The Azuero Mélange is a tectonic mélange separating the Azuero Accretionary Complex from the Azuero Plateau along the Azuero-Sona Fault Zone, a seismically active NW-SE striking, high angle, left-lateral strike slip fault zone. The Azuero Mélange is comprised of volcano-sedimentary sequences and deformed portions of adjacent units (Buchs et al. (2011)).

5.2.4.3 The Azuero Accretionary Complex (Kedenburg (2016))

The Azuero Accretionary Complex is located in the southwest portion of the peninsula and consists of fault-bounded slices of accreted oceanic terranes including pillow basalts, gabbroic intrusions, lava flows, and clastic basaltic breccias. Biochronologic data indicate a Middle Eocene age for accretion of these oceanic rocks (Buchs et al. (2011)).

5.2.4.4 Overlap sedimentary sequences (Kedenburg (2016))

Three overlap sedimentary sequences, deposited in the Eocene–Miocene, exist in the Azuero Peninsula, which unconformably overlay (Figure 051) the basement igneous provinces (Kolarsky et al. (1995a, 1995b)).

- The Covachón Formation is an Early to Middle Eocene sequence in the southwestern section of the peninsula that unconformably overlays and underlies the Azuero Accretionary Complex and Tonosí Formation respectively (Buchs et al. (2011)). The Covachón is characterized by three facies: 1) siltstone and sandstone interbedded with volcaniclastic lutite 2) chaotic deposits of variable thickness, and 3) sandstones with frequent round basalt and shallow marine limestone pebbles (Buchs et al. (2011)).
- The Late Eocene to Miocene Tonosí Formation is the more laterally extensive of the two units, covering the majority of the peninsula, and consists of two distinct units (Buchs et al. (2011)).
    - The Late Eocene lower unit consists of a 40 to 400 m thick conglomerate, minor sandstones and siltstones, rare coal seams, and marine limestones.
    - The Late Oligocene to Miocene upper unit consists of a 500 to 800 m thick turbidite sequence (Kolarsky et al. (1995a, 1995b)).
- Finally comes the deposition of the Santiago Formation of Upper Oligocene to Middle Miocene age. This unit has few known exposures. Being covered by vegetation most of the time makes it a difficult formation to study (Guerrero et al. (2016))

Pleistocene deposits are also encountered over the Azuero Peninsula. The Pleistocene sites of Coca, Al Hatillo, Trinidaita and Llano Hato, discovered by Gazin (1957) near the towns of Ocú and Pesé, are important for our knowledge of fossil mammals from that time period (Figure 049). All localities overlay the Tonosí Formation and are found in surficial beds of clay associated with pond and creek deposits. The most common fossils are of the giant ground sloth *Eremotherium laurillardi* while the second most abundant are of horses *Equus conversidens*. Near Ocú *Eremotherium* remains are associated with the notoungulate *Toxodon*, near Pesé with mylodontids (*Glossotherium*, *Scelidotherium*?), glyptodonts, a capybara (*Neochoerus*), a mastodon (*Cuvieronius*), a horse, a peccary and a deer (Woodring (1960)). Most of these assemblages appear to be of Rancholabrean age in the North American land-mammal (NALMA) biochronology and Lujanian in the South American (SALMA) biochronology (APP-A). Thus, in some of these assemblages, Bison is present, providing *prima facie* evidence of a Rancholabrean age. Therefore, a Late Pleistocene age, between 250,000 and 10,000 years is assigned but most are likely younger than 100,000 years old. They represent a mixed fauna of grazers and browsers that was common across Central America during one or more of the late Pleistocene interstadials (Lucas (2014a, 2014b)).

Figure 049. The Pleistocene sites of Coca, Al Hatillo, Trinidaita and Llano Hato, discovered by Gazin (1957) near the towns of Ocú and Pesé. Pearson (2005)'s map on Google Earth.

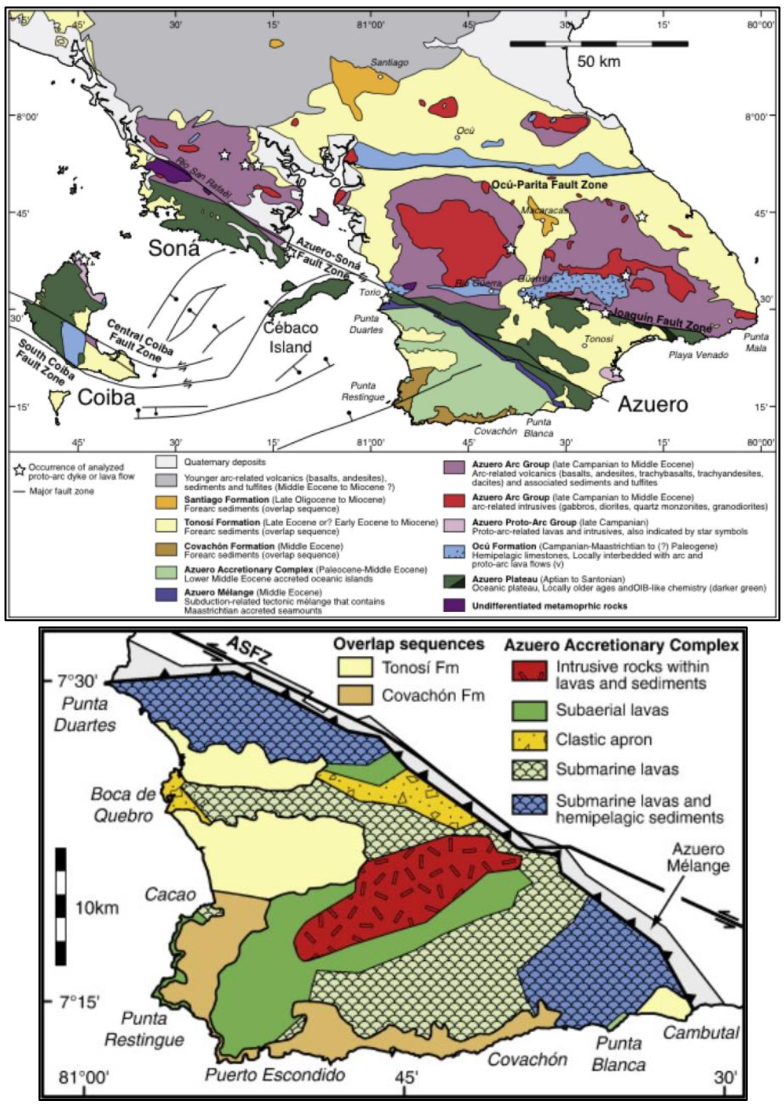

Figure 050. **Top**: Simplified geological map of the Azuero/Sona Peninsulas. **Bottom**: A zoom-in of the Azuero Accretionary Complex which forms the SW edge of the Azuero Peninsula. It represents an accretionary complex composed of Cretaceous to Eocene accreted seamounts and oceanic islands. Modified from Buchs et al. (2008, 2011). Also in Barat (2013).

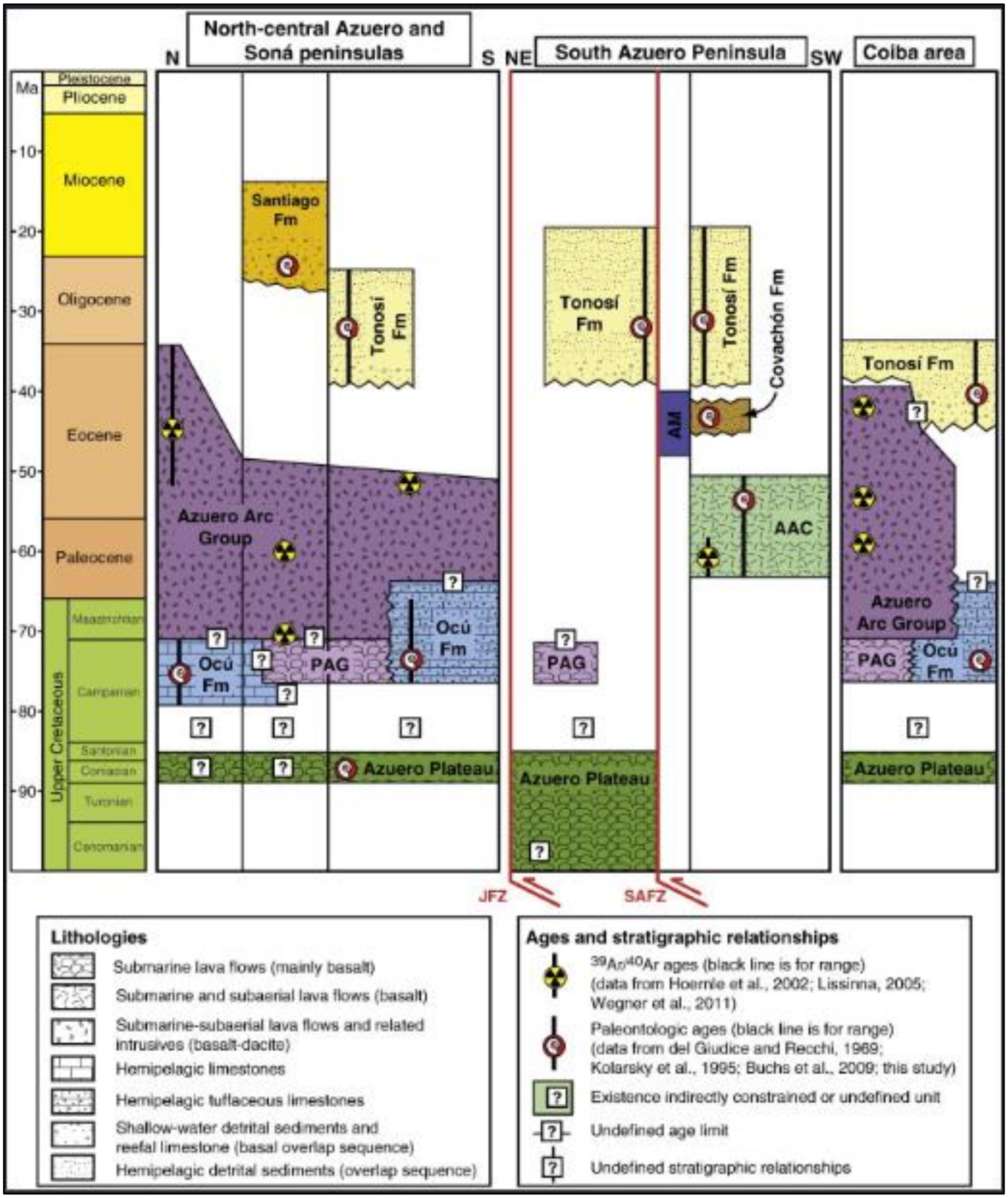

Figure 051. Tectonostratigraphic chart showing the igneous complexes exposed on the Azuero Peninsula and surrounding areas as well as the sedimentary formations overlapping them. The ages of all formations/complexes were measured either by $^{40}Ar/^{39}Ar$ or Paleontologic methods (Barat (2013) and Modified from Buchs et al. (2008)). Note that Buchs et al. (2011) and Barat (2013) now includes the Pesé Formation as part of the Tonosí Formation, and the Macaracas Formation as the equivalent of the Santiago Formation.

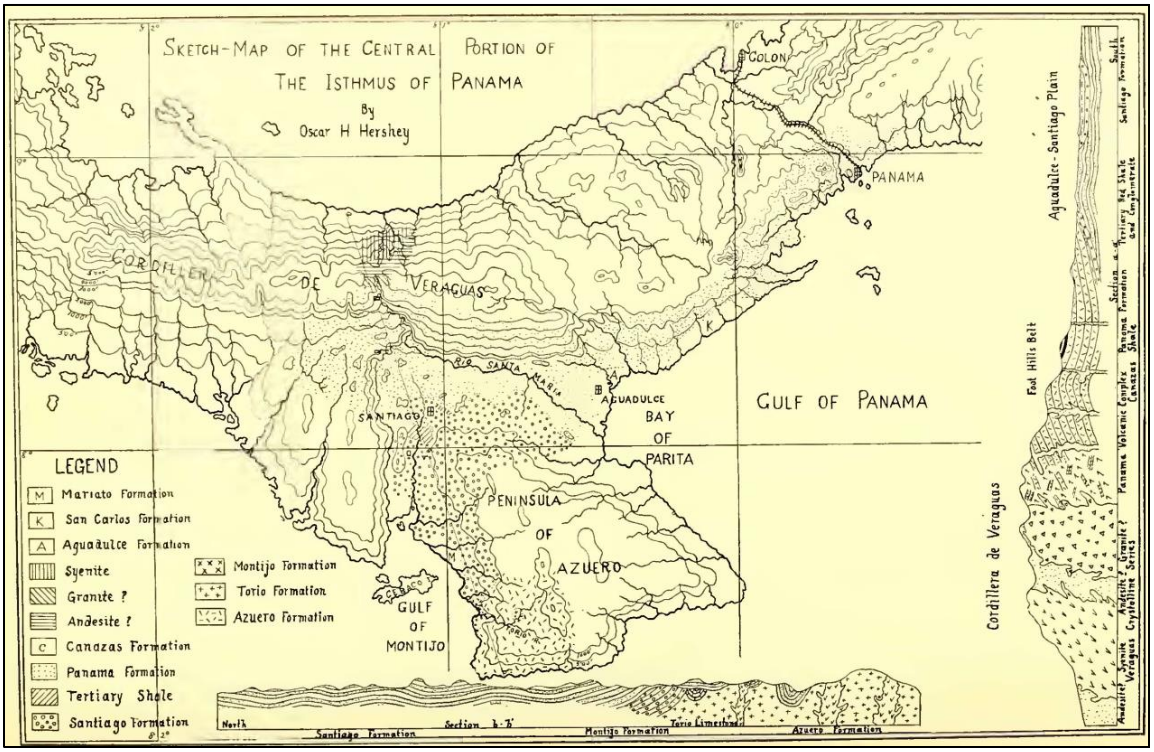

Figure 052. The earliest known geological sketch map of the Central Portion of the Isthmus of Panama zoomimg in on the Azuero Peninsula. The map displays the formations known at that time and described by Hershey (1901).

6 Lexicon

Obsolete names, or names recommended to be made obsolete, are marked with an asterisk (*).

Unit: AGUADULCE GROUP
Epoch/Age/Author: Holocene to Recent - Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)
Original Author and/or Origin of the Name: Hershey O.H. (1901) (Figure 052) defines it as a formation rather than a group (p. 258). "*In this formation near Aguadulce are many small, smooth, subangular pieces of limonitic chert and hardened clay which have a peculiar semi-glazed surface and a uniform light brown color. A great number of these same water-worn brown pebbles are scattered over the plain far from the sea, particularly in the vicinity of the more important stream courses. They appear to be the river deposits of a certain age, as none were formed before or since*."
Relevant documents discussing the Unit:

- Woodring (1960) states "Poorly defined name for surficial deposits. Pleistocene(?)" (p. 322)
- Keroher *et al.* (1966)
- Ministerio de Comercio e Industrias (1991) uses the name as a Group and includes in it the (1) Las Lajas (above), (2) Río Hato (middle) and (3) Boca de Chucara (below) Formations. These are described as:
  1) alluvium, consolidated sediments, sandstones, corals, mangroves, conglomerates, carbonaceous shales, deltaic type depositions
  2) Conglomerate, sandstones, shales, tuffs, semi-consolidated sandstones, pumice
  3) Alluvium, sand, carbonaceous shales, organic deposits with pyrite, deltaic type.
- Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)'s map keeps it as a Group and includes in it only the Las Lajas (above) and Río Hato (below) Formations in it. There is no mention of the Boca de Chucara Formation and the reason why it was removed from the Group.

Remarks: Occurs in Aguadulce Plain, Coclé province

Unit: *AGUAGUA FORMATION (see "Aquaqua Member")

Epoch/Age/Author: Miocene - Woodring (1960)
Synonymy: Aquaqua, Aqaqa

Unit: ALAJUELA FORMATION
Epoch/Age/Author: Late Miocene (Tortonian) - MacFadden *et al.* (2017)
Original Author and/or Origin of the Name: Schuchert Charles (1935). P. 586. "*Alajuela Formation consists principally of sandstones which become more calcareous below and have a barnacle limestone at their base. In part, marine equivalent of Caimito Formation. Lower Miocene.*"
Relevant documents discussing the Unit:

- Pilsbry (1918).
- A. Olsson (1942b). Correlation chart shows Alajuela as uppermost Member of Caimito Formation. Lower Miocene.
- Woodring W.P, Thompson T.F. (1949) (in their Figure 2). Uppermost Member of Caimito Formation in Madden Basin. Present only in type area. Consists of massive fine- to coarse-grained tuffaceous sandstone. Thickness 275 feet. Late early Miocene or possibly early middle Miocene. The Alhajuela is the Gatún(?) Formation of Reeves and Ross (1930, U.S. Geol. Survey Bull. 821) and Member 1 of sandstone formation of Kellogg (1931, Final report on field investigations of the Madden Dam and Reservoir site at Alhajuela, Panama Canal Zone, Panama Canal Rept.).
- Jones S.M. (1950); Wilson et al. (1957); Woodring (1957);
- Woodring (1960); "Alajuela" was casually used for sandstone at Madden Dam, Panama. The name was later altered to "Alhajuela", the name of the former village on Río Chagres near the present site of Madden Dam.
- Keroher et al. (1966); Smith (1991); Collins et al. (1996);
- MacFadden et al. (2015a & 2017). Renames the formation back to "Alajuela".
- Rodríguez-Reyes et al. (2017a, 2017b); Velez-Juarbe et al. (2019)

Synonymy: Alhajuela Formation; Alhajuela Sandstome Member; Previously included in the Caimito Formation; the Gatún(?) Formation of Reeves and Ross (1930, U.S. Geol. Survey Bull. 821) and Member 1 of sandstone formation of Kellogg (1931, Final report on field investigations of the Madden Dam and Reservoir site at Alhajuela, Panama Canal Zone, Panama Canal Rept.)
Location of the type section / Stratotype / Reference Section / Other localities:
Lago Alajuela region (Figure 054)
Lithology
The Alajuela Formation includes a >25 m-thick basal package of interbedded, clast-supported conglomerates and litharenite sandstones that grades into an ~85 m-thick package of calcareous sandstones and calcarenites, representing a transition from tide-dominated, potentially estuarine, coastal environments to wave-dominated, shallow-water carbonate environments. The 82 m-thick composite section (Figure 053), measured in proximity to the fossil localities on the southern extent of Lago Alajuela, is subdivided into three distinctive lithological intervals to summarize major facies transitions during this transgression.

Within the basal **Interval 1**, laterally extensive horizons of amalgamated conglomerate lenses fine upwards into fine-medium grained sandstones (Unit A), truncated by erosional contacts with overlying units. The best exposed amalgamated conglomerate (near the 15 m level in the composite section) exhibits substantial variability in thickness (1±6 m) with an average thickness of ~3 m. The amalgamated conglomerates are generally clast-supported, but locally matrix-supported, with the coarse grain fraction rarely exceeding 5 cm in diameter. Weathered exposures of the conglomeratic horizons erroneously appear matrix-supported due to diagenetic dissolution of aragonitic shell material. Prior to such dissolution, the coarse fraction would likely have been dominated by mollusk shells, whereas well-rounded, pebble- to cobble-sized volcanic fragments (welded tuff and andesite) and silicified woods comprise the minor component of the coarse fraction. Fossil invertebrate remains primarily consist of internal and external molds of mollusk shells preserved in fine-grained sand matrix as well as some original calcitic shell material of scallops and oysters. The amalgamated conglomerates contain the most abundant vertebrate fossils both well-preserved remains of marine vertebrates (e.g., sharks) and highly weathered remains of terrestrial vertebrates. Interval 1 is tentatively interpreted as sediment deposited in the distal area of a tide-dominated estuary. The amalgamated conglomerate horizons with variable thickness likely represent lag deposits within tidal channels whereas the overlying bioturbated sandstones represent tidal sand bars with lateral accretionary surfaces. (MacFadden et al. (2017))

The base of **Interval 2** exhibits a highly irregular, erosional contact with either a poorly sorted, bioturbated sandstone of Unit A lithologies or a laterally discontinuous unit of clastsupported conglomerate (Unit C). This interval typically occurs well above lake levels in the study area and is covered by vegetation. Consequently, continuous fresh exposures exhibiting diagnostic sedimentary structures are relatively rare. The dominant lithology in Interval 2 appears to be a well-cemented, fine-grained litharenite that coarsens upwards into a medium-grained sand capped by a shell lag horizon of fragmented bivalves and gastropods (Unit D). The density of shell fragments at the top of the coarsening-upwards sequences locally approaches that of a coquina. A minimum of three coarsening-upward sequences is preserved in Interval 2, and although the litharenite appears massive in most exposures, trough cross-bedding and low-angle planar cross-bedding are evident locally. (MacFadden et al. (2017))

The base of **Interval 3** is marked by a cm-scale gradational contact between an underlying shell lag in Interval 2 and an overlying fine-grained calcareous sandstone with lithics and occasional trough cross-bedding and ripple marks (Unit E). A calcarenite occasionally interbedded with sandy limestone (Unit F) occurs stratigraphically above, separated from the underlying calcareous sandstone by an irregular, erosional contact. Sedimentary structures vary within the calcarenite from trough cross-bedding to wavy bedding to low-angle planar cross-bedding, suggesting substantial changes in flow velocities at the time of deposition. The lithologies in Unit F were originally described by Woodring (1957) as the “Alhajuela” Sandstone Member of the Caimito Formation. However, based on the age constraints presented below for the Alajuela Formation, this attribution to the late Oligocene - early Miocene Caimito Formation is no longer supported. (MacFadden et al. (2017))

Deposits within **Intervals 2 and 3** in the composite section are interpreted to have been deposited in wave-dominated nearshore environments. (MacFadden et al. (2017)).

Thickness: 85 metres

Macro Fossils: Marine and terrestrial fossils of plants (silicified fossil woods, Jud et al. (2017a) & Rodríguez-Reyes et al. (2017a, 2017b)), invertebrates (bryozoans, scallops (Smith (1991)), oysters, decapods, echinoderms, corals and mollusks), and vertebrates (turtles, crocodiles, dugongs, and several taxa of shark teeth, dominated by the diagnostic *Carcharocles megalodon*, and horses, birds and proboscidean *Gomphotherium sp* [lat. 9.21236°, long. −79.59358°, MacFadden et al. (2015a)]). These taxa indicate predominantly estuarine and shallow marine paleoenvironments, along with terrestrial influences based on the occurrence of land mammals.

Overlying Unit: Gatún Formation (Collins et al. (1996))

Underlying Unit: Cucaracha Formation (Collins et al. (1996))

Remarks: Taken together, the plant, invertebrate, and vertebrate fossils from the Alajuela Formation are diagnostic in terms of reconstructing the paleoenvironments and paleoecology during the late Miocene of Panama. The sharks, sirenians, and some of the invertebrates (e.g., *Clypeaster*) indicate a shallow-marine environment. The land mammals, other invertebrates (e.g., *Crassostrea*), and ichnofossils indicate an estuarine environment with local influence from terrestrial environments. Terrestrial vertebrate fossils include the proboscidean, horses, peccary, carnivoran, and tortoise. The trionychid turtle indicates freshwater habitats. The crocodilians and some of the other turtles confirm the presence of transitional estuarine and shallow marine environments. Preliminary interpretations suggest the Alajuela Formation represents a higher energy, near-shore, marine setting that episodically received riverine/terrestrial input and was perhaps shallower and more proximal to a coastline than either the Chucunaque or Gatún Formations (MacFadden et al., 2017).

Maps, Cross-Sections & Pictures

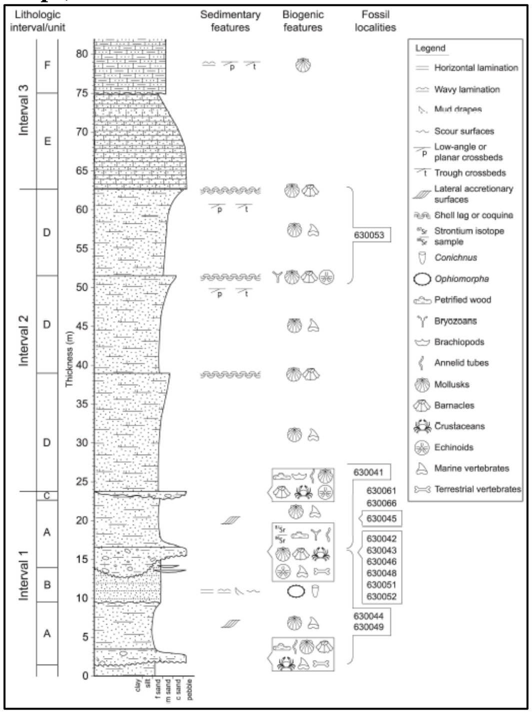

Figure 053. Composite lithostratigraphic section of the Alajuela Formation as exposed in northeastern Chagres National Park, along Lago Alajuela. MacFadden *et al.* (2017)

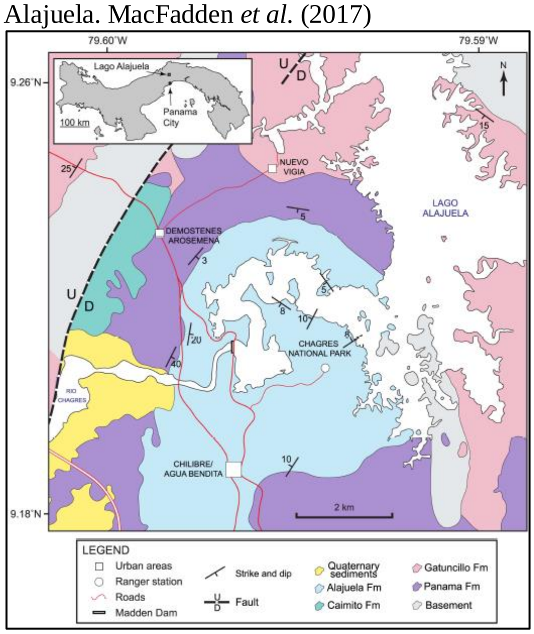

Figure 054. Geological map of Lago Alajuela region (previously Lake Madden). MacFadden *et al*. (2017).

Unit: *ALHAJUELA FORMATION
Epoch/Age/Author: Late Miocene (Tortonian)
Synonymy: See "Alajuela Formation"

Unit: ANCON HILL RHYOLITE or DACITE
Epoch/Age/Author: Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Thompson, T. F. (1943). pt. 2, chap. 3, p. 25. Dense porphyritic much-jointed hard light-gray material. Pre-Pliocene
Relevant documents discussing the Unit:

- Woodring (1960). p.323. Though the rock forming the stock at Ancon Hill was described by Howe (1908, pp. 230-231) and MacDonald (1915, pp. 28-29) as a rhyolite, and was named by Thompson (1943) as a rhyolite, it is a dacite (Woodring, 1957, p. 53). Miocene.
- Keroher et al. (1966)

Remarks: Forms rocks at Ancon Hill, located between towns of Panama and Balboa

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Unit: *ANOMIA zone
Epoch/Age/Author: Pliocene - Woodring (1960)
Original Author and/or Origin of the Name: Schuchert. (1935). p. 583. Calcareous strata, at top of Gatún Formation west of Gatún Lake, characterized by abundance of Anomia.
Relevant documents discussing the Unit:

- Olsson (1942b).
- Woodring (1960). It has been suggested that these shallow-water deposits are to be assigned to the overlying Toro limestone Member of the Chagres sandstone (Woodring & Thompson, 1949, p. 243; Woodring, 1957, p. 44).

Remarks: Panama Canal Zone

Unit: AQUAQUA MEMBER (of Darien Formation) (formerly Aquaqua Formation)
Epoch/Age/Author: Late Oligocene–Early Miocene - Barat (2014)
Original Author and/or Origin of the Name: Sapper Karl (1937). Correlation chart shows "Aquaqua" Formation above "Arusa" Formation and below Tuira Formation. Upper Oligocene and lower Miocene
Relevant documents discussing the Unit:

- Olsson A.A. (1942b), p. 241. Tapaliza can be divided into an upper or Miocene part and a lower or Oligocene part. These are known respectively as the Aguagua and the Arusa.
- Shelton (1952). Named it as "Aquaqua Formation".

- Terry (1956). Pgs 44-45. Used the name "Aquaqua Formation" and published a list of subsurface foraminifera.
- Wilson et al. (1957).
- Woodring (1960). p. 322. Undefined early Miocene fine-grained deposits. Age based on foraminifera.
- Keroher et al. (1966);
- Barat (2013 & 2014) incorporates it as a Member of the Darien Formation. (See Figure 016)

Synonymy: Aguagua, Aqaqa

Lithology: A calcareous unit, with conglomerate, black sandstone and gray to white medium-grained tuff unconformably overlies the oldest volcaniclastic unit of the Darien Formation. This calcareous unit suggests a hemi-pelagic depositional environment, and the nannofossil assemblages indicate a Late Oligocene–Early Miocene age. Barat (2014).

Unit: ARMUELLES FORMATION (part of the Charco Azul Group)

Epoch/Age/Author: Pleistocene (Calabrian to Middle Pleistocene) (Figure 046) **-** Cortés et al. (2019)

Original Author and/or Origin of the Name:
Terry (1941). p. 381 (Figure 5), 382. Conglomerate that passes upward into sandstones and shales. Overlies Charco Azul Formation. Thickness more than 4000 feet. Pleistocene

Relevant documents discussing the Unit:

- Olsson (1942a). Beds consist principally of gray well-bedded foraminiferal shales and soft sandstones. Fossils described
- Coryell et al. (1942);
- Woodring (1960). The name was used in a brief description of the geology of the Burica Peninsula, southwestern Panama. The Armuelles Formation, made up principally of foraminiferal siltstone and sandstone, crops out on the Burica Peninsula southward from Puerto Armuelles. It has a maximum thickness of about 4,000 feet and unconformably overlies the Pliocene Charco Azul Formation. The molluscan fauna represents a shallow-water assemblage. The mollusks, nearly all of which are Recent species, have been listed by Olsson (1942a, pp. 9-12) and some species were described in the same publication. The high percentage of Recent species indicates that the age is not older than early Pleistocene.
- Obando (1986); Jung (1989)
- Corrigan et al. (1990), originally named the "Charco Azul Group" as the "Charco Azul Formation" and included in it its three Members "Peñita", "Burica" and "Armuelles". It is only later that it was renamed as a Group, while each of its members were given the designation of "Formation".
- Kolarsky (1992); Coates et al. (1992); Collins et al. (1995) ; Kolarsky et al. (1995a, 1995b); Schlegel (1996); Lattig et al. (2000); Todd & Collins (2005) ; O'Dea et al. (2007) ; Beu (2010); Morell et al. (2011) ; Landau et al. (2012c); Okamura et al. (2013); Cortés et al. (2019).

Synonymy: Armuelles Member; See "Charco Azul Group" for some additional comments on synonymy.

Location of the type section / Stratotype / Reference Section / Other localities:
Burica Peninsula (Figure 046, Figure 047)

Lithology: The Armuelles Formation consists of ∼500 m of sandstones and siltstones with abundant shelly fragments and shelfal facies sediments (Figure 055). The facies within the formation record deposition within sequentially shallower water depths, with middle bathyal foraminifera in the lowermost Armuelles Formation indicating a record of slope to shelf transition since the Early Pleistocene. Corrigan et al. (1990); Olsson (1942a).

Thickness: ~370 to 500. Morell et al. (2011) ; Cortés et al. (2019)

Macro Fossils: The Armuelles Formation is a fossil-rich deposit that rests on the Burica Formation. Its fossils show that it was deposited in very shallow marine waters. It is best exposed along the Rabo de Puerco river in Armuelles, where a complete section of different fossil horizons can be crossed by walking a couple of kilometers upstream from where it intersects the road (8º 16.801'N, 82º 51.995'W) . At the base of the section you can find large boulders that still retain abundant oysters, corals and bryozoans (Okamura et al. (2013)). Going up the section, you can find a wide bed of bivalve mollusks of the *Pinna* genus with exceptionally well-preserved specimens of this large filter mollusk (Figure 055). Today, *Pinna* inhabits shallow sandy and muddy areas. Above the *Pinna* bed are a series of clam and snail horizons dominated by oyster shells and gastropods of the *Oliva* genus (Figure 055) (O'Dea et al. (2007)). Crabs can also be found. Todd & Collins (2005).

Overlying Unit: Monte Verde Formation (Morell et al. (2011)) (Figure 046)

Underlying Unit: Burica Formation (Figure 046, Figure 047)

Remarks: The change from deep-sea turbidite sediments (<2,000m) from the Burica Formation to coastal sediments from the Armuelles Formation demonstrate that during the late Pliocene the Burica region underwent rapid uplift due to regional movements of tectonic plates in the region. For more information on the geological history of the region see Collins et al. (1995). See also footnote under "Burica Formation".

Maps, Cross-Sections & Pictures:

Figure 055: Representative fossils of the Armuelles Formation. Part of a valve from *Pinna* (left). Gastropod from the genus *Oliva* (family Olividae) (top right). *Ostra* (bottom right). All of them are locally abundant. Scale = 2cm. O'Dea et al. (2007).

Unit: *ARUSA FORMATION

Epoch/Age/Author: Oligocene - Woodring (1960)

Original Author and/or Origin of the Name: Sapper Karl (1937). Arusa Formation shown on correlation chart below Aquaqua Formation and above Clarita Formation (both new). Upper Oligocene

Relevant documents discussing the Unit:

- Olsson (1942b). Tapaliza can be divided into an upper or Miocene part and a lower or Oligocene part, known respectively as the Aguagua and the Arusa.
- Wilson et al. (1957). Referred to as Arusa Formation.

Synonymy: Aruza Member

Remarks: Darien Area. The term "Arusa Formation" has not been used since the 1950's and never properly defined. It should be discarded.

Unit: *ARUZA MEMBER (of Tapaliza Formation)

Epoch/Age/Author: Oligocene - Woodring (1960)

Original Author and/or Origin of the Name: Terry (1956). Referred to as Aruza Formation.

Relevant documents discussing the Unit:

- Woodring (1960). An undefined name for Oligocene fine-grained deposits in the Darién area. The age is based on foraminifera, which have not been described or listed.
- Keroher et al. (1966). Indicate correct spelling is Aruza.

Synonymy: Arusa Formation. The term "Aruza Member" has not been used used since the 1960's and never properly defined. It should be discarded. Also, if it is a member of the Tapaliza Formation, its age would now have to be shown as Middle Miocene (see "Tapaliza Formation").

Remarks: Darien Area

Unit: ATLANTIC MUCK

Epoch/Age/Author: Pleistocene to Recent (0.13 Ma) - Woodring (1960); Hendy (2014)

Original Author and/or Origin of the Name: The following description is as valid for the Atlantic Muck as for the Pacific Muck: MacDonald (1913a, 1913b, 1915) observed "e*xtensive unconsolidated deposits of black, organic-rich marine mud with horizontal bedding*" but does not name them. Thompson (1943, 1947) named them and described them as "*Heterogeneous mixture of alluvially deposited silts, clays, and carbonaceous material within which are beds of marine origin containing Pleistocene and early Recent forms of mollusks and corals"*. He divides the muck into four phases. The lower phase, adjacent to its contact with older formations, consists of grey to bluegrey silty clay. The phase deposited in brackish marine waters contains abundant mollusk shells in an organic, black-silt matrix. The littoral swamp deposit is composed of semi-decayed wood and other organic vegetable matter, intermixed with silt and is characteristically dark brown to black. A soft, light-grey, weak, plastic clay overlies the organic phase. The four phases intergrade, with sand lenses locally present. The muck was deposited upon a stream-eroded topography of considerable relief. Old core borings reveal depths of over 200 feet for this deposit. Hills of the Gatún

Formation protrude thru the black muck and in the area south of Gatún these hills form islands that are completely surrounded by the swamp muck deposits.

Relevant documents discussing the Unit:

- Jones S.M. (Sept 1950). Pleistocene and Recent formation consisting of swamp deposits, both alluvial and marine, largely composed of clays, silts, and fine sands irregularly intermixed, uniformly soft and weak, and having a very high moisture content. Observation of drill cores throughout the Gatún Lake area indicates that Thompson (1943)'s four phases of the Muck are present in all thick muck deposits. In addition, the top and bottom phases appear to be thinnest and most widespread; the two middle phases are much the thickest, form the bulk of the formation, and interfinger so extensively that individual drill holes may show interbedding of these two phases. The brackish marine phase is north, or downstream from the littoral swamp phase and inter-fingers seaward with extensive beds of unconsolidated finger- and brain-coral fragments north of Gatún.
- Wilson et al. (1957).
- Woodring (1960). Informal name for swamp, stream, and marine Pleistocene deposits on the Caribbean, or Atlantic, side of the Canal Zone. Marine deposits contain numerous species of mollusks, nearly all of which are Recent. Brown and Pilsbry (1913)
- Keroher et al. (1966); Kirby (2006); Hendy (2014); Redwood (2020).

Synonymy: Mount Hope Formation. See also "Pacific Muck"

Remarks: Present on Atlantic side of Panama Canal. See a discussion under section "Brief Geological background" about "Pacific Muck" and "Atlantic Muck"

Unit: *AZUERO FORMATION

Epoch/Age/Author: Cretaceous - Woodring (1960)

Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). So far as now known, the oldest rock on the Isthmus of Panama is a green eruptive formation of unknown but immense thickness assumed to be late Jurassic or early Cretaceous. The whole formation is streaked by many exceedingly irregular veinlets of white quartz and calcite. Some veins contain a red mineral of the color of cinnabar, but the staining matter is probably iron oxide. Up the Torio River, the green rock sometimes assumes a schistose character, sometimes that of a non-laminated slaty rock, and again is clearly an eruptive. It is possible that the complex may include highly metamorphic sedimentaries. Everywhere it is characterized by the veinlets of quartz. Cotains large irregular masses of structureless, hard, bright red quartz.

Relevant documents discussing the Unit:

- Wilmarth (1938).
- Woodring (1960). Poorly defined name for basement altered volcanic rocks. Late Jurassic or Early Cretaceous age was suggested.
- Keroher et al. (1966).

Remarks: On west side of Azuero Peninsula

Unit: *BARBACOAS FORMATION

Epoch/Age/Author: Oligocene(?) - Woodring (1960)

Original Author and/or Origin of the Name: Hill (1898). Loosely cemented white earthy rock composed of firm fine particles, apparently siliceous, but water sorted, and showing distinct lines of lamination, in alternating degrees of fineness and coarseness. Grades down into mass of brownish rock called San Pablo phase of Barbacoas. The name "Barbacoas Formation" was suppressed in favor of "Panamá Formation" in Hill (1898, p.206) which name is to be used to include the analogous deposits of Barbacoas, San Pablo, and Miraflores.

Relevant documents discussing the Unit:

- Wilson et al. (1957). Mentions it as "Pre-Eocene"
- Woodring (1960). An informal name for tuff at a now submerged locality in Canal Zone. Oligocene(?).
- Keroher et al. (1966).

Synonymy: Panamá Formation

Location of the type section / Stratotype / Reference Section / Other localities: At Barbacoas, Canal Zone.

Unit: BAS OBISPO FORMATION

Epoch/Age/Author: Latest Oligocene – Earliest Miocene (Chattian – Aquitanian; 24.6 to 21.1Ma) - Buchs et al. (2019)

Original Author and/or Origin of the Name: Howe (1907c); Howe (1908). "Obispo Formation" was named for its characteristic occurrence near Obispo, Canal Zone. It consists of andesitic breccias and flows. A thickness of 200 feet was penetrated, and the base was not reached. The age was not specified, but it is the oldest formation along the Panama Canal.

Relevant documents discussing the Unit:

- MacDonald (1913a, 1913b), Wilmarth (1938).
- Jones (1950). Thickness of formation is 2,500 feet in Gatún Lake area where it underlies Las Cascadas Formation and base is not exposed. Underlain by Gatuncillo Formation west of Madden Basin only.
- Woodring (1957). Volcanic rocks now included in Bas Obispo Formation and Las Cascadas agglomerate were named Obispo Formation or breccia by Howe (1907c). Emendation to Bas Obispo Formation and splitting off of younger part as Las Cascadas agglomerate were proposed by MacDonald (1913a, 1913b). These volcanic rocks are interpreted to represent pyroclastic rocks that accumulated at periphery of a volcanic pile. Bas Obispo is thought to grade into Bohío Formation. Thickness unknown. Volcanic rocks now included in Bas Obispo Formation and Las Cascadas agglomerate were named Obispo Formation or Obispo breccia by Howe (1907c). Emendation to Bas Obispo Formation and splitting off of younger part as Las Cascadas agglomerate were proposed by MacDonald (1913a, 1913b). Doubtfully referred to Oligocene because of inferred relations to Bohío Formation
- Woodring (1960). The name was changed to Bas Obispo, the name of the locality for which the formation was named, and the formation was restricted so as to be made up mostly of agglomerate having a matrix of hard tuff. Northern Gaillard Cut is the type region. The Bas Obispo Formation is recognized along and near the Canal. Toward the SW it is not differentiated in a volcanic complex. Toward the NW it grades into the Bohío Formation.
- Keroher et al. (1966), Stewart and Stewart (1980); Montes et al. (2010); Rooney et al. (2011); Farris et al. (2017); Buchs et al. (2019).

Synonymy: Obispo Formation, Obispo Breccia, Obispo Limestone

Location of the type section / Stratotype / Reference Section / Other localities:

Culebra Cut (Figure 003, Figure 030, Figure 034, Figure 035, Figure 040)

Lithology: The Bas Obispo Formation was previously interpreted as an agglomerate, but well-rounded imbricated pebbles and cobbles in new exposures unambiguously record the occurrence of bedload fluvial sediments throughout the unit (Figure 056, Figure 057). These deposits are interbedded with poorly layered, coarse pebbly sandstone that forms most of the unit, and are rarely associated with siltstones and mud drapes (Figure 058). These deposits are typical of debris to hyperconcentrated flows in a fluvial volcano-sedimentary environment (Buchs et al. (2019)).

The Bas Obispo sandstone is an immature lithic arenite with angular fragments of andesite, feldspar, clinopyroxene and opaque minerals with dark gray to black welded basaltic pyroclastic (Figure 059)deposits that contain abundant rounded and vesiculated lava clasts and blocks. Individual volcanic beds are not clearly defined. A general westward dip of between 14 to 50 degrees can be identified depending on outcrop. The unit is also folded (Farris et al. (2017)). The clasts in the sandy matrix are composed of porphyritic andesite with multiply zoned plagioclase and clinopyroxene. Lithification of the Bas Obsipo Formation is highly variable (hard to crumbly) due to heterogenous cementation by authigenic clay (no volcanic welding). The andesite clasts have a very consistent geochemical signature which is distinct from other units of the Culebra Cut. These observations indicate that this sedimentary unit was formed by proximal reworking from a volcanic sequence without younger equivalent along the Culebra Cut. (Buchs et al. (2019)).

Thickness: Unit thickness is estimated at between 300±1500m, with the large range being due to structural uncertainty and the difficulty in correlating individual outcrops.

Macro Fossils: None

Overlying Unit: Las Cascadas Formation

Underlying Unit: Gatuncillo Formation or Cretaceous basement

Remarks: Northern Culebra Cut area, Canal Zone.

The Late Oligocene Bas Obispo Formation is the oldest geologic unit that outcrops along the Panama Canal from Panama City to Gamboa (Figure 033). Stewart and Stewart et al. (1980) assigned an Oligocene age based on stratigraphic relationships to fossiliferous strata. However, the Bas Obispo Formation does not contain fossils and is fault bounded making stratigraphic age determinations difficult. Rooney et al. (2011) examined rocks from Cerro Patacon that yielded an Ar/Ar age of 25.37 ± 0.13 Ma. However, Buchs et al. (2019)'s measurements confirmed that the Bas Obispo Formation was deposited in the latest

Oligocene-earliest Miocene (24.6–21.1 Ma). This formation could grade laterally to the terrestrial to shallow-marine deposits of the Bohío Formation and lower to middle Members of the Caimito Formation in the Lake Gatún area. The Cerro Patacon rocks are hornblende bearing andesite that sit stratigraphically below the Las Cascadas Formation. Traditionally, rocks at Cerro Patacon have been mapped as part of the poorly defined Panamá Formation (Stewart and Stewart et al. (1980)), however compositional, stratigraphic, and temporal similarities to the Bas Obispo Formation indicates geologic continuity. Farris et al. (2017)

Maps, Cross-Sections & Pictures:

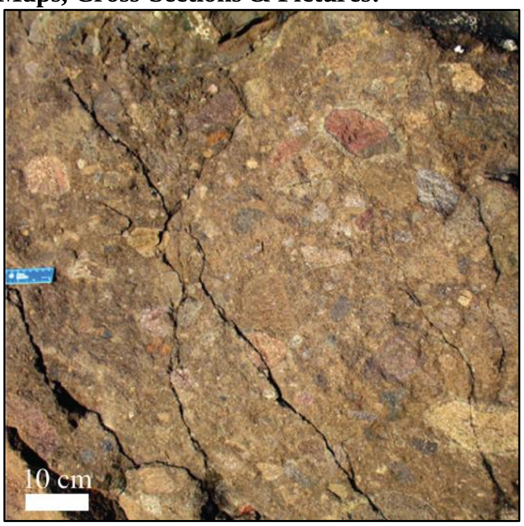

Figure 056. Field photo of the welded basaltic pyroclastic rocks characteristic of the Bas Obispo Formation. Photo from Farris et al. (2017)

Figure 057. Volcanogenic fluvial conglomerate in the Bas Obispo Formation, with clast imbrication. Buchs et al. (2019)

Figure 058. Layered volcanogenic pebbly sandstone in the Bas Obispo Formation. Inset shows mud drapes. Buchs et al. (2019)

Figure 059. Pyroclastic breccia outcropping at the level of the Panama Canal. Barat (2013)

Unit: *BASTIMENTOS SHALE

Epoch/Age/Author: Miocene **-** Terry (1956)

Original Author and/or Origin of the Name: Terry (1956). Massive, poorly bedded soft gray clay shale at base of Gatún Formation [see "Remarks" below]. Interfingers with Minitimi limestone. Overlies Conch Point shale, which it resembles closely. On Columbus Island, surface structure is gently rounded dome on which early Miocene Conch Point shale crops out at crest, over an area about 1 mile in diameter, surrounded by middle Miocene Bastimentos shale. Seismograph survey indicated structure is cut by fault striking N. 24° E.

Relevant documents discussing the Unit: Woodring (1960); Keroher et al. (1966)

Synonymy: N/A

Remarks: Occurs on Isla Colon (Columbus Island) and Isla Bastimentos (Provision Island) (Figure 042). **Note:** The Gatún Formation mentioned for these two islands may be equivalent to the Gatún Formation in the Canal Zone but is not the same.

Unit: *BOCA DE CHUCARA FORMATION
(Part of the Aguadulce Group)
Epoch/Age/Author: Holocene to Recent - Ministerio de Comercio e Industrias (1991)
Original Author and/or Origin of the Name: Ministerio de Comercio e Industrias (1991) includes the name as the basal formation of the Aguadulce Group and describes it as “alluvium, sand, carbonaceous shales, organic deposits with pyrite, deltaic type”. (APP-B3).
Relevant documents discussing the Unit: Map of Ministerio de Comercio e Industrias (1991)
Overlying Unit: Río Hato Formation (part of the Aguadulce Group)
Underlying Unit: Chagres Formation
Remarks: See “Aguadulce Group”. Occurs in Aguadulce Plain, Coclé province
The formation is not present on the 1996 map of the Instituto Geografico Nacional (IGN) "Tommy Guardia", suggesting that the term is now obsolete.

Unit: *BOCAS FORMATION
Epoch/Age/Author: Pliocene - Olsson (1942b)
Original Author and/or Origin of the Name: Olsson (1942b)
Synonymy: See “Bocas Del Toro Group”

Unit: BOCAS DEL TORO GROUP
Epoch/Age/Author: Upper Miocene (Tortonian/Messinian) to Pleistocene (7.26 to 1.4 Ma) - Coates (1999)
Original Author and/or Origin of the Name: Olsson (1942b). Name “Bocas Formation” appears on chart for sediments on Bocas Island [Isla Colon].
Relevant documents discussing the Unit:

- Woodring (1960). “Bocas Formation” is an undefined name for strata of Pliocene age
- Jung (1989);
- Coates et al. (1992); Renamed “Bocas Formation” as “Bocas del Toro Group” and subdivided it as seen below (with some adjustments from subsequent authors).
- Collins (1993); Cairns (1995); Collins et al (1999); Coates (1999); Budd et al. (1999); Collins et al. (1999a & 1999b); Coates et al. (2003 & 2005) ; Beu (2010); Kiessling et al. (2011); Klaus et al. (2012); Landau et al. (2012b); Jaramillo et al. (2014);

Synonymy: Coates et al. (1992) sub-divide the Bocas del Toro Group (Figure 043) as seen below from oldest (bottom) to youngest (top), however subsequent authors brought some minor changes to it (as indicated):

- Swan Cay (now part of the Urraca Formation; Klaus et al. (2012))
- Isla Colon Formation (Klaus et al. (2012))
- Escudo de Veraguas Formation. A shallowing upward sequence, culminating in extensive, shallow marine, mixed volcaniclastic and coral reef deposits, about 2 Ma, many of which are exposed in unnamed units on Bastimentos and Colon islands. (Figure 042)
- Cayo Agua Formation / Shark Hole Point Formation. A shallowing upward sequence.
- Nancy Point Formation. Upper bathyal facies (Collins (1993))
- Tobabe Formation. Transgressive, near-shore marine facies (7.26-5.32 Ma).

Location of the type section / Stratotype / Reference Section / Other localities: The Caribbean Bocas del Toro Group lies nonconformably on the underlying volcanics of the Valiente Formation. It has about 1000 m of sediments, ranging from 8.5 to about 1.5 Ma. Extinction, cooling, and subsidence of the volcanic arc locally in the region of the Bocas del Toro archipelago engendered a marine transgression represented by the Bocas del Toro Group. Coates (1999)
Lithology: See individual formations (mentioned above) within the Group
Thickness: About 1000 m
Macro Fossils: See individual formations (mentioned above) within the Group
Overlying Unit: None
Underlying Unit: Valiente Formation. An unconformity between the Valiente Formation and the Bocas del Toro Group can be clearly observed in the inner islands of the Plantain Cays and along the coast to the west. The underlying columnar basalt of the Valiente Formation can be seen on the north side of the Cays and the fossiliferous conglomerate and sandstone of the Tobabe Sandstone on the south side (Figure 043). Coates (1999)
Remarks: The Bocas del Toro Group signifies a new depositional cycle as a marine transgression submerged the older eroded volcanic arc rocks. The oldest sediments thus represent the first shallow-water, beach, and near-shore sand deposits. As the transgression developed, subsequent overlying marine units reflect deeper

water deposition until the reverse occurred and the sea regressed to shallow water again. Thus, the units of the Bocas del Toro Group are genetically related and document a single marine transgressive/regressive event. The most continuous section lies along the east and west coasts of the Valiente Peninsula (Figure 043; Figure 042) where it ranges from late Miocene (Messinian, 7.2-5.3 Ma) to late Pliocene (~3.5 Ma). Coates (1999)

Unit: BOHÍO FORMATION

Epoch/Age/Author: early Upper or late Lower Oligocene - Jones S.M. (1950)

Original Author and/or Origin of the Name: The formation was named by R. T. Hill, the first American geologist to study the geology of the canal route (Hill (1898), p. 183). He used the spelling "Bujio" which appears on some early maps. Woodring (1949).

Relevant documents discussing the Unit:

- Vaughan (1918) correlating the "Bohío Conglomerate".
- Ross and Reeves (1931) gave the name Bohío (originally Bohío Soldado), for a village on the Panama Railroad, located on a bluff overlooking Río Chagres, to the entire group of sediments in the Chagres Valley above Madden Dam, and referred them to the Oligocene.
- The samples of Foraminifera which were collected from Ross & Reeves (1931)'s "Bohío Formation" by Coryell et al. (1937b), however, showed that it included both an upper Eocene and an Oligocene fauna. The Oligocene beds are well exposed near Bohío Switch; the Eocene beds appear farther east along the Río Chagres, near the town of Tranquilla. Therefore, Coryell et al. (1937b) reduced the thickness of the Bohío Formation and named the shale unit the "Tranquilla Shale Formation". The Bohío Formation is since restricted to include only the Oligocene sediments which overlie the Tranquilla shale (obsolete name; now included in the Gatuncillo Formation) and which outcrop farther downstream the Chagres River.
- Woodring (1949). Formation consists of massive or poorly bedded conglomerate, tuffaceous sandstone, and tuffaceous siltstone. Estimated thickness as much as 1,000 feet. Overlies Gatuncillo Formation; base of the Bohío not exposed along Panama Canal. Underlies Caimito Formation. Grades laterally into Bas Obispo Formation. Upper Eocene and lower Oligocene.
- Jones S.M. (1950);
- Woodring (1957). Basal part of Bohío in Quebrancha syncline contains smaller Foraminifera of early Oligocene age and upper part of formation in Pacific coastal and Gatún Lake areas, respectively, contains late Oligocene larger Foraminifera and mollusks. Whether formation represents so great a time span in each of areas where it crops out is not known at present. It represents, however, more than the early Oligocene age previously suggested (Woodring and Thompson, 1949). That it does not include all of the Oligocene is shown by late Oligocene age of overlying Caimito Formation.
- Woodring (1958, 1959);
- Woodring (1960); The Bohío Formation, consisting chiefly of boulder-conglomerate and greywacke grit, for the most part evidently is nonmarine. In the Quebrancha syncline, a few kilometers east of the Canal Zone, some 80 species of early Oligocene smaller foraminifera have been found in sandy siltstone in the basal part of the Bohío. These fossils include *Bolivina alazanensis*, *Bulimina alazanensis*, *Globigerina ciperoensis*, and *Gümbelina cubensis* [*Chiloguembelina cubensis*]. On Barro Colorado Island, in Gatún Lake, subgraywacke in the upper part of the Bohío contains late Oligocene marine fossils: larger foraminifera, including *Lepidocyclina canellei*, *L. vaughani*, and *Miogypsina antillea*, and about 70 species of mollusks, including *Globularia* aff. *G. fischeri*, *Orthaulax* cf. *O. pugnax*, and *Chione* cf. *C. spenceri*. The widely distributed late Oligocene (formerly middle Oligocene) eulepidine orbitoid fauna — *Lepidocyclina favosa*, *L. gigas* and associated species — is found in thin lenses of algal limestone in conglomerate of the Bohío at the continental divide a few kilometers east of the Canal Zone.
- Woodring (1964); Keroher (1966); Woodring (1973, 1982);

Synonymy: Bohío Conglomerate (Vaughan (1918); Wilmarth (1938)); Bujio

Location of the type section / Stratotype / Reference Section / Other localities: Bohío Peninsula. Bohío or Bohío Soldado, was a station on original line of Panama Railroad, near southwest end of ridge forming present Bohío Peninsula. Many localities described by early writers, including French quarries at Bohío and excavation at near-by lock site, are covered by Gatún Lake

Lithology: The Bohío Formation is characterized by siltstones, sandstones, and sandstone-conglomerates, very hard and massively bedded and jointed. It contains angular to rounded pebbles, cobbles, and boulders, locally up to as much as 6 feet in diameter, in a dark-gray, generally coarse-grained, angular-grained sandstone matrix. Both the sandstone matrix and conglomeratic fragments are notably basaltic. Some tuff-siltstone interbeds as much as 90 feet [28m] thick are present. Exposures of the Bohío Formation show dips of 15° to 20°. The formation is characteristically transected by basalt intrusions ranging in width from a few inches to an observed maximum of 200 feet [61m]. These intrusions are more or less localized, being very numerous, for example, in the vicinities of Gamboa and Darien. They are so numerous and discontinuous that only the large ones are mappable units. The Bohío Formation in localities containing numerous faults and basalt dikes has been highly indurated over broad areas by incomplete fusion and by other igneous effects. From Darien to Gamboa the overall outcrop picture is one of uneven increase in both coarseness of matrix and angularity of fragments of all sizes. At Darien some fused sandstone-agglomerate is present; at the Obispo High locality, some hard, friable sandstone conglomerate is exposed. But eastward from Gamboa, angularity of fragments and induration of the Bohío Formation by basalt intrusives are progressively greater to the extent that at Obispo Point, across the Chagres River Bridge from Gamboa, and at Bas Obispo and eastward therefrom, the rock is considered to be the Bas Obispo (agglomerate) Formation. That the Bas Obispo and Bohío Formations are different facies of the same stratigraphic sequence has become apparent through field mapping along the west bank of the present canal in the vicinity of and opposite from the town of Gamboa. Here numerous rock exposures have demonstrated a gradual change in character from that of the typical Obispo agglomerate to that of the Bohío sandstone-conglomerate. (Jones S.M. (1950)).

Thickness: The thickness of the formation is about 75 to 450 metres (246 to 1,476 ft). Smaller foraminifera from the basal part of the formation yielded an early Oligocene age. The upper part of the formation, from which the collections are derived yields larger foraminifera of late Oligocene age.

Macro Fossils: The fossils in the marine deposits, inferred to represent a lower marine member, include *Nummulites striatoreticulatus*, *Fabiana cubensis*, *Lepidocyclina pustulosa*, *Glyptostyla panamensis*, *Mactrella dariensis*, *Pitar hilli* and *Cardium gatunense*. *Lepidocyclina favosa* and *L. gigas* are found in thin marine deposits in the upper part of the formation in the Pacific coastal area. Woodring (1960).

Overlying Unit: Bas Obispo Formation. The unconformity at the top of the Bohío Formation is irregular and represents a period of erosion during which the Obispo-Bohío Formation land surface was dissected to maturity with a relief of an undetermined number of scores or possibly hundreds of feet (Jones S.M. (1950)).

Underlying Unit: The Gatuncillo Formation underlies the Bohío Formation conformably in most areas, although the Bohío Formation may also lap onto the basement in some other areas.

Unit: *BRUJA ISLAND DIORITE or DOLERITE

Epoch/Age/Author: Oligocene or Miocene **-** Woodring (1960)

Original Author and/or Origin of the Name: Thompson (1943). Diorite represents massive dike that has cut through and distorted lower beds of the Gatún sandstone.

Relevant documents discussing the Unit:

- Jones (1950, page 898, 901). Referred to as dolerite. Lower Miocene. Basaltic rock of diabasic (or doleritic) texture quarried on Bruja Grande Island, in Gatún Lake.
- Wilson et al. (1957). Lower Miocene
- Woodring (1960). Oligocene or Miocene
- Keroher et al. (1966).

Unit: *BÚCARO FORMATION

Epoch/Age/Author: Eocene **-** Woodring (1960)

Original Author and/or Origin of the Name: Sapper (1937). Name Búcaro appears in correlation chart. Underlies Tonosí Formation.

Relevant documents discussing the Unit:

- Senn (1940, pages 1578, 1589). Used the misspelled name of "Bucarú Formation", without accent.
- Olsson (1942b, pages 235-236). Referred to as Bucarú Formation. Exposed thickness of Eocene rocks north of Guanico Point is about 2,000 feet. Lower beds are coarse dark-gray sandstones, conglomerates, and sandy shales. These beds are followed by about 1,500 feet

of blue-green or black shales with thin gritty sandstones; in their lower part are several fossil zones, the lower about 50 feet above base of section. Underlies David Formation. The mollusks include *Aturia peruviana* [nautiloid], *Noetiopsis woodringi*, and *Venericardia tonosiensis*.

- Terry (1956, page 29). Used the spelling Búcaru
- Wilson et al. (1957).
- Woodring (1960). On north side of Point near Búcaro, is in fault contact with volcanics; to south grades downward into volcanics. Lexicon uses Búcaro as preferred spelling. Near village of Búcaro, Los Santos Province. Confirmed that the proper spelling is Búcaro Formation. The formation extends northward up the lower part of the valley of Río Tonoso. Near Búcaro the basal part grades downward into basaltic agglomerate.
- Keroher et al. (1966).

Synonymy: Bucaru, Bucarú, Búcaru
Remarks: Near the town of Tonosí, Azuero Peninsula

Unit: *BUCARÚ FORMATION
Epoch/Age/Author: Eocene **-** Woodring (1960)
Relevant documents discussing the Unit: Woodring (1960)
Synonymy: See "Búcaro Formation"

Unit: *BUJIO FORMATION
Epoch/Age/Author: early Upper or late Lower Oligocene **-** Jones S.M. (1950)
Relevant documents discussing the Unit: Jones S.M. (1950)
Synonymy: See "Bohío Formation"

Unit: BURICA FORMATION (part of the Charco Azul Group)
Epoch/Age/Author: Late Pliocene – Middle Pleistocene (Piacenzian – Gelasian) (Figure 046) **-** Cortés et al. (2019)
Original Author and/or Origin of the Name: Terry (1941). Name "Burica Sandstone" was listed on map explanation as Upper Miocene but not defined.
Relevant documents discussing the Unit:

- Olsson (1942a). Sandstone transitional with overlying Charco Azul shales. Base of sand stones and basement on which they rest not exposed. Age tentatively considered as lower Pliocene or uppermost Miocene.
- Olsson (1942b). Lower part sandstones and conglomerate; upper part tuffaceous shale. The "Burica Sandstone" is defined as the oldest formation cropping out on the Burica Peninsula at and near Burica Point and Burica Island. The formation is made up of sandstone, which gradationally underlies finer grained rocks of the Pliocene Charco Azul Formation. The base is not exposed, and the exposed thickness was not specified. The mollusks include *Phos gatunensis*, *Turritella cf. gatunensis*, *Solemya burica*, and *Thyasira bisecta*.
- Coryell et al. (1942); Wilson et al. (1957);
- Woodring (1960); Obando (1986)
- Corrigan et al. (1990), originally named the "Charco Azul Group" as the "Charco Azul Formation" and included in it its three Members "Peñita", "Burica" and "Armuelles". It is only later that it was renamed as a Group, while each of its members were given the designation of "Formation".
- Coates et al. (1992); Kolarsky (1992); Collins et al. (1995) ; Kolarsky et al. (1995a, 1995b) ; Schlegel (1996); Leon-Rodríguez (2007) ; O'Dea et al. (2007); Buchs (2008); Buchs et al. (2009); Morell et al. (2011) ; O'Dea et al. (2012); De Gracia (2015) ; Cortés et al. (2019) ; Timmons (2019) ;

Synonymy: Burica Member; Burica sandstones; See "Charco Azul Group" for some additional comments on synonymy.
Location of the type section / Stratotype / Reference Section / Other localities: Burica Peninsula (Figure 046) at or near Burica Point and Burica Island.
Lithology: The Burica Formation represents the extraordinary sum of 2,800m of deposits dominated by volcaniclastic turbidites (Figure 060, left). A turbidite is a group of sediments originating from the coast and the shelf, but which have been precipitated by the steep slope of the marine shelf and have been redeposited in deep seas (Coates et al. (1992)). As a result of this, the fossils that occur in the Burica Formation are usually a combination of species from shallow seas. For example, the mollusk fauna is dominated by the Nuculidae (Figure 060, right) and Tellinidae families, shallow-water bivalves, as well as the gastropods Columbellidae, Calyptraeidae and Nassariidae, but it is also possible to find very deep indicator fossils such as the planktonic gastropod *Cavolinia* (Cavoliniidae) (Figure 060, right), and the deep-sea scaphoid *Cadulus* (Emerson (1957)) (Figure

060, right), and certain benthic foraminifera showing that the lowest part of the Burica Formation was deposited at a depth of about 2,000m (Collins et al. (1995)). The Burica Formation is best exposed in an impressive 20km section on the east side of the Burica Peninsula (Figure 060, left), although the small number of horizons rich in mollusks can make it difficult to collect fossils through this succession.

Coates et al. (1992), O'Dea et al. (2012) and De Gracia (2015) subdivide the formation into two members without elaborating on their respective fabric, while Buchs (2008) and Buchs et al. (2009) only briefly describe the Chancha Member. See Charco Azul Group

Thickness: 2800 m according to Coates et al. (1992).

Macro Fossils: A horizon in which fossils occur in abundance can be found outcropping in areas near the mouth of the Corotú ravine (8º 7,821'N, 82º 52,292'W) and the Calabazo ravine (8º 8,777'N, 82º 52,497'W). Foraminifera, mollusks, crustaceans, fish otoliths, shark teeth (Carcharodon) and whale (a mysticete, which has been assigned to Balaenopteridae; Cortés et al. (2019); Timmons (2019)). The whale fossil (balaenopterid) was found in a coastal outcrop near Quebrada Calabazo[2] creek in Playa Limones (8°08'53.6"N, 82°52'27.4"W). The specimen was found in the late Pliocene lower member, which was deposited at water depths around 2000 m and consists of coarse-grained proximal turbidites (Corrigan et al. (1990); Collins et al. (1995); Leon-Rodríguez (2007); O'Dea et al. (2007)). Based on the stratigraphic column of Leon-Rodríguez (2007) and the geographic location of the site, the approximate stratigraphic position of the fossil is in the lower part of the lower member of the Burica Formation (~700 m above the base of the 2800 m thick formation). The specimen was collected in a poorly consolidated, fine-grained green glauconitic siltstone with abundant mollusks, echinoids, and crustacean remains (Figure 046).

Overlying Unit: A transitional, time-transgressive unconformity separates the deep water turbidites of the Burica Formation from the overlying Armuelles Formation (Morell et al. (2011))

Underlying Unit: La Peñita Formation

Maps, Cross-Sections & Pictures:

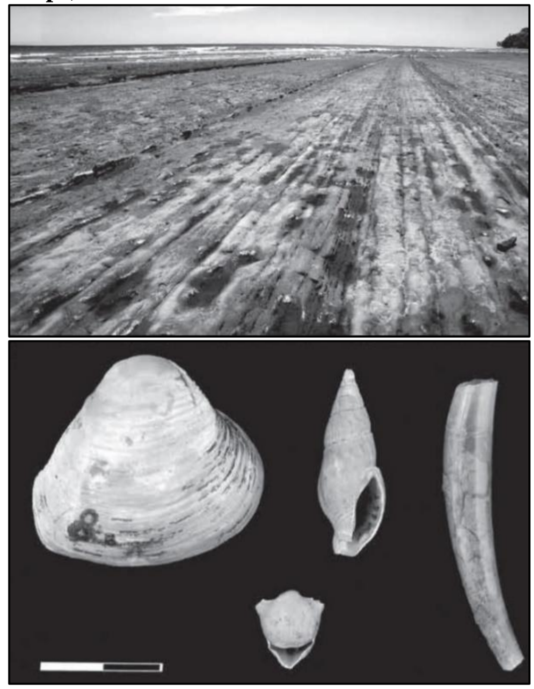

Figure 060. The Burica Formation (to) and some representative fossils (bottom). A succession of 20 kms of turbidite deposits exposed at low tide along the eastern coast of the Burica Peninsula (left). The Burica Formation has a mixture of shallow water taxa which include *Nuculidae* (top left) and *Columbellidae* (centre) as well as deep water taxa such as the rare planktonic gastropod *Cavolinia* (bottom) and the Lidophile scaphopod *Cadulus* (right). Scale = 1cm. O'Dea et al. (2007).

Unit: *BURICA SANDSTONE

Epoch/Age/Author: Late Miocene or Early Pliocene - Woodring (1960)

Synonymy: See "Burica Formation".

Unit: CAIMITO FORMATION

Epoch/Age/Author: Upper Oligocene and Lower Miocene - Jones S.M. (1950)

Original Author and/or Origin of the Name: The Caimito Formation takes its name from a construction-period junction on the Panama Railroad near the Darien station (of 1958), 8 kilometers west of Gamboa. The formation was named by MacDonald (1913a, p. 569, 1913b).

[2] December 14th 2020 & January 1st 2021 Personal Communications from Dr. Aaron O'Dea: The Quebrada Calabazo exposure in Burica Peninsula is actually an isolated part of the Armuelles formation not part of the Burica formation and it has been confidently dated to be young at late Pleistocene (https://www.pnas.org/content/116/15/7377, Taylor et al. (2019)) and therefore unconformably sits on the Pliocene there. More sedimentological studies are needed but there is no reason to believe that the whale is in the Armuelles formation.

The name was proposed but not adequately defined. The age was shown as Oligocene on plate 69.

Relevant documents discussing the Unit:

- Berry (1921) studies some plants from the Caimito Formation
- Olsson (1942b). As shown on correlation chart, comprises (ascending) Chilibrillo, Caimito, and Alajuela.
- Thompson (1943). MacDonald (1913a, 1913b) considered the Caimito to overlie immediately the Emperador Formation. Recent studies have indicated that this is incorrect, and that the formation bears closer affinity to the Panamá tuff. These two formations overlap many of the Oligocene beds within the Pacific area of the Canal Zone, locally lying upon the Emperador and thin only because of transgressive overlap. Gradational with overlying Panamá tuff.
- Woodring (1949). Formation name was introduced by MacDonald (1913a, 1913b) but was not properly defined then or later (MacDonald (1919), U.S. Natl. Mus. Bull. 103). Type region was not specified. Most of MacDonald's brief description of formation is description of strata on Pacific side of Canal Zone now assigned to La Boca Formation. MacDonald's statement that the Caimito overlies Emperador limestone—now assigned to Member rank in Culebra Formation—was based on misidentification of limestone in the La Boca Formation and in the Caimito itself. Caimito Formation and Emperador limestone Member of Culebra are nowhere in contact. On account of these confusing formation assignments, published data on fossils of Caimito and Culebra Formations and Emperador limestone Member are misleading or erroneous. In Madden Basin, formation comprises (ascending) unnamed calcareous sandstone-siltstone, unnamed pyroclastic clay, Chilibrillo limestone, unnamed calcareous sandstone, and Alhajuela sandstone Members. In Quebrancha syncline, comprises (ascending) Quebrancha limestone Member and calcareous siltstone Member. In Gatún Lake area and Caribbean coast, Canal Zone, comprises three unnamed members. Thickness as much as 1,000 feet. Overlies Bohío Formation. Formation in Madden Basin includes considerable time span—late Oligocene to late early Miocene, or possibly early middle Miocene.
- Jones S.M. (1947); Jones S.M. (1950, pgs 900-901); Woodring & Thompson (1949); Woodring (1957, pgs 28-31, 32-34); Woodring (1958, 1958, 1960, 1973, 1982); Keroher et al. (1966); Montes et al. (2010);

Synonymy: Caraba Facies

Location of the type section / Stratotype / Reference Section / Other localities: Though no type locality was specified in MacDonald (1913a, 1913b), he evidently intended Caimito and its vicinity to be the type region (in those days, Caimito, or Caimito Junction, was located on the present alignment of Panama Railroad and Darien.). It is not a good type region, but the characteristic lithology is shown there and, according to the regional relations near Darien, it is evident that the Caimito overlies the Bohío Formation (Woodring (1958)

Lithology: The Caimito Formation is a series of tuffs (here acidic tuff, the predominant constituent of this formation), tuff-agglomerates, tuff-conglomerates, and limestones, all thinly and thickly bedded and closely to moderately jointed. All are probably marine. Some beds contain sparse, poorly preserved, marine megascopic and microscopic fossils. The attitude of the beds is highly variable due to cross-lamination, faulting, and folding. Dips range from 5° to over 40°. The formation is divisible lithologically into three Members: lower, middle, and upper (Jones S.M. (1950))

Lower Member: Formerly designated "basal" phase (Jones (1947b), p. 24), is a tuffaceous sandstone-conglomerate of local extent containing pebbles, cobbles, and boulders of basalt and pebbles of tuff. The basalt fragments are reworked from the underlying Bohío Formation. All exposures are highly weathered indicating that this member of the Caimito Formation either weathers very deeply upon exposure or was completely weathered during its deposition. It is present only along the bottoms and side slopes of the Bohío surface where the pebbles, cobbles, boulders, and some of the sand weathered out of the Bohío Formation, were reworked and deposited with the first of the tuff which marked the new era of deposition. It is probably a marine facies of the Las Cascadas Formation.

Middle Member (also called "Quebrancha Member"): Formerly designated "lower phase" (Jones (1947b), p. 25), is a series of slightly fossiliferous tuffaceous sandstones and limestones. This member may be local and may intergrade in part with the lower member although the former is more widespread. But whether or not it was originally deposited throughout the Gatún Lake area has not been determined. The limestone beds within it are discontinuous. The zones of abundant *Lepidocyclina candid*, *L. pancanalis*, and *L. vaughani* appear in this member and are found on the peninsula jutting into Zetek Bay, Barro Colorado Island, in the Panama Railroad cut at the east side of Bohío Peninsula, and at other points.

Upper Member: (Jones (1947b, p. 25) It is a widely distributed series of tuffs and tuff-agglomerates, with sandy limestone beds interspersed throughout at irregular intervals. It is the thickest, most widely distributed part of the formation. When sufficiently detailed field mapping, laboratory study, or core drilling can be undertaken, it may be mappable as one or more other formations. The entire formation appears to be increasingly uniform and fine grained toward the northwest, away from Barro Colorado and Bohío Peninsula. In these areas it is essentially a tuff-siltstone series.

Thickness: At least 1,000 feet [300 m] (Woodring (1960))

Macro Fossils: Foraminifera, mollusks, corals. *Lepidocyclina canellei* and *L. vaughani* are widespread and abundant in the upper Oligocene part (Cole (1952, 1953), pg 7), and *Turritella meroensis*, a weakly sculptured form of *T. altilira*, *Orthaulax cf. pugnax*, and *Globularia* are found in that part (Woodring & Thompson (1949), pg 234)

Overlying Unit: N/A

Underlying Unit: Bohío Formation (Woodring (1960))

Unit: *CAÑAZAS FORMATION

Epoch/Age/Author: Miocene(?) - Woodring (1960)

Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). The village of Cañazas is situated in the foothills belt in the midst of mountains composed of the Panama series of volcanics. Beginning at about one mile east of the village, there is a small area, several miles in diameter, of finely laminated light gray and brown shale. It is evidently composed of volcanic ash which was deposited in a body of water, probably a small lake. There are slight traces of fossils. In the midst of the shale is a three-foot stratum of coarse volcanic ash, representing apparently a single shower. On the eastern and northern sides of the area, a coarse basal conglomerate composed of water-worn boulders of the lower portion of the volcanic series, is developed to a thickness of 50 to 100 feet. The formation dips southward 10° to 30°, having been concerned in the orographic movement which lifted the Cordillera de Veraguas. It is evident from the way in which the Cañazas Formation is included in the Panama series that it represents local conditions - merely a lake of short duration in which was deposited several hundred feet in thickness of finely laminated tuff or shale. Its age is, therefore, probably Eocene.

Relevant documents discussing the Unit:

- Woodring (1960). A poorly defined name for deposits, mostly pyroclastics. An Eocene age was suggested but Woodring (1960) opted for Miocene(?).
- Keroher et al. (1966).

Remarks: Occurs near Cañazas, Veraguas Province.

Unit: CAOBANERA FORMATION

Epoch/Age/Author: Upper Cretaceous / Paleocene - Ministerio de Comercio e Industrias (1991)

Original Author and/or Origin of the Name: Esso Exploration and Production Panama (1970, 1971a, 1971b); Bandy and Casey (1973).

Relevant documents discussing the Unit: Ministerio de Comercio e Industrias (1991); Barat et al. (2014);

Synonymy: N/A

Location of the type section / Stratotype / Reference Section / Other localities: San Blas Complex

Lithology: Volcano-clastic rocks (Barat et al. (2014))

Overlying Unit: N/A

Underlying Unit: San Blas Complex

Remarks: The name is not mentioned in Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) however it is still used by Barat et al. (2014).

Unit: *CAPETÍ FORMATION

Epoch/Age/Author: Oligocene - Ministerio de Comercio e Industrias (1991)

Original Author and/or Origin of the Name: Olsson (1942b). Name of "Capetí limestones" appears on correlation chart. Occurs below Arusa Formation [or Member of Tapaliza Formation]. Middle Oligocene. The name would come from the Capetí River or the town of Capetí on the Capetí River in the Darien Region. (See map of DRFigure 49 in Appendix 1 of Coates et al. (2004)).

Relevant documents discussing the Unit:

- Woodring (1960). Undefined name applied to limestones in Darien area. Oligocene.
- Keroher et al. (1966).
- Ministerio de Comercio e Industrias (1991) has it as a low production aquifer composed of clayey sandstones, tuffs, limolite, lutolytic conglomerates and interstratified limestones (APP-B3)

Remarks: There is no mention of it in any of the other Woodring (1955, 1957, 1959, 1964, 1970, 1973, 1980, 1982) publications. Unless new/good evidence favor to keep the name, it is suggested to abandon the term.

Unit: *CARABA FACIES (of Caimito Formation)

Epoch/Age/Author: Upper Oligocene to Lower Miocene **-** Jones (1950)

Original Author and/or Origin of the Name: Jones (1950). Facies presumably of parts of the middle and upper members of the Caimito. Where exposed at Río Caraba, consists of a thick massive very sparsely jointed sandstone-conglomerate-breccia overlain by a thick section of thin-bedded limestone and limy fine-grained sandstone. The limestone overlying the facies has fossil assemblage characteristic of the Caimito Formation. If facies is later demonstrated to be a mappable unit, it should be given formational status, although it is included in Caimito Formation on plate 2 (geol. map).

Relevant documents discussing the Unit:

- Wilson et al. (1957);
- Woodring (1960). A name proposed for locally thick conglomerates in the Caimito Formation of the Canal Zone.
- Keroher et al. (1966).

Synonymy: See “Caraba Formation”

Remarks: Panama Canal Zone. Typically exposed along the minor stream Río Caraba which is flowing northward into the upper part of Gatún Lake about 1km southwest of Gamboa, and in gullies along south bank of Chagres Crossing Reach due south of Canal Beacons 29 and 30.

Unit: CARABA FORMATION

Epoch/Age/Author: Late Oligocene or early Miocene **-** Woodring, W. P. (1970)

Original Author and/or Origin of the Name: The formation was first defined by Jones (1950, p. 901) as a facies member of the Caimito Formation. “Caraba Formation” is adopted by Woodring, W. P. (1970) for strata formerly assigned to the Caimito Formation.

Relevant documents discussing the Unit: Woodring, W. P. (1957, 1970, 1982); Stewart et al. (1980)

Synonymy: Caraba Facies of the Caimito Formation

Location of the type section / Stratotype / Reference Section / Other localities: The thickest well exposed section so far found is in the type region. It is located south of the Gamboa Reach of the Panama Canal, along a tributary of Río Mandinga, about 4 kilometers southwest of Gamboa and about 750 meters east of Río Caraba.

Lithology:

Unit	Lithology	Thickness (m)
8	Andesitic lava	15
7	Agglomerate	60
6	Sandy Siltstone	8
5	Hard, dense, buff limestone; *Clypeaster* fragments	3
4	Sandy siltstone and calcareous, pebbly sandstone; *Clypeaster concavus* and few mollusks (locality 60)	18
3	Hard, dense, buff limestone; Clypeaster fragments	8
2	Sandy siltstone and poorly sorted, silty sandstone; many *Heterostegina israelskyi*, also *Lepidocyclina asterodisca* (locality 59)	18
1	Conglomerate and coarse-grained, poorly sorted conglomeratic sandstone; boulders have maximum length of 60 cm, but cobbles having length of 3 to 6 cm more common than boulders; dacite prophyry conspicuous among clasts	70
	TOTAL	200

Table 1. The section exposed along a tributary of Río Mandinga, as recorded by Stewart *et al.* (1980) and Woodring (1982).

These strata, characterized by the exceptional thickness of conglomerate and conglomeratic sandstone, presumably interfinger with the Caimito Formation. The total thickness of the Caraba is unknown, even in the type region, as the base and top have not been recognized.

Where the Caraba Formation reappears northeast of the Canal (Table 1), it consists almost wholly of agglomerate, in which blocks and slabs of decite porphyry generally predominate, and agglomeratic tuff. North of Pedro Miguel the agglomerate is shown on some geologic map as part of the Pedro Miguel agglomerate, and in the area straddling the part of Madden Highway south of the Transisthmian (or Boyd-Roosevelt) Highway overpass as part of the Caimito Formation. Exposures may be seen at the falls on the east side of Madden Highway at the monument site four kilometers south of the overpass and on abandoned Army roads east of the highway.
Thickness: >200 m
Macro Fossils:
- Larger foraminifera: *Nummulites panamensis* Cushman, *Heterostegina israelskyi* Gravell and Hanna, *Lepidocyclina asterodisca* Nuttall,
- Coral: *Goniopora* cf. *G. cascadensis* Vaughan
- Gastropods: *Pachycrommium?* aff., *P.? trinitatensis* (Mansfield), *Ficus sp*., group of *F. ventricosa* (Sowerby)
- Echinoid: *Clypeaster concavus* Cotteau

Overlying Unit: Caimito Formation
Underlying Unit: Panamá Formation

Unit: *CARIBBEAN LIMESTONE
Epoch/Age/Author: Pliocene - Woodring (1960)
Original Author and/or Origin of the Name: MacDonald (1913a, 1913b).
Relevant documents discussing the Unit:
- Wilmarth (1938).
- Thompson (1943). Names Toro limestone and Caribbean limestone have been used to describe deposits of shell breccia or cemented coquina that overlies Gatún sandstone in region between Limon Bay and Chagres River. Formation [Toro] has been assigned to upper Miocene.
- Woodring (1960). Informal name for limestone in Canal Zone later named Toro limestone and still later assigned to Member rank in the Chagres sandstone.
- Keroher et al. (1966).

Synonymy: Toro Limestone
Remarks: Between Limon Bay and Chagres River, Canal Zone

Unit: *CASA LARGA MARLS
Epoch/Age/Author: Upper Eocene - Woodring (1960)
Original Author and/or Origin of the Name: Thompson (1943). Oldest known sedimentary formations known to rest upon the Basement Complex occur within the vicinity of the Tranquilla shales, which formerly cropped out at a point in the Chagres River Valley now inundated by the waters of Madden Lake, and in so-called Casa Larga marls to the southeast of Tranquilla shale locality. On basis of their fossil content, the marls are considered to be upper Eocene.
Relevant documents discussing the Unit:
- Wilson et al. (1957).
- Woodring (1960). Expression used by Thompson was "so-called Casa Larga marls". An undefined name for calcareous strata in Gatuncillo Formation.
- Keroher et al. (1966).

Synonymy: Gatuncillo Formation
Remarks: Madden hydrological Basin (now Alajuela hydrological Basin)

Unit: *CATIVA MARL (in Gatún Formation)
Epoch/Age/Author: Middle Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Coryell et al. (1937a). Fossiliferous marl from Cativa in lower part of Gatún Formation
Relevant documents discussing the Unit:
- Wilson et al. (1957).
- Woodring (1960). Undefined name for calcareous siltstone in Gatún Formation.
- Keroher et al. (1966).

Synonymy: Gatún Formation

Unit: CAYO AGUA FORMATION (part of the Bocas del Toro Group)
Epoch/Age/Author: Pliocene (5.0-3.4 Ma) - Coates et al. (2005)
Original Author and/or Origin of the Name: The Cayo Agua Formation was named by Coates et al. (1992) for the island of the same name in the Bocas del Toro archipelago, that lies about 6 kms

to the west of Toro Point, Valiente Peninsula (Figure 043; Figure 042). The formation is well exposed along the east coast. Coates et al. (2005)
Relevant documents discussing the Unit: Olsson (1922); Jung (1989); Cairns (1995); Collins et al. (1999a & 1999b); Coates (1999); Coates et al. (2005) ; Todd & Collins (2005); O'Dea et al. (2007); Beu (2010); Landau et al. (2012b) ; Schwarzhans et al. (2013); Aguilera et al. (2016).
Location of the type section / Stratotype / Reference Section / Other localities: A detailed section measured on Cayo Agua has revealed that the stratotype is slightly more complex structurally than indicated by Coates et al. (1992). The stratotype for the formation (Section 19 in Coates (1999)) is now calculated to be slightly thinner because a small block immediately to the south of Nispero point is rotated to dip to the northeast and repeats a portion of the section (Section 20 in Coates (1999)). The defined stratotype (Section 19 in Coates (1999)) (Figure 061) runs from just south of North Point along the east coast southward to Nispero Point, and then from the northernmost to the southernmost exposures on the coast surrounding Tiburon Point. Additional reference sections described by Coates (1999) are Section 16, immediately west of North Point; Section 18, north of Red Rock Point; and Section 17, on the south coast immediately west of Red Rock Point.
Lithology: The Cayo Agua Formation is distinguished lithogically as a pervasively bioturbated gray blue, muddy, silty lithic sandstone with common horizons of abundant thick shelled mollusks and ahermatypic corals. Occasional horizons of pebble conglomerate and very coarse-grained volcaniclastic sandstone are common in the middle of the formation. Compared to the Shark Hole and Escudo de Veraguas Formations, the Cayo Agua Formation is consistently coarser-grained, with common basalt grains and granules, phosphatic pebbles, and wood fragments. A distinctive marker bed of packed ahermatypic corals occurs near the top of the formation and is well exposed at Tiburon Point and the unnamed point to the south (Coates et al. (2005)). In addition, the mollusks and corals in the Cayo Agua Formation are larger and more heavily calcified than those of the Shark Hole and Escudo de Veraguas Formations. Evidence from benthic foraminifera (Collins (1993)) confirms the inference from grain size and fauna that the Cayo Agua Formation represents a more shallow-water facies than either the Shark Hole or Escudo de Veraguas Formations. It represents onshore and offshore siliciclastic shelf sediments deposited at palaeobathymetries of 10-80 m and 100-150 m respectively (Todd & Collins (2005))
Thickness: 293 m according to Section 19 in Coates (1999).
Macro Fossils: Wood fragments, Corals, Mollusks (Figure 062) (Vermeij, 1988), Crabs (Todd & Collins (2005) suggest burial of whole crabs in gravity flows). Landau et al. (2011 & 2012b) study the Strombus and Cancellariidae gastropods from the Cayo Agua Formation. According to O'Dea et al. (2007), the best localities to collect fossils from the Cayo Agua Formation are from the faces of the cliffs and fallen blocks of rocks in Punta Tiburon (9º 9.11’N, 82º 1.427’W), Punta Piedra Roja (9º 8.364’N, 82º 1.004’W), and Punta Norte (9º 10.493’N, 82º 2.545’W), where fresh material can always be found.
Underlying/Overlying/Equivalent Unit(s): The Cayo Agua Formation is equivalent in age to the upper part of the Shark Hole Point and the lower part of the Escudo de Veraguas Formations and represents a shallower water facies. No contacts are known.
Remarks: The stratigraphic order of the Tobabe, Nancy Point and Shark Hole Formations (three of the five formations which make up the Bocas del Toro Group) has been determined by physical superposition. The two remaining formations of the Bocas del Toro Group (Escudo de Veraguas and Cayo Agua) as well as the younger Pleistocene Swan Cay Formation are known only on islands and their position relative to the other units has been determined by biostratigraphic evidence (Figure 044). The age of the Cayo Agua Formation is dated at the base ~5.0-3.5 Ma and at the top 3.7-3.4 Ma, which suggests it is a contemporary, shallow water equivalent of the Shark Hole Point Formation and the lowermost part of the Escudo de Veraguas Formation.
Maps, Cross-Sections & Pictures:

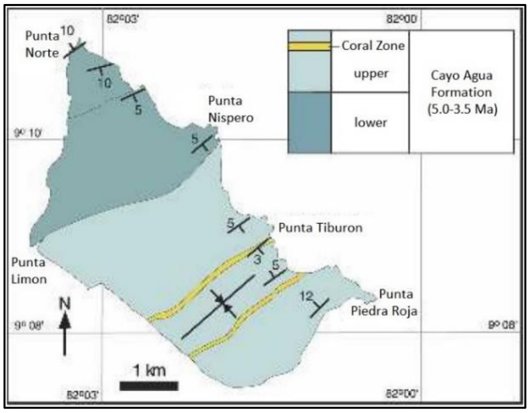

Figure 061. Geological map of Cayo Agua Island. Coates et al. (2005)

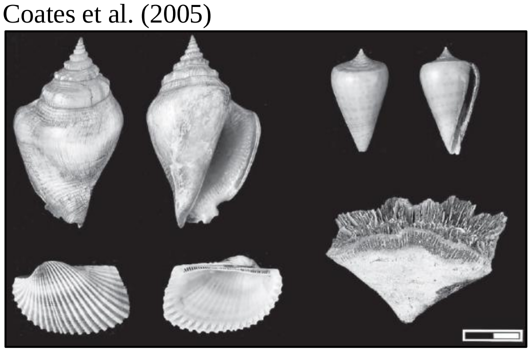

Figure 062. Representative fossils of the Cayo Agua Formation, Bocas del Toro. Nicely preserved shells of the herbivorous *Strombus* sp. (top left). Species of the predator gastropod *Conus* sp. (top right). The filtering bivalve *Anadra* (Arcidae family) (bottom left). An ahermatipic coral (which lives without symbiotic algae) of the family Caryophyllidae (bottom right). Scale = 2cm. O'Dea et al. (2007)

Unit: *CERRO GIGANTE BASALT

Epoch/Age/Author: Oligocene or Miocene - Woodring (1960)

Original Author and/or Origin of the Name: Jones (1950). Unit is discussed under general heading "Bruja Island dolerite, Cerro Gigante basalt, and related igneous rocks." These include lower Miocene flows, plugs, and dikes of basic rock, hard and generally moderately joined; unconformable below Gatún Formation and above upper Caimito Member. "Basalt" is used in this paper as a field term applied to basic fine-grained igneous rocks including "andesite" and "basalt." Cerro Gigante is the name of a peak about 8 kilometers southwest of Barro Colorado Island.

Relevant documents discussing the Unit:

- Wilson *et al*. (1957).
- Woodring (1960). An undefined name for intrusive basalt in the Gatún Lake area.
- Keroher et al. (1966)

Remarks: In Gatún Lake area.

Unit: *CHAGRES ALLUVIUM

Epoch/Age/Author: Pleistocene to Recent - Wilson et al. (1957)

Original Author and/or Origin of the Name: Jones (1950). Alluvial deposits in Gatún Lake area of interbedded clays, silts, sands, and gravels, variably loose to well compacted. Intergrades locally with Atlantic muck. In Jones' Table 2, however, the name was extended to cover alluvium on the Pacific side of the Canal Zone. This Table shows a thickness of the Chagres alluvium, Chagres gravel [see note below], Atlantic muck, and Pacific muck to be 300 feet. Pleistocene and Recent.

Relevant documents discussing the Unit: Wilson et al. (1957); Woodring (1960); Keroher et al. (1966)

Synonymy: As per Woodring (1960), the undefined name of "Chagres gravel" appeared only on a chart and is not to be taken seriously.

Remarks: Present along Chagres River valley and its tributaries, the Río Gatún, and Río Trinidad, and other principal valleys, vicinity of Lake Gatún.

Unit: CHAGRES FORMATION

Epoch/Age/Author: Late Miocene (Tortonian to Messinian), ~8.3 to 5.3 Ma - Collins et al. (1996)

Original Author and/or Origin of the Name: The name "Chagres Sandstone" was proposed by MacDonald in 1919 for the sandstone forming the hills that overlook the coast from Toro Point to the mouth of the Chagres River. Outcrop area lies west of Canal and extends from Canal Zone southwestward along Caribbean coast to between Río Indio and Río Miguel. Its Toro Member at the base was named by Woodring (1957)

Relevant documents discussing the Unit:

- Woodring & Thompson (1949). Includes Toro limestone Member at base. Chagres proper above Toro Member consists of very massive mostly line-grained sandstone and some siltstone. Thickness difficult to determine; MacDonald considered it to be 1,000 feet or more. Overlies and partly overlaps Gatún Formation; base sharply defined. Fossil evidence indicates late Miocene age; however, it may be early

Pliocene if the coastal Gatún west of Canal Zone is late Miocene.

- Jones S.M. (1950);
- Woodring (1955). Lower Pliocene
- Woodring (1957).
- Woodring (1960). Most of the sandstone is fine-grained. Unlike the unconformably underlying Miocene Gatún Formation, the Chagres sandstone includes no tuff or conglomerate. The sandstone extends along the Caribbean coast at least as far as 23 miles southwest of Colon. The fossils include *Acila isthmica*, *Aequipecten cactaceus*, and *Dentalium rimosum*. This molluscan fauna indicates an early Pliocene age.
- Woodring (1982); Fierstine (1978); Smith (1991); Collins et al. (1996); Coates (1999); Beu (2010); Landau et al. (2010 & 2012c); Montes et al. (2010); Jaramillo et al. (2014); Vigil & Laurito (2014); Carrillo-Briceno et al. (2015) ; Velez-Juarbe et al. (2015); Pyenson et al., (2015); Velez-Juarbe et al. (2015 & 2019).

Synonymy: Chagres Sandstone of MacDonald (1919) as listed in Wilmarth (1938). The “Chagres Sandstone” Member of Carrillo-Briceno et al. (2015) within the Chagres Formation is equivalent to the “Piña” Member/facies of Pyenson et al. (2015).

Location of the type section / Stratotype / Reference Section / Other localities: The stratotype is diagrammed in Section 3 of Coates (1999). It is exposed from Toro Point to Naranjitos Point (Figure 063). A distinctive lateral facies of the Chagres Formation is exposed at Boca del Río Indio (Figure 063) on the north coast of Panama, approximately 40 km west of Colon. The Río Indio facies is diagrammed in Section 5 of Coates (1999). Sections 3, 4, and 5 of Coates (1999) make up the Reference Section of the Chagres Formation which was revised by Collins et al. (1996). The formation also crops out along the coast as prominent cliffs between Toro Point, at Colon, and the mouth of the Chagres River.

Lithology: The Chagres Formation consists of indurated, conglomeratic, coarse-grained, volcanic sandstone with quartz, feldspar, and lithic grains. It is pervasively bioturbated and is relatively poor in macrofossils. Toward the west, in the region of the Indio River and Gobea, the average grain size of the Chagres Formation markedly decreases, and the macrofossil content increases. These sandstones and siltstones were deposited in a shallow marine environment.

The base of the Chagres Formation at the stratotype is distinguished by a distinctive calcareous strata of echinoid-mollusk-barnacle coquina, about 60 m thick, which Woodring (1957) separated as the Toro Member (deep water). It is well exposed in the cliffs west of Toro Point, the headland on the northwest side of Colon Harbor. The Toro Member has a middle portion characterized by about 10 m of steeply cross-bedded, prograding foreset beds, 2-50 cm thick, consisting of alternating coquina and shelly, coarse, volcaniclastic sandstone.

The Toro Member (Figure 064) wedges out about 15 km to the southwest of Toro Point. Its restricted distribution at the northern end of the Panama Canal Basin, with high energy cross bedded coquina and very coarse volcaniclastics associated with bathyal Pacific benthic foraminifera, led Collins et al. (1996) to suggest deposition from a transisthmian strait in which strong currents flushed Pacific sediments and benthos into deep Caribbean waters.

The sandstone Piña Facies (Figure 064) (40-50m thick and ~7.9-5.3 Ma at locality 9° 16' 53.4"N, 80° 2' 40.9"W) is stratigraphically above the Toro Member and is characterized by well preserved benthonic and nektonic fossil invertebrate assemblages (Pyenson et al. (2015)). The high abundance of benthic foraminifera assemblages with modern or ancient upper and middle bathyal depth ranges led Collins et al. (1996) to conclude that the Piña Facies of the Chagres Formation was deposited in deeper waters. Collins et al. (1996) suggested that the Piña Facies were preserved as the Central American Seaway deepened following the deposition of the underlying shallow-water Gatún Formation, and therefore represented the ephemeral formation of a fairly deep (~125 m of water depth) oceanic connection from the Pacific Ocean into the Caribbean Sea, prior to final closure of the Isthmus of Panama. In Carrillo-Briceno et al. (2015), however, paleobathymetry was calculated to be in the shelf, and the Chagres representing a bay rather than a channel.

The Río Indio Member (Figure 064), which laterally replaces the Toro Member to the west, has an age of ~7.64 Ma. This member consists of fine silty-sandstone deposited inwaters of ~50-80 m depth (Collins et al. (1996)). New outcrops of this member, exposed in 2008 during Miguel de la Borda road construction, were studied. They are located on the coast of Punta Mansueto, Donoso

District, Colon Province (9° 9' 23.4"N, 80° 17' 36.6"W) (Carrillo-Briceno et al. (2015))

Thickness: The sandstone portion of the Chagres is so massive that estimates of thickness are uncertain. The stratotype in Section 3 of Coates (1999) shows a thickness of 215 m however, Collins et al. (1996) state that the Chagres Formation is ~250 m thick, marine, and predominantly an arc-derived, volcaniclastic sandstone. The basal unit is the Toro Member, 60 m of lime-cemented barnacle and echinoid coquina interbedded with shelly, coarse sandstone. A distinctive feature of this unit is a 10m-thick, steeply cross-bedded unit that has prograding foresets ~2–50 cm thick. Field observations indicate that the Toro Member wedges out to the west, and the average grain size of the Chagres Formation progressively decreases from very coarse sandstone and coquina at Toro Point to medium to coarse sandstone northeast of Palmas Bellas, to silty fine sandstone and silty claystone at Río Indio.

Macro Fossils: Fish; Mammals (dolphin *Isthminia panamensis*); Invertebrates (echinoids, mollusk (Smith (1991)), barnacle). Carrillo-Briceno et al. (2015) also describe a shark fauna from the Río Indio and Chagres Sandstone (Piña) Members just east and west of the town of Piña. Velez-Juarbe et al. (2015 & 2019) mention a cetacean from the formation (Kogiid Sperm Whales). Vigil & Laurito (2014) describe a fragment of a crown and an isolated lower commissural tooth of a sperm whale of the Family Physetheridae. Fierstine (1978), describes a Marlin (Fish - *Makaira panamensis*) from a single neurocranium found on the Atlantic shoreline of Panama, approximately 17 km southwest of Colon, Canal Zone.

Overlying Unit: N/A

Underlying Unit: The Chagres Formation sits disconformably on the Gatún Formation; a marked change in lithology and a temporal hiatus characterizes the disconformity.

Maps, Cross-Sections & Pictures:

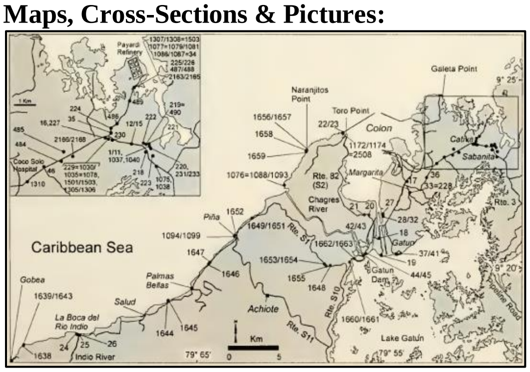

Figure 063. Colon to Gobea map, Panama Canal area. Appendix A in Coates (1999). (Reproduced with permission of the Paleontological Research Institution, Ithaca, New York).

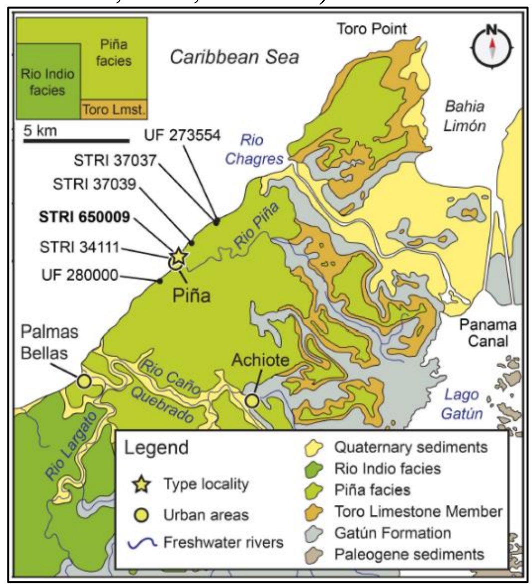

Figure 064. Distribution of the Chagres Formation, with type locality of *Isthminia panamensis* (dolphin) with other fossil vertebrates. The relation between the three facies is shown on the top left. Pyenson et al. (2015).

Unit: CHARCO AZUL GROUP

Epoch/Age/Author: Pliocene – Pleistocene (Zanclean to Middle Pleistocene) (Figure 046) **-** Cortés et al., (2019)

Original Author and/or Origin of the Name: Terry (1941). The name "Charco Azul Formation" was used in a brief description of the geology of the Burica Peninsula.

Relevant documents discussing the Unit:

- Olsson (1942a). Base is heavy conglomerate, grades upward into sandstones and foraminiferal shales. Maximum thickness more than 4,000 feet. Overlies Armuelles Formation. Pliocene.
- Coryell et al. (1942); Terry (1956, pgs 55-59); Wilson et al. (1957);
- Woodring (1960). The Charco Azul Formation, consisting chiefly of foraminiferal siltstone, crops out along the shore of Charco Azul Bay elsewhere in the Burica Peninsula. It grades downward into sandstone of the Burica Formation or overlaps that formation and rests on Eocene limestone or the pre-Tertiary basement. The maximum thickness is about 4,000 feet. Foraminifera and mollusks represent a fairly

deep-water facies and indicate a Pliocene age. The foraminifera have been described by Coryell et al. (1942) and the mollusks by Olsson (1942a). These fossils include *Bolivina foraminata*, *B. pomposa*, *Cassidulina californica*, *Hanetia alternata*, *Cancellaria terryi*, *Acila isthmica burica*, and *Macoma medioamericana*.
- Obando (1986); Jung (1989);
- Corrigan et al. (1990) named and redefined the "Charco Azul Formation" as the interval which included the La Peñita, Burica and Armuelles Members. Later, this "Charco Azul Formation" was renamed as a Group, while each of its members were given the designation of "Formation".
- Coates et al. (1992); Kolarsky (1992); Collins et al. (1995); Schlegel (1996); O'Dea et al. (2007) ; Leon-Rodríguez (2007); Hendy et al. (2008); Buchs (2008); Buchs et al. (2009); Beu (2010); Morell et al. (2011); De Gracia et al. (2012); Cortés et al. (2019); Timmons (2019).

Synonymy: Charco Azul Formation. **NOTE**: Ministerio de Comercio e Industrias (1991) and Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) have the whole Burica Peninsula sub-divided into different formation names (Charco Azul Formation, Gatún-Uscari Formation, Senosri-Uscari Formation, David Formation). Their history, background, and definition, however, are not described anywhere. The use of these names over the Burica Peninsula should be abandoned. Instead, the most recent formation names of La Peñita, Burica and Armuelles should be applied.

Location of the type section / Stratotype / Reference Section / Other localities: Burica Peninsula

Lithology: The Charco Azul Group was comprehensively studied by Corrigan (1986) (Figure 048), Corrigan et al. (1990), Coates et al. (1992) and Collins et al. (1995). It has been subdivided into: (1) the Early Pliocene Peñita Formation, which rests uncomformably upon basement rocks (*in Costa Rica it also rests upon the Pavones Formation*), (2) the Late Pliocene Burica Formation, conformable on the Peñita Formation and (3) the Early Pleistocene or younger Armuelles Formation, conformable on the Burica Formation (Figure 046). <u>The Peñita Formation</u> is composed of as much of 1200 m of clayey, bluegreen siltstone and litharenite consistently rich in benthic and planktic foraminifers, deposited in a forearc slope environment (Coates et al. (1992)). This basal formation is coarse with locally channelled conglomerates, some of which form a distinctive suite defined as the La Vaca Member by Coates et al. (1992). These coarse deposits record a detrital paralic and fan-delta depositional environment at the base of the Charco Azul Group. <u>The Burica Formation</u> consists of about 2800 m of mostly fine-grained, volcaniclastic turbidite deposits with local megabreccias formed by large-scale intraformational slumps (Coates et al. (1992)). The La Chancha Member is a distinctive coarse facies interpreted to represent canyon fill within the trench slope on which the Burica turbidites were deposited (Coates et al. (1992); Buchs (2008); Buchs et al. (2009)). Finally, the <u>Armuelles Formation</u> consists of ~370 m of channelled pebbly conglomerate and unconsolidated greenish-blue litharenite and siltstone in the lower part and predominant grey-blue, clayed siltstone and fine litharenites in the upper part (Coates et al. (1992)). The Charco Azul Group defines a transgressive–regressive cycle between the Early Pliocene and the Pleistocene (Coates et al. (1992); Collins et al. (1995))

Thickness: ~4500 m

Macro Fossils: See details of each formations belonging to the Group (La Peñita, Burica and Armuelles)

Overlying Unit: Monte Verde Formation

Underlying Unit: Basement rocks

Unit: CHIGUIRI FORMATION

Epoch/Age/Author: Paleocene - Ministerio de Comercio e Industrias (1991)

Original Author and/or Origin of the Name: The term first appeared in Ministerio de Comercio e Industrias (1991) and is used as well in Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) (Appendix B). In both cases, no reference is given regarding the origin of the name. It is included in the "Chiguiri Group" (which also includes the "Punta Matanza" Formation) which also makes its first appearance in the same document and with no details with regards to the origin of the name.

Relevant documents discussing the Unit: Unknown.

Synonymy: Unknown

Location of the type section / Stratotype / Reference Section / Other localities: Found on the Caribbean coast, west of "Punta de San Blas" area.

Lithology: Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) describes it as "deformed shales" (In Spanish - Lutitas deformadas).

Unit: *CHILIBRILLO LIMESTONE MEMBER or FORMATION

Epoch/Age/Author: Miocene - Woodring (1957)

Original Author and/or Origin of the Name: Olsson (1942b). Name Chilibrillo used on correlation chart. Used casually for the limestone on Río Chilibrillo.

Relevant documents discussing the Unit:

- Woodring & Thompson (1949, pg 235); The few mollusks indicate an early Miocene age. They include *Lyropecten cf. nodosus* and *Ostrea cf. gatunensis*.
- Wilson et al. (1957);
- Woodring (1957). Chilibrillo limestone Member is the Emperador limestone of Reeves and Ross (1930) and Chilibrillo Formation of Kellogg (1931). Maximum thickness 100 feet; pinches out on either side of Madden Basin. Overlies unnamed pyroclastics clay member; underlies unnamed calcareous siltstone member. Fossil evidence favors Miocene age, presumably early Miocene.
- Woodring (1960). Limestone in the Caimito Formation of Madden Basin, east of the Canal Zone, is designated the Chilibrillo limestone Member. The limestone is lenticular and has a maximum thickness of 100 feet.
- Keroher et al. (1966)

Synonymy: Emperador limestone of Reeves and Ross (1930); Chilibrillo Formation of Kellogg (1931)

Remarks: East side of Madden Basin (Alajuela Basin), between Madden Lake (Alajuela reservoir) and Río Chilibrillo, Canal Zone. See also Caimito Formation.

Unit: *CHIVA CHIVA ANDESITE

Epoch/Age/Author: Oligocene or Miocene - Woodring (1960)

Original Author and/or Origin of the Name: Thompson (1943). Light-gray andesite porphyry. In intrusive contact with an agglomerate of basement complex. Occurs as thick dike or elongated plug. Pre-Pliocene. Type locality: Quarry 6.5 kilometers northeast of Pedro Miguel, Canal Zone. Chiva Chiva is the name of a group of houses about 3 kilometers northeast of Pedro Miguel. Road that runs by quarry is called Chiva Chiva Road.

Relevant documents discussing the Unit:

- Wilson et al. (1957);
- Woodring (1960); Intrusive hornblende andesite on the Pacific side of the Canal Zone.
- Keroher et al. (1966)

Unit: *CHORRERA BASALT

Epoch/Age/Author: Oligocene or Miocene - Woodring (1960)

Original Author and/or Origin of the Name: Jones (1950). Listed on correlation chart together with Cerro Gigante basalt and Bruja dolerite. Units are unconformable below Gatún Formation and above upper Caimito Members. Lower Miocene. "Basalt" is used in this paper as field term applied to basic fine-grained igneous rocks including "andesite" and "basalt."

Relevant documents discussing the Unit:

- Wilson et al. (1957)
- Woodring (1960); An undefined name for extrusive and intrusive basalt on Pacific side of Panama immediately west of Canal Zone.
- Keroher et al. (1966)

Remarks: Occurs in Gatún Lake area.

Unit: CHUCUNAQUE FORMATION

Epoch/Age/Author: Upper Miocene (Tortonian-Messinian ; 10-5.6 Ma) - Coates et al. (2004)

Original Author and/or Origin of the Name: Sapper (1937) named it informay on a correlation chart for strata in the Darien area. Underlies Piliguilla conglomerate; overlies Pucro sandstone. Upper Miocene. The formation was formally named for the Chucunaque River by Shelton (1952) without defining a stratotype.

Relevant documents discussing the Unit:

- Terry (1956) used the name again without defining it.
- Wilson et al. (1957), Woodring (1960), Coates et al. (2004); Perez et al. (2015 & 2017);

Synonymy: Chuqunaque (misspelling)

Location of the type section / Stratotype / Reference Section / Other localities: Coates et al. (2004) propose as stratotype the sequence on the Chucunaque River from south of El Salto to above Caleta on the Tuquesa River (CT on Figure 066 & Figure 067). A reference section is located on the Chico River (CR on Figure 067).

Lithology: The Chucunaque Formation consists of gray weathering, greenish blue to black, blocky to massive, silty claystone and siltstone, with minor thin horizons and stringers of volcanic sandstone. Slabby to oval calcareous concretions are common, and the formation contains abundant gypsum crystals at some horizons. In the north, along the Membrillo River, the lower part of the formation is dominated by cobble conglomerate and cross-bedded sandstone.

The Chucunaque Formation was deposited at an inner neritic depth around the Chico River valley region, and at upper bathyal depths in deeper portions of the Basin (Membrillo River section). It commonly contains oxygen-deficient assemblages. In the Membrillo River and Chucunaque River sections, samples contain characteristic upper bathyal taxa.

In the southeastern-most portion of Lago Bayano (Figure 065), exposed uneroded blocks comprise strongly weathered and sparsely fossiliferous orange mudstone. The islands in the northern portion of southern Lago Bayano contain a more varied range of facies, including fossiliferous, gritty orange sandstone and a fine-grained tuffaceous white sandstone.

The age span of the Chucunaque Formation in most of the Chucunaque-Tuira Basin can be broadly estimated as ca. 7.1 Ma to ca. 5.6 Ma. To the north, where the Chucunaque Basin changes over to the Bayano Basin, the base of the Chucunaque, with a calcareous nannofossil assemblage, appears to be older than 9.4 Ma. Perez et al. (2017) confirms an age of 10–9.5 Ma (Tortonian) for the chonrichthyan-bearing sandstone strata in Lago Bayano area. Therefore, from the Bayano Basin to the Chucunaque-Tuira Basins, the Chucunaque Formation spans an age of 4.4 Ma from 10 to 5.6 Ma.

Thickness: The thickness of the Chucunaque Formation is not less than 400m in the northwest and not less than about 1200m in the center of the Chucunaque-Tuira Basin.

Macro Fossils: Calcified thalassinoid burrows are typical and many levels are packed with clearly visible foraminifera, scattered small mollusks, including cancellarriids, naticids, Tellina, and turrids. Crabs, pteropods and the deepwater *Pectén* and *Palliolum* have also been observed (Coates et al. (2004). Perez et al. (2017) describe the chondrichthyan fauna of Lago Bayano as the first such Miocene fauna from the Pacific shelf of Panama. The authors confirm that shark teeth material originates from a sandstone within the formation but that the chondrichthyan remains are left as a residue among reworked gravel, sand, and mud grains along island shorelines on Lago Bayano. The chondrichthyan fauna is correlative with the other important chondrichthyan-bearing units in Central and South America, including the Gatún Formation and Alajuela Formation of central Panama.

Overlying Unit: None. The upper contact of the Chucunaque Formation is nowhere exposed in the area in Coates et al. (2004)'s studied area.

Underlying Unit: Yaviza or Membrillo Formations. The lower contact of the Chucunaque Formation is nowhere exposed in the area in Coates et al. (2004)'s studied area.

Remarks: On the basis of evidence from fossil sharks, the paleobathymetry of the Chucunaque Formation in the Bayano Basin is from the littoral zone, with a mean depth of about 100 m (Perez et al. (2015)).

Maps, Cross-Sections & Pictures:

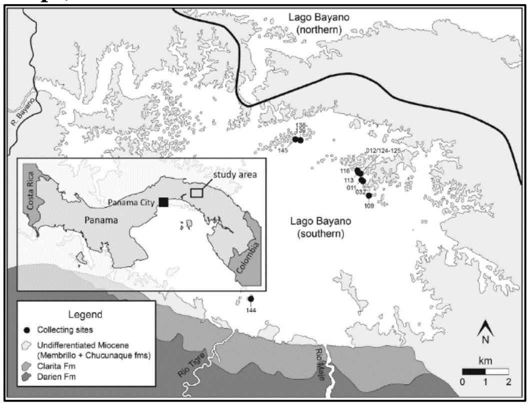

Figure 065. Map of Lago Bayano, Panama with collecting sites denoted by black circles. Numbers labelling each collecting site refer to the last three digits of the Smithsonian Tropical Research Institute (STRI) field number. Perez et al. (2017).

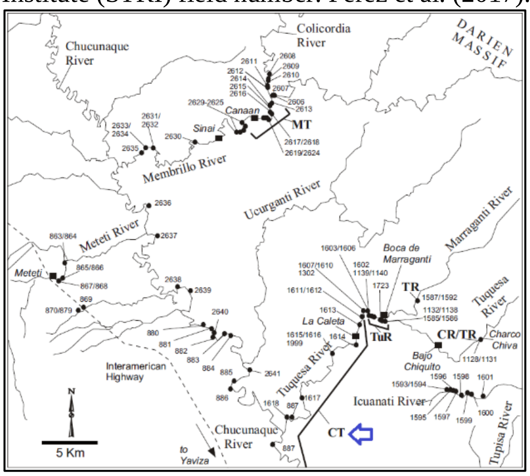

Figure 066. Stratotype (CT marked by blue arrow) of the Chucunaque Formation (see continuation on Figure 067). Coates *et al.* (2004).

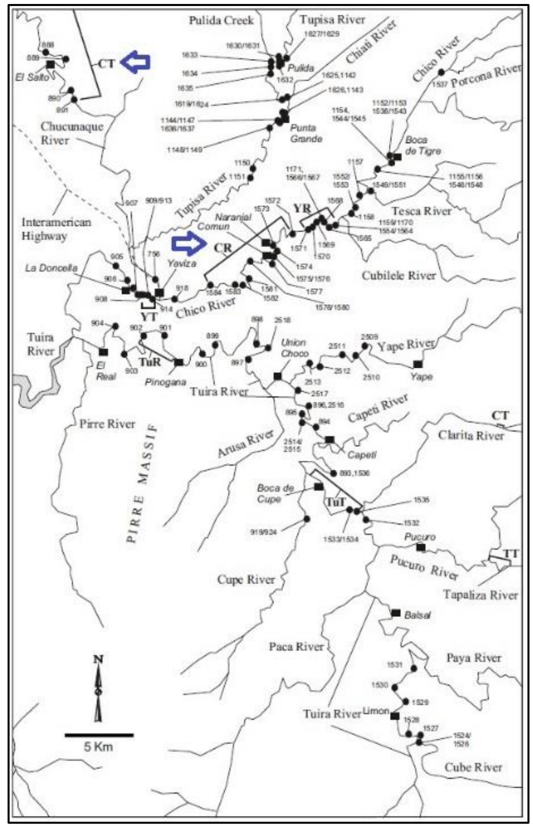

Figure 067. Reference Section (CR) and continuation of the Chucunaque stratotype (CT) (Figure 066). Coates et al. (2004).

Unit: CLARITA FORMATION

Epoch/Age/Author: Lower Miocene to lower part of the Middle Miocene (Aquitanian/Burdigalian/Langhian) **-** Coates et al. (2004) & Barat et al. (2014)

Original Author and/or Origin of the Name:

- Sapper (1937). Clarita Limestone is an undefined name which appears on correlation chart for calcareous strata of Middle Oligocene age in the Darien area. Underlies Arusa Formation.
- The formation was named by Shelton (1952) for the Clarita River and redefined by Coates et al. (2004). Río Clarita is a small stream about 30km ESE of El Real de Santa Maria. It flows into Río Capetí, which is a southwestward flowing tributary of Río Tuira.

Relevant documents discussing the Unit:

- Wilson et al. (1957) mentions Clarita Limestone of Lower Oligocene age.
- Woodring (1960). Río Clarita is a small stream about 30 kilometers east southeast of El Real de Santa Maria, in Darien area.

- Barat et al. (2014);

Synonymy: Clarita Limestone

Location of the type section / Stratotype / Reference Section / Other localities: The Clarita Formation crops out in the area of the Massifs of Majé and Sanson Hills, and the Basins of Chucunaque–Tuira and Sambu. The stratotype ("CT" on Figure 068) is located on the Clarita River. A reference section studied and named in Coates et al. (2004) is exposed at Charco Chiva ("CR" on Figure 069), about 9 km east southeast of Boca de Marraganti, on the Tuquesa River.

Lithology: On the northeastern flank of the Chucunaque-Tuira Basin, the Clarita Formation is generally indurated, gray-white weathering, pale blue, thick-bedded, crystalline limestone, but may range from chalky to bioclastic with occasional intercalated sandy and shaly units. In the Tuquesa River and Marraganti River sections, it has tuffaceous units interbedded in the upper 50 m. In the lower part, foraminiferal, calcareous, and tuffaceous mudstone are more abundant. On the western flank of the Basin the unit becomes a fine bioclastic limestone, often with a micritic matrix, and with minor components of glauconite, feldspar, and lithic fragments. The limestone clasts may consist of up to 60% foraminifers. The formation is well bedded in units from 10 cm to 2 m and often forms prominent ridges in the field.

The Clarita Formation was deposited at lower to middle bathyal depths. Water depth was greatest toward the center of the Chucunaque-Tuira Basin (Membrillo River section). Depths there and in the Sambu Basin were lower bathyal, 1500-2000 m. Clarita Formation sediments were probably deposited at a middle bathyal depth (500-1500 m) in the Tuquesa River section.

The Membrillo River, Tuquesa River, and Sambu-Venado River sections provide biostratigraphic data indicating that the Clarita Formation in these areas ranges through the lower part of the middle Miocene.

Barat et al. (2014) summarize the Clarita Formation has being made up of clastic sediments with a high content of carbonate fossiliferous clasts. The base of the Clarita Formation is composed of conglomerates and reworked adakitic-like volcanic clasts, as noted in the Majé Massif. The remaining higher stratigraphic sequence alternates between breccia, conglomerate (Figure 070), sandstone, thick layers of calcarenite (Figure 071) and fossiliferous sandstone dated as Early Miocene. The very top of this formation consists of siliceous and calcareous fine tuff and mudstone, located in the Sanson Hills Massif (Figure 072).

Thickness: Its thickness has a minimum of 200 m and a maximum of 2000 m at the center of the Chucunaque–Tuira Basin, according to Coates et al. (2004).

Macro Fossils: Not mentioned

Overlying Unit: Its upper contact with the Tapaliza Formation is not exposed in the Tuquesa River. In the Membrillo River it is not exposed in one of the fault slices, but is represented in the other by an abrupt lithological change. In the Sambu Basin, it sits nonconformably or with a faulted contact on the Darien Formation. Contact with the overlying Tuira Formation in this Basin is not observed but is probably strongly disconformable given a gap of more than 6 m.y. between the units and their generally parallel strike. Barat et al. (2014)

Underlying Unit: In the Chucunaque Basin, the Clarita Formation conformably overlies the Porcona Formation. In western Darien, it rests with angular unconformity on the Darien Formation. In the Majé Massif, this formation unconformably overlies the Darien Formation, and in the southern flank of the Sapo Massif in the Sambu Basin, the Clarita Formation unconformably overlies the San Blas Complex.

Maps, Cross-Sections & Pictures:

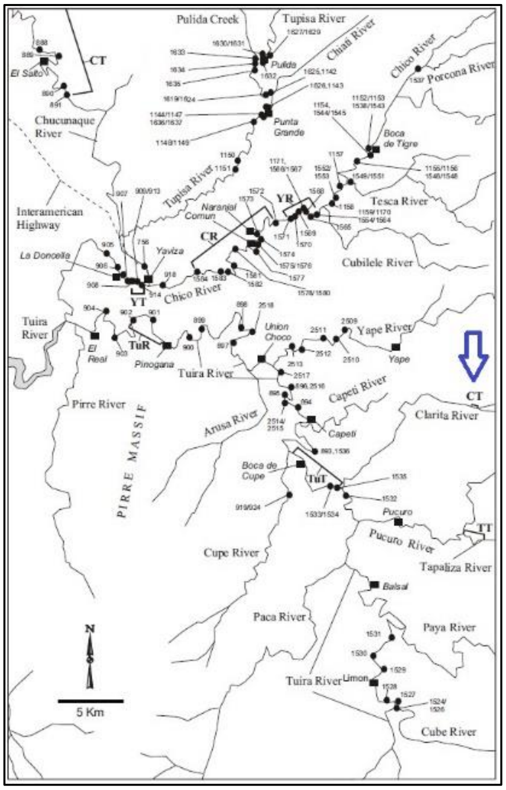

Figure 068. Locality of the Clarita Formation's stratotype (CT, marked with a blue arrow). Coates et al. (2004)

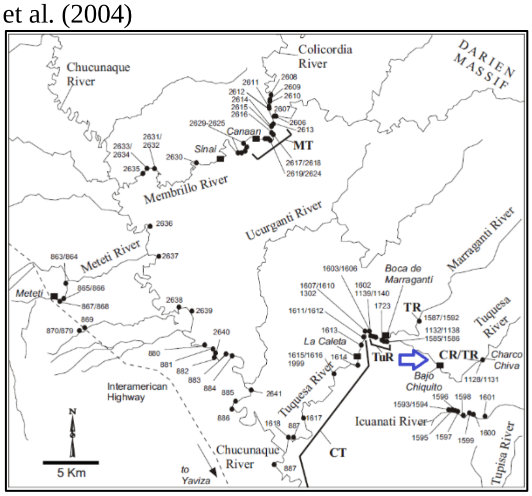

Figure 069. Locality of the Clarita Formation's Ref. Section (CR, marked with a blue arrow). Coates et al. (2004)

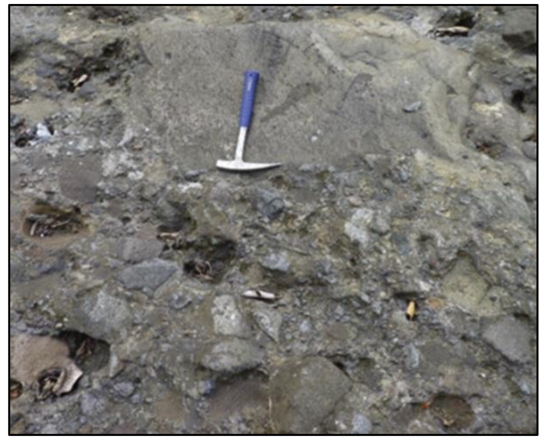

Figure 070. Outcrops of breccias to conglomerates from the Majé Massif, Clarita Formation (8.94667°, −78.53119°, WGS84). Barat (2013) and Barat et al. (2014).

Figure 071. Calcarenites of Burdigalian from the Majé Massif, Clarita Formation (8.94656°, −78.52829°, WGS84). Barat (2013) and Barat et al. (2014).

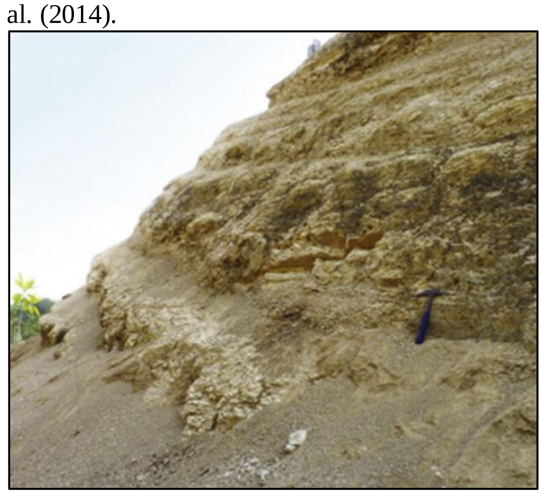

Figure 072. Calcareous shales of Early–Middle Miocene, from the Sanson Hills, top of the Clarita Formation (8.61528°, −78.12849°, WGS84). Barat (2013) and Barat et al. (2014).

Unit: *CONCH POINT SHALE

Epoch/Age/Author: Lower Miocene - Woodring (1960)

Original Author and/or Origin of the Name: Terry (1956). Massive poorly bedded soft gray clay shale underlying Bastimentos shale which it resembles closely. On Columbus [Colon] Island (Figure 042), surface structure is gently rounded dome on which early Miocene Conch Point shale crops out at crest, over an area of about 1 mile, surrounded by middle Miocene Bastimentos shale. Seismograph survey indicates structure is cut by fault striking N. 24° E.

Relevant documents discussing the Unit:

- Woodring (1960). If these strata are of the same age as the early part of Uscari shale of Costa Rica, the name Conch Point should be suppressed. Note on derivation of name.
- Keroher et al. (1966)

Remarks: Conch Point is on west side of Isla de Colon (Figure 042), 8 kilometers northwest of town of Bocas del Toro.

Unit: COVACHÓN FORMATION

Epoch/Age/Author: Early/Middle Eocene (Figure 051) **-** Buchs et al. (2011)

Original Author and/or Origin of the Name: It was originally considered to pertain to the lower Tonosí Formation but was eventually defined by Buchs et al. (2011) as a separate formation.

Relevant documents discussing the Unit: Ramirez (2013); Ramirez et al. (2016)

Synonymy: Wrongly spelled "Cobachon" in post-2011 literature

Location of the type section / Stratotype / Reference Section / Other localities: The formation is exposed mostly in the southwest corner of the Azuero Peninsula but may also occur as deformed slices in contact with the Azuero Mélange in the northwest edge of the Azuero Accretionary Complex (Buchs et al. (2011)). Facies 1, Covachón (539765/799275, UTM WGS84); Facies 2, Covachón (540545/799335, UTMWGS84); and Facies 3, close to the mouth of the Río Lajas (531490/796780, UTM WGS84). Covachón is accessible by an unpaved road from Cambutal. The mouth of the Río Lajas is accessible by boat from Cambutal or Búcaro. Exposures are accessible at low tide exclusively.

Lithology: The Covachón Formation is a >300 m thick shallowing-upward, folded and faulted sedimentary succession that unconformably rests on top of the Azuero Accretionary Complex and is separated by an unconformity from the overlying Tonosí Formation (Buchs et al. (2011)). It represents a package of detrital sediments that, in general, unconformably encroaches on the Azuero Accretionary Complex and is in turn separated by an unconformity from the overlying Tonosí Formation. The Covachón Formation includes three facies: **Facies 1**: interbeds of volcaniclastic calcareous lutite, siltstone and sandstone (Figure 073). The beds are typically 3 to 50 cm thick and define parallel layers that extend over several hundreds of meters. It has been interpreted as turbiditic deposits. **Facies 2**: is composed of 50 cm to ~50 m (?) thick chaotic deposits, which are interbedded with Facies 1 and 3. The deposits are matrix supported and contain abundant fragments of basalt, shallow marine limestone and soft-deformed sediments. It has been interpreted as mass-flow deposits (Figure 074). **Facies 3**: Is composed of sandstones with abundant rounded and well-rounded pebbles of basalt and shallow marine limestone. The sediments are matrix-supported. It has been interpreted as slope, near littoral deposits (Figure 075). On the basis of these observations, the Covachón Formation represents a shallowing-upward sequence deposited on top of the Azuero Accretionary Complex (Buchs et al. (2011)).

An Early to Middle Eocene age can be determined from reworked larger benthic foraminifera near the base of the section, whereas a Middle Eocene age, results from the analysis of large benthic foraminifera in the matrix of chaotic deposits (Buchs et al. (2011) and Ramirez (2013)).

Thickness: >300 m

Macro Fossils: Larger benthic foraminifera

Overlying Unit: Tonosí Formation

Underlying Unit: Azuero Accretionary Complex

Maps, Cross-Sections & Pictures:

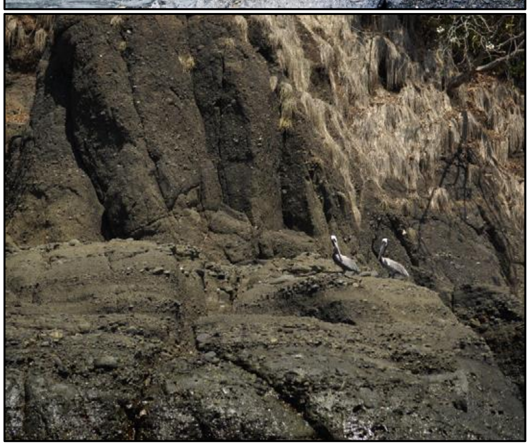

Figure 073 (top). Lithic sandstones and siltstones from Facies 1 of the Covachón Formation at the mouth of the Lajas River on West Azuero Peninsula at 7°12'49.57"N 80°42'0.86"W. Ramirez (2013)

Figure 074 (center). Mass-flow deposit (facies 2) from the Covachón Formation (Covachón, south Azuero Peninsula). Buchs (2008) and Buchs et al. (2011).

Figure 075 (bottom). Pebbly sediments (facies 3) of the Covachón Formation (coastal exposure west of Río Lajas, south Azuero Peninsula) (Buchs (2008) and Buchs et al. (2011)). The conglomeratic sandstone of facies 3 can be observed at the mouth of the Lajas River at 7°12'45.07"N 80°42'5.47"W. Ramirez (2013)

Unit: CUCARACHA FORMATION

Epoch/Age/Author: Early/Middle Miocene (Burdigalian; 19–17.9 Ma) **-** Buchs et al. (2019)

Original Author and/or Origin of the Name: MacDonald (1913a, 1913b). According to Graham *et al*. (1985), the formation is named after a railroad station and a small town that existed prior to Canal construction.

Relevant documents discussing the Unit:

- Wilmarth (1938).
- Woodring & Thompson (1949). Chiefly massive generally greenish-gray waxy highly slickensided bentonitic clay. Bed of agglomeratic andesitic tuff, 10 to 35 feet thick, occurs about 200 feet below top of formation. Maximum thickness about 625 feet. Overlies Culebra Formation; underlies La Boca Formation. Early Miocene. Most of the Cucaracha Formation appears to be non-marine. Poorly preserved specimens of Anadara, Lucina ?, and Tellina ? have been found in the lower part of the formation.
- Woodring (1957). Underlies La Boca Member of Panamá Formation. Assigned to early Miocene because both underlying Culebra Formation and overlying Panamá Formation are considered to be of that age.
- Woodring (1960); Woodring WP (1957–1982); Whitmore & Stewart (1965); Slaughter (1981); Graham (1988a); Collins et al. (1996); MacFadden (2003, 2004a, 2004b); Kirby & MacFadden (2005); MacFadden (2006 & 2009); Retallack GJ, Kirby MX (2007); Kirby et al. (2008); Cadena (2009); Montes et al. (2010); Uhen et al. (2010); Cadena et al. (2012); Head et al., (2012); Hastings et al. (2013 & 2016); Jaramillo et al. (2014); Herrera et al. (2010, 2014a, 2014b, 2019); MacFadden et al. (2010, 2014 & 2015b); Rincon et al. (2015a, 2015b); Jud et al. (2016); Steadman et al. (2016); Jud et al. (2017b); Rodríguez-Reyes et al. (2014, 2017a, 2017b); Farris et al. (2017); Buchs et al. (2019)

Synonymy: Cucuracha (a misspelling)

Location of the type section / Stratotype / Reference Section / Other localities: Along Culebra Cut south of Continental Divide where village of Cucaracha was located near site of Cucaracha slide. Cucaracha was a canal-construction period village, now abandoned, on the east side of Culebra Cut. For the location see Woodring (1957, p. 39), cited under the name.

Lithology: The Cucaracha Formation is the continental volcaniclastic upper part of the Gaillard Group (See "Gaillard Group"). It is about 180 m thick (Head et al. (2012)) and consists mostly of terrestrial tan, reddish and green mudstones and claystones interbedded with fluvial conglomerates, sandstones, lignite and welded tuff (Figure 076). The "Cucaracha Ash" is a distinctive silicic welded tuff located in the upper portion of the Cucaracha Formation (Figure 031). Lenticular beds of conglomerate and sandstone are more common in the lower half of the formation (progradational deltaic and nearshore wetland deposits) below a distinctive welded tuff bed of volcanic origin, whereas tabular beds of claystone and lignite are more common in the upper half (fluvial and associated floodplain deposits) above the welded tuff bed [*A 1-m-thick tuff, here referred to as the Cucaracha tuff (or ignimbrite), is a prominent marker horizon that allows unambiguous correlation between the measured sections at Centenario Bridge and Hodges Hill*]. This ignimbrite (5–8 m thick) is locally found on top of fallout tuff and/or charcoaled tree stumps (Figure 080). The ignimbrite is an important stratigraphic marker in the Culebra Cut, and has been dated at 17.86 ± 0.05 to 17.98 ± 0.05 Ma at one locality by Buchs et al. (2019). The base of the Cucaracha Formation is marked by a distinctive pebble conglomerate bed that lies unconformably over the Culebra Formation. This conglomerate bed is widely distributed and contains volcanic pebble clasts with rare fragments of carbonized wood (without teredinid borings) and oysters. This and other pebble conglomerate beds higher up in the Cucaracha Formation commonly become finer upsection, grading into lithic wacke, siltstone and claystone. Medium to coarse-grained, lithic wacke beds are commonly cross-bedded, which show an average paleocurrent direction to the east (N87°E+/-6.4°). These interbedded channel deposits contain permineralized logs of up to 1 m in length and 30 cm in diameter oriented parallel to bedding. Pebble conglomerate and lithic wacke also contain rare fossils of land mammals. Olive-gray to blackish red claystone is the most common lithology in the Cucaracha Formation. This claystone is commonly structureless to slickensided, but may contain mottling and drab-haloed root traces. Horizons of calcite nodules and rhizoconcretions are common throughout the claystone. Two horizons contain spherical to platy barite nodules (~2 cm in diameter) in olivegray claystone. Fossils of land mammals, turtles, fish, crocodiles and gastropods (*Hemisinus* (*Longiverena*) *oeciscus*) are present locally in claystone, as noted by Whitmore and Stewart (1965), Woodring WP (1957–1982) and MacFadden BJ (2006). Four lignite beds are present in the upper half of the Cucaracha Formation. The Cucaracha Formation contains a distinctive bed of welded tuff 4.3 to 7.7 m thick (also known colloquially as the ''ash flow''), which is broadly distributed and serves as a useful marker bed (Kirby et al. 2008).

Thickness: 180 m (Head et al. (2012))

Macro Fossils: Terrestrial animal and plant fossils such as trees are abundant (Figure 079). The fauna recovered to date from the Cucaracha Formation is entirely continental and includes an assemblage of land mammals that indicate an early Miocene, early Hemingfordian North American land mammal age (APP-A) (Whitmore & Stewart (1965) and MacFadden et al. (2014)). After Whitmore & Stewart (1965) reported the discovery of Miocene land mammals from outcrops along the banks of the Panama Canal, the layers have since been called the Gaillard [Culebra] Cut Local Fauna. All other fossil evidence indicates terrestrial and freshwater environments; there are no marine units known from the Cucaracha Formation (MacFadden et al. (2015b)). Fossil vertebrates are usually concentrated within the coarser intervals (conglomeratic sandstones and conglomerates) of the upper part of the Cucaracha Formation (Figure 078), above the prominent Cucaracha tuff, and are dominated by freshwater turtles represented exclusively by cryptodires inhabiting delta plain environments (Cadena (2009); Cadena et al. (2012)), crocodilians (Hastings et al. (2013)), and freshwater ichthyofauna. Mammals, although rare, are represented by dental and postcranial elements that exhibit evidence of moderate to intense hydrodynamic transport. Among these fossils, diagnostic dental elements include small artiodactyls (protoceratids, moschids, and floridatraguline camels), followed in abundance by rodents (Slaughter (1981): *Texomys stewarti*), rhinoceroses, anchitherine horses, tayassuids, carnivores, oreodonts, and bats. Snake specimens (Boa) from the Curacacha Formation were found in terrestrial facies (upper part of the formation) within a variably thick (~20-85 m) section of predominantly terrestrial volcaniclastic sediments, lignite, and paleosols at the Cartagena Hill and Hodges Hill localities (Figure 076). Steadman et al. (2016) discuss the discovery of the remains of a bird (large eagle) along the west side of the Panama Canal in the Centenario fauna. Kirby et al. (2008) found fossils of land mammals throughout the Cucaracha Formation. Land mammal fossils of the peccary cf. *Cynora* sp., the artiodactyl *Paratoceras wardi*, the oreodont *Merycochoerus matthewi* and the rhinoceroses *Menoceras barbouri* and *Floridaceras whitei*. These mammals of the Cucaracha Formation are the same as those found in Nebraska, Kansas, and Florida, where climate was drier and cooler and vegetation more open (Retallack & Kirby (2007)). The fossil assemblage at the Lirio East locality includes at least 61 morphotypes of fossil fruits, seeds, flowers, and fungi (Herrera (2010, 2014a, 2014b)), 52 pollen types (Jaramillo et al. (2014)), and calcareous fossil wood (Jud et al. (2017a, 2017b) & Rodríguez-Reyes et al. (2014, 2017a, 2017b)). The fruits are preserved as calcareous three-dimensional permineralizations in poorly sorted volcaniclastic sandstones and conglomerates. The best age indicators for the Cucaracha Formation are its fossil mammals. Taken together, the age of these land mammals indicates a Burdigalian-Langhian age (19 to 14 Ma), with a middle Burdigalian age (18 to 17 Ma) likely.

Overlying Unit: At the Culebra Cut it is overlain by the Pedro Miguel Formation.

Underlying Unit: At the Culebra Cut it is underlain by the Culebra Formation

Remarks: The Cucaracha Formation represents a coastal delta plain that consists of channel, levee, flood plain and marsh deposits. Abundant paleosols indicate that soils commonly developed on these deposits. Retallack and Kirby (2007) recognized 12 different pedotypes that represent as many vegetation types, including mangrove, freshwater swamp, marine-influenced swamp, early successional riparian woodland, colonizing forest, dry tropical forest and woodland (Figure 077). The pebble conglomerate bed at the base of the Cucaracha Formation represents a fluvial-channel deposit that is broadly distributed (based on its geometry and sedimentology, which are typical of fluvial-channel deposits). Incision of this channel into underlying marine mudstone and sandstone of the Culebra Formation indicates that part of the underlying section has been eroded by the channel. The pebble conglomerate contains fragments of wood that show no evidence of teredinid borings (unlike the wood found in the underlying Culebra Formation), suggesting that this basal conglomerate was deposited above sea level. The presence of oyster fragments probably represents reworking of the underlying marine Culebra Formation. Interbedded lenses of pebble conglomerate and lithic wacke further upsection represent small fluvial channels, based on their lenticular geometry and sedimentology. The small ratio of channel deposits to claystone (the sandstone/claystone ratio for the entire formation is 18.4%) suggests that these were small meandering channels (there is generally a good correlation between channel pattern and sediment load, such that the sandstone/shale ratio provides a clear view of stream type, where meandering channels have relatively low ratios and braided channels have high ratios). Thick sequences of claystone represent flood-basin deposits on the coastal delta plain. Most intervals of claystone show some evidence of soil development. Evidence for paleosols include horizons of calcite and barite nodules, rhizoconcretions, drab-haloed root traces, mottling and relict bedding. Paleosols indicate periods of stability in between fluvial events of thousands to tens of thousands of years when soils developed on flood-basin or channel deposits. The four lignite interbeds represent histosols of tidal or poorly drained distributaries that penetrated the coastal delta plain, where thick vegetation resulted in the accumulation of much organic matter into layers of peat within marshes. The single interbed of welded tuff represents a pyroclastic, ash-flow deposit (ignimbrite) produced by a nearby explosive eruption. Conformably overlying the Cucaracha Formation is a basalt flow of the Pedro Miguel Formation. Underlying claystone in the Cucaracha Formation shows baking and the overlying basalt shows hydrothermal alteration.

Maps, Cross-Sections & Pictures:

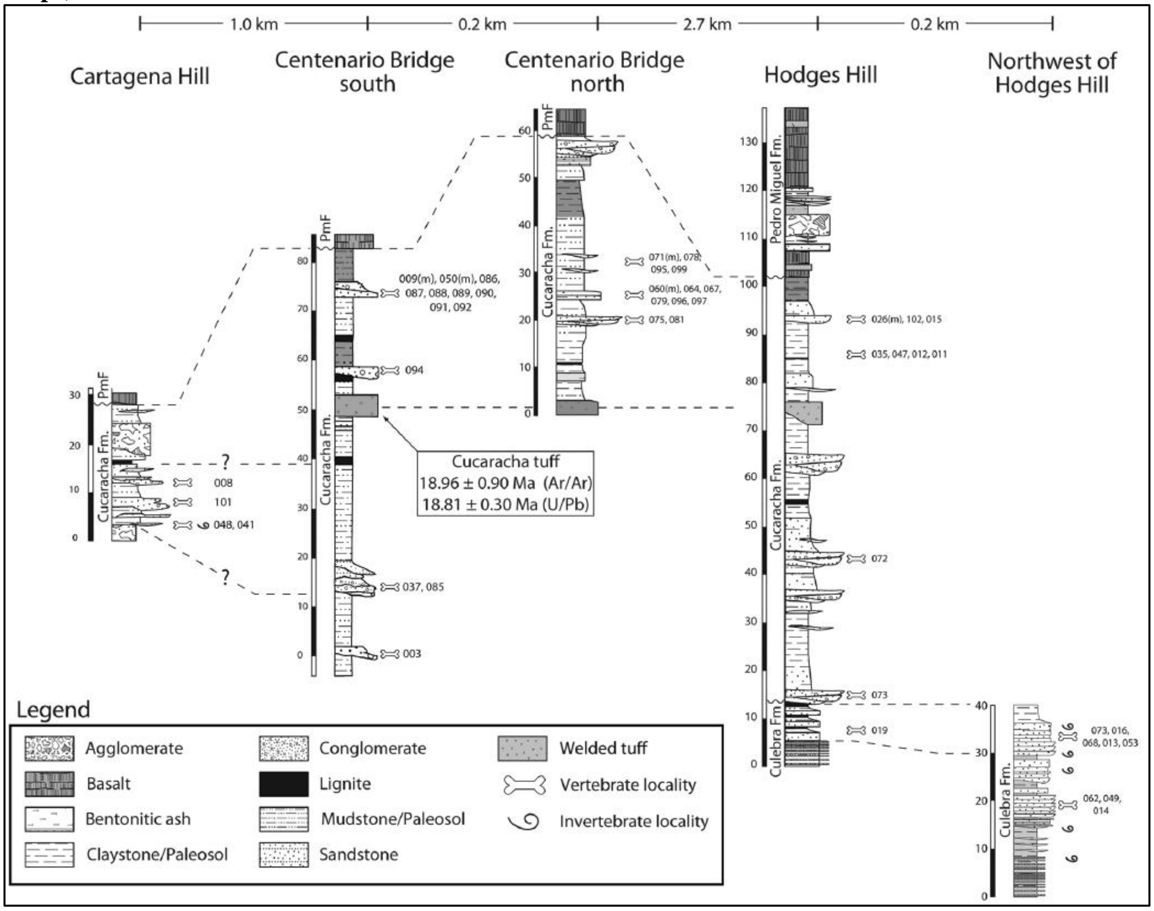

Figure 076. Stratigraphic correlations among MacFadden et al. (2014)'s measured sections containing the Centenario Fauna from the localities depicted in Figure 031. The Centenario Fauna extends from the lowest stratigraphic locality in the Culebra Formation, at 20m above the base of the measured section northwest of Hodges Hill to several localities at ~75 m above the base of the measured section at Centenario Bridge (see also Kirby et al. (2008)). PmF = Pedro Miguel Formation; Fm = Formation.

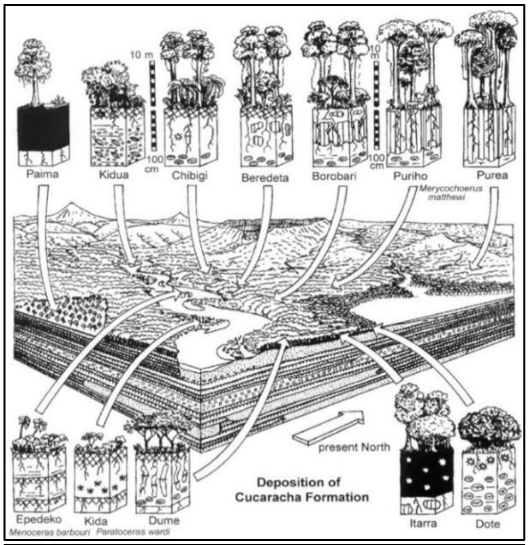

Figure 077 (top). Reconstruction of soils and vegetation in the coastal delta plain of the middle Miocene Cucaracha Formation. Retallack & Kirby (2007).

Figure 078 (bottom). Conglomerate in the uppermost part of the Cucaracha Formation, with scoriaceous clasts (arrow) at Cerro Hodges. Buchs et al. (2019).

Figure 079 (top). Fossilized tree trunk within the Cucaracha Formation. Barat (2013).

Figure 080 (bottom). Ignimbrite of the Cucaracha Formation. Insets show the eutaxitic texture of the ignimbrite and charcoaled tree stump below the ignimbrite. Buchs *et al.* (2019).

Unit: CULEBRA FORMATION

Epoch/Age/Author: Lower Miocene (Aquitanian-Burdigalian – 21 to 19 Ma) **-** (Kirby et al. (2008) ; Montes et al. (2012b); Buchs et al. (2019))

Original Author and/or Origin of the Name: Hill (1898) was the first to name and describe the "Culebra clays" and "Empire limestone". MacDonald (1919) later described, mapped and renamed these units as the "Culebra Formation" and "Emperador Limestone" when the formation was completely exposed during construction of the Panama Canal in the first decades of the twentieth century (1904-1914).

Relevant documents discussing the Unit:

- Jackson (1917); Pilsbry (1918); Rathbun (1918); Vaughan (1918); Cushman (1919); Vaughan (1924); Wilmarth (1938).
- Woodring and Thompson (1949) placed the "Emperador limestone Member" within the "Culebra Formation". They estimated

maximum thickness of about 500 feet. Conformably overlies Las Cascadas agglomerate; underlies Cucaracha Formation.

- Cork (1953); Woodring (1957, 1959).
- Woodring (1960). It unconformably overlies the Oligocene (?) Las Cascadas agglomerate. It consists of dark colored thin-bedded fine-grained rocks and calcareous sandstone, all tuffaceous. It is recognized only along and near the Canal. Its early Miocene age is based on foraminifera, corals, and mollusks. Part or all of the formation is considered late Oligocene by some paleontologists. The fossils include *Lepidocyclina miraflorensis*, *L. waylandvaughani*, *Miogypsina cushmani*, *Amphisorus americanus*, *Turritella cf. subgrundifera*, *Orthaulax cf. aguadillensis*, *Anadara cf. chiriquensis*, *Macrocallista cf. macul*ata, *Nemocardium cf. diversum*, and *Trachycardium cf. dominicense*. Though the town of Culebra was headquarters during the construction of the canal, it is abandoned. For the location, on the west side of Culebra Cut, see Woodring (1957, p. 34), cited under the name.
- Blacut and Kleinpell (1969); Woodring (1964, 1970, 1973);
- Bold (1973) demonstrated that the restricted Culebra Formation is correlative with sections containing the Emperador Limestone and overlying sediments, based on ostracode biostratigraphy.
- Woodring (1982); Graham et al. (1985); Graham (1987); Graham (1988b); Collins et al. (1996); Johnson & Kirby (2006); Kirby et al. (2008); Cadena (2009); MacFadden et al. (2010); Montes et al. (2010); Uhen et al. (2010); Cadena et al. (2012); Head et al. (2012); Hastings et al. (2013); Pimiento et al., (2013b); MacFadden et al. (2014); Jaramillo et al. (2014); Rincon et al. (2015a, 2015b); Jud et al. (2016); Farris et al. (2017); Buchs et al. (2019); Velez-Juarbe & Wood (2019);

Synonymy: Culebra Clays; Culebra Beds. Also, Kirby et al. (2008) re-interpreted what was called the ‘‘La Boca Formation’’ (with the Emperador Limestone) by earlier authors, as being the lower part of the Culebra Formation.

Location of the type section / Stratotype / Reference Section / Other localities: The type region is Central Culebra Cut area, where the town of Culebra was located on west side of the canal during its construction.

Lithology: The Las Cascadas, Culebra, and Cucaracha Formations, together with the overlying volcanic Pedro Miguel Formation comprise what Woodring and Thompson (1949) referred to as the **Gaillard Group**, a sequence of volcanic rock, and marine to terrestrial sediments and paleosols that fill the southeastern part of the Panama Canal Basin.

The Culebra Formation is comprised of a ~200 m thick section (Woodring (1957)) of mixed siliciclastic (organic rich black sandstones) and carbonate (mudstones) marine sediments. Early in its stratigraphic sequence there exist limestone and patchy coral reefs that are collectively referred to as the Emperador Limestone (Figure 083). Together with the predominantly terrestrial Cucaracha Formation, that conformably overlies it, they comprise what is thought to be a transgressive-regressive sequence with environments of deposition that include fringing reef, neritic, upper bathyal (Lower Culebra) (Figure 082) and lagoonal (Figure 081) to fluvial-deltaic (Upper Culebra-Cucaracha) (Uhen et al. (2010)) that likely included mangrove swamps in the near-shore areas and tropical forests Head et al. (2012). The Culebra Formation includes the nearshore, coralline Emperador Limestone Member and the upper bathyal La Boca unit (Blacut and Kleinpell (1969))

At Kirby et al. (2008)'s Las Cascadas locality (along the Culebra Cut), the Culebra Formation consists of nine facies (Figure 083).

BASE

1) The lowermost facies in the Culebra Formation is a black lignitic mudstone bed, which lies conformably over paleosols of the Las Cascadas Formation.
2) The lignitic mudstone bed is overlain by a medium-grained calcarenite and pebbly calcirudite. Both beds contain fragments of corals [*Acropora saludensis* Vaughan, 1919 and *Montastraea imperatoris* (Vaughan, 1919)], mollusks, echinoderms, and larger benthic foraminifera.
3) These beds are overlain by a thick sequence of carbonaceous mudstone with thin tabular interbeds of fossiliferous lithic wacke. Bivalves, gastropods, and carbonized compressions of sea grasses and wood are common in the carbonaceous mudstone. Bottom contacts of the lithic-wacke beds with underlying mudstone are sharp and scoured, whereas upper contacts are gradational with overlying mudstone. Thalassinoides burrows are common in the mudstone beneath each

lithic-wacke interbed and burrows are typically infilled with lithic wacke.

EMPERADOR LIMESTONE

4) Overlying these beds are five facies of the Emperador Limestone. The first facies consists of a branching-coral boundstone containing nine species of coral with abundant *Acropora saludensis* and *Montastraea canalis* (Vaughan, 1919) dominating in a very fine-grained calcarenite matrix.
5) The second facies consists of white, rhodolithic limestone. Algal rhodoliths range 1-4 cm in diameter.
6) The third facies consists of branching-coral boundstone, including abundant *Acropora salu-densis*, *Stylophora granulata* Duncan, 1864, and *Porites douvillei* Vaughan, 1919 as part of a diverse assemblage containing 20 species of corals in a mud matrix. Isolated coral heads of *Montastraea imperatoris* are present in life position, especially near the contact with the underlying rhodolithic limestone. Thin interbeds (10 cm) of fine-grained calcarenite containing wavy bedding of mudstone are locally present in this facies.
7) The fourth facies consists of platy-coral boundstone, which contains 18 species of coral.
8) The fifth facies consists of calcirudite containing 17 species of corals in a calcarenite matrix. Displaced head corals of *Montastraea* species and massive *Porites* species are common.

TOP

9) Alternating beds of sandstone and mudstone overlie the Emperador Limestone, and the sandstone beds become thinner and more fine-grained up-section. In contrast, the mudstone beds become thicker as one moves upsection (Figure 083). In addition, the sandstone beds grade up-section from a medium-grained calcarenite to a fine- grained lithic wacke, such that carbonate grains decrease in abundance up-section, whereas quartz and lithic grains increase up-section. There is also a lateral facies change between these two facies, such that the sandstone beds thin and pinch out and the grey mudstone beds thicken to the north over 1-2 km. The upper Culebra Formation, represented by a transition from predominant lithic wackes (lowermost upper Culebra Formation) to either amalgamated lenses of bioturbated litharenites or fining-upward sequences of conglomeratic to medium-grained litharenites, carbonaceous mudstones, and lignites (uppermost upper Culebra Formation), has been interpreted to indicate a regressive transition from shelf marine environments to estuarine and deltaic-front environments (Kirby et al. (2008); Pimiento et al. (2013b)).

   The lowermost sandstone bed overlying the Emperador Limestone (medium-grained calcarenite) contains six species of corals and abundant mollusks (bivalves and gastropods). Massive *Porites* species and head corals of *Montastraea canalis* are clearly not in life position, as they show different orientations with respect to bedding. Mollusks remain common in the sandstone beds up-section, but corals decrease in abundance. The grey mudstone beds contain abundant mollusks, echinoids, shark teeth, bioturbation, and rare volcanic lithics. A white ash bed (4 cm thick) is present at the base of the second-highest sandstone bed. Although the sequence of the upper Culebra Formation has produced an abundant marine invertebrate fauna (Woodring (1982)), ichthyofauna (Pimiento et al. (2013b)), and occasional marine mammals (Uhen et al. (2010)), the conglomeratic litharenite strata have also yielded significant dental and post cranial elements of terrestrial mammals, including peccaries (tayassuids; MacFadden et al. (2010)), rhinocerotids, and extinct protoceratids.

Thickness: Thickness estimates for this unit also vary depending on how fault bounded stratigraphic sections are correlated. Kirby et al. (2008) suggests a unit thickness of >250 m based on the correlation of sections in the Hodges and Empire sectors of the Canal. Whereas, Montes et al. (2012b) suggest a minimum thickness of 88 m based on a contiguous section in the Hodges Hill sector. A Culebra Formation thickness of 130 m is used in the Figure 031 stratigraphic section. This thickness is constrained by drill cores from Lutton and Banks (1970), but it is a minimum. On the west side of the canal near the former site of the town of Las Cascadas (9°4'28''N; 79°40'31.1''W), the Culebra Formation is 150 m thick (Figure 083) (Johnson & Kirby (2006)), The top of the Culebra Formation was not seen.

Macro Fossils: Cadena (2009) and Cadena et al. (2012) describe cryptodires (trionychids) and pleurodires (podocnemidids) turtles inhabiting prodelta to delta environments. A sirenian vertebra and additional sirenian rib fragments were found in a volcaniclastic pebble conglomerate in the Upper Culebra Formation in the El Lirio Norte reach of the Panama Canal in the Panama Canal Basin (see map under "Gaillard Group"). The sirenian rib fragments were found in both the Lower and Upper Culebra Formation. The sirenian vertebra was found in the Upper Culebra Formation approximately 40 m below the upper contact with the Cucaracha Formation. The vertebra was found in a volcaniclastic, clast-supported, pebble conglomerate located within a section of interbedded shallow marine marls and lignitic shales that contain abundant relic plant material, including carbon compressions of sea grasses, wood and scattered individual ostreids, ostreid beds, and crabs, and some thin beds of volcaniclastic sandstone (Head et al. (2012) and Velez-Juarbe Jorge, Wood Aaron R. (2019)). Another complete dugong (*Culebratherium alemani*) was later found by Dr. Steven Manchester, curator of paleobotany at the Florida Museum of Natural History (Figure 084). Crocodile specimens are also described in Hastings et al. (2013). Woodring (1957-1982) described over 150 species of mollusks from old and new collections from the Culebra Formation. Johnson & Kirby (2006) collected corals on the west side of the canal at their Las Cascadas locality (9°4'28"N; 79°40'31.1"W) and on the east side of the Gaillard Cut, where the Río Masambi Grande flows into the canal (9°3'50.2"N, 79°39'41.4"W). Pimiento et al. (2013b) studied the chondrichthyan (shark) fauna composed of teeth and vertebral centra representing 12 taxa. Jackson (1917) describes echinoids from the Emperador Limestone.

Overlying Unit: The mostly-terrestrial Cucaracha Formation

Underlying Unit: The Culebra Formation sits unconformably on the terrestrial beds of pebbly green and red claystone paleosols of Las Cascadas Formation, an Early Miocene sequence of predominantly volcanic agglomerates, tuffs, and paleosols.

Remarks: The sedimentary facies and fossils indicate a relatively shallow marine lagoonal or estuarine environment of deposition (Johnson and Kirby (2006); Kirby et al. (2008); Strong et al. (2008)). The clast-supported pebble conglomerate that the sirenian vertebra was found in suggests that it was likely deposited as depositional lag in a nearshore fluvial-deltaic distributary-channel. Assuming minimal transport of the sirenian fossil, its presence in the strata also indicates a coastal marine, estuarine, or fluvial environment of deposition (MacFadden et al. (2004)).

Maps, Cross-Sections & Pictures:

Figure 081. Tuffaceous sediment in the lagoonal facies; Lower Member. Buchs et al. (2019)

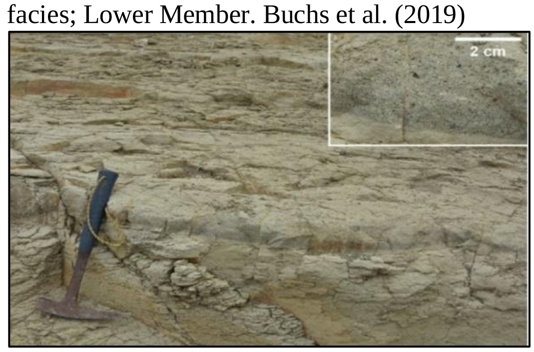

Figure 082. Tuffaceous turbidites in a bathyal facies; lower Upper Mbr. Buchs et al. (2019)

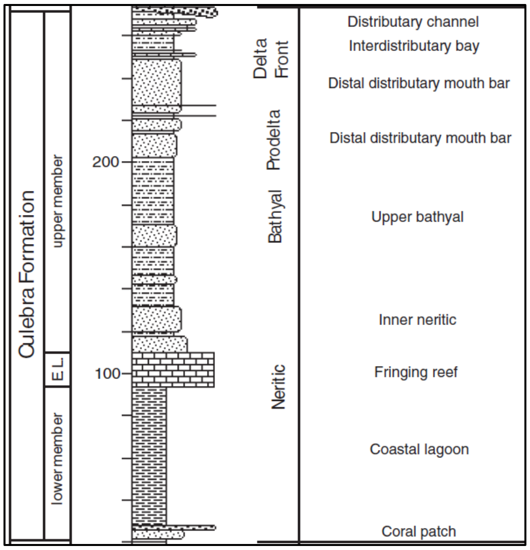

Figure 083 (top). Stratigraphic section of the Culebra Formation along the Gaillard Cut, including paleoenvironmental interpretations. Kirby et al. (2008). E.L. = Emperador Limestone
Figure 084 (bottom). The sea cow (dugong) *Culebratherium alemani* being excavated along the Panama Canal. Barnes (2019) & Velez-Juarbe Jorge, Wood Aaron R. (2019).

Unit: DARIEN FORMATION
Epoch/Age/Author: Middle Eocene to Oligocene - Barat et al. (2014)
Original Author and/or Origin of the Name: Esso Exploration and Production Panama (1970, 1971a, 1971b), who estimated its thickness as between 500 m and 1500 m.
Relevant documents discussing the Unit: Bandy (1970); Bandy and Casey (1973); Ministerio de Comercio e Industrias (1991); Coates, Anthony G. et al. (2004); (APP-B4 and APP-B3); Barat et al. (2014);
Synonymy: Eocene units of the Darien Formation were first referred to as the Morti Tuffs, and Oligocene units (occurring only in the southwest of the Chucunaque-Tuira Basin) as the Pacific Tuffs (Bandy (1970); Bandy and Casey (1973)).
Location of the type section / Stratotype / Reference Section / Other localities: Occurs on the northeastern flank of the Chucunaque–Tuira Basin, in the fore-arc region and in the Majé Massif
Lithology: It consists dominantly of fine and medium tuff, agglomerate, radiolarian chert, and basalt in its lower part and of calcareous and siliceous mudstone, micritic calcarenite, and volcaniclastics in its upper part. Radiolaria indicate mostly early to middle Eocene deposition at bathyal depths on the southwestern flank of the Chucunaque Basin (Bandy and Casey (1973)). In the Majé massif, its stratigraphy and composition is described with (from oldest to youngest) abundant breccia and agglomerate, wackestone, blackish volcaniclastic sandstone, conglomerate (Figure 085), chert (Figure 086), dark green fine-grained and medium grained tuff, green pebble conglomerate and fine sandstone. In the upper part of this sequence, the rounded pebbles suggest a distant clastic source, such as the San Blas–Darien Massif. The abundance of Globigerina sp. fossils in the sandstone indicates an open pelagic marine paleo-environment. A calcareous unit, with conglomerate, black sandstone and gray to white medium-grained tuff unconformably overlies the oldest volcaniclastic unit of the Darien Formation. This calcareous unit suggests a hemi-pelagic depositional environment, and the nannofossil assemblages indicate a Late Oligocene–Early Miocene age (Figure 087; Figure 088). This calcareous unit could correspond to the old Aquaqua Formation, which was first named by Shelton (1952), and which is now referred to as the Aquaqua Member of the Darien Formation. Barat et al. (2014)
Thickness: up to ~ 1500 m
Overlying Unit: The formation is unconformably overlain by either the Porcona or the Clarita Formation.
Underlying Unit: The formation is usually faulted against or nonconformably overlies the igneous basement of the San Blas Formation
Remarks: In the Majé Massif, mesocratic to leucocratic dykes and andesites to dacites cross-cut the San Blas Complex and the Darien Formation. These andesitic dykes are fine grained with phenocrysts of amphiboles and plagioclases. A few dacitic dykes are rich in quartz and show flow structures (Barat et al. (2014)).
Maps, Cross-Sections & Pictures:

Figure 085 (top). Conglomerates with green weathered andesite pebbles in the Majé Massif, Darien Formation (8.93588°, −78.55220°, WGS84). Barat (2013) and Barat *et al*. (2014).
Figure 086 (bottom): Green and red siliceous azoic cherts in the Majé Massif, Darien Formation (8.93013°, −78.56126°, WGS84). Barat (2013) and Barat et al. (2014).

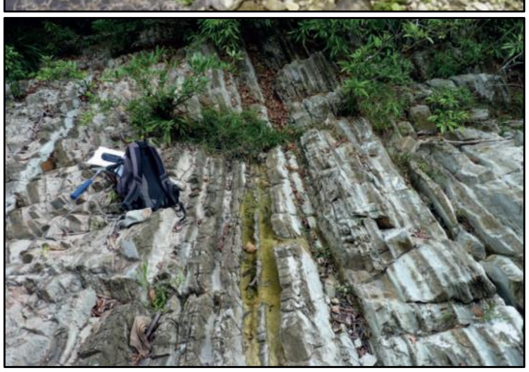

Figure 087 (top). Gray and white fine-grained and medium-grained calcareous tuffs of the Late Oligocene, Aquaqua Mb, Darien Formation, (8.89477°, −78.52817°, WGS84); Barat (2013) and Barat et al. (2014).
Figure 088 (bottom). Layered micritic limestone outcrop in the Curti river of the Majé Massif, Late Oligocene. Barat (2013).

Unit: DAVID FORMATION
Epoch/Age/Author: Upper Eocene (may be late Middle Eocene) **-** Olsson (1942b); Woodring (1960)
Original Author and/or Origin of the Name: Sapper (1937). Limestone named in a correlation chart. Below Majagua Formation.
Relevant documents discussing the Unit:

- Olsson (1942b). David Formation applied in broad sense to the younger upper Eocene rocks of Panama, consisting generally of foraminiferal limestones in their entirety or of shale and sandstone formations in which the limestones may be entirely missing or restricted to reeflike masses. In vicinity of David and Brenon, occurs above Bucarú Formation; in Veraguas and Los Santos area occurs below Tonosí limestones.
- Cooke (1948). Though this is believed to be the first published record of Eocene echinoids in Panama, the collections in the United States National Museum include a few specimens collected many years ago in Los Santos Province, evidently from late Eocene limestone assigned to the David Formation by Olsson (1942b).
- Terry (1956). In western Panama, recognized Eocene begins three miles north of David, the capital of Chiriqui Province. This is about 100 miles west of the nearest Eocene, on the shore of Montijo Bay. The intervening sedimentary area of Chiriqui and Veraguas is surfaced with Oligocene and Miocene, and the Eocene may underlie them, but is not known to outcrop. The well-known David Eocene exposure near km 12 on the Chiriqui National Railway is in a much-faulted area with tepid sulfur springs which have created a swamp surrounding the small outcrop of orbitoidal limestone from which *Lepidocyclina panamensis*, *L. duplicata*, and *L. macdonaldi* have been identified. Farther west, for a distance of five or six miles, a more complete section is exposed on various tributaries of Río Platanal; and near the Costa Rica border, on the Río Blanco de Brenon, a small tributary of the Chiriqui Viejo, an apparently complete section of late Eocene

can be seen in the axial part of a large anticline. Three limestone beds, separated by coarse barren sandstones, yielded the following:
  - Basal bed (lying on andesite) - *Eodictyoconus*, *Camerina*, *Heterostegina*, *Discocyclina* sp. near *D. minima* Cushman, *Lepidocyclina* 2 spp.
  - Bed 2 - *Discocyclina* sp., *Lepidocyclina trinitatis* (?), *Lepidocyclina (Nepthrolepidina)* sp., *Lepidocyclina* sp. Possibly a fourth species of *Lepidocyclina*.
  - Bed 3 - *Lepidocyclina trinitatis* (?) and *L. (Nephrolepidina)*.

Above Bed 3 is another barren sandstone and then a conglomerate with lime cement, carrying *Lepidocyclina gigas* and marking the base of the Oligocene.
- Wilson *et al*. (1957).
- Woodring (1960). Poorly defined name. The David Formation, which consists of fossiliferous limestone and shale separated by barren sandstone, has yielded the type material of *Lepidocyclina macdonaldi*, *L. duplicata* [*L. pustulosa tobleri*], *Orthophragmina minima* [*Asterocyclina minima*], and *Nummulites davidensis* [*Operculinoides floridensis*]. In oral an communication, C.W. Cooke reports that the David Formation contains *Oligopygus cf. O. wetherbyi*. The David Formation has been referred to the upper Eocene, but, like the Búcaro Formation, may be late middle Eocene or may include late middle Eocene. The fossils from the David include a small species of *Velates* which has a very eccentric apex similar to that of the much larger *V. vokesi*.
- Keroher *et al*. (1966)

Synonymy: David foraminiferal limestone (Olsson (1942b, pg 234 & 236)), Davidkalk = David Limestone

Location of the type section / Stratotype / Reference Section / Other localities: Most likely as per Terry (1956)'s description above

Macro Fossils: Though the formation contains foraminifera, mollusks, and echinoids, only the foraminifera are recorded: *Lepidocyclina macdonaldi*, *L. pustulosa* («*panamensis*» and «*duplicata*»), and *Asterocyclina minima*. Woodring (1960). Shallow-water Eocene carbonate deposits with rich assemblages of larger benthic foraminifera are seen, although they are not as continuous through time. The type section of the Upper? Eocene David Formation of southwestern Panama has yielded the larger foraminifera *Lepidocyclina panamensis*, *L. duplicata* and *L. macdonaldi*, and the probable extension of this limestone unit to near the border with Costa Rica contains a richer assemblage. Bundschuh et al. (2012).

Remarks: In Chiriqui Province.

In Costa Rica, the coastal range of Fila Costeña exposes the largest shallow-marine carbonate platform sequence known in te country: the "Fila de Cal" limestones - named the David Formation in Panama (Bolz et al. (2018)). Eames et al. (1968) considered some equatorial sections of specimens from samples 2 miles north of David (Panama) that Cole (1960, pl. 3, Figure1) previously illustrated to probably belonging to the subspecies *panamensis* rather than *L. (Pliolepidina) tobleri* (s.s.). As authors stated, *L. tobleri* subsp. *panamensis* Cushman differs from *L. tobleri* s.s. in having a more inflated test and a large pliolepidine embryo showing a thinner wall. These deposits belong to the David Formation (Domínguez (1978)).

Unit: *EL BARRO FORMATION

Epoch/Age/Author: Mid-Late Oligocene(?) - Ministerio de Comercio e Industrias (1991)

Original Author and/or Origin of the Name: Ministerio de Comercio e Industrias (1991)

Relevant documents discussing the Unit: No other publication was found to discuss this formation.

Overlying Unit: The formation is overlain by Pesé Formation. Ministerio de Comercio e Industrias (1991)

Underlying Unit: The formation is underlain by the Senosri-Uscari Formation. Ministerio de Comercio e Industrias (1991)

Remarks: The term should be disregarded. It is not well described, and a formation of the same name exists in The Department of Huila in Colombia. Fuquén JA, Osorno JF (2002).

Unit: EMPERADOR LIMESTONE

Epoch/Age/Author: Lower Miocene (Aquitanian-Burdigalian – 21 to 19 Ma) - Kirby et al. (2008)

Original Author and/or Origin of the Name: Hill (1898) was the first to name and describe the "Culebra clays" and "Empire limestone" which takes its name from quarries at Empire, now unrecognizable, a village on original line of Panama Railroad near Culebra and about 2kms west of Culebra Cut. MacDonald (1919) later described, mapped and renamed these units as the "Culebra Formation" and "Emperador Limestone" when the formation was completely exposed during construction of the Panama Canal in the first decades of the twentieth century (1904-1914). He changed the name to “Emperador Limestone”, from the Spanish name of the village, apparently to avoid possible confusion with the Empire Formation of Oregon.

Relevant documents discussing the Unit:

- Vaughan (1918); Wilmarth (1938).
- Woodring and Thompson (1949) placed the "Emperador limestone Member" within the "Culebra Formation" [*other authors placed it within the La Boca Formation*]. Massive cream-colored limestone. Limestone is rare along the Panama Canal and is so conspicuous in the predominantly tuffaceous rocks that such beds in different regions were formerly correlated with the Emperador. As a result of these correlations, limestones in Caimito and La Boca Formations, and even in Gatuncillo Formation in Madden Basin, were designated Emperador limestone. Even when limestones in other formations are eliminated there remains residue of limestones in the Culebra, the relative stratigraphic position of which is uncertain. Early Miocene. Formerly exposed in shallow quarries at Empire.
- Woodring (1957). Limestone agreeing with descriptions of the Emperador is still exposed along canal. These beds of relatively pure coralliferous limestone probably are at different horizons in upper part of Culebra Formation and probably grade southeastward into calcareous sandstone. Should it be demonstrated that the name is being used for limestone at different horizons, the name should be abandoned, except for limestone at type locality.
- Woodring (1960). The name at present is restricted to coralliferous limestone, 20 to 40 feet thick, in the Culebra Formation. Whether the limestone referred to the Emperador is at the same horizon as the now inaccessible limestone at Empire is not known. An early Miocene age is based on foraminifera, corals, and mollusks, but some paleontologists assign the limestone to the late Oligocene. The fossils include *Lepidocyclina miraflorensis* (Cole (1953)), *Stylophora imperatoris, Pocillopora arnoldi* (Vaughan (1919)), *Dosinia*, *Chione*, *Lirophora*, and *Nemocardium* (Woodring & Thompson (1949, p. 239)).
- Bold (1973) demonstrated that the restricted Culebra Formation is correlative with sections containing the Emperador Limestone and overlying sediments, based on ostracode biostratigraphy.
- Kirby et al. (2008) re-interpreted with 100% certainty what was called the ‘‘La Boca Formation’’ (with the Emperador Limestone) by earlier authors, as being the lower part of the Culebra Formation, as per Woodring and Thompson (1949)’s interpretation.
- Others: See “Culebra Formation”.

Synonymy: Empire Limestone (Wilmarth (1938)) and Culebra clays (both terms now obsolete). Woodring (1957) - Chilibrillo limestone Member is the Emperador limestone of Reeves and Ross (1930) and Chilibrillo Formation of Kellogg (1931). “Emperor” is a misspelling.

Remarks: See “Culebra Formation” for a description of its lithology and fossils

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Unit: *EMPIRE LIMESTONE

Epoch/Age/Author: Miocene - Woodring (1960)

Original Author and/or Origin of the Name: Hill (1898).

Relevant documents discussing the Unit:

- Woodring (1960). Limestone in Gaillard [Culebra] Cut area now referred to lower Miocene. MacDonald (1919) renamed unit Emperador limestone. Credits name to R. T. Hill.
- Keroher *et al*. (1966)

Synonymy: Emperador Limestone. See “Culebra Formation”

Remarks: Named for Empire, now abandoned, a village on original line of Panama Railroad near Culebra and about 2.4 kms west of Culebra Cut.

Unit: ESCUDO DE VERAGUAS FORMATION (part of the Bocas del Toro Group)

Epoch/Age/Author: Upper Pliocene to Lower Pleistocene (Piacenzian to Gelasian; 3.5-1.8Ma) - Coates et al. (2005)

Original Author and/or Origin of the Name: The Escudo de Veraguas Formation was named by Coates et al. (1992) for the island of the same name that lies about 27 km east of Nancy Point (Figure 089). It is located along the north coast, from Long Bay Point one km eastward (lower part of the formation), and for two km south of Long Bay Point on the west coast (upper part of the formation).

Relevant documents discussing the Unit: Coates (1999); Coates et al. (1992 & 2005); Todd & Collins (2005); Landau et al. (2012a, 2012b); Schwarzhans et al. (2013);

Location of the type section / Stratotype / Reference Section / Other localities: After Coates (1992) named the formation, Coates (1999) carried out more detailed field work that indicated that the coastal section immediately east of Long Bay Point is essentially along strike and thus probably exposes the same sequence of beds several times. A continuous section for the lower part of the formation is best obtained along the coast on the east side of the V-shaped embayment situated in the center of the north coast about 1 km east of Long Bay Point. This locality is now defined as the stratotype for the lower part of the Escudo de Veraguas Formation. The stratotype for the upper part of the formation remains that originally defined by Coates et al. (1992) along the west coast for 1 km south of Long Bay Point. Between these upper and lower stratotypes, both of which have clearly documented physical superposition of strata, there is a small but unknown amount of section missing. The exposures along the north coast of Escudo de Veraguas, immediately east of Long Bay Point, and west of the V-shaped embayment in the center of the north coast, which were part of the original stratotype defined by Coates et al. (1992), are estimated to fall in this gap. However, because the coast is irregular and only approximately parallel to strike, the stratigraphic order of samples from these exposures can not be determined.

Lithology: The lowest 10 m of the formation at the stratotype is moderately indurated, fine, silty sandstone and clayey siltstone, pervasively bioturbated and containing frequent, cemented, irregular burrow-concretions and horizons with dense *thalassinoid* burrow systems. The overlying 30 m of clayey siltstone, silty claystone and silty, fine sandstone is also pervasively bioturbated, with frequent concretions, *thalassinoid* burrows and scattered mollusks with a distinctive basal 2 m thick marker bed rich in corals and mollusks.

Following 70 m of no exposure, the section continues with 13 m of clayey bioclastic siltstone, with some angular basalt grains, scattered mollusks and cupuladrian bryozoans. The section is massive and pervasively bioturbated with scattered fine shell hash. About 5 m from the top, a second marker horizon is defined by a densely packed coral biostrome that is also rich in echinoids and mollusks. The lower part of the Escudo de Veraguas Formation 2.6-3.5 Ma.

The upper part of the Escudo de Veraguas Formation (Section 10 of Coates (1999)) consists of about 8 m of blue-gray, clayey siltstone and silty claystone, sparsely shelly and intensely burrow-mottled. Thalassinoid-type burrows are common, as are echinoids; the latter are very fragile and almost impossible to collect. Two distinctive marker beds within this section consist of slightly more indurated burrow zones, suggesting minor disconformities or slower depositional rates. It represents onshore and offshore siliciclastic shelf sediments deposited at palaeobathymetries of 10-80 m and 100-150 m respectively (Todd & Collins (2005))

Thickness: About 131 m

Macro Fossils: *Thalassinoid* burrows, mollusks, corals, echinoids, Crabs (Todd & Collins (2005) suggest burial of whole crabs in gravity flows). Landau et al. (2011 & 2012b) study the Strombus and Cancellariidae gastropods from the Escudo de Veraguas Formation.

Overlying Unit: Not exposed

Underlying Unit: Not exposed

Remarks: The stratigraphic order of the Tobabe, Nancy Point and Shark Hole Formations (three of the five formations which make up the Bocas del Toro Group) has been determined by physical superposition. The two remaining formations of the Bocas del Toro Group (Escudo de Veraguas and Cayo Agua) as well as the younger Pleistocene Swan Cay Formation are known only on islands and their position relative to the other units has been determined by biostratigraphic evidence (Figure 044)

Maps, Cross-Sections & Pictures:

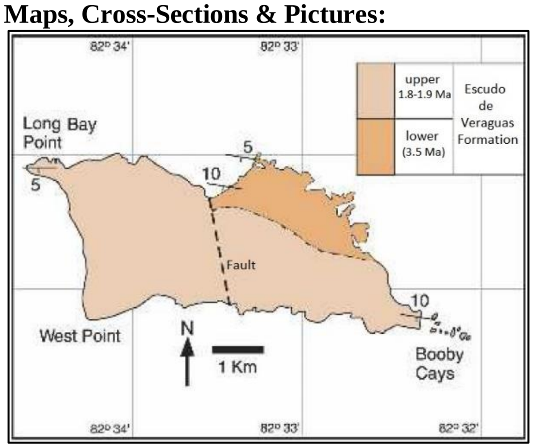


Figure 089. Geological map of Escudo de Veraguas island. Coates et al. (2005).

Unit: FISH HOLE MEMBER (of Old Bank Formation)

Epoch/Age/Author: Late Miocene (Messinian, 5.8 to 5.6 Ma) **-** Klaus et al. (2012)

Original Author and/or Origin of the Name: Klaus et al. (2012)

Relevant documents discussing the Unit: See « Old Bank Formation »

Location of the type section / Stratotype / Reference Section / Other localities: Bastimentos Island

Lithology: The Fish Hole Member outcrops on the northeastern rim of Bastimentos (Figure 042) and consists of ~4 m of thick-bedded, rubbly, bioclastic, limestone containing volcanic sand and silt grains in varying amounts. Pristine shells collected from within the reef unit (Figure 117) of the Fish Hole Member provide strontium isotope ages ranging from 5.8 to 5.6 Ma. (Messinian) (Klaus et al. (2012)).

Thickness: 4m

Macro Fossils: Corals

Overlying Unit: See « Old Bank Formation »

Underlying Unit: See « Old Bank Formation »

Unit: GAILLARD GROUP

Epoch/Age/Author: Early to Middle Miocene (21.05 Ma to 17.9 Ma) **-** Rincon et al. (2012a, 2012b)

Original Author and/or Origin of the Name: Woodring and Thompson (1949)

Relevant documents discussing the Unit: Woodring et al. (1982); Kirby et al. (2008); MacFadden et al. (2010); Rooney et al. (2011); Montes et al. (2012a, 2012b); Rincon et al. (2012a, 2012b);

Location of the type section / Stratotype / Reference Section / Other localities: The stratigraphic sequence cropping out along the Culebra Cut (Figure 090), in the Panama Canal, encompasses Eocene to middle-late Miocene volcanic, volcanosedimentary, and clastic units (Woodring and Thompson (1949); Woodring et al. (1982); Kirby et al. (2008); MacFadden et al. (2010); Montes et al. (2012a, 2012b)). This stratigraphic interval (Figure 093) represents one of the most complete and best exposed Oligocene and Miocene volcanic sequences within the Central American arc (Rooney et al. (2011)). The northern part of the Culebra Cut is composed mainly of Eocene–early Miocene volcanic and volcaniclastic formations (Bas Obispo and Las Cascadas Formations), whereas the southern part is mainly characterized by shallow marine and volcaniclastic continental sequences of the Culebra and Cucaracha Formations (Kirby et. Al. (2008)). The Las Cascadas, Culebra, and Cucaracha Formations, together with the overlying volcanic Pedro Miguel Formation comprise the **Gaillard Group** in the Culebra Cut, a sequence of volcanic rock, and marine to terrestrial sediments and paleosols that fill the southeastern part of the Panama Canal Basin. (Figure 090, Figure 091, Figure 092, Figure 093). The Culebra Cut stratigraphic sequence encompasses a mosaic of environments including mangrove forest, forests, shallow marine, and transitional environments.

Lithology: See the individual description of the four formations comprising the Gaillard Group (Las Cascadas, Culebra, Cucaracha, Pedro Miguel Formations)

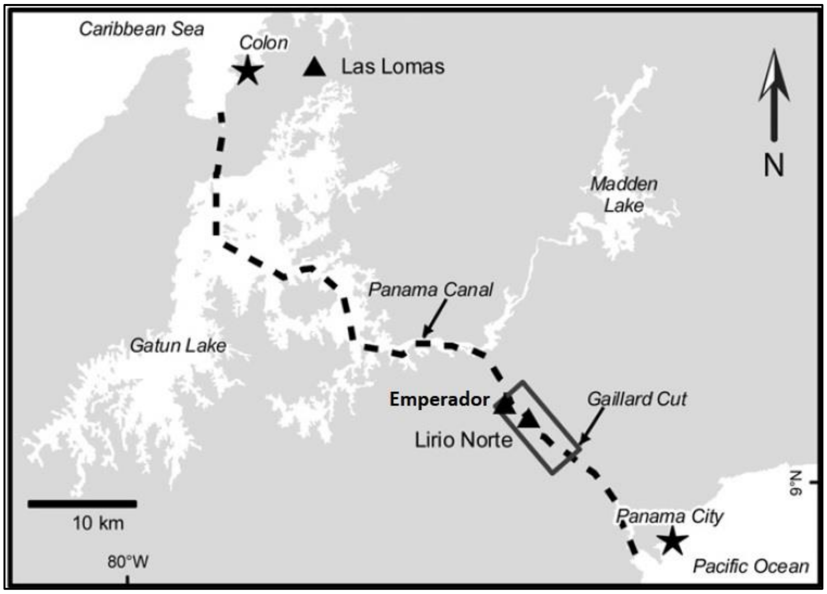
Thickness: Up to 1,175 metres

Macro Fossils: See the individual description of the four formations comprising the Gaillard Group (Las Cascadas, Culebra, Cucaracha, Pedro Miguel Formations)

Overlying Unit: N/A

Underlying Unit: Bas Obispo Formation

Maps, Cross-Sections & Pictures:



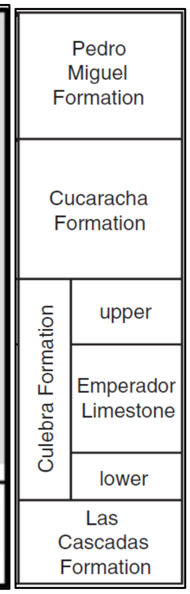
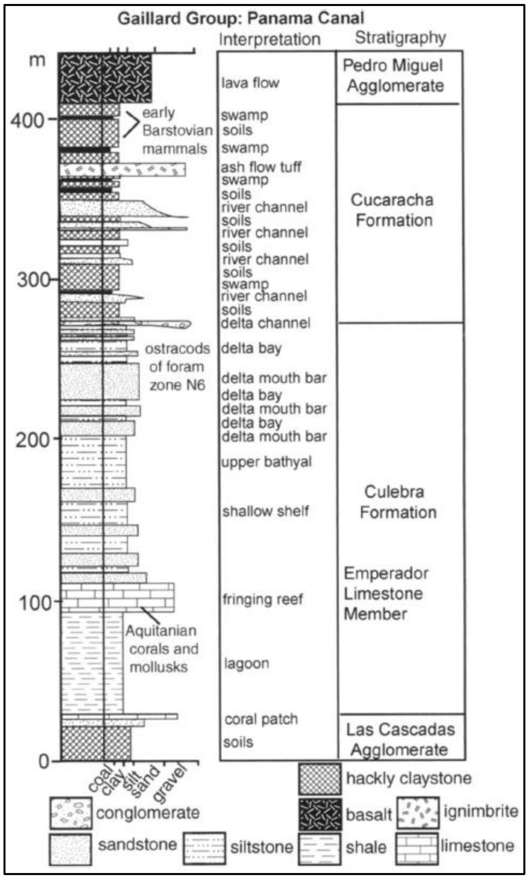


Figure 090 (left). The Panama Canal showing the location of the Culebra Cut (Gaillard Cut) together with the Emperador and Lirio Norte faunal areas. Modified from Uhen *et al*. (2010).
Figure 091 (right): General stratigraphy of the Gaillard Group. Kirby *et al*. (2008).



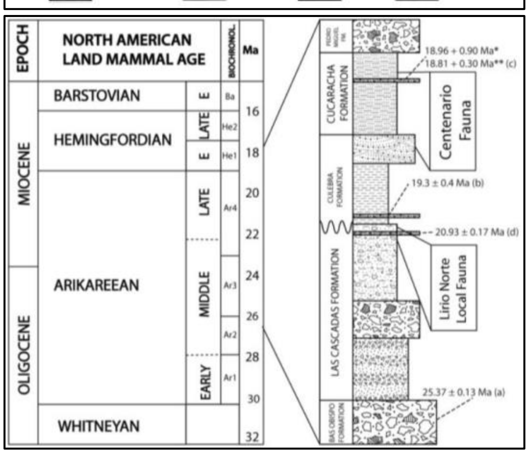


Figure 092 (top). Stratigraphy and paleoenvironments of the Miocene Gaillard Group. Retallack & Kirby (2007).

Figure 093 (bottom). Stratigraphic section of the Gaillard Group at the Culebra Cut area showing the stratigraphic position of the Las Cascadas fossil assemblage (Lirio Norte Local Fauna), the Emperador Limestone (19.3 Ma) within the Culebra Formation, and the Centenario Fauna. Rincon (2016).

Unit: GALIQUE FORMATION

Epoch/Age/Author: Early Miocene (Burdigalian?) - Ministerio de Comercio e Industrias (1991)

Original Author and/or Origin of the Name: Unknown

Relevant documents discussing the Unit:

- Ministerio de Comercio e Industrias (1991). The legend of the map places the formation in the Upper Eocene to Oligocene.
- Florida Museum (2011) states "*Roger and Austin continued westward to the city of David, in Panama's Chiriqui Province, where the PCP-PIRE team has recently begun paleontological reconnaissance. The rocks exposed to the east and north of David are of the Galique Formation, which appears to be intermediate in age between the Culebra and Gatún Formations we have been studying in the Panama Canal. Courtesy of AES Panama we were able to access outcrops at Presa Baragon, north of Gualaca, and make large collections of rich mollusk and crab assemblages. The Galique Formation appears to have a diverse Early-Middle Miocene fauna, which has never been described, and therefore is a critical new element to Panama's Neogene fossil record*".
- Making reference to a section of the western Azuero Peninsula, Perez-Consuegra et al. (2018) state "Mollusks associated with this section — *Leopecten* sp., *Crassostrea* sp., *Ampullinopsis spenceri*, *Galeodea* sp. and *Ficus* cf. *F. carbasea* and gastropod fossils of Naticidae, Muricidae, *Antillophos* aff. *A. gatunensis*, *Conus* sp., and Turridae — are similar to other faunas in Miocene strata from Panamá (e.g., Culebra, **Galique**, Gatún and Chucunaque Formations; Hendy (2013)). The presence of *Ampullinopsis spenceri* in the lower part of the succession indicates an Early Miocene (Aquitanian – Burdigalian) age. Based on the data, we assign an Early Miocene age (Burdigalian?) to the sedimentary sequence in the Torio Beach". See also Góngora-Blanco (2016) for a study on Torio Beach and Palo Seco Beach

Overlying Unit: Since Ministerio de Comercio e Industrias (1991) places the formation in the Upper Eocene to Oligocene and that more recent studies by Florida Museum (2011) and Perez-Consuegra et al. (2018) confirm it as Early Miocene, and that no formal description of the formation has been found so far, it is unclear what formation overlies it.

Underlying Unit: Since Ministerio de Comercio e Industrias (1991) places the formation in the

Upper Eocene to Oligocene and that more recent studies by Florida Museum (2011) and Perez-Consuegra et al. (2018) confirm it as Early Miocene, and that no formal description of the formation has been found so far, it is unclear what formation underlies it.

Remarks: No formal description of the formation could be found.

Unit: *GAMBOA FORMATION

Epoch/Age/Author: Oligocene(?) **-** Woodring (1960)

Original Author and/or Origin of the Name: Sapper (1905)

Relevant documents discussing the Unit:

- Wilson et al. (1957).
- Woodring (1960). Volcanic rocks (pyroclastic rocks and flows) at and near the big bend in Río Chagres at Gamboa, Canal Zone. Name has not been used in recent literature but is available as a name to include Bas Obispo Formation and Las Cascadas agglomerate.
- Keroher et al. (1966)

Synonymy: Bertrand & Zurcher (1899) used the informal designation "roche de Gamboa". Sapper (1905) used "Gesteine von Gamboa" (p. 38), "Gamboa Formation" (p. 39), and "Gamboagesteinen" (p. 39).

Location of the type section / Stratotype / Reference Section / Other localities:

Remarks: If it was meant to include both Bas Obispo and Las Cascadas Formations, an age of Late Oligocene to Early Miocene would be better appropriate.

Unit: GATÚN FORMATION

Epoch/Age/Author: Middle to Upper Miocene (Serravallian to Tortonian**) -** Coates et al. (1992)

Original Author and/or Origin of the Name: The Gatún Formation was first defined and named as such by Howe (1907a, 1907b) after the village of Gatún which lies at the northern margin of Gatún Lake, 12 km southwest of Colon. He excluded oldest strata near Gatún from Gatún Formation and grouped them into Bohío Formation. Before it was named, however, the formation was already known. When William Phipps Blake traveled across Panama in 1853 on his way to California to join one of the transcontinental railroad surveying parties, he collected a few Gatún Formation invertebrate fossils. Vertebrates (shark teeth) fossils were unknown in the Gatún fauna until the discovery and excavation that led to Gillette (1984)'s study.

Relevant documents discussing the Unit:

- Toula (1908, 1911); Brown and Pilsbry (1911, 1912); Dall (1912); Vaughan (1918); Rathbun (1918); Pilsbry (1918); Jackson (1917 & 1919); Cushman (1919); Pilsbry (1919); Vaughan (1919); Olsson (1922).
- Coryell et al. (1937a). At Cativa, includes Cativa marl in lower part.
- Thompson (1943); Jones S.M. (1950).
- Woodring (1957). Chiefly massive medium to very line grained sandstone and siltstone. Estimated thickness at least 500 meters. On faunal basis, divided into lower, middle, and upper parts; lower part not represented at type region; middle part includes best known strata. Overlies Caimito Formation with contact covered by waters of Gatún Lake; farther east, overlaps Caimito and lies directly on Cretaceous(?) basement: underlies Chagres sandstone. Lower and middle Miocene. It is now known that oldest outcropping part of formation is not represented in type region.
- Woodring (1959).
- Woodring (1960). Siltstone, sandstone, conglomerate, and tuff, extending from Gatún, Canal Zone, northward to Monkey Hill [Mount Hope] were described as the Gatún Formation. According to Dall (1912), the age is Oligocene. Most of the sandstone is fine-grained. The sandstone and siltstone are more or less calcareous. The formation crops out on the Caribbean side of the isthmus of Panama in an area that has a length of 40 miles [68 kms]. A thickness of 1,400 feet [426m] was penetrated near Mount Hope, and the base was not reached. Fossils, particularly mollusks, are abundant. These mollusks include *Turritella altilira*, *T. gatunensis*, *Conus molis*, *Anadara dariensis*, *Clementia dariena*, and *Lirophora mactropsis*. On a faunal basis the formation is divided into lower, middle, and upper parts. The lower part, not represented in the type region, overlaps onto the pre-Eocene basement east of the Canal Zone. In the Canal Zone the three parts are assigned to the middle Miocene, but the upper part west of the Zone is considered late Miocene.
- Woodring (1964, 1970, 1973, 1982); Keroher (1966); van den Bold (1967); Gertman (1969); Petit (1976); Roth (1981); Vokes (1969, 1970, 1983a, 1983b, 1989a, 1989b);

Gillette (1984); Graham et al. (1985); Jung (1989); Graham (1991); Collins (1999); Collins et al. (1996 & 1999); Aguilera et al. (1999); Coates A.G (1999); Fierstine (1999); Todd & Collins (2005); O'Dea et al. (2007); Beu (2010); Montes et al. (2010); Pimiento (2010); Uhen et al. (2010); Pimiento et al. (2010 & 2013a); Cadena et al. (2012); Landau et al. (2012a); Hastings et al. (2013); Hendy (2013); Todd et al. (2013); Jaramillo et al. (2014); Herrera et al. (2014b); Aguilera et al. (2017); Anderson et al. (2017); Alberti et al. (2018); Redwood Stewart D. (2019);

Synonymy: The name of Gatún has come to supersede other earlier informal names for this unit, such as Monkey Hill, Mindi Beds, Mindi Hill Beds (Hill, 1898). The "Sabanitas Formation" of Thompson (1947) and Jones (1950) is now the Lower Member of the Gatún Formation.

Location of the type section / Stratotype / Reference Section / Other localities:

- The type area is from Gatún to Mount Hope (Monkey Hill of Howe's time), Canal Zone (Keroher, 1966).
- The stratotype of the Gatún Formation was defined by Coates et al. (1992). It runs from Sabanita on the main transisthmian highway 12 km east of Colon, to 0.7 km west of the junction with Route 77 (the turnoff for Portobelo).
- Four reference sections were measured by Coates (1999) that include both the Gatún and the Chagres Formations and reflect the lateral changes that the formations undergo from Gobea, 40 km west of Colon, to Sabanita, 12 kms east of Colon. The formation can be observed in roadside construction sites, and quarries from Colon to Sabanitas (north-south), and from Maria Chiquita to Gobea (east-west).

Lithology: The lower 5 metres of the lower Gatún Formation (formerly called "Sabanitas Formation" by Jones (1950) and later lowered to Member status of the Gatún Formation) consists of volcanic conglomerate, with 1 to 5cm clasts and a tuffaceous, arkosic matrix, cross-bedded, laminated, tuffaceous siltstone, and alternating laminated sandstone and siltstone, mostly deeply weathered. The overlying 40 m consists of massive, grey-green, clayey siltstone, with minor claystone and fine sandstone units. Zones of densely packed large concretions, pervasive bioturbation, and extensive thalassinoid burrow systems, as well as simple vertical and lateral hash-filled burrows, are typical of this part of the section. Shell hash of varying grain size and density is almost ubiquitous, as are units packed with diverse, whole mollusks.

The middle Gatún Formation is described in Section 2 of Coates (1999) and covers the composite section from Gatún to Margarita. The middle Gatún Formation is about 350 m thick and consists of alternating siltstone and sandstone with occasional 4 to 5m units of interbedded sandstone and conglomerate. Concretion zones like those of the lower Gatún Formation are largely absent. Shell hash and diverse molluscan assemblages are somewhat less abundant than in the lower Gatún Formation, but pervasive bioturbation is still very extensive. Bentonitic horizons and a higher wood fragment content are also typical of the middle Gatún Formation.

The upper Gatún Formation is exposed around Mount Hope (upper part of Section 2 in Coates (1999)) and more extensively on the western side of the canal, along and adjacent to the road to Pina, and is about 40m thick. The lithology is more consistently volcaniclastic sandstone or fine conglomerate, with minor mudstone and siltstone. Thin bentonite horizons and shell hash are common but diverse, whole mollusks are relatively rare. A distinctive horizon is exposed below the overflow dam on the Chagres River west of Gatún Locks and has conglomeratic, tuffaceous sandstone beds with extensive thalassinoid burrows, wood, and scattered coral colonies up to 50 cm in diameter. Armored mudballs, 6-10 cm in diameter, are also abundant at one horizon that has numerous pockets filled with conglomerate.

Thickness: The thickness of the Gatún Formation varies between localities and authors. Woodring (1957) states that the total thickness of the Gatún Formation, recorded in a borehole near Colon City, is about 500m. Hendy (2013) notes a total thickness of at least 600 m of which the basal half belongs to the lower Gatún Formation.

Macro Fossils: The sedimentary succession of the lower Gatún Formation contains a highly diverse fossil record including remains of foraminifers, sponges, corals, mollusks (Figure 094), polychaetes, crustaceans, bryozoans, echinoderms (Jackson (1917)), turtles, and vertebrates including sharks (for a complete list, and with pictures of the mollusks, see Alberti et al. (2018)). This fauna points to fully marine conditions in the Panama Canal Basin with water depths less than 50 m. The area was surrounded by volcanoes of the Central American Isthmus, but several fossil groups indicate that a connection to the Pacific was still present (Alberti et al. (2018) and Woodring (1957, 1959, 1964, 1970, 1973, 1982)). van den Bold (1967) describes ostracodes from a section of the Gatún Formation and states that the most regularly occurring species is *Costa walpolei* and continues to describe 35 other species. The water energy in the Gatún was mostly low, possibly due to the sheltered position of the Basin (Hendy (2013)). Trace fossils include abundant drill holes of naticid and muricid gastropods which exhibit a strong prey selectivity potentially caused by the victim's life habits and/or shell features (e.g. thickness, ornamentation). In addition, several gastropod shells were found with traces of predation by crustaceans. The trophic web reconstructed on the basis of the fossil fauna is complex. The benthos is dominated by suspension-feeding bivalves and carnivores including mainly gastropods and crustaceans. Herbivores are scarce among macrofossils. The nektonic life is highly diverse including nautilids, fishes (Fierstine (1999), Aguilera et al. (2017)), rays, sharks, sea turtles, crocodiles (Hastings et al. (2013)), and toothed whales (Uhen et al. (2010)). The top of the food chain is formed by *Carcharocles megalodon*. Few herbivorous taxa point to the potential presence of seagrass and/or algae growing on the substrate. Pimiento et al. (2010, 2013a) proposed the Miocene Gatún Formation, as a nursery area that offered juvenile *Carcharocles megalodon* (sharks) protection from larger predators and ample food resources (i.e. fishes) (Figure 095). Herrera et al. (2014b) describe endocarps of *Vantanea cipaconensis* (a plant belonging in the family of the Humiriaceae) which were found at the Gatún Third Lock locality (lat. 9°26.847'N, long. 79°91.235'W) together with fruits of Arecaceae and abundant shallow marine invertebrate and shark tooth fossils. These fossils were accumulated in a shallow-water embayment; therefore, these endocarps might represent local elements of the coastal flora of central Panama or elements transported by sea currents from nearby floras of northern South America.

According to O'Dea et al. (2007), the best outcrops of the Gatún Formation for the purpose of fossil collecting can be found in the area of Sabanitas and near the community of Gatún in the extreme north of the Panama Canal. For instance, on a small hill about 50m before the gates of the "Isla Payardi" refinery (9° 22.957'N, 79° 49.288'W) can be found an extremely rich mollusks bed. Also, when new commercial or residential constructions take place along the highway between the cities of Panama and Colon new sites become exposed.

Overlying Unit: The Chagres Formation sits disconformably on the Gatún Formation; a marked change in lithology and a temporal hiatus characterizes the disconformity.

Underlying Unit: The Gatún Formation rests unconformably on formations of different ages in different parts of the Panama Canal Basin. To the east of Colon, the Gatún Formation rests nonconformably on the unnamed Cretaceous volcanics. To the west of Colon, including several islands in Lake Gatún, the Gatún Formation rests with angular unconformity on the upper Oligocene Caimito Formation. Westwards, the Gatún Formation can be traced as far as Gobea. The contact between the Gatún and the underlying Caimito Formation is covered by the waters of Lake Gatún and even before the flooding of the lake perhaps all of the contact was concealed by swamps.

Remarks: The Gatún Formation is typically interpreted to represent relatively shallow marine paleoenvironments (e.g., <100m; Pimiento et al. 2013a), although through detailed stratigraphic analysis Hendy (2013) has demonstrated fine-scale bathymetric fluctuations within this part of the sequence (MacFadden et al. (2015b)). The Gatún Formation represents a coastal to marginally marine sandstone, siltstone, claystone, tuff and conglomerate environment. Basalt intrudes older formations in the Lake Gatún area, but is not known to penetrate the Gatún Formation

Maps, Cross-Sections & Pictures:

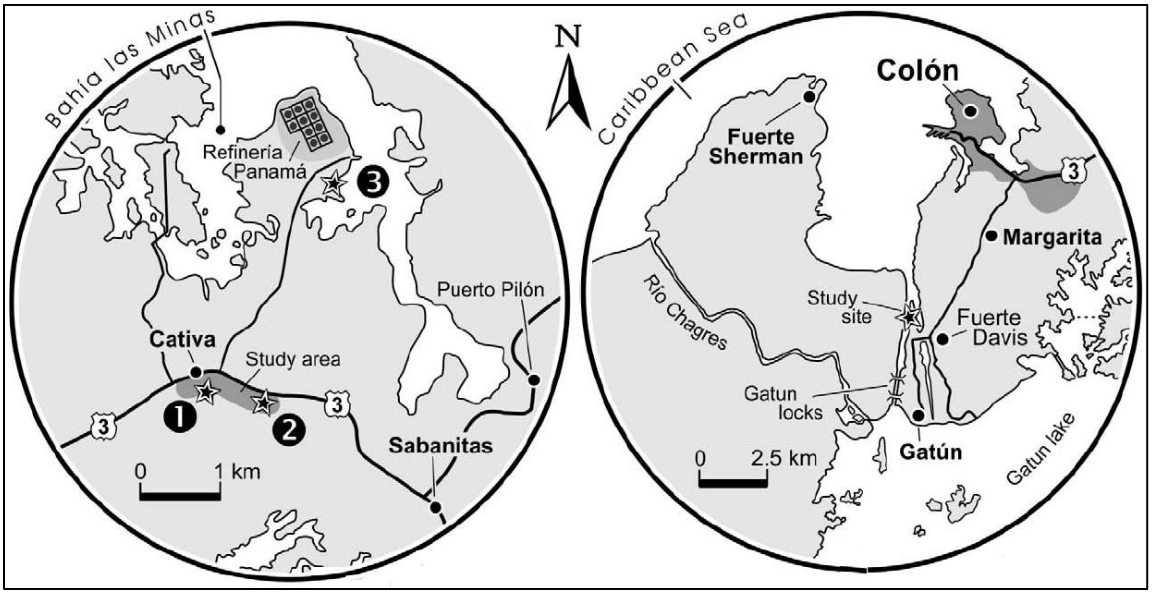


Figure 094. Geographic map of Landau et al. (2012a)'s mollusks collecting area of Cativa-Sabanita area (Left), Panama. 1) Cativa-Las Lomas 09°21'20.74"N, 79°50'20.69"W; 2) Cativa-Sabanitas 09°21'36.87"N, 79°49'52.65"W; 3) Refineria Panama 09°22'57.17"N, 79°49'16.42"W and the one of Gatún area (right) 09°17'40.40"N 79°55'07.66"W.

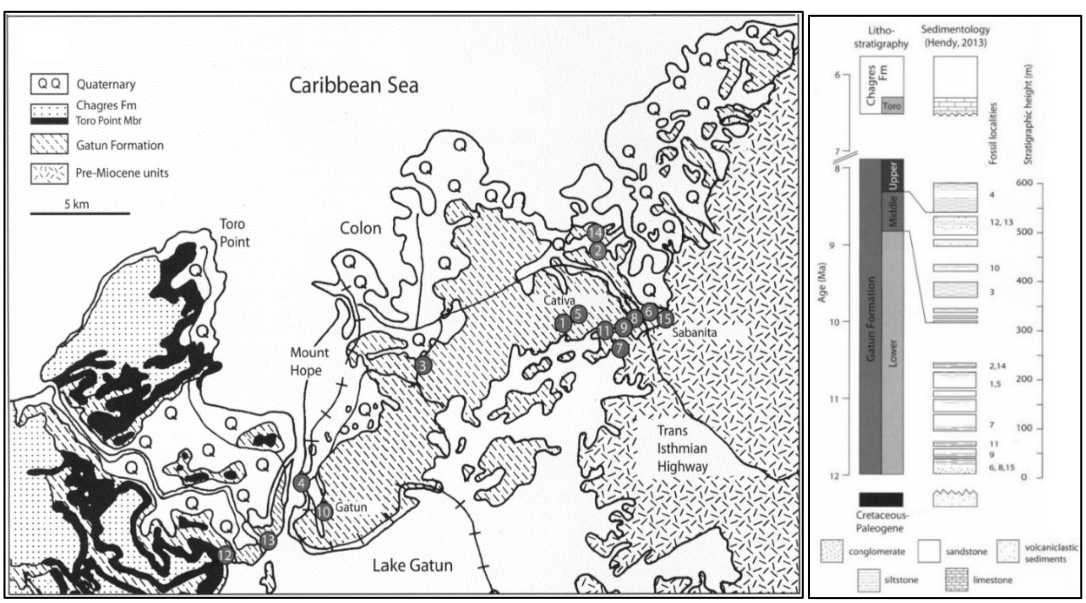


Figure 095. Geological map and stratigraphic section showing the 15 fossil shark teeth localities where Pimiento et al. (2013a) (also partly in Pimiento C. (2010)) collected 800 specimens from the Gatún Formation : **1)** 9°21'15.66"N, 79°50'11.34"W; **2)** Isla Payardi: 9°22'57.18"N, 79°49'16.50"W; **3)** Cuatro Altos: 9°20'7.08"N, 79°52'58.80"; **4)** Banco EE: 9°17'59.11"N, 79°55'5.36"W; **5)** San Judas: 9°2115.66"N, 79°5011.3274"W; **6)** Sand Dollar Hill: 9°21'2.628"N, 79°48'35.532"W; **7)** Alborada: 9°20'27.024"N, 79°49'0.804"W; **8)** Texaco: 9°20'58.8474"N, 79°48'47.304"W; **9)** I.D.A.A.N.: 9°20'35.5194"N, 79°48'45"W; **10)** Third Set of Locks: 9°16'46.92"N, 79°54'48.24"W; **11)** Highway Extension 9°20'37.5"N, 79°49'0.99"W; **12)** Gatún Dam: 9°15'46.08"N, 79°56'26.16"W; **13)** Gatún Dam: 9°15'53.2794"N, 79°55"54.4794"W; **14)** Panama: 9°22'56.64"N, 79°49'16.32"W; **15)** Sabanitas (Gillette, 1984) 9°20'59.99"N, 79°47'59.9994"W. Lower Gatún localities include 1, 2, 5, 6, 7, 8, 9, 11, 14, 15; middle Gatún localities include 3, 10, 12, 13; and the upper Gatún locality is 4.

Unit: GATUNCILLO FORMATION

Epoch/Age/Author: Upper Eocene to Oligocene - Barat (2013) and Barat et al. (2014)

Original Author and/or Origin of the Name:

- Thompson (1944) named the shale "Gatuncillo Shale" which consists of thick sequence of soft, finely bedded, uniformly fine, and even grained yellowish-gray or buff-colored shales and impure bentonite beds with occasional thin siltstone layers. Overlies basement complex. Older than Quebrancha limestone (new). Many forms of microfossils are related to those identified from the so-called Tranquilla shales of upper Eocene age, which formerly cropped out within Madden Reservoir Basin now inundated.
- Woodring & Thompson (1949) first published it as Gatuncillo Formation and states that at the type region, it consists chiefly of mudstone, siltstone, impure bentonite, and thin lenses of limestone. Unless it is duplicated by faults, which would be difficult to detect, its thickness is as much as 3,000 feet. Unconformably overlies basement complex (made up principally of altered volcanics); underlies Bohío Formation. Upper Eocene. Name Tranquilla shale was proposed for late Eocene strata in Madden Basin (Coryell et al. (1937b)). That name was inadequately defined, and specified type locality is now flooded by Madden Lake. The "Tranquilla Shale" is now included within the Gatuncillo Formation.

Relevant documents discussing the Unit:

- Coryell et al. (1937b); Cooke (1948); Cole (1953); Wilson et al. (1957);
- Woodring (1957). Middle and upper Eocene.
- Woodring (1959)
- Woodring (1960). Mudstone and siltstone are the prevailing lithologic types, but the formation includes sandstone, conglomerate, and limestone. The Gatuncillo is widely distributed in the eastern part of the Canal Zone and in Panama east of the Zone. The fossils include foraminifera, corals, mollusks, and echinoids: *Bulimina jacksonensis*, *Hantkenina alabamensis*, *Yaberinella jamaicensis*, *Fabiania cubensis*, *Helicostegina soldadensis*, *Lepidocyclina pustulosa*, *L. chaperi*, *Asterocyclina georgiana*, *Velates cf. perversus*, *Ectinochilus cf. gaudichaudi*, *Corbis cf. jamaicensis*, *Peronella acunai*, and *Eupatagus clevei*. According to these fossils, middle and late Eocene are represented.
- Woodring (1964, 1973, 1982); Graham (1984); Graham et al. (1985); Budd et al. (1992); Tripati & Zachos (2002); Montes et al. (2010); Cadena et al. (2012); Ramirez (2013); Barat et al. 2014; Ramirez et al. (2016); Erdei et al. (2018); Redwood (2019);

Synonymy: Gatuncillo Shale, Tranquilla Shale, Río Duque Shales.

Location of the type section / Stratotype / Reference Section / Other localities:

- The type region is the Quebrancha syncline.
- Erdei et al. (2018)'s cycad locality is 1.5 km South of Buena Vista, on the NE side of the Madden-Colón road (Transisthmica), and 46 km SE of Colón (9°16′4.80″N, 79°41′15.83″W). This section has now been destroyed through continued quarrying of rock for construction fill, but previously exposed some 20 m of mudstone and carbonaceous sandstone (Figure 098).

Lithology: Sedimentation in the Panama Canal Basin started with Upper Eocene to Oligocene coarse detrital sediments with limestones and volcaniclastic rocks of the Gatuncillo Formation, followed by Oligocene subaerial volcanic and volcaniclastic rocks of the Bas Obispo, Bohío and Las Cascadas Formations (Redwood (2019)). The Gatuncillo Formation consists mainly of a 150-800m sequence of mudstones and siltstones that extends across the eastern part of the Chagres River valley and unconformably overlies a Cretaceous basement (Woodring (1957)). In the Lago Alahuela area (Figure 097), limestones are more extensive within the formation, and are largely algal or algal-foraminiferal in composition.

The formation outcrops around Lake Alahuela north of Panama City. The Río Gatún fault terminates the exposure to the north, and the Azota fault defines portions of its western limits. A few isolated outcrops occur to the west along Gatún Lake and at the north end of Culebra Reach. Elsewhere the formation has been identified in cores to the south as far as Gold Hill and north of Gamboa. In addition, it has been recognized eastward into the Bayano River Basin and westward as far as the Costa Rica-Panama border. There are also massive outcrops in the southern part of the Azuero Peninsula (Graham et al. (1985)).

The Gatuncillo sediments consist of mudstones, siltstones, quartz sandstone, impure bentonite, and coralline and foraminiferal limestone (Figure 096; Figure 100). Interbedded are lenses of lignite ranging from a few centimeters to 1-2 m in thickness. Locally there are overlying deposits of marine limestone. The sequence is typical of nearshore deposition in tropical environments, since lignites presently form under such conditions and those in the Gatuncillo sediments contain *Rhizophora* pollen. The tropical temperatures seasonally varied by 6°–8°C, and mean annual surface temperatures were >26°C. These temperatures reflect shallow water conditions (middle-outer shelf), probably in the intermediate photic zone (Tripati & Zachos (2002)). The corals fringing the volcanic islands that occupied the region of present-day central Panama during the Eocene and contributing to the coralline component of the Gatuncillo Formation, further reflect tropical depositional environments. Surrounding most of the Gatuncillo Formation to the east, north, and west are extensive areas mapped as pre-Cenozoic. These include altered basaltic and andesitic lavas and tuff, and other dioritic and dacitic intrusives (Graham et al. (1985)).

From the Gatuncillo Formation Woodring (1957 to 1982) reports a mollusk fauna most similar to those elsewhere of middle to late Eocene age. Cole (1952) studied the larger foraminifera of the Gatuncillo Formation. He reported 21 species, 18 of which are recorded elsewhere in the late Eocene. The remaining three occur in the middle Eocene, and two of these (*Yaberinella jamaicensis* and *Fabiania cubensis*) are known only from the middle Eocene. Consequently, Cole (1952) refers the Gatuncillo Formation to the middle(?) and late Eocene (Graham et al. (1985)).

Samples for pollen and spore analysis were obtained from a roadcut section near Alcalde Diaz just off the Boyd-Roosevelt highway (9°7'N, 79°32'W). The concurrence of the mollusk and foraminifera data, in the absence of any conflicting stratigraphic information, indicates the palynomorphs recovered from the Gatuncillo Formation represent remnants of a middle to late Eocene plant community growing in the region approximately 40 Ma (Graham et al. (1985)).

Thickness: 150-800m

Macro Fossils: Cadena et al. (2012) describe turtles. Corals (at least 43 species of 25 genera) (Budd et al. (1992)); Cycads (*Zamia*) (Erdei et al. (2018)). Compression fossils of various plants were collected at Erdei et al. (2018)'s locality from a steeply dipping carbonaceous sandstone bed, along with infrequent molds of bivalves and gastropods of nearshore affinity. These overlay a thick succession of mudstone, with sparse mollusks, including nuculanid and corbulid bivalves, turrid gastropods, Dentalium (Scaphopoda), and Aturia (Cephalopoda). This fauna, together with the fine and massive siliciclastic sediments indicate an offshore (mid-shelf to outer shelf) setting for the overlying mudstone facies. Budd et al. (1992) states that less commonly associated with the limestones of the Gatuncillo Formation are echinoid- or coral-rich beds. Cooke (1948) describes these echinoids while Woodring (1957) provides a spectacular sample (Figure 099).

Overlying Unit: Bohio Formation

Underlying Unit: Cretaceous formation - According to Woodring and Thompson (1949) the formation unconformably overlies the San Blas Complex basement.

Maps, Cross-Sections & Pictures:

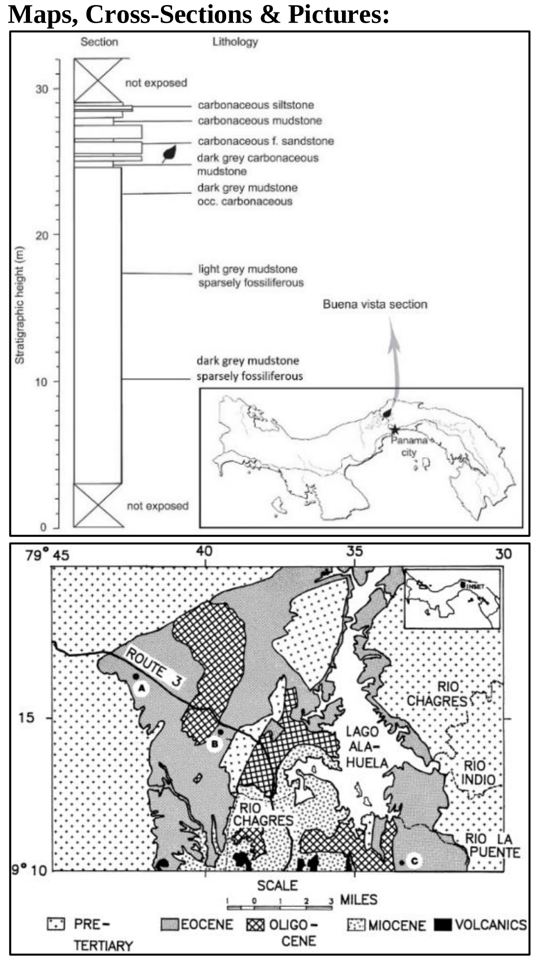


Figure 096 (top): Erdei *et al.* (2018)'s geological section of the Gatuncillo Formation. The leaf symbol indicates layers yielding plant fossils including Cycads (*Zamia nelliaea*).

Figure 097 (bottom). Map of Budd et al. (1992)'s coral collecting area. The three towns indicated are: **A-** Buena Vista; **B-** Gatuncillo; **C-** Calzada Larga.

Figure 098. Outcrop located at abandoned quarry on the new highway to Colón. Gray, slightly calcareous siltstones underlying foraminiferal limestones of the Gatuncillo Formation. Ramirez (2013).

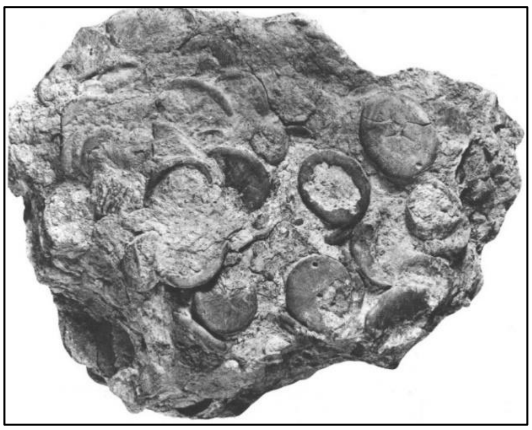


Figure 099 (top): Echinoids (*Cubanaster aruñai*) from the Gatuncillo Formation. Woodring (1957)
Figure 100 (bottom): Quarry showing a limestone outcrop of the Gatuncillo Formation near the Panama Canal, Upper Eocene. Barat (2013).

Unit: GROUND CREEK MEMBER (now part of the Isla Colon Formation; Klaus et al. (2012))

Epoch/Age/Author: Pleistocene **-** Coates et al. (2005)
Original Author and/or Origin of the Name: Coates et al. (2005) states that it is an informal field name and that the process is on-going to have the name formalized. Klaus et al. (2012) uses the term in a formal maner.
Relevant documents discussing the Unit: Klaus et al. (2012)
Synonymy: N/A
Location of the type section / Stratotype / Reference Section / Other localities:
Lithology: On Colon Island, interbedded with and overlapping onto the La Gruta Member are back reef/reef flank deposits, dominantly shelly coral bearing bioclastic carbonate and volcaniclastic sandstone and siltstone. They are typically exposed in several stream courses in the northwest of Colon Island in a region known as Ground Creek (Figure 042). Near Ground Creek, the unit has yielded 90 genera of bivalves and gastropods in siliciclastic mudstone and fine sandstone, where they are intercalated with thin carbonate sand containing poritid thickets and other reef patches with platy *Caulastraea portoricensis, Porites baracoaensis, Agaricia, ?Cladocora*, small domed *?Favia, Manicina (Teleiophyllia)* and *serpulids*. Also occasionally interbedded are horizons of reworked large coral heads (Coates et al. (2005)).

The Ground Creek Member also crops out on Bastimentos Island (Figure 042), where it is interbedded with and overlying the La Gruta Member on Wild Cane Key, and it may also crop out around the Valiente Formation outlier at the northern end of Long Beach and overlie the reefs at Fish Hole (Coates et al. (2005)).
Thickness: Unknown
Macro Fossils: See "Lithology" above, and description of "Isla Colon Formation" for fossil pictures.
Overlying Unit: Urraca Formation
Underlying Unit: Old Bank Formation
Remarks: See more description under "La Gruta Member" and "Isla Colon Formation".

Unit: HILL POINT MEMBER (of Urraca Formation)
Epoch/Age/Author: Mid-Pleistocene (Calabrian; ~1 Ma) **-** Klaus et al. (2012)
Original Author and/or Origin of the Name: See Urraca Formation
Relevant documents discussing the Unit: See Urraca Formation

Location of the type section / Stratotype / Reference Section / Other localities: See Urraca Formation
Lithology: The Hill Point Member is the middle Member of the Urraca Formation and occurs along the southeast coast of Colon Island as well as along the north coast as a series of pinnacle-barrier reefs (Figure 042). These shallow reef units correlate with deeper fore-reef deposits found on Swan Cay north of Colon Island.
Overlying Unit: Swan Cay Member of the Urraca Formation
Underlying Unit: Mimitimbi Member of the Urraca Formation

Unit: ISLA COLON FORMATION (part of the Bocas del Toro Group)
Epoch/Age/Author: Pleistocene (Gelasian – Calabrian; ~2.2 to 1.4 Ma) **-** Klaus et al. (2012)
Original Author and/or Origin of the Name: Coates et al. (2005)
Relevant documents discussing the Unit: Budd et al. (1999); Klaus et al. (2012); Budd et al. (2019);
Location of the type section / Stratotype / Reference Section / Other localities: Bocas del Toro Basin (Colon & Bastimentos Islands) (Figure 042)
Lithology: The Isla Colon Formation includes two members: the La Gruta Member and the Ground Creek Member. They are contemporaneous and represent windward and leeward facies of the same formation. Both members outcrop on Bastimentos and Colon Islands (Figure 042). The La Gruta Member is a more carbonate-rich unit composed of abundant coral, red algae, and skeletal sand (Figure 101). The carbonate is heavily leached, densely cemented, and often highly fractured. The Ground Creek Member in the northwest part of Colon leeward of the La Gruta reef tract (Figure 042) has a siliciclastic matrix containing greater amounts of mud and very fine volcanic sand than the La Gruta Member, resulting in less cementation and excellent preservation of corals (Figure 101) and mollusks. Based on strontium isotopes and magnetostratigraphy, the Isla Colon Formation ranges in age from ~2.2 to 1.4 Ma. Klaus et al. (2012)
Macro Fossils: The most comment coral specimens found in the Ground Creek Member are *Acropora cervicornis*, *Undaria agaricities*, *Thysanus navicula* and *Porites porites*, while those in the La Gruta Member are *Solenastrea bournoni* and *Acropora palmata* (Figure 101). Klaus et al. (2012)
Overlying Unit: Mimitimbi Member of the Urraca Formation
Underlying Unit: Old Bank Formation
Remarks: See a more detailed description under "La Gruta Member" and the "Ground Creek Member".
Maps, Cross-Sections & Pictures:

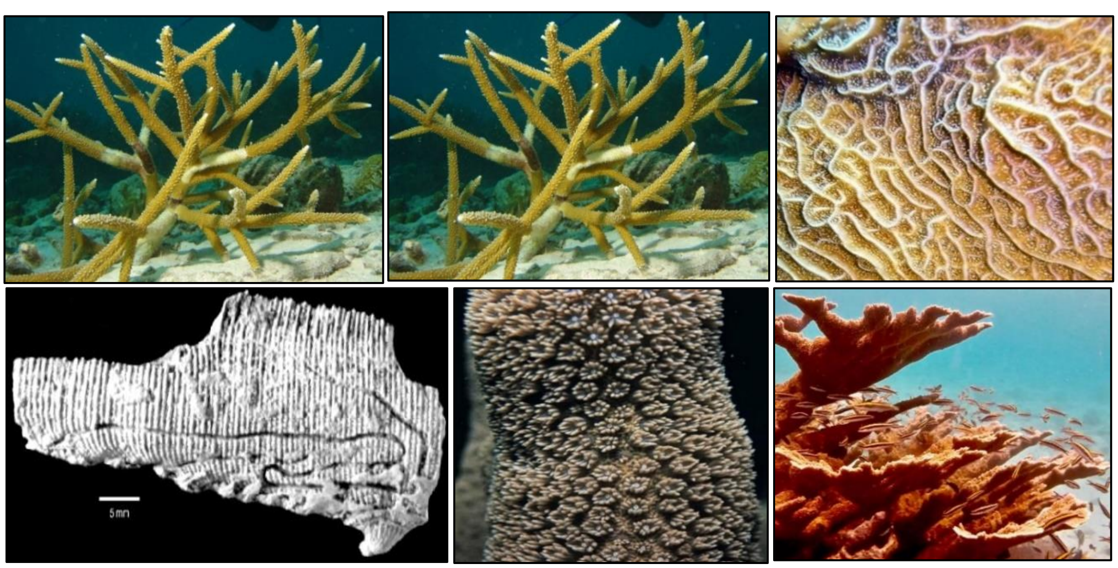


Figure 101. Modern day equivalents of the corals found in La Gruta and Ground Creek Members of Isla Colon Formation. Information from Klaus et al. (2012). **Top (left to right) -** *Acropora cervicornis* (Ground Creek Mbr), *Solenastrea bournoni* (La Gruta Mbr), *Undaria agaricities* (Ground Creek Mbr). **Bottom (left to right) -** *Thysanus navicula* (Ground Creek Mbr), *Porites porites* (Gr. Creek Mbr), *Acropora palmata* (La

Gruta Mbr). www.wikipedia.org, www.coralsoftheworld.org, https://edis.ifas.ufl.edu/fa210, https://nmita.rsmas.miami.edu

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Unit: *ISLA SOLARTE FORMATION
Epoch/Age/Author: Upper Pliocene (Piacenzian, 3.6 - 2.6 Ma) - Ingram (1939)
Original Author and/or Origin of the Name: The name would come from Isla Solarte just south of Isla Bastimentos (Figure 42) in Bocas del Toro area. The name was informally used by Ingram (1939) and is now included within the Old Bank Formation.
Relevant documents discussing the Unit: http://fossilworks.org/bridge.pl?a=collectionSearch&collection_no=179615
Synonymy: Old Bank Formation
Location of the type section / Stratotype / Reference Section / Other localities: Bocas del Toro area. As per above link, located at approximate coordinates 9.3° N, 82.2° W
Lithology: See Old Bank Formation
Thickness: See Old Bank Formation
Macro Fossils: See Old Bank Formation
Overlying Unit: See Old Bank Formation
Underlying Unit: See Old Bank Formation
Remarks: North shore of Nancy's Cay (Isla Solarte) (Pliocene of Panama)
Maps, Cross-Sections & Pictures: See Old Bank Formation

Unit: *LA BOCA FORMATION (see newer definition of this name below)
Epoch/Age/Author: Lower Miocene (Aquitanian - 23.07 to 20.62 Ma) - Kirby *et al.* (2008)
Original Author and/or Origin of the Name:

- Thompson (1943). The name La Boca Formation applied to group of marine deposited sediments stratigraphically overlying Culebra Formation, as originally defined. Composed largely of medium-hard silty or sandy dark gray tuffaceous shales, with occasional massive cross-bedded sandstone members present in lower parts. It may represent essentially the marine equivalent of the Cucaracha Formation. The name is derived from the town of La Boca, near the entrance of Balboa Harbor.
- Woodring & Thompson (1949). Strata assigned to La Boca were formerly referred to Culebra Formation, Emperador limestone Member of Culebra Formation, and Caimito Formation. Maximum thickness 600 feet.
- Woodring (1955). Rank reduced to Member status in the lower part of the Panamá Formation. Consists principally of silty or sandy tuffaceous mudstone, flaggy tuffaceous sandstone, calcareous tuffaceous sandstone, conglomerate, and coralliferous limestone. Agglomerate and tuff, presumed to represent tongues from Pedro Miguel agglomerate Member and main part of formation, respectively, are other constituents. Overlies Cucaracha Formation or interfingers with upper part of formation. Nevertheless, if La Boca is correctly identified, it also overlaps Cucaracha and Culebra Formations and rests directly on Bas Obispo Formation. The Miraflores Locks area was re-designated the type region.
- Wilson et al. (1957); Woodring (1957);
- Woodring (1960). The La Boca has been identified along and near the Canal from Gaillard [Culebra] Cut to the Pacific Ocean. The member contains foraminifera, corals, and mollusks, which are considered late Oligocene by some paleontologists and early Miocene by others. The fossils include *Siphogenerina transverse*, *Lepidocyclina miraflorensis*, *L. parvula*, *Miogypsina panamensis*, *Acila cf. isthmica*, and *Aequipecten cf. gibbus*.
- Kirby et al. (2008) re-interpreted what was called the ‘‘La Boca Formation’’ (which included the Emperador Limestone) by earlier authors, as being the lower part/Member of the Culebra Formation (Figure 031, Right; Figure 102) (see the newer definition of “La Boca Formation” below).

Relevant documents discussing the Unit: Graham et al. (1985); Graham (1989); Jud et al. (2016); Buchs et al. (2019);
Synonymy: Lower Member of the Culebra Formation; La Boca Marine Member (of Panamá Formation). Not to confuse with the other, still valid, “La Boca Formation” described below.
Location of the type section / Stratotype / Reference Section / Other localities: The type region is Miraflores Locks area, Culebra Cut, Canal Zone.
Lithology: See “CULEBRA FORMATION” and “LA BOCA FORMATION”. Graham et al. (1985) and Graham (1989), who state (erroneously) that the La Boca Formation at the centre of the Culebra Cut is younger than the

Culebra and Cucaracha Formations, describe it as follows: "*The La Boca outcrops along both sides of the Panama Canal from the Pacific entrance to the Las Cascadas Reach. The sediments were deposited in an estuarine environment and include an alternating sequence of mudstones, siltstones, sandstones, lignitic shales, tuffs (waterlain volcanic ash), and limestones typical of that environmental setting. The presence of the coralliferous Emperador limestone Member in the lower part of the formation and Rhizophora-containing lignitic shales indicate deposition in warm temperate to tropical, shallow seas and in adjacent coastal, brackish-water habitats*".
Thickness: Maximum thickness 600 feet (183 m). Woodring & Thompson (1949)
Macro Fossils: The flora is estuarine in aspect and reflects low-lying volcanic islands fringed seaward by mangroves, with freshwater fern and palm swamp marshes in the lowlands and versions of the tropical wet, tropical moist, and premontane forests on the adjacent slopes. Elevations of 1,200 to 1,500 m would accommodate all taxa present in the La Boca and other fossil floras (Graham (1989))
Overlying Unit: N/A
Underlying Unit: Cucaracha Formation
Remarks: La Boca Formation (now the lower Member of the Culebra Formation) is 23.07 to 20.62 Ma while the Middle (Emperador) to Upper Members of the Culebra are 19.83 to 19.12 Ma
Maps, Cross-Sections & Pictures:

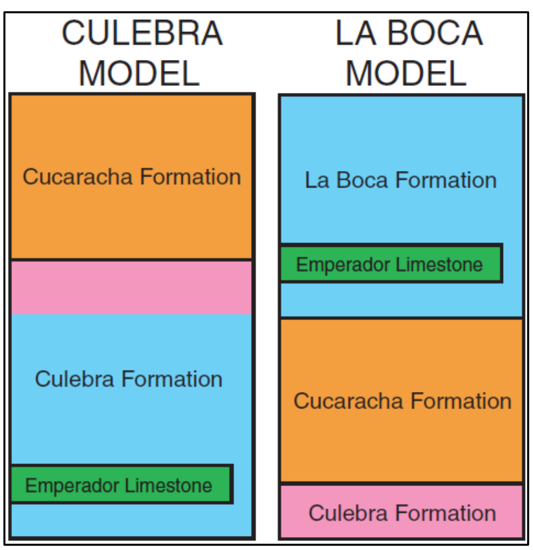

Figure 102. The two alternative stratigraphic models for the formations exposed along the Culebra Cut portion of the Panama Canal; the Culebra model (left) and the La Boca model (right). Equal color between the two models refer to the same stratigraphic unit. Kirby et al. (2008) confirm that the Culebra Model is the valid one and interpret the rock interval known as La Boca Formation in the Culebra Cut to be the lower part of the Culebra Formation. However, he does not go as far as naming this Lower Member the "La Boca Member" of the Culebra Formation.

Unit: LA BOCA FORMATION (see older definition of this name above)
Epoch/Age/Author: Lower Miocene (Burdigalian - ~18Ma) - Woodring (1955); Buchs et al. (2019)
Original Author and/or Origin of the Name: Woodring (1955)
Relevant documents discussing the Unit: Stewart et al. (1980); Smith (1991); Farris et al. (2017); Buchs et al. (2019);
Synonymy: Not to confuse with the other, now obsolete, "La Boca Formation" described above
Location of the type section / Stratotype / Reference Section / Other localities: Near the mouth of the Panama Canal (Pacific locks area)
Lithology: The La Boca Formation has been interpreted by Kirby et al. (2008) to be the lower part/Member of the Culebra Formation, which (Figure 031, Right; Figure 102) has an age of approximately 19±20.5 Ma (see "*LA BOCA FORMATION"). However, what has been previously mapped (Stewart et al. (1980)) as La Boca Formation near the mouth of the Panama Canal is lithologically different than the rocks Kirby et al. (2008) reassigned. The Culebra Formation in the central part of the Culebra Cut is composed of dirty grey marine sandstones with interbeds of limestone, whereas near the Pacific mouth of the Panama Canal, dacitic plugs intrude into bedded tuffs and volcani-clastic sedimentary rocks. Therefore, the stratigraphic tie from rocks in the central Culebra Cut to the mouth of the Canal is not particularly strong. Buchs et al. (2019). The Cucaracha Formation in the central part of the Culebra Cut likely extends laterally to the south (Pacific locks area) to layered sequences of tuffaceous sandstone with planar bedding to conglomerate. Marine shells and larger benthic foraminifera locally occur in the coarser sandstone and conglomerate. Significantly, a unique 17.90 ± 0.08 Ar-Ar Ma age for a brown intermediate (?) tuff from this unit indicates at least partly synchronous deposition with the Cucaracha Formation. Therefore, this unit is interpreted to represent the La Boca Formation, as originally recognised by canal geologists

(Woodring (1955); Stewart et al. (1980)) based on cores from this area. Buchs et al. (2019)
Thickness: Unknown
Macro Fossils: Marine shells (Smith (1991)) and larger benthic foraminifera locally occur in the coarser sandstone and conglomerate.
Overlying Unit: Pedro Miguel Formation. Also, the upper part of the Cucaracha Formation in the central part of the Culebra Cut is likely a lateral extension (Figure 030).
Underlying Unit: Cucaracha Formation
Remarks: Together, the La Boca and Cucaracha Formations record sedimentation along a palaeo-shoreline during the Early Miocene (ca. 18 Ma), under the influence of continued distal volcanic activity (Buchs et al. (2019)).

Unit: LA CHANCHA MEMBER (of Burica Formation)
Epoch/Age/Author: Lower/Middle Pleistocene (Gelasian) **-** Coates et al. (1992)
Original Author and/or Origin of the Name: The name is most likely related/correletable to the marine sedimentary rocks of the "Punta La Chancha Formation" on the Osa Peninsula (Lew (1983)) which are equivalent in age and lithology to the Charco Azul Group of the Burica Peninsula
Relevant documents discussing the Unit: Coates et al. (1992); Morell et al. (2011)
Synonymy: Chanca (a misspelling in Morell et al. (2011))
Location of the type section / Stratotype / Reference Section / Other localities:
Lithology: The La Chancha Member is a distinctive coarse facies interpreted to represent canyon fill within the trench slope on which the Burica turbidites were deposited (Coates et al. (1992); Buchs (2008); Buchs et al. (2009)).
Remarks: See Burica Formation, Charco Azul Group and also Figure 104

Unit: LA GRUTA MEMBER (now part of Isla Colon Formation; Klaus et al. (2012))
Epoch/Age/Author: Pleistocene **-** Coates et al. (2005)
Original Author and/or Origin of the Name: Coates et al. (2005) states that it is an informal field name and that the process is on-going to have the name formalized. Klaus et al. (2012) uses the term in a formal manner.
Relevant documents discussing the Unit: Coates et al. (2005); Klaus et al. (2012)
Location of the type section / Stratotype / Reference Section / Other localities: On Colon Island (Figure 042), an extensive recrystallized reef and reef rubble deposit is exposed in the north central part of the island. Eastward from Hill Point it forms distinctive ridge running parallel to the north coast towards Mimitimimbi Creek. The limestone extends southward as far as La Gruta, a locally famous bat cave (Coates et al. (2005)).

On Bastimentos Island (Figure 042), similar reef deposits appear to sit directly on the Miocene basalt of the Valiente Formation where they are well exposed on Wild Cane Key and along the coast for 2 kms to the east. A particularly well preserved example of the La Gruta reef, packed with large and diverse coral colonies is exposed at the base of the cliffs in three small bays at Fish Hole, at the southern end of Long Beach (Coates et al. (2005)).
Lithology: On Colon Island, around La Gruta, the limestone is a reef deposit with numerous large coral colonies but the limestone grades into fore-reef rubble northeastwards toward the mouth of Mimitimimbi Creek where it is well exposed on the coast. Both the reef and fore-reef deposits are heavily fractured to produce a rubbly rock unit when exposed. Earthquakes and uplift are likely responsible for this pervasive fracturing (Coates et al. (2005)). On Bastimentos Island (Figure 042), the reef limestone is extensively recrystallized but many coral colonies can be observed (Coates et al. (2005)).
Thickness: Not mentioned
Macro Fossils: On Colon Island (Figure 042), twenty species of corals have been identified from the limestone near Hill Point, the most abundant being *Caulastraea portoricensis, Stylophora granulata, Agaricia (= Undaria agaricites), Colpophyllia natans, Montastraea faveolata*, and *Mycetophyllia danaana*. Exposure of similar limestone also occurs immediately to the North of Paunch, on the east coast of Colon Island, and on Carenero Cay (Figure 042). At Paunch, an entirely extant fauna of corals includes *Colpophyllia natans, Diploria strigosa, Meandrina meandrites, Montastraea faveolata*, and *Agaricia (Undaria) agaricites* (Coates et al. (2005)).

On Bastimentos Island (Figure 042), the most abundant species are *Dichocoenia stokesi, Manicina (Teleiophyllia) geisteri, Montastraea faveolata, M. canalis, Placocyathus variabilis, Porites waylandi, P. macdonaldi, Antillia gregorii, Goniopora imperatoris, Agaricia (Undaria) crassa*, and *Stylophora granulata*. Because >50% of this fauna is extinct, the La

Gruta Member on Bastimentos appears to be older than that on Colon Island (Coates et al. (2005)).
Overlying Unit: Urraca Formation
Underlying Unit: Old Bank Formation
Remarks: See more description under "Ground Creek Member" and "Isla Colon Formation".

Unit: LA PEÑITA FORMATION (part of the Charco Azul Group)
Epoch/Age/Author: Pliocene (Zanclean) (Figure 046) **-** Cortés et al. (2019)
Original Author and/or Origin of the Name: Coryell et al. (1942) believe it to correlate with the Charco Azul Formation. Corrigan et al. (1990), originally named the "Charco Azul Group" as the "Charco Azul Formation" as well as its three Members "La Peñita", "Burica" and "Armuelles". It is only later that it was renamed as a Group, while each of its members were given the designation of "Formation".
Relevant documents discussing the Unit: Olsson (1942a); Obando (1986); Coates et al. (1992); Kolarsky (1992); Kolarsky et al. (1995a, 1995b); Schlegel (1996); O'Dea et al. (2007); Morell et al. (2011); Cortés et al. (2019);
Synonymy: "Peñita Member"; "Peñitas Formation"; Peñitas Formation"; See "Charco Azul Group" for some additional comments on synonymy.
Location of the type section / Stratotype / Reference Section / Other localities: The Stratotype of the "La Peñita" Formation is located along the La Peñita river (8 ° 14.283'N, 82 ° 57.852'W) on the Burica Peninsula (Chiriqui Province). On that same Peninsula, the formation also outcrops along La Peña river (8º 12.794'N, 82º 56.820'W) (Figure 046). The formation can also be found at least at one location in the Osa Peninsula in Costa Rica. Coates et al. (1992)
Lithology: It is mainly composed of limolite with sutures of conglomerate (Olsson (1942a)). Clayey, bluegreen siltstone and litharenite consistently rich in benthic and planktic foraminifers, deposited in a forearc slope environment. This basal formation is coarse with locally channelled conglomerates, some of which form a distinctive suite defined as the La Vaca Member. These coarse deposits record a detrital paralic and fan-delta depositional environment at the base of the Charco Azul Group. Coates et al. (1992)
Thickness: 1200m
Macro Fossils: Locally rich in mollusks and other fossils that suggest deposition occurred in a shallow water coastal environment. For example, cirripeds, typically living in intertidal and subtidal conditions, are common, and numerous spines of the echinoderm *Eucidaris* can be found; these usually live in areas exposed to strong waves (Figure 103). Filtering mollusks such as *Arca* and *Chione* dominate but predatory gastropods such as *Olivella*, *Conus* and *Cancellaria* are also common. The distribution of these mollusks today also suggest that the La Peñita Formation was deposited in a shallow coastal sea. Coates et al. (1992)
Overlying Unit: Burica Formation (Figure 046), also part of the Charco Azul Group
Underlying Unit: Cretaceous Seamount Complex
Maps, Cross-Sections & Pictures:

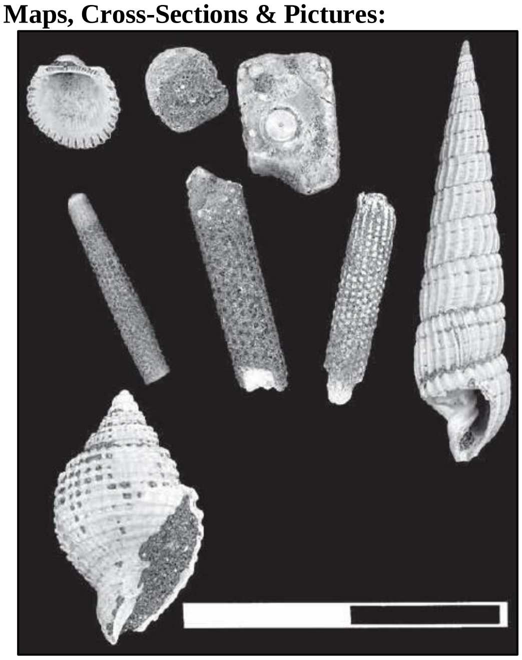

Figure 103. Representative fossils of the La Peñita Formation. Spines and plates of the marine/inter-tidal echinoderm *Eucidaris* sp., known as the sea urchin "Pencil point" (top left). The carnivorous gastropod *Terebra* sp. (family Terebridae) (top right). The *Anadara* bivalve (family Arcidae) (bottom left). The predator gastropod *Cancellaria* (family Cancellariidae) (bottom right). Scale = 2cm. O'Dea et al. (2007).

Unit: LA VACA MEMBER (of the La Peñita Formation)
Epoch/Age/Author: Pliocene **-** Coates et al. (1992)
Original Author and/or Origin of the Name: Incidental mention in Terry (1956) as "La Vaca Formation".
Relevant documents discussing the Unit:

- Woodring (1960). A «tentative » undefined formation name of unknown origin for strata, referred to middle Miocene on unspecified grounds, in the Burica Peninsula, Chiriqui Province.
- Keroher et al. (1966); An undefined formation name. Miocene(?).
- Coates et al. (1992) rename it "La Vaca Member" of the La Peñita Formation.
- Morell et al. (2011)

Synonymy: La Vaca Formation.
Lithology: The La Peñita Formation (basal formation of the Charco Azul Group) is coarse with locally channelled conglomerates, some of which form a distinctive suite defined as the La Vaca Member by Coates et al. (1992). These coarse deposits record a detrital paralic and fan-delta depositional environment at the base of the Charco Azul Group
Remarks: On Burica Peninsula, Chiriqui Province.
Maps, Cross-Sections & Pictures:

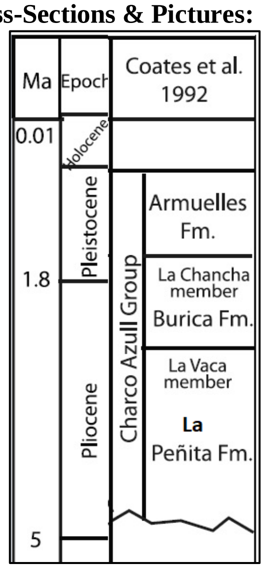

Figure 104. Stratigraphic column of the Charco Azul Group showing the location of the "La Vaca" Member within the "La Peñita" Formation according to Coates et al. (1992). Modified from Morell et al. (2011).

Unit: *LARA GROUP
Epoch/Age/Author: At least Upper Miocene (Tortonian)
Remarks: Under https://www.mindat.org/paleo_strat.php?id=22296 the Tuira Formation is listed as belonging to the "Lara Group", however no information could be found about this group in the literature. Other formations included in this Group are unknown.

Unit: LAS CASCADAS FORMATION
Epoch/Age/Author: Early Miocene (Aquitanian, 21.05 Ma to >20.93 Ma) - Buchs et al. (2019)
Original Author and/or Origin of the Name: MacDonald (1913a, 1913b).
Relevant documents discussing the Unit:

- Woodring & Thompson (1949). Las Cascadas agglomerate, Bas Obispo Formation, and Bohío Formation, all tentatively considered early Oligocene in age, are the oldest formations along the Canal. Las Cascadas agglomerate and pyroclastic Bas Obispo Formation are interpreted to represent accumulation of volcanic products at periphery of a volcanic pile. Unconformably underlies Culebra Formation.
- Jones S.M. (1950);
- Woodring (1957). Overlies Bas Obispo Formation. Las Cascadas agglomerate and the Bas Obispo probably would ordinarily be combined as one formation; however, they differ in induration. Matrix of Las Cascadas consists of soft fine-grained altered tuff and bentonitic clay. Thickness not determined. According to plate 1, near Gamboa agglomerate rests on Bohío Formation, Gatuncillo Formation, or basement complex; confirmation of this overlap is needed; in eastern part of Gatún Lake area, appears to grade into Caimito Formation. No fossils present; doubtfully referred to Oligocene because of inferred relations to Bohío and Caimito Formations.
- Woodring (1960); Woodring (1982); Kirby et al. (2008); Montes et al. (2010); Rincon (2011); Rincon et al. (2012a, 2012b, 2013); Head et al. (2012); Montes et al. (2012b); Hastings et al. (2013); Rincon et al. (2015a, 2015b); Wood et al. (2015); Bloch et al. (2016); Farris et al. (2017); Buchs et al. (2019);

Synonymy: Las Cascadas Agglomerate; Las Cascades
Location of the type section / Stratotype / Reference Section / Other localities: The type region is the Northern part of Culebra Cut, Canal Zone.
Lithology: The Las Cascadas Formation is composed of the oldest terrestrial deposits of central Panama, and probably registers the initial uplift of the Panamanian volcanic arc that was previously submerged (Figure 093). The oldest fossil-bearing formation in the Culebra Cut, the Las Cascadas Formation is composed of reddish

ropey andesitic lava flows (Figure 106, right; Figure 107), silicic ash and agglomeratic tuffs with cobbles of andesite and basalt set in a fine-grained tuffaceous matrix (Montes et al. (2012b)), which constitutes the main lithology associated with the vertebrate fossils. Many of the silicic tuffs have been weathered into yellow to red paleosols. Also present are distinctive black vitreous obsidian layers. In comparison to the Bas Obispo Formation, Las Cascadas Formation volcanic rocks are significantly more silicic, more highly welded and lack hydrous minerals (Farris et al. (2017)). The structural complexity of the area, as well as the limited and ephemeral outcrops along the canal, restrict the exposures of the Las Cascadas fossiliferous interval to the northern part of the Culebra Cut, where volcaniclastic sequences are more common and paleosols are well developed. The lower part of the Las Cascadas Formation is characterized by massive accumulations of volcanic rocks (mainly agglomerated breccias) and fluvial sediments. Conversely, the upper part of the Las Cascadas Formation is characterized by massive accumulations of volcanic blocks ranging from welded tuffaceus agglomerates to pyroclastic fall deposits (Figure 106, Left) and discrete intervals of fluvial sediments (Woodring (1982); Kirby et al. (2008)). The Las Cascadas Formation is overlain by the Culebra Formation and separated from it by a slightly angular unconformity (Montes et al. (2012b)). The overlaying volcaniclastic sequence is composed of the marine transgressive system of the Culebra Formation and the prograding sequence of the Cucaracha Formation (Kirby et al. (2008)).

In Buchs et al. (2019), the Las Cascadas Formation is characterised by an abundance of welded pyroclastic density currents (PDC) deposits, or ignimbrites, that are generally thick (locally > 10 m). The Las Cascadas ignimbrites are commonly interbedded with fallout fine tuff to coarse lapilli-tuff, with locally large cm-sized accretionary lapilli and intermediate-felsic lithics (Figure 108, left). These deposits are associated with red to white tuffaceous paleosols that often preserve an original pumiceous fabric or are mottled (Figure 108, right & Figure 109). The paleosols are locally interbedded with lenses of cross-stratified sandstone to breccia, with abundant clasts of dacites and occasionally amoeboid/juvenile andesite (?) clasts (Figure 109). Agglomerates were not observed, but rare possible occurrences of channelized lahar deposits are found. All of the preceding tuffaceous deposits are grouped here in the newly-defined Tuff Member of the Las Cascadas Formation (Figure 030). This unit corresponds to the original Las Cascadas Formation on the regional geological map and could extend laterally to the upper (tuffaceous) Member of the Caimito Formation in the Lake Gatún area.

Other volcanic deposits in the Las Cascadas Formation consist of flow-banded greenish dacite lavas that are restricted to the NE side of the central Culebra Cut (Figure 108, right), and rare brecciated dacite dykes in fault zones. These rocks are interbedded with, or crosscut, tuffs similar to those described above. The dacite lavas can be followed to the NE of the Canal in river exposures, where they are associated with dacitic-rhyolitic intrusions and correlate to a topographic high (Figure 029; Figure 030). These dacite-rich sequences are part of a newly-defined Dacite Member of the Las Cascadas Formation (Figure 030), which replaces some of the undifferentiated felsic igneous units on the original geological map (Buchs et al. (2019)).

Thickness: ~390m

Macro Fossils: Snake (Boa) specimens were recovered from a conglomeratic and tuffaceous interval located in the upper part of the formation, which crops out in the northern part of the Gaillard Cut (Head et al. (2012)). Crocodile specimens are also described in Hastings et al. (2013). A fossil monkey (*Panamacebus*) was discovered within the Lirio Norte Local Fauna of the Las Cascadas Formation and described in Bloch et al. (2016) (Figure 105). The Las Cascadas fossil assemblage represents the oldest fossil vertebrate fauna found in southern Central America. Mammals from the Las Cascadas Formation include the first immigrants from higher-latitude North American continental terrains that reached marginal tropical areas in the early Miocene (Rincon et al. (2012a, 2012b))

Overlying Unit: CulebraFormation

Underlying Unit: The Las Cascadas Formation sits directly above the Bas Obispo Formation, but is fault bounded (Figure 033)

Remarks: New Ar-Ar ages of a tuff (20.91 ± 0.06 Ma) and lava flow (21.05 ± 0.06 Ma) are consistent with a 20.93 ± 0.17 Ma U-Pb zircon age of a tuff in the upper part of Las Cascadas Formation. This indicates that this unit was quickly deposited in the Early Miocene (ca. 21 Ma). Although detailed stratigraphic relationships along the Canal are obscured by faults, new cores suggest that there is significant lateral variability within the Las Cascadas Formation. Overall, geochemical, lithofacies, geomorphological, and geochronological constraints from the Las Cascadas Formation support existence of an Early Miocene volcanic complex in the NE of the Culebra Cut, introduced in Buchs et al. (2019) as the "Las Cascadas Volcanic Complex" (Figure 029). Volcanic and volcaniclastic observations indicate that this complex is composed of subaerial stratovolcano(es) that were associated with explosive volcanism most likely during dome collapses to Plinian eruptions (Buchs et al. (2019)).

Maps, Cross-Sections & Pictures:

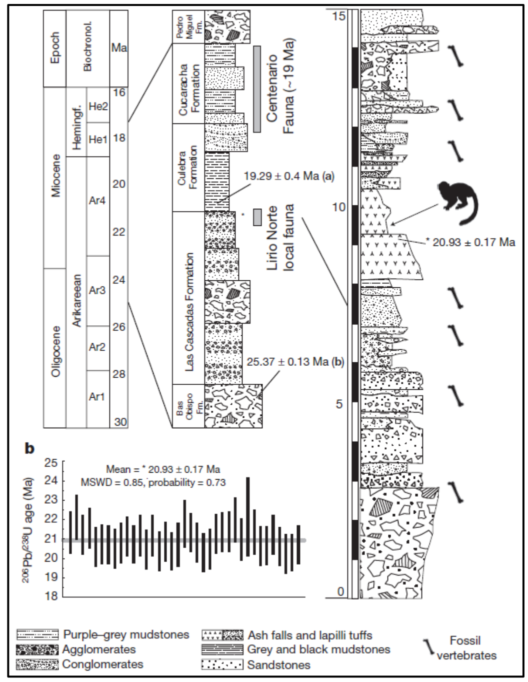

Figure 105. Stratigraphy of the primate-bearing locality in central Panama. Measured stratigraphic section (in metres) in the Las Cascadas Formation showing the positions of the dated rock sample (asterisk) and of the *Panamacebus* fossils as a silhouette of a monkey (right), correlated to a schematic stratigraphic position of the Lirio Norte Local Fauna and the Centenario Fauna with previously published radiometric dates indicated (centre), and North American land mammal faunal zonation (left). Hemingfordian North American Land Mammal Age. Bloch et al. (2016)

Figure 106. Field photo of the contact between a welded silicic pyroclastic bed and an ash fall tuff layer typical of the Las Cascadas Formation (left). Ropey andesitic lava. Photos from Farris et al. (2017) (right).

Figure 107. Lithic-rich pyroclastic density current deposit in the Las Cascadas Formation. Inset shows a large lithic of flow-banded dacite (left). Pumice-rich pyroclastic density current deposit in the Las Cascadas Formation. Buchs et al. (2019) (right).

Figure 108. Fallout coarse lapilli-tuff with accretionary lapilli in the Las Cascadas Formation (up). Flow-banded dacite lava flow on top of a paleosol in the Las Cascadas Formation. Thickness of the flow is approximately 5 m. Buchs et al. (2019) (down).

Figure 109. Tuffaceous paleosols of the Las Cascadas Formation. Inset shows a lens of cross-bedded volcanogenic sedimentary breccia (left). Cross-bedded volcanogenic sedimentary breccia and coarse sandstone in the Las Cascadas Formation, with clasts of amoeboid andesite/dacite in the inset. Buchs et al. (2019) (right).

Unit: LAS LAJAS FORMATION (of the Aguadulce Group)

Epoch/Age/Author: Holocene to Recent - Ministerio de Comercio e Industrias (1991)

Original Author and/or Origin of the Name: Ministerio de Comercio e Industrias (1991) has the name within the Aguadulce Group and describes it as “alluvium, consolidated sediments, sandstones, corals, mangroves, conglomerates, carbonaceous shales, deltaic type depositions” (APP-B3).

Relevant documents discussing the Unit: Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) ’s map keeps it as the top formation within the Aguadulce Group.

Overlying Unit: None
Underlying Unit: Río Hato Formation (part of the Aguadulce Group)
Remarks: See "Aguadulce Group". Occurs in Aguadulce Plain, Coclé province
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Unit: LATE BASALT FORMATION (Informal name; Farris et al. (2017))
Epoch/Age/Author: Lower/Middle Miocene (Burdigalian-Langhian; >15 Ma) **-** Farris et al. (2017)
Original Author and/or Origin of the Name: Woodring (1957). Some of the basalt in the southern part of the Canal Zone consists of remnants of flows and the undifferentiated volcanic rocks in the southwestern part of the map area include much basaltic lava.
Relevant documents discussing the Unit: Stewart et al. (1980); Wörner et al. (2009); Montes et al. (2012b); Farris et al. (2017).
Lithology: The Late Basalt Formation (Figure 011; Figure 031; Figure 033; Figure 110) is composed of basaltic to basaltic andesite sills, dikes and flows. The sills and dikes intrude locally into the Culebra, Cucaracha and Pedro Miguel Formations, and where present, bedded lava flows occur conformably on top of the Pedro Miguel Formation pyroclastic units. In addition, the Late Basalt Formation occurs over a large area west of the Panama Canal. The unit can be differentiated from basaltic lava flows within the Pedro Miguel Formation both in terms of stratigraphic position, structural configuration, and texture / composition. The Late Basalt is most identifiable as larger sills / plugs that are several hundred meters thick and can be up to 500±1000 m in diameter. These sills often have well developed, near vertical columnar jointing in the upper parts of individual intrusions. The Late Basalt Formation is the youngest volcanic unit along the southern Panama Canal (Farris et al. (2017)).
Thickness: 135m
Macro Fossils: None
Underlying Unit: Pedro Miguel Formation (however, the sills and dikes intrude locally into the Culebra, Cucaracha and Pedro Miguel Formations)
Remarks: The Late Basalt Formation is an informal name for the stratigraphically youngest volcanic unit exposed along the Culebra Cut
Maps, Cross-Sections & Pictures:

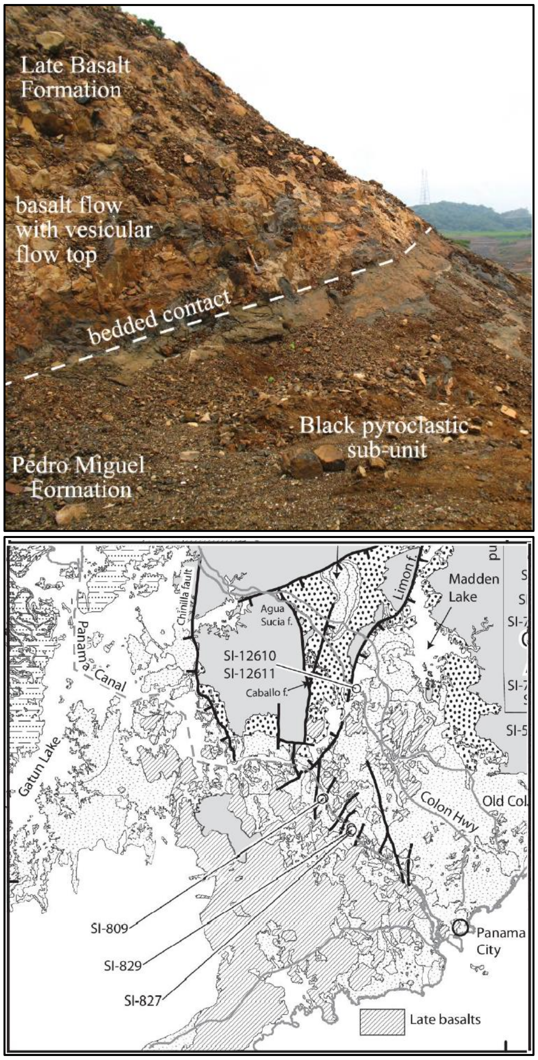

Figure 110. **Late Basalt Formation:** Top) Columnar basalts within a large sill. Second from top) Near vertical marginal contact between a Late Basalt sill and the Cucaracha Formation. Second from bottom) A stratigraphic contact between underlying Pedro Miguel Formation pyroclastic deposits and overlying Late Basalt Formation lava flows. Photos from Farris et al. (2017). Bottom) Geological map of part of Central Panama showing the location of the Late Basalt Formation. Modified from Montes et al. (2012b).

Unit: *LIMON BOCAS FORMATION
Epoch/Age/Author: Pliocene **-** Wilson et al. (1957)
Original Author and/or Origin of the Name: Senn (1940), on p. 1578 (correlation chart)
Relevant documents discussing the Unit: Wilson et al. (1957).

Remarks: No additional information has been found. Most probably an old name of a formation occurring at the border between Panama and Costa Rica.

Unit: *LIMONES SHALE
Epoch/Age/Author: Miocene(?) **-** Woodring (1960)
Original Author and/or Origin of the Name: Coryel et al. (1942). Underlies Charco Azul Formation [as per his own correlation at that time; Figure 111]. Upper Miocene. Most likely takes its name from Playa Limones near Quebrada Calabazo creek (8°08'53.6"N, 82°52'27.4"W)
Relevant documents discussing the Unit:

- Durham (1950), pt. 2, table 10
- Wilson et al. (1957).
- Woodring (1960). An undefined name. Miocene(?).
- Keroher et al. (1966); Morell et al. (2011)

Synonymy:
Location of the type section / Stratotype / Reference Section / Other localities:
Lithology:
Thickness:
Macro Fossils:
Overlying Unit: Peñita Formation
Underlying Unit: Unknown
Remarks: Burica Peninsula, Chiriqui Province.
Maps, Cross-Sections & Pictures:

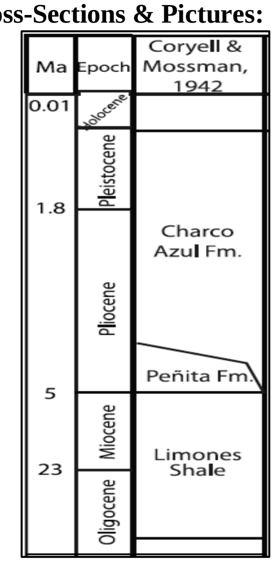

Figure 111. Stratigraphy of the Burica Peninsula as it was described by Coryel *et al.* (1942). Modified from Morell *et al.* (2011).

Unit: *MACARACAS FORMATION

Epoch/Age/Author: Upper Oligocene to Middle Miocene - Buch et al. (2011)
Original Author and/or Origin of the Name: Krawinkel et al. (1999)
Relevant documents discussing the Unit: Recchi and Miranda (1977); Ministerio de Comercio e Industrias (1991); Kolarsky et al. (1995a, 1995b); Krawinkel et al. (1999); Buch et al. (2011); Rodríguez-Reyes et al. (2020a, 2020b)
Synonymy: Santiago Formation
Location of the type section / Stratotype / Reference Section / Other localities: Near Macaracas village
Lithology: Sediment of the Macaracas Basin (north-central Azuero Peninsula, also reported as “Macaracas Formation” by Krawinkel et al. (1999)) was considered by Recchi and Miranda (1977) to be part of the Santiago Formation described in the northern part of the Azuero Peninsula. Buchs et al. (2011) also considers it the case (Figure 050: Top). The Macaracas Basin is composed of sandstone, siltstone, shale, and coal that deposited in a neritic to terrestrial environment, possibly concomitantly with the upper Tonosí Formation during the Late Oligocene and Miocene (Kolarsky et al. (1995a, 1995b)). Buch et al. (2011)
Thickness: See Santiago Formation
Macro Fossils: See Santiago Formation
Overlying Unit: N/A
Underlying Unit: The formation is underlain by the Pesé Formation. Ministerio de Comercio e Industrias (1991)
Remarks: The term should be disregarded. Mention of the term on maps and legend should be replaced by Santiago Formation. The name is not mentioned on Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)

Unit: *MAJAGUA FORMATION
Epoch/Age/Author: Middle Oligocene - Woodring (1960)
Original Author and/or Origin of the Name: Sapper (1937). Name appears on chart above David Formation. Middle Oligocene. In Chiriqui Province, the Río Majagua (presumed source of name) is one of numerous streams flowing southward from Volcan de Chiriqui, a tributary of Río David.
Relevant documents discussing the Unit:
- Woodring (1960). Undefined name. Oligocene (?).
- Keroher et al. (1966)

Unit: *MARIATO FORMATION
Epoch/Age/Author: Pleistocene(?) - Woodring (1960)
Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). On the eastern side of the Gulf of Montijo, about seven miles [11 kms] north of the mouth of the Torio River, there is a grassy and level but dissected old coastal plain, occupied by the hacienda of Mariato. It is elevated 20 to 40 feet [6 to 8m] above sea-level. On the seaward margin it has been much eroded, and at "the port" it is seen to be composed of horizontally stratified, reddish colored clay, which is very sandy above and gravelly below. The pebbles are well rounded, but mostly of soft rock which can be broken with the point of a knife. This marine deposit rests on an ancient submarine shelf carved from the Santiago Formation, upon whose nearly flat surface it thins out in passing inland.
Relevant documents discussing the Unit:
- Wilmarth (1938).
- Woodring (1960). Poorly defined name for surficial deposits. Pleistocene (?).
- Keroher et al. (1966)

Remarks: Present on Mariato Plain, Veraguas Province.

Unit: *MATA CHIN FORMATION
Epoch/Age/Author: Quaternary(?) - Woodring (1960)
Original Author and/or Origin of the Name: Hill (1898). Black basic rounded igneous boulders. Thickness 110 feet [33m] in face of hill at Juan Grande; 100 feet [30m] south of Bas Obispo. Believed to be contemporaneous with basic igneous eruptions of Cretaceous and Eocene time. Matachin was a pre-Canal village on Río Chagres. The site is flooded by Gatún Lake. Woodring (1960).
Relevant documents discussing the Unit:
- Wilson et al. (1957).
- Woodring (1960). Considered informal name for concentrations of boulders of black igneous rock at a now submerged locality in the Canal Zone. Quaternary (?). Boulders may have weathered from conglomerate of Bohío Formation or may be exfoliated masses weathered out of basalt. Name should be “Matachin”.
- Keroher et al. (1966)

Remarks: Matachin was a pre-Canal village on Río Chagres. Site is now flooded by Gatún Lake.

Unit: MEMBRILLO FORMATION
Epoch/Age/Author: Lowest part of the Upper Miocene (Tortonian) **-** Coates et al. (2004)
Original Author and/or Origin of the Name: Named for the Membrillo River by Coates et al. (2004)
Relevant documents discussing the Unit: Gurocak-Orhun et al. (2017).
Synonymy:
Location of the type section / Stratotype / Reference Section / Other localities: The stratotype lies on the Membrillo River (Figure 112).
Lithology: The base of the Membrillo Formation denotes the transition from the coarser thicker sediments of the shallow zone of the Chucunaque-Tuira Basin around the Chico and Tupisa Rivers region, westward into finer-grained (and deeper-water) deposits of the Bayano Basin. The Membrillo Formation is the lateral equivalent of the Tuira Formation. It consists mainly of blue gray, conchoidally fracturing, blocky and shelly mudstone with abundant slabby concretions in the upper portion. In the lower portion, there are frequent mollusk shell beds, 20 cm thick sandstone units, and occasional volcanic cobble horizons.

Sediments of the Membrillo Formation were deposited under middle bathyal (500-1500 m), oxygen-deficient conditions. Whereas many of the benthic foraminiferal taxa are most abundant at upper bathyal depths, others are characteristic of middle bathyal depths.

Coates et al. (2004) tentatively assigns it to the lowest part of the upper Miocene.
Thickness: About 150m. Its upper contact consists of blue-gray, blocky and shelly mudstone similar to that of the Tuira Formation (the upper contact of the Membrillo Formation is not exposed at the stratotype but there is an abrupt transition from mudstone to cobble conglomerate). The lower portion includes volcanic cobbles with frequent molluscan shell beds and 20-cm-thick sandstone units (the lower contact is not exposed at the stratotype). Gurocak-Orhun et al. (2017)
Overlying Unit: Chucunaque Formation
Underlying Unit: Tapaliza Formation
Remarks: The Membrillo Formation is known only from the Membrillo River but extends westward into the Bayano Basin
Maps, Cross-Sections & Pictures:

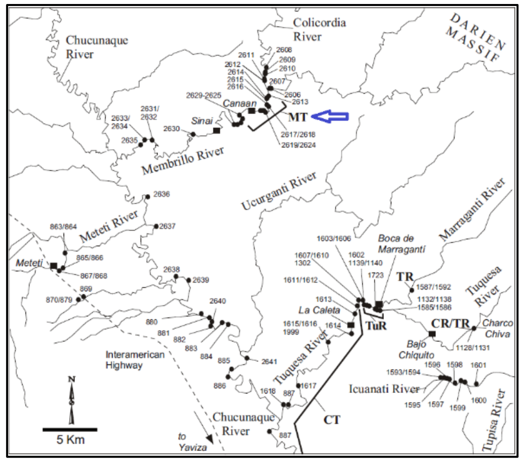

Figure 112. Locality of the Membrillo Formation stratotype (MT). Coates et al. (2004).

Unit: MIMITIMBI MEMBER (of Urraca Formation)
Epoch/Age/Author: Mid-Pleistocene (Calabrian; ~1.2 Ma) **-** Klaus et al. (2012)
Original Author and/or Origin of the Name: See Urraca Formation
Relevant documents discussing the Unit: See Urraca Formation
Synonymy: It is suspected that "Mimitimbi Member" is the equivalent of Terry (1956)'s "Minitimi Limestone".
Location of the type section / Stratotype / Reference Section / Other localities: See Urraca Formation
Lithology: The Mimitimbi Member is the bottom Member of the Urraca Formation and is exposed along the banks of the Mimitimbi River on the northeastern coast of Colon Island (Figure 042). The unit is marked by abundant corals (Figure 155) and skeletal debris admixed with carbonate and siliciclastic mud. The unit consists of alternating coral-rich beds and muddy siliciclastic beds at its base and transitions up-section to a series of shallowing-upward burrowed-crossbedded units of carbonate sand.
Overlying Unit: Hill Point Member of the Urraca Formation
Underlying Unit: Isla Colon Formation

Unit: *MINDI HILL BEDS
Epoch/Age/Author: Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Hill (1898). Green sand marls of fine, uniform homogeneous texture and structure; no lamination; fossiliferous.
Relevant documents discussing the Unit:

- Wilson et al. (1957) list it as Eocene.
- Woodring (1960). An informal name for strata at Mindi, north of Gatún, Canal Zone. Suppressed in favor of Gatún. Miocene
- Keroher et al. (1966)

Synonymy: Gatún
Remarks: Near Gatún, Canal Zone

Unit: *MINITIMI LIMESTONE
Epoch/Age/Author: Middle Miocene - Terry (1956)
Original Author and/or Origin of the Name: Terry (1956). A coralline limestone which interfingers with Bastimentos shale at base of Gatún Formation
Relevant documents discussing the Unit:

- Woodring (1960). An undefined name for coralline [coralliferous] limestone at base of middle Miocene strata (referred to the Gatún Formation) on Isla de Colon and Isla Bastimentos, Archipiélago de Bocas del Toro. The limestone is said to interfinger with the undefined Bastimentos shale. The name seems to be derived from a Minitimi creek on the Isla de Colon.
- Keroher et al. (1966)

Synonymy: It is suspected that "Mimitimbi Member" is the equivalent of Terry (1956)'s "Minitimi Limestone".
Remarks: Occurs on Isla Colon (Columbus Island) and Isla Bastimentos (Provision Island)

Unit: *MIRAFLORES BASALT
Epoch/Age/Author: Lower Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Thompson (1943). Consists of thick mass of dense hard dark-gray to blue-black rock that has intruded sedimentary rocks. Represents either laccolith or sill.
Relevant documents discussing the Unit:

- Jones (1950), Wilson et al. (1957),
- Woodring (1960). Intrusive basalt near Miraflores Locks and elsewhere on Pacific side of Canal Zone.
- Keroher et al. (1966)

Synonymy: Sosa Hill Basalt
Remarks: Underlies site of Miraflores Locks and composes Cocoli Hill and Aguadulce Hill, Pacific side of Canal Zone.

Unit: *MIRAFLORES PUMICE
Epoch/Age/Author: Miocene(?) - Woodring (1960)
Original Author and/or Origin of the Name: Hill (1898). Stratified pink, salmon, and magenta. An informal name for tuff at Miraflores, Canal Zone. It was suppressed in the same publication in favor of Panamá Formation (p. 206). Term "Panamá Formation" used to include analogous deposits of Barbacoas, San Pablo, and Miraflores.
Relevant documents discussing the Unit:

- Wilson et al. (1957) has it listed as pre-Eocene.
- Woodring (1960). Considered informal name. Miocene (?).
- Keroher et al. (1966)

Remarks: In bluffs at Miraflores, Canal Zone

Unit: *MONA SHALE
Epoch/Age/Author: Oligocene - Woodring (1960)
Original Author and/or Origin of the Name: MacDonald et al. (1919) named the shale from Mona Creek; the local name for a small stream flowing eastward into Caño San San, Bocas del Toro Province, Panama.
Relevant documents discussing the Unit:

- Woodring (1960). An undefined name of unspecified origin for fine-grained rocks, assigned on unspecified grounds to the lower Oligocene. The name, in the expression « Watsi and Mona shales » in MacDonald et al. (1919), appeared only in a table, showing that the shales overlie the Sensori agglomerate and limestone [Sinosri Formation] and underlie the Tigre limestone. A.A. Olsson, who worked in the type region, under the direction of MacDonald in 1917, reports in a personal communication that the fine-grained rocks, for which MacDonald used the name Mona shale, underlie the Tigre limestone in the hills in the Bocas del Toro area, about 15 kilometers southwest of the mouth of Río Sixaola. Both the overlying Tigre limestone and the underlying Sinosri Formation are considered of Oligocene age and therefore the Mona shale is assigned to the Oligocene.
- Keroher et al. (1966)

Unit: *MONKEY HILL FORMATION
Epoch/Age/Author: Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Hill R.T. (1898)
Relevant documents discussing the Unit: Woodring (1960). An informal name for strata at

Monkey Hill (Mount Hope), Canal Zone. Suppressed in favor of Gatún Formation

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Unit: MONTE VERDE FORMATION
Epoch/Age/Author: Quaternary (Pleistocene-Holocene, younger than 60,000 Ya) - Morell et al. (2011)
Original Author and/or Origin of the Name: Morell et al. (2011)
Location of the type section / Stratotype / Reference Section / Other localities: On the Burica Peninsula - as many as eight laterally extensive marine terraces (Qt1 to QY8) (Figure 046, RIGHT)
Lithology: Most terraces are generally composed of 1–3 m thick magnetite-rich, quartz-poor, parallel-laminated sandstones, with occasional lenses of fossiliferous subtidal sands (Figure 114). Locally around Puerto Armuelles, bay fill sediments beneath terrace sands can reach up to ∼10 m in thickness and often contain laterally discontinuous ∼1–3 m conglomeratic gravel bases with well-rounded andesitic or basaltic cobbles. Morell et al. (2011)
Thickness: Variable from 1 to 10 m (Figure 113).
Macro Fossils: Lenses of undefined fossils in subtidal sands
Overlying Unit: None
Underlying Unit: Armuelles Formation
Maps, Cross-Sections & Pictures:

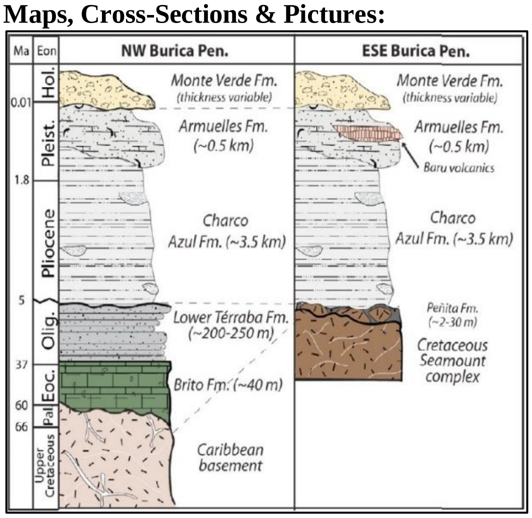


Figure 113. Stratigraphic column of the Burica Peninsula showing the position of the Monte Verde Formation. (See also Qt1 to Qt8 in Figure 046, Right). Morell *et al*. (2011).

Figure 114. Photos of marine terraces on Burica Peninsula that make up the Monte Verde Formation showing (a) tread surface of extensive marine terrace Qt4. (b) Close-up from "a" showing unconformity between underlying mudstones of the Charco Azul Formation and magnetite-rich marine terrace sands for terrace Qt4. (c) Coastal outcrop of Holocene marine terrace near Pavones, Costa Rica, northwestern Burica Peninsula. (d) Photo showing soil profile within Qt1b, second highest terrace in southern Burica Peninsula. Note the lack of red soil development. (e) Photo showing modern marine platform and wave-cut notch associated with marine terrace Qt7 on the Costa Rican beach, with view looking south. Morell *et al.* (2011).

Unit: *MONTIJO CONGLOMERATE or FORMATION
Epoch/Age/Author: Oligocene(?) - Woodring (1960)
Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). On the eastern shore of the Gulf of Montijo, opposite the island of Cebaco, about one mile north of the Torio River, there is a great formation, hundreds of feet thick, of fine conglomerate, hard and gray in color. It is well stratified and dips usually at a high angle. There are occasional fossils, but, I fear, too imperfect for specific identification. Coarse conglomerate and fine sandstone are both rare. The outcrop in the sea has a reddish tint. The conglomerate formation is newer than the Torio limestone and is distinctly seen to rest on it. The Montijo conglomerate is separated from the next

newer formation by a non-conformity represented by a tilting of the formation and sub-aerial erosion.

Relevant documents discussing the Unit:

- Wilmarth (1938).
- Olsson (1942b). Referred to it as formation; unconformably overlies Torio Limestone (upper Eocene). Middle Oligocene.
- Woodring (1960). A poorly defined name for conglomerate exposed on the west side of the Azuero Peninsula. An Early Cretaceous age was initially suggested. Later correlation with the Oligocene Bohío Formation was suggested.
- Keroher et al. (1966)

Synonymy: Possible correlation with the Bohío Formation

Remarks: Exposed on West side of Azuero Peninsula, Veraguas Province.

Unit: *MOUNT HOPE FORMATION

Epoch/Age/Author: Quaternary/Pleistocene - Woodring (1960)

Original Author and/or Origin of the Name: Brown and Pilsbry (1913) casually used the name Mount Hope Formation, which they attributed to W. B. Scott, for fossiliferous Pleistocene strata in the Black Swamp near Mount Hope, Canal Zone.

Relevant documents discussing the Unit:

- Brown and Pilsbry (1913), Vaughan (1919), Wilmarth (1938), Woodring (1957)
- Woodring (1960). Fossiliferous Pleistocene deposits.
- Keroher et al. (1966); Beu (2010)

Synonymy: "Pacific Muck" and "Atlantic Muck"

Location of the type section / Stratotype / Reference Section / Other localities: See "Pacific Muck" and "Atlantic Muck"

Lithology: See "Pacific Muck" and "Atlantic Muck"

Thickness: See "Pacific Muck" and "Atlantic Muck"

Macro Fossils: Contains numerous species of mollusks (bivalve, gastropod (*Monoplex comptus*) and crustacean fossils), nearly all of which are Recent. Brown and Pilsbry (1913)

Overlying Unit: None

Underlying Unit: See "Pacific Muck" and "Atlantic Muck"

Remarks: See discussion under section "**Brief Geological background of Panama**" about "Pacific Muck" and "Atlantic Muck"

Unit: NANCY POINT FORMATION (part of the Bocas del Toro Group)

Epoch/Age/Author: Upper Miocene (Messinian; 7.2-5.3Ma) **-** Coates et al. (2005)

Original Author and/or Origin of the Name: The Nancy Point Formation was named by Coates et al. (1992), for the promontory called Nancy Point which lies 2.5 km south of the village of Tobabe.

Relevant documents discussing the Unit: Collins et al. (1999a & 1999b); Coates (1999); Coates et al. (2005); Todd & Collins (2005); Beu (2010); Landau et al. (2012a, 2012b); Schwarzhans et al. (2013); https://en.wikipedia.org/wiki/Nancy_Point_Formation

Location of the type section / Stratotype / Reference Section / Other localities: The stratotype of the Nancy Point Formation lies along the northern coast of the Valiente Peninsula, starting at Nancy Point and running south to near Chong (or Nispero) Point (Figure 043; Figure 042).

There are no exposures between the stratotypes of the Nancy Point and the Tobabe Sandstone along the north coast of the Valiente Peninsula. Assuming a constant dip (the type Tobabe and Nancy Point Formations have the same strike and dip), 400 m of section is not exposed. Much of this missing interval is exposed on the southern coast of the Valiente Peninsula between Warrie Point and the southern headland of the small peninsula of Toro Point (Figure 043; Figure 042), and is diagrammed in Section 15 of Coates (1999). Lithologically it appears to be more typical of the Nancy Point Formation.

Lithology: The Nancy Point Formation consists of massive, pervasively bioturbated, shelly, muddy and silty sandstone, muddy siltstone, with scattered mollusks and occasional leaves and plant fragments, and occasional coarse volcaniclastic and bioclastic sandstone beds. There are several low-diversity shell beds near the base and several diverse moderately abundant molluscan assemblages throughout the section. The base of the section (Section 15, Coates (1999), on the south coast of the Valiente Peninsula (Figure 043; Figure 042) has a faulted contact with the underlying volcanics so that no typical Tobabe Sandstone crops out.

The transition from Tobabe Formation to Nancy Point Formation deposits is best seen on Toro Cay (Figure 043), where dark blue-gray, silty sandstone, typical of the Nancy Point Formation,

contains occasional, clearly defined 50-cm-thick *thalassinoid* burrow systems and extremely abundant and diverse mollusks. It overlies coarse, channeled Tobabe sandstone with only a 10m gap. The transition from the Tobabe sandstone to the Nancy Point Formation thus appears to be conformable and to involve relatively rapid deepening from nearshore to upper slope facies.
Thickness: 500 m
Macro Fossils: See "Lithology" above. Scattered mollusks and occasional leaves and plant fragments, crabs. Landau et al. (2012b) study the Cancellariidae gastropods from the Nancy Point Formation.
Overlying Unit: Conformable with the Shark Hole Point Formation
Underlying Unit: Conformable with the Tobabe Formation
Remarks: The stratigraphic order of the Tobabe, Nancy Point and Shark Hole Formations (three of the five formations which make up the Bocas del Toro Group) has been determined by physical superposition. The two remaining formations of the Bocas del Toro Group (Escudo de Veraguas and Cayo Agua) as well as the younger Pleistocene Swan Cay Formation are known only on islands and their position relative to the other units has been determined by biostratigraphic evidence (Figure 044).

Unit: *OBISPO FORMATION
Epoch/Age/Author: Oligocene - Woodring (1960)
Remarks: See "Bas Obispo Formation"

Unit: OCÚ FORMATION
Epoch/Age/Author: Cretaceous-Paleogene(?) (Campanian / Maastrichtian to (?) Paleogene) (Figure 051) - Buchs et al. (2011)
Original Author and/or Origin of the Name: Del Giudice & Recchi (1969) named it for the town of Ocú on the Azuero Peninsula (Figure 050, Top)
Relevant documents discussing the Unit: Weyl (1980); Bourgois et al. (1982); Kolarsky et al. (1995a, 1995b); Buchs David et al. (2010 & 2011); Corral et al. (2011); Barat F. et al. (2014).
Location of the type section / Stratotype / Reference Section / Other localities:
Lithology: The Ocú Formation was initially described as well bedded fine-grained limestones with locally interbedded siltstones, tuffs and intermediate lava flows, deposited on top of basaltic basement rocks (Del Giudice and Recchi (1969)). In more details, it is described as volcanic breccia with andesite basalt clasts overlain by hemipelagic limestone (with Late Campanian foraminifera) and siliceous tuffs cut by basaltic andesite dikes. The formation probably rests upon the Azuero Plateau (Figure 050). Paleomagnetic data indicate the Ocú Formation formed at ∼2°N. The Ocú Formation limestones locally contain a tuffaceous component (Figure 116) and volcanic clasts derived from an intermediate-silicic volcanic source. The Ocú Formation locally contain fragments of larger benthic foraminifera, which are evidence for nearby shallow water environments. Locally the Ocú Formation contains interbeds of basaltic lava flows and is crosscut by basaltic dykes of the Azuero Protoarc Group. A hemipelagic limestone of the Ocú Formation in NW Coiba Island (location indicated by 6 in Figure 050) is intruded by a mafic dyke of the Azuero Protoarc Group. The limestone, which shows synvolcanic soft deformation, has been dated as late Campanian (∼75–73 Ma); so it is concluded that this also corresponds to the age of emplacement of the Azuero Protoarc Group. (Buchs et al. (2010)).

In general, the formation is composed of hemipelagic biomicrite that includes various amounts of clastic and tuffaceous material. The biomicrite is composed of a calcareous matrix that bears planktic foraminifera, radiolaria and sponge spicules. Reworking and breaking of the fossils is locally observed and probably occurred in response to bottom sea currents. Locally the limestones have an abundant siliceous component of biogenic origin (Figure 115). Bioturbation of the sediment is common. (Buchs et al. (2010))

Tuffaceous and detrital components of the Ocú Formation include sandy and silty grains of plagioclase, pyroxene, quartz, Fe oxide/sulfide minerals, amphibole, fragmented larger benthic (shallow water) foraminifera, and pumice. The detrital component is 3–10 cm sized turbiditic layers. An ashy component is recognized in the field by a greenish color of the limestone that results from the alteration of glass into chlorite. Rarely, red shales and rounded basaltic pebbles occur in the limestones, and attest to an increased terrigenous influence. (Buchs et al. (2010))
Thickness: N/A
Macro Fossils: The hemipelagic limestone forming the Ocú Formation (from the active quarries south of the town of Ocú) yielded rich and well preserved assemblages of planktic foraminifera.

Overlying Unit: When not outcropping, the Ocú Formation is overlaid by rocks of the Azuero Arc Group in the Azuero Peninsula (Figure 051) and the Volcanic arc in all regions east of the Canal Zone (Figure 011).

Underlying Unit: The Ocú Formation is is underlaid by rocks of the Azuero Plateau in the Azuero Peninsula (Figure 051) and the Oceanic Basement in all regions east of the Canal Zone (Figure 011).

Maps, Cross-Sections & Pictures:

Figure 115. Silicified limestone of the Portobelo Peninsula, Ocú Formation (9.56593°, −79.52145°, WGS84). Barat et al. (2014).

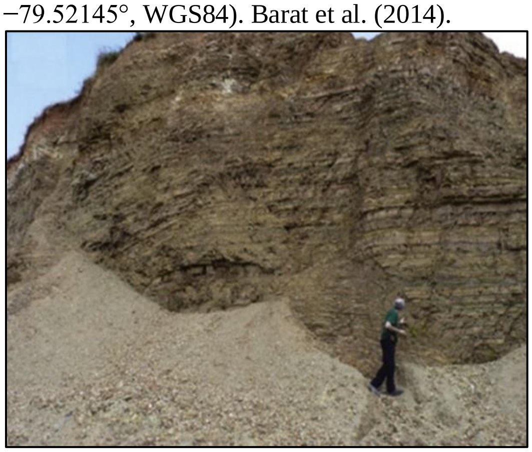


Figure 116. Calcareous and siliceous volcanic tuffs of the Portobelo Peninsula, Ocú Formation (9.56263°, −79.55680°, WGS84). Barat et al. (2014).

Unit: OLD BANK FORMATION

Epoch/Age/Author: Late Miocene – Early Pleistocene (Messinian to Gelasian; ~6 to 2.4 Ma) **-** Klaus et al. (2012)

Original Author and/or Origin of the Name: Coates et al. (2005) states that it is an informal field name and that the process is on-going to have the name formalized. Klaus et al. (2012) use it as a formal name.

Relevant documents discussing the Unit:

- Canu & Bassler (1928). Describe Bryozoans from the Minnitimmi Creek, Almirante Bay in Isla Colon which is most likely from the Old Bank Formation (Figure 042) [see also "Minitimi Limestone"]
- Ingram (1939); Coates et al. (2005); Klaus et al. (2012) ;

Synonymy: Isla Solarte Formation

Location of the type section / Stratotype / Reference Section / Other localities: The Old Bank Formation crops out extensively in the southern half of Colon Island (Figure 041; Figure 042) where it is crossed by the Bocas del Drago road along which there are several good exposures. It also occurs in the northeast of the island where it forms a distinct escarpment parallel to the coast. Many streams have waterfalls where they cross this scarp with good exposures. The same unit crops out on Bastimentos Island (Figure 041; Figure 042). There are exposures from Juan Brown Point eastwards along, and inland of the south coast, in steep stream courses flowing down from the ridge formed by its outcrop, which parallels the coast (Coates et al. (2005)).

Lithology: On Colon Island the Old Bank Unit consists mostly of a blue-grey mudstone with occasional thin sandstone stringers, fine volcanic conglomerate and volcanic boulder beds. On Bastimentos, it may be micaceous and sandier, with wood fragments and sparse mollusks including turritellids and *Anadara*. Preliminary field observations suggest it is an inner shelf deposit flanking volcanic islands and that it is about 3.5-2.0 Ma (Coates et al. (2005)). The Fish Hole Member outcrops on the northeastern rim of Bastimentos (Figure 042) and consists of ~4 m of thick-bedded, rubbly, bioclastic, limestone containing volcanic sand and silt grains in varying amounts. Pristine shells collected from within the reef unit (Figure 117) of the Fish Hole Member provide strontium isotope ages ranging from 5.8 to 5.6 Ma. (Messinian) (Klaus et al. (2012)).

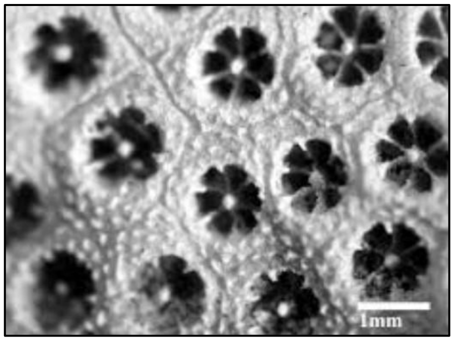
Thickness: N/A

Macro Fossils: Wood fragments and sparse mollusks including turritellids and *Anadara*

Overlying Unit: The Ground Creek and La Gruta Members of the Isla Colon Formation

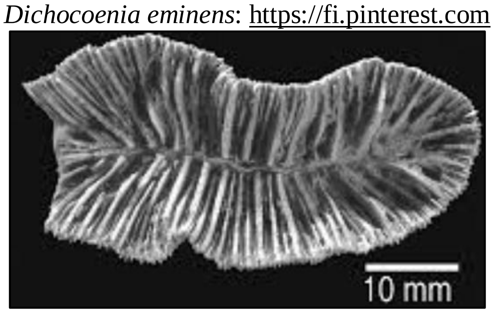
Underlying Unit: Disconformably overlies the Valiente Formation.

Maps, Cross-Sections & Pictures:



Stylophora minor:
https://nmita.rsmas.miami.edu,

Dichocoenia eminens: https://fi.pinterest.com



Placocyathus costatus:
https://nmita.rsmas.miami.edu

Figure 117. Modern equivalent of corals from the Fish Hole Mbr of the Old Bank Formation. Information from Klaus et al. (2012).

Unit: PACIFIC MUCK

Epoch/Age/Author: Pleistocene and Recent (0.13 Ma) **-** Woodring (1960); Hendy (2014)

Original Author and/or Origin of the Name: The following description is as valid for the Atlantic Muck as for the Pacific Muck: MacDonald (1913a, 1913b, 1915) observed "e*xtensive unconsolidated deposits of black, organic-rich marine mud with horizontal bedding*" but does not name them. Thompson (1943, 1947) named them and described them as "*Heterogeneous mixture of alluvially deposited silts, clays, and carbonaceous material within which are beds of marine origin containing Pleistocene and early Recent forms of mollusks and corals"*. He divides the muck into four phases. The lower phase, adjacent to its contact with older formations, consists of grey to bluegrey silty clay. The phase deposited in brackish marine waters contains abundant mollusk shells in an organic, black-silt matrix. The littoral swamp deposit is composed of semi-decayed wood and other organic vegetable matter, intermixed with silt and is characteristically dark brown to black. A soft, light-grey, weak, plastic clay overlies the organic phase. The four phases intergrade, with sand lenses locally present. The muck was deposited upon a stream-eroded topography of considerable relief. Old core borings reveal depths of over 200 feet for this deposit. Hills of the Gatún Formation protrude thru the black muck and in the area south of Gatún these hills form islands that are completely surrounded by the swamp muck deposits. In addition to the above, Thompson (1943) states the following regarding the Pacific Muck: "*Near city of Panama, soft silt and claymuck blanket covers underlying older agglomerates and tuffs. This layer deposited in late Pleistocene embayment and contains well-preserved fossils*".

Relevant documents discussing the Unit:

- Jones (1950); Wilson et al. (1957)
- Woodring (1960). Pleistocene. Informal name.
- Keroher et al. (1966); Kirby (2006); Hendy (2014); Redwood (2020).

Synonymy: Mount Hope Formation. See also "Atlantic Muck"

Remarks: See a discussion under section "Brief Geological background" about "Pacific Muck" and "Atlantic Muck"

Unit: PANAMÁ FORMATION

Epoch/Age/Author: Early to Late Oligocene **-** Stewart, Stewart, Woodring (1980)

Original Author and/or Origin of the Name: Hill (1898). Tuff and other pyroclastics exposed along the water front in the city of Panama were described as the Panamá Formation. A pre-Tertiary age was suggested.

Relevant documents discussing the Unit:

- Hershey (1901) (Figure 052); Wilmarth (1938); Olsson (1942b)
- Woodring & Thompson (1949). Referred to as Panamá tuff.

- Woodring (1957). Formation proper includes tuff, tuffaceous sandstone, tuffaceous siltstone, and agglomerate. They evidently represent nonmarine, essentially fine-grained tuff and tuffaceous strata that interfinger with and overlie La Boca marine Member and Pedro Miguel agglomerate Member. Estimated thickness at least 300 meters. Geologic map suggests that formation proper overlaps part of Caimito Formation, but that relation needs confirmation. La Boca marine Member apparently overlaps Cucaracha and Culebra Formations. La Boca Member and presumably entire Panamá Formation is not much younger than the Culebra Formation and like the Culebra is considered early Miocene. Entire succession above Las Cascadas agglomerate (Culebra, Cucaracha, and Panamá Formations) is believed to represent early half of early Miocene time; that is, the disputed Oligocene or Miocene.
- Woodring (1960). The Panamá Formation is made up of acidic tuff of varying grain size, agglomerate, and tuffaceous mudstone and sandstone. The outcrop area extends from the Pacific terminus of the Canal northeastward beyond the city of Panama. The thickness is undetermined. The lower part of the pyroclastics is inferred to be the equivalent of the La Boca marine Member. The designation Panamá tuff has been used, but Panamá Formation is preferable.
- Keroher et al. (1966); Stewart, Stewart, Woodring (1980); Woodring WP (1982)
- Woodring (1970). The Panamá Formation is redefined to include strata formerly assigned not only to the Panama itself, but also to the Bohío and Caimito Formations, and the Pedro Miguel agglomerate. As redefined the Panama consists chiefly of agglomerate and tuff, extending from the Miraflores Lake area to Panama City, and also northeastward across the continental divide and eastward in the Pacific coastal area to and beyond the limit of plate 1. The formation also includes tuffaceous sandstone, tuffaceous siltstone, lenses of stream deposits, and lenses of marine limestone.
- Stewart RH, Stewart JL, Woodring WP (1980)'s map describes the Panamá Formation as early to late Oligocene, principally an agglomerate, generally andesitic in fine-grained tuff. Includes stream-deposited conglomerate. The marine facies of the Panamá Formation is also early to late Oligocene. Tuffaceous sandstone, tuffaceous siltstone, algal and foraminiferal limestone. Sandy siltstone in basal part of formation in Quebrancha syncline.
- Woodring WP (1982) reconfirms the age of the formation as late to early Oligocene.

Synonymy:

- Panamá tuff (Wilmarth (1938)); Pedro Miguel Agglomerate Member of the Panamá Formation (which has been renamed as Pedro Miguel Formation (see description))
- "Panamá Formation" to include the analogous deposits of Barbacoas, San Pablo, and Miraflores Hill (1898, p.206)

Location of the type section / Stratotype / Reference Section / Other localities: The type area is with the exposures along the waterfront in the city of Panama, Panama Province.

Unit: PANAMA CITY FORMATION (Informal name; Farris et al. (2017))

Epoch/Age/Author: Not determined - amongst the youngest along the Canal

Original Author and/or Origin of the Name: Unknown

Relevant documents discussing the Unit: Stewart et al. (1980); Kirby et al. (2008); Farris et al. (2017);

Synonymy: N/A

Location of the type section / Stratotype / Reference Section / Other localities: Ancon Hill in Panama City

Lithology: The largest volcanic body of the Panama City Formation is the Ancon Hill dacite. It forms the most topographically significant hill in Panama City and is composed almost entirely of a fine-grained porphyritic dacite/rhyolite. The Ancon Hill dacite contains euhedral phenocrysts of mostly plagioclase with minor potassium feldspar surrounded by a matrix of plagioclase microlites (Figure 118). The microlites are of moderate size and form a quasi-interlocking framework, but still have minor amounts of glass within interstial spaces. Also, present are eudedral to subhedral square phenocyrsts of opaque oxide minerals.

Other Panama City Formation volcanic rocks include a series of andesite/ dacite lava bodies that comprise the three islands at the end of the Amador Causeway, and an andesitic intrusive body near the western abutment of the Bridge of the Americas (Figure 033). The Amador Causeway bodies are intruded by 10+ m wide basaltic-andesite dikes, and well developed columnar andesites are present at this location.

The Bridge of the Americas intrusion exhibits sharp near vertical contacts that truncate the host tuff and volcani-clastic sedimentary rocks. This intrusion also contains well-developed magma mingling structures with dacitic liquids locally injected into the dominant andesitic body (Figure 118). Farris et al. (2017)

Thickness: Not mentioned in Farris et al. (2017), however the altitude of Ancon Hill is 199 metres.

Macro Fossils: None

Overlying Unit: None. Amongst the youngest along the Canal

Underlying Unit: Late Basalt Formation / Pedro Miguel Formation

Remarks: The Panama City Formation is an informal name for a group of compositionally similar andesitic-dacitic plugs and lava flows located near the Pacific entrance to the Panama Canal (Figure 033). It is the southernmost Canal volcanic unit. Also, this formation is spatially associated with the Late Basalt Formation but lacks clear stratigraphic relationships with other volcanic units along the Panama Canal. The Panama City Formation has not been dated radiometrically but intrudes into what is mapped by Stewart et al. (1980) as the La Boca Formation. The La Boca Formation has been interpreted by Kirby et al. (2008) to be the lower part of the Culebra Formation, which has an age of approximately 19±20.5 Ma. However, what has been previously mapped as La Boca Formation near the mouth of the Panama Canal is lithologically different than the rocks Kirby et al. (2008) reassigned. The Culebra Formation in the central part of the Culebra Cut is composed of dirty grey marine sandstones with interbeds of limestone, whereas near the Pacific mouth of the Panama Canal, dacitic plugs intrude into bedded tuffs and volcani-clastic sedimentary rocks. Therefore the stratigraphic tie from rocks in the central Culebra Cut to the mouth of the Canal is not particularly strong. However, due to the spatial association and geochemical links with the Late Basalt Formation, Farris et al. (2017)'s interpretation is that Panama City Formation rocks are amongst the youngest along the Canal. Overall, the Panama City Formation bodies are largely intrusive, but observed characteristics suggest a shallow origin.

Maps, Cross-Sections & Pictures:

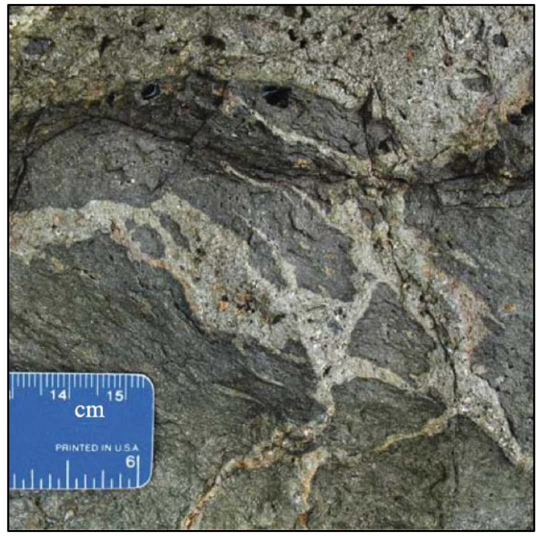


Figure 118. The intermingling of dacitic and andesitic magmas within a shallow intrusive body (Ancon Hill) of the Panama City Formation. Photo from Farris et al. (2017).

Unit: *PANAMÁ TUFF

Epoch/Age/Author: Early to Late Oligocene - Stewart RH, Stewart JL, Woodring WP (1980)

Remarks: See "Panamá Formation"

Unit: *PARITA FORMATION

Epoch/Age/Author: Recent(?) - Woodring (1960)

Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). The best developed is at the head of the Bay of Parita. It consists of dark bluish gray silty muck and gray sand. This has been built up to a level mainly a few inches above that of high tide, although on the inland borders there are extensive tracts which are flooded at spring tide, as at the Aguadulce Salt Works. The plain is traversed by deep, narrow tidal channels.

Relevant documents discussing the Unit:

- Hershey (1901); Wilmarth (1938).
- Woodring (1960). Poorly defined name for surficial deposits. Recent age implied. Hershey (1901) mentioned the head of the Bay of Parita in his description. Golfo de Parita is at the northeast border of the Peninsula de Azuero. There also is a town of the same name 10 km NW of Chitré.
- Keroher *et al.* (1966)

Remarks: Coclé Province.

Unit: PEDRO MIGUEL FORMATION (of the Gaillard Group)

Epoch/Age/Author: Middle Miocene (Burdigalian, </~17.9 Ma) **-** Buchs et al. (2019)

Original Author and/or Origin of the Name: Thompson (1943). "Pedro Miguel agglomerate" was proposed for extensive occurrence of this rock type in vicinity of Pedro Miguel Lock and its approach channels. The agglomerate overlies and interfingers with the upper part of the Cucaracha Formation in the Pedro Miguel area. To the southeast in the La Boca area, the agglomerate appears near the base of the La Boca Formation.

Relevant documents discussing the Unit:

- Woodring & Thompson (1949). Lens of pyroclastics formerly referred to Las Cascadas agglomerate. In type region, pyroclastics overlie Cucaracha Formation, but lower part apparently equivalent to upper part of Cucaracha sections. Farther south, pyroclastics occur as tongue in basal part of La Boca Formation. Thickness varies; maximum averages about 300 feet.
- Woodring (1955). Rank reduced to Member status in Panamá Formation.
- Woodring (1960). The Pedro Miguel agglomerate is now interpreted as a relatively thick lenticular agglomerate in the Panamá Formation. It is recognized along and near the Panama Canal from the Pedro Miguel area (the type region) to the Pacific terminus. The average maximum thickness is 300 feet [92m]. According to the stratigraphic relations, it is of the same age as the upper part of the Cucaracha Formation and the lower part of the La Boca marine Member of the Panamá Formation.
- Stewart RH, Stewart JL, Woodring WP (1980). It is unclear when the Pedro Miguel was termed as a "Formation", however on this 1980 map, it is now named "Pedro Miguel Formation".
- Kirby (2006 & 2008); Montes et al. (2010); Head et al. (2012); Montes et al. (2012b); MacFadden et al. (2014); Rincon et al. (2015a); Farris et al. (2017); Buchs et al. (2019).

Synonymy: Pedro Miguel Agglomerate Member (of Panamá Formation)

Location of the type section / Stratotype / Reference Section / Other localities: The type region is the Pedro Miguel area. Recognized along and near Panama Canal from Pedro Miguel area to Pacific terminus. The Hodges Hill location contains what is considered to be the "type" volcanic stratigraphy for the Pedro Miguel Formation (Figure 036).

Lithology: The Pedro Miguel Formation is terrestrial and consists principally of sequence of basaltic lava flows and subaerially deposited basaltic through andesitic tuffs together with interbeds of paleosol and fine-grained sediment (Head et al. (2012), Farris et al. (2017)). The Pedro Miguel Formation also has a definite sequence of volcanic sub-units. These sub-units were initially defined based on field mapping and observations at Hodges Hill (Figure 031, Figure 036) (Farris et al. (2017)). The stratigraphy observed at Hodges Hill contains the following five sub-units from oldest to youngest: **1)** Initial silicic layered pyroclastic deposits, **2)** Basaltic lava flows (Figure 119), **3)** Steeply dipping welded tan pyroclastic deposits with well developed bedding planes (Figure 119), **4)** Massive pyroclastic deposits composed of angular fragments and large remobilized blocks (1+ m), and **5)** Shallowly bedded black to gray pyroclastic deposits composed of angular fragments. These five units are found at Hodges Hill, and are present to a lesser degree at other locations. The most common sequence is the transition from stratigraphically lower layered and highly welded tan pyroclastic deposits to the overlying massive and highly fragmented black pyroclastic deposits (Farris et al. (2017)).

The volcanic agglomerate and the basalt flows indicate that this area began to experience volcanism before the formation of the delta (Kirby (2006)). It was deposited after the accumulation of the continental paleosols of the upper part of the Cucaracha Formation, and represents the youngest lithostratigraphic unit in the Culebra Cut area (Montes et al. (2012b); Kirby et al. (2008); MacFadden et al. (2014); Rincón et al. (2015a).

Several areas of the Pedro Miguel Formation were mapped by Farris et al. (2017) along the Culebra Cut, where they were interpreted as maar-diatreme pyroclastic pipes with large basaltic sills and bedded tuffs. Buch et al. (2019)'s detailed lithostratigraphic observations of these areas and the Pacific locks exposures provide additional constraints on volcanic processes associated with this unit, showing that it is mostly composed of tuff cones and large mafic intrusions, with only limited evidence for diatremes. Volcanic edifices of the Pedro Miguel Formation are predominantly composed of basaltic to basaltic andesitic tuffs and large mafic intrusions with olivine ± pyroxenes ± plagioclase phenocrysts.

Due to geochemical and age similarities and apparent parental linkage of the tuffs and mafic intrusions, the Pedro Miguel unit is subdivided into Tuff and Basalt Members (Figure 030). Volcaniclastic deposits of the Pedro Miguel Tuff Member are predominantly composed of fine tuff to primary volcanic breccias with a distinctive layered structure (Figure 120; Figure 121; Figure 122; Figure 123; Figure 124; Figure 125; Figure 130). Low angle cross-stratification is common in fine tuff to coarse lapilli-tuff (Figure 120; Figure 121; Figure 122; Figure 129; Figure 131; Figure 132; Figure 134), whereas the primary volcanic breccias are generally matrix-supported and massive (no grading).

Accidental clasts in the tuff include larger benthic foraminifera and red algae in the Pacific locks area, suggesting reworking from an underlying shallow-marine (La Boca?) unit. Very rare lava flows are locally interbedded with the tuffs (Figure 125; Figure 128). The occurrence of mafic ash, small accretionary lapilli and low angle cross-stratification in the tuffs, with only very rare lavas, are compelling evidence for common phreatomagmatic to rarer strombolian eruption deposits in the Pedro Miguel Formation.

Peperitic textures (a range of ductile to brittle structures typical of interaction of wet material (here tuff) with magma) were observed in some of the Pedro Miguel dykes that crosscut older units of the Culebra Cut (Figure 126; Figure 127; Figure 133). At Cerro Hodges (Culebra Cut) and Cerro Fabiana (Pacific locks area) (Figure 135), new excavations reveal large scale (100–500 m wide) volcanic structures with mega lenses of tuff embedded in peperitic sills (Buchs et al. (2019)).

Thickness: 355 m. The top of the Pedro Miguel Formation is not present, as it has been removed by erosion in the Panama Canal area. (Kirby (2006)). The thickness of the unit has significant spatial variability, but is locally greater than 200 m. The thickest portions of the unit occur in locations that exhibit inward dipping bowl-shaped stratigraphy and are interpreted as individual volcanic breccia pipes or maars. Away from these locations, the unit thins considerably (Farris et al. (2017)).

Macro Fossils: A “mummified” fossil forest represented by an angiosperm-bearing tuffaceous conglomerate is exposed in a fault-bound stratigraphic section within the Pedro Miguel Formation, Panama Canal Basin (9.0047°N, 79.6051°W). Carbonized tree root in life position and fossil leaf assemblage within a tuffaceous mudstone are described by Londoño et al. (2018).

Overlying Unit: N/A

Underlying Unit: Cucaracha Formation

Maps, Cross-Sections & Pictures:

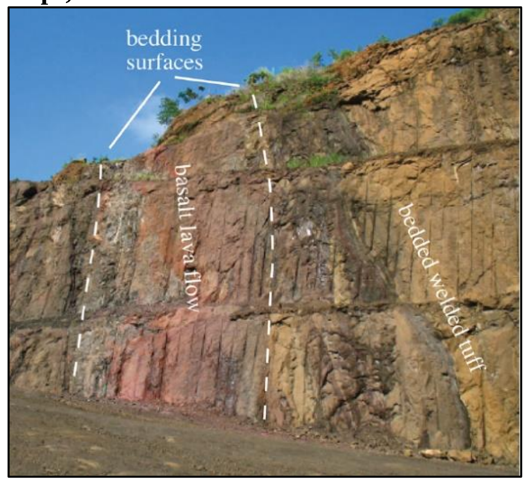


Figure 119. Inward dipping basaltic lava flows and welded pyroclastic deposits in the Pedro Miguel Formation. Photo from Farris et al. (2017).

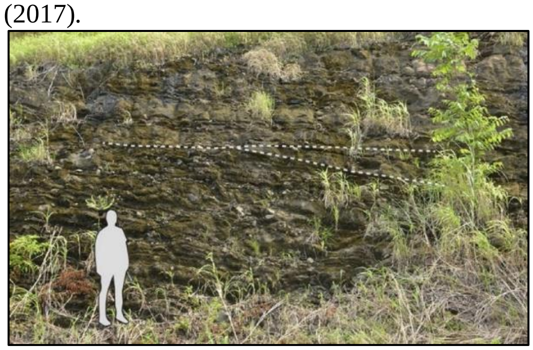


Figure 120. Coarse lapilli-tuff with low angle cross-stratification. Buchs et al. (2019).

Figure 121. Fine to very coarse tuff with low angle cross-stratification. Buchs et al. (2019).

Figure 122. Layered fine to medium lapilli-tuff (Cerro Hodges). Buchs et al. (2019).

Figure 123. Coarse lapilli-tuff with amoeboid juvenile clasts. Buchs et al. (2019)

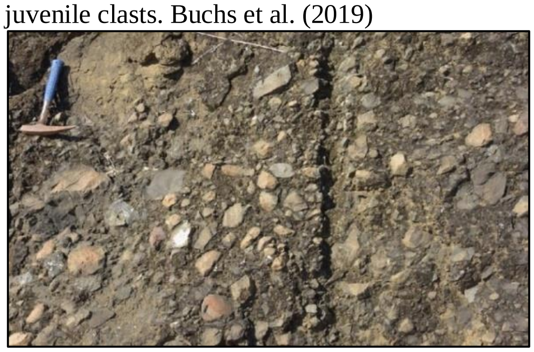


Figure 124. Lens of primary volcanic breccia (with reworked blocks of basalts) in Cerro Hodges. Buchs et al. (2019).

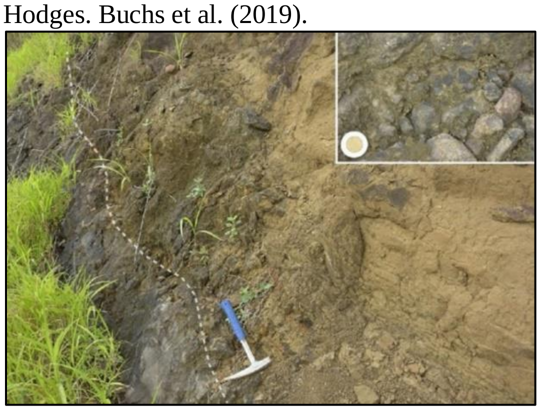


Figure 125. Lava flow overlapped by conglomerate (inset) and layered fine to medium tuff at Cerro Hodges. Buchs et al. (2019).

Figure 126. Peperitic intrusion in tuffaceous sediment at Cerro Hodges. Buchs et al. (2019).

Figure 127. Peperitic intrusion in tuff at Cerro Hodges. Buchs et al. (2019).

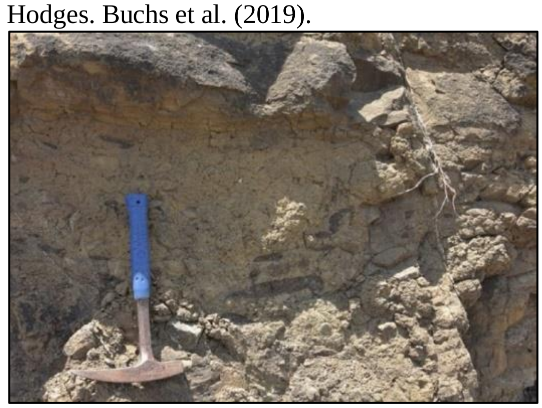


Figure 128. Debris flow deposit with reworked fragments of tuff at Cerro Hodges. Buchs et al. (2019).

Figure 129. Coarse lapilli-tuff with large block of basalt at Cerro Hodges. Buchs et al. (2019).

Figure 130. Fine tuff to fine lapilli-tuff with evidence for soft-sedimentation and water escape structure (arrow) at Cerro Fabiana. Buchs et al. (2019).

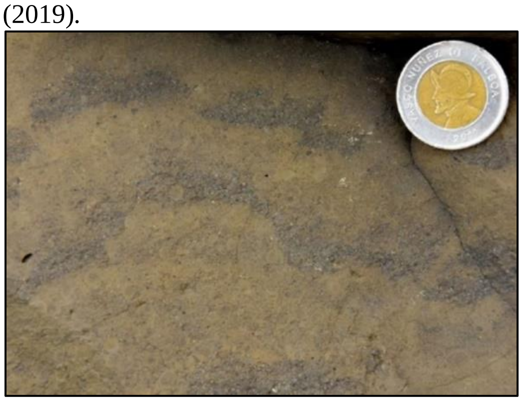


Figure 131. Fine tuff to medium lapilli-tuff with accretionary lapilli at Cerro Fabiana. Buchs et al. (2019).

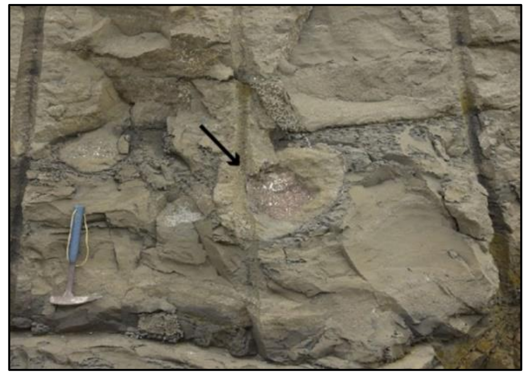


Figure 132. Fine tuff to medium lapilli-tuff with block sag (arrow) at Cerro Fabiana. Buchs et al. (2019).

Figure 133. Peperitic intrusion at Cerro Fabiana. Buchs *et al*. (2019).

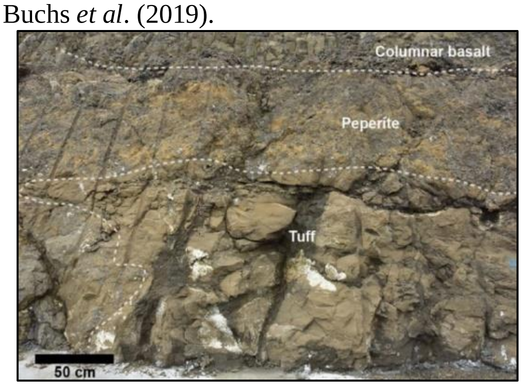


Figure 134. Relationship between tuff, peperitic contact of basalt sill and interior of the sill with columnar basalt at Cerro Fabiana. Buchs et al. (2019).

Figure 135. Subvertical columnar jointing in a large basaltic sill (man for scale) at Cerro Fabiana. Buchs et al. (2019).

Unit: *PEÑA BLANCA MARLS

Epoch/Age/Author: Oligocene - Woodring (1960)

Original Author and/or Origin of the Name: Howe (1907a, 1907b, 1907c).

Relevant documents discussing the Unit:

- Bertrand & Zurcher (1899); Wilmarth (1938).
- Woodring (1960). In original reference, name appeared only on map explanation. That it was not intended as formal name is indicated by expression "marls of Peña Blanca" in text (p. 113). Strata at Peña Blanca are presumed to represent part of Caimito Formation. Peña Blanca was a village on Río Chagres at a site off the NW end of the present Barro Colorado Island. The site is now submerged by the waters of Gatún Lake. The calcareous strata at Peña Blanca (the type locality of *Lepidocyclina canellei*) are presumed to represent part of the Caimito Formation (Woodring, 1957, p. 29)
- Keroher et al. (1966)

Synonymy: Part of Caimito Formation. Bertrand & Zurcher (1899, p. 87) used "Calcaires à Orbitoïdes de Peña Blanca" for the same strata at the same locality.

Remarks: Peña Blanca was a village on Río Chagres at site off northwest end of Barro Colorado Island. Site is now submerged by waters of Gatún Lake, Canal Zone. Woodring (1960)

Unit: *PEÑITAS FORMATION or *PENITAS FORMATION (part of the Charco Azul Group)

Epoch/Age/Author: Pliocene - Woodring (1960)

Original Author and/or Origin of the Name: Coryell et al. (1942) believe it to correlate with the Charco Azul Formation.

Relevant documents discussing the Unit: Woodring (1960). An undefined name for strata said to be the equivalent of the Charco Azul Formation in the Burica Peninsula.

Synonymy: See "La Peñita Formation". "Peñita Member"; See "Charco Azul Group" for some additional comments on synonymy.

Unit: (*) PESÉ FORMATION

Epoch/Age/Author: Oligocene (Rupelian; 23 Ma) - Buchs et al. (2008, 2011); Castrellon-Romero et al. (2019)

Original Author and/or Origin of the Name: Unknown Author. The name is not mentioned in Woodring (1960)'s Lexicon nor in Keroher et al. (1966)'s lexicon. Its first appearance seems to be in the 1970's in documents such as IUREP (1977). Name assigned after the Pesé stream (Figure 136) and Pesé village on the Azuero Peninsula

Relevant documents discussing the Unit: IUREP (1977); Sjunnesson & Svendenius (2004); Buchs et al. (2008, 2011); Iizuka (2013 & 2017); Castrellon-Romero et al. (2019).

Synonymy: The Pesé Formation is differentiated from the Tonosí Formation in Ministerio de Comercio e Industrias (1991) (APP-B3; APP-B4) and in Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) (APP-B1; APP-B2); however, it is later described as part of "*Late Eocene or? Early Eocene to Miocene Forearc sediments of the Tonosí Formation*" by Buchs et al. (2008 & 2011:33), thus the reason it is not shown in Figure 050. Nonetheless, the term keeps being used after 2011 by several authors specializing in the field of archeology rather than geology (Iizuka (2013 & 2017); Castrellon-Romero et al. (2019)).

Location of the type section / Stratotype / Reference Section / Other localities: The Pesé stream area (Figure 136). Also, IUREP (1977) states "*The best areas for exploration for La Yeguada-derived sandstone-type uranium deposits would be in the Pesé Formation between Santiago and Chitre in the Azuero Basin*".

Lithology: Mainly andesite, pyroclastic material (lapilli tuffs), turbidites and some limestone. In western Panama the Azuero Basin (and possibly the David Basin) was the scene of early Cenozoic continental and shallow marine volcaniclastic sedimentation (Del Giudice & Recchi (1969)), culminating with the Oligocene Pesé Formation on which fossil wood is found IUREP (1977)

(APP-B1; APP-B3). The lapilli tuffs of the Pesé Formation are rather compact, so they are expected to have a low hydraulic conductivity, however the tuffs usually have a high specific yield, which favors groundwater storage. Castrellon-Romero et al. (2019)
Thickness: The formation is at least 300 meters deep within the Macaracas Valley, near the town of Macaracas. Castrellon et al. (2019)
Macro Fossils: Fossil woods lie on the surface, associated with volcanic tuffs. However, none have been found in-situ and most likely belong to the Santiago Formation
Overlying Unit: N/A
Underlying Unit: It is unclear when comparing APP-B1 with APP-B3, however the Tonosí Formation is certainly involved.
Remarks: Unless new/good evidence favors to keep the name, it is suggested to abandon the term "Pesé Formation". Buchs et al. (2008, 2011) also seem to recommend abandoning the term; their map (Figure 050) incorporates the Pesé Formation into the Tonosi Formation.
Maps, Cross-Sections & Pictures:

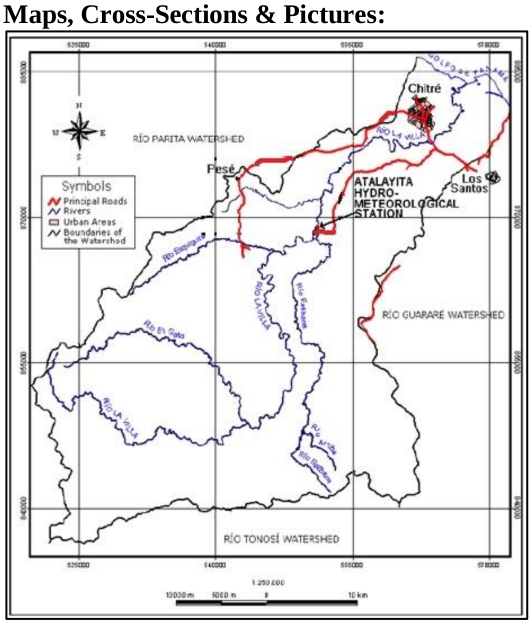


Figure 136. Location of the Pesé stream near the villages of Pesé and Chitré on the Azuero Peninsula. Modified from Sjunnesson & Svendenius (2004).

Unit: *PILIGUILLA CONGLOMERATE
Epoch/Age/Author: Pliocene (?) - Woodring (1960)
Original Author and/or Origin of the Name: Sapper (1937). Name appears on correlation table. Overlies Chucunaque Formation. Pliocene.
Relevant documents discussing the Unit:

- Sapper (1937), Wilson et al. (1957)
- Woodring (1960). Undefined name. Pliocene(?).
- Keroher et al. (1966)

Synonymy: Wilson et al. (1957) and Keroher et al. (1966) mention "Piliguilla Conglomerate" with "g", while Woodring (1960) mentions "Piliquilla Conglomerate" with "q". It is assumed that there is a misspelling in Woodring (1960).
Remarks: In Darien area.

Unit: PIÑA SANDSTONE FACIES (or MEMBER) (of the Chagres Formation)
Epoch/Age/Author: Late Miocene (Tortonian to Messinian, ~7.9-5.3 Ma) - Collins et al. (1996)
Remarks: See "Chagres Formation"

Unit: *POINT FARFAN DIORITE
Epoch/Age/Author: Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Thompson (1943). Grades regularly from coarse texture to fine grained and andesitic. Probably a small neck or intrusive plug. Pre-Pliocene.
Relevant documents discussing the Unit:

- Thompson (1943); Wilson et al. (1957)
- Woodring (1960). Diorite at Point Farfan. Augite-quartz diorite and presumably intrudes Panamá Formation. Miocene.
- Keroher et al. (1966)

Remarks: Quarried at Point Farfan, near southern terminus of Thatcher Ferry, Point Farfan is on the west side of the Pacific entrance to Panama Canal.

Unit: PORCONA FORMATION
Epoch/Age/Author: Middle Eocene to Late Oligocene - Barat et al. (2014)
Original Author and/or Origin of the Name: This formation was named by Shelton (1952) the "Corcona" Formation for a tributary of the Chico River. However, since all regional maps spell the name "Porcona" it is assumed that Shelton's name is a misspelling. Coates et al. (2004)
Relevant documents discussing the Unit: Esso Exploration and Production Panama (1970); Oxoco International Report (1983); Coates, Anthony G. et al. (2004); Barat et al. (2014).
Synonymy: Corcona
Location of the type section / Stratotype / Reference Section / Other localities: The Porcona Formation crops out mainly on the northeastern flank of the Chucunaque-Tuira

Basin. However, Barat et al. (2014) have also observed that Porcona Formation occasionally appears along the southern flank of the Chucunaque–Tuira Basin, marking the beginning of sedimentation in this Basin. The unit was interpreted by Esso Exploration and Production Panama (1970) to be middle-upper Oligocene and deposited at lower bathyal depths.

Lithology: It consists mainly of gray and black, calcareous, foraminiferal shale, limestone (Figure 138), and glassy tuff with radiolarians. It also contains probable resedimented blocks of shelly glauconitic sandstone and "*orbitoid*" sandstone. Barat et al. (2014) could not obtain a complete stratigraphic sequence of the Porcona Formation; however they described several outcrops: (i) bioclastic limestone that contains larger benthic foraminifera and red algae, which indicates a shallow marine depositional environment, which they dated as Late Oligocene; (ii) marl of the Late Middle Eocene and Late Oligocene, determined by the nannofossil assemblages (Figure 137). Similar marls also appear in the area between the San Miguel Gulf and the Sanson Hills, overlying the Early Eocene cherts.

Thickness: The earlier works in this area suggested a thickness of between 300 and 700 m for the Porcona Formation, however the Oxoco International Report (1983) revealed a thickness of over 2000 m of Late Middle Eocene to Late Oligocene sediments and the presence of oil circulation in the Chucunaque–Tuira Basin.

Macro Fossils: N/A

Overlying Unit: The Darien and Porcona Formations are regionally overlain by the Clarita Formation.

Underlying Unit: The Porcona Formation unconformably overlies the deformed rock of the San Blas Complex.

Maps, Cross-Sections & Pictures:

Figure 137. Marls from the Chucunaque–Tuira Basin, Porcona Formation (9.20737°, −78.88950°, WGS84). Barat (2013) and Barat et al. (2014).

Figure 138. Late Oligocene alternating finely layered limestones and marls in an outcrop of the Pacora river in the Chucunaque Basin. Barat (2013)

Unit: *PUCRO SANDSTONE MEMBER (of Gatún Formation)

Epoch/Age/Author: Middle Miocene - Woodring (1960)

Original Author and/or Origin of the Name: Sapper (1937). (correlation chart). Overlies Tuira Formation; underlies Chucunaque Formation. Contains typical Gatún fauna. Middle Miocene.

Relevant documents discussing the Unit:

- Sapper (1937)
- Terry (1956). Uppermost Member of Gatún Formation. Thickness 1,500 to 2,000 feet
- Wilson et al. (1957)
- Woodring (1960). An undefined name for strata in Darién area containing a fauna of Gatún age (middle Miocene). Miocene. The Pucro [sandstone] was later assigned Member rank for the uppermost of the three parts of the Gatún Formation of the Darién area (Terry, 1956, pp. 50, 51, 55).
- Keroher et al. (1966)

Remarks: Río Pucro is south westward flowing tributary of Río Tuira. American Geographic Society's sheet N. B-18 shows village of same name on Río Pucro. Woodring (1960) and Keroher et al. (1966).

Unit: PUNTA ALEGRE FORMATION

Epoch/Age/Author: Lower Miocene (Aquitanian-Burdigalian; 21,5-18.5) - Coates et al., (2003)

Original Author and/or Origin of the Name: The formation was named by Coates et al. (2003)

for the nearest village, Punta Alegre, and the prominent low bluffs that lie along the coast of the western limit of the Valiente Peninsula (Figure 043; Figure 042), north of Bluefield Bay form the stratotype (Llorona Hill). They lie 1 km south of Bluefield Point (known locally as Punta Valiente) and 1.3 km northwest of the village of Punta Alegre. This is the only exposure of the formation.
Relevant documents discussing the Unit: Coates et al. (2005).
Location of the type section / Stratotype / Reference Section / Other localities: Llorona Hill
Lithology: The Punta Alegre Formation consists of thin- to medium-bedded, gray-weathering, blue-green, siliceous, clayey siltstone and blocky mudstone. Harder, conchoidal-fracturing, 3–5 cm thick horizons, spaced 5–20 cm apart, are common and are probably bentonitic (Figure 139). Many horizons contain very abundant, diverse, benthic and planktic foraminifera, but macrofossils and burrowing structures are absent. The Punta Alegre is interpreted to be a pre-isthmian lower-bathyal oceanic deposit; several horizons approach foraminiferal ooze in lithology. From its abundant planktonic foraminifera and calcareous nannofossils, the age of the Punta Alegre Formation is 19-18.3 Ma (Coates et al. (2003)), and by its benthic foraminifera it is interpreted to have been deposited in water depths of 100 to 2000 m. Coates et al. (2003).
Thickness: The formation is 19 m thick at the type locality
Macro Fossils: Macrofossils and burrowing structures are absent.
Overlying Unit: A disconformable upper contact is marked by the scoured basal surface of the Valiente Formation and an overlying coarse sand unit with up to 30cm in diameter slumped blocks. Laterally, the Valiente Formation lies with up to 20° of angular unconformity on the Punta Alegre Formation. Coates et al. (2003).
Underlying Unit: The lower contact of the Punta Alegre Formation is not exposed.
Maps, Cross-Sections & Pictures:

Figure 139: Stratotype of the Punta Alegre Formation, 1 km south of Bluefield Point, Valiente Peninsula, Bocas del Toro (Figure 043; Figure 042). Possible bentonite appears as a dark horizon above the hammer. Coates et al. (2003).

Unit: PUNTA MATANZA FORMATION
Epoch/Age/Author: Paleocene **-** Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) (APP-B1; APP-B2)
Original Author and/or Origin of the Name: The term first appeared on the map of Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996). No reference is given regarding the origin of the name. It is included in the "Chiguiri Group" (which also includes the Chiguiri Formation) which also makes its first appearance on the same map and with no details with regards to the origin of the name.
Location of the type section / Stratotype / Reference Section / Other localities:
Lithology: Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) describes it as "Graywacke, shales and limestone".
Remarks: Found on the Caribbean coast, west of "Punta de San Blas" area.

Unit: *QUEBRANCHA FORMATION (Now "Quebrancha Member of the Caimito Formation")
Epoch/Age/Author: Upper Oligocene **-** Woodring & Thompson (1949)
Original Author and/or Origin of the Name: Thompson (1944). The so-called Quebrancha limestone deposit consists of a 350 to 450 feet [110 to 135 meters] -thick layer of variably argillaceous, sandy, or semi-crystalline limestone. Separated from underlying Gatuncillo shale (new) by an interval of gritty sandstone, basalt, and conglomerate, and from overlying Río Duque shales (new) by interval by calcareous siltstone.
Relevant documents discussing the Unit:

- Woodring & Thompson (1949). Member of Caimito limestone. Thickness 350 to 450 feet. Grades upward into unnamed calcareous siltstone member; overlies, probably without marked discontinuity, volcanic Member of Bohío Formation.
- Jones S.M. (1950); Wilson et al. (1957, 1959);
- Woodring (1960). The name, as a separate formation name, was proposed for 350 to 450 feet of calcareous strata on the south limb of the Quebrancha syncline, east of the Canal Zone. They overlie thin volcanic rocks later treated as a Member of the Bohío Formation. The bulk of the calcareous strata consists of lepidocycline limestone. The Quebrancha limestone was later given Member rank in the Caimito Formation. The limestone is recognized only in the Quebrancha syncline. It contains late Oligocene larger foraminifera and mollusks. *Lepidocyclina vaughani*, *L. canellei*, *Turritella meroensis*, and a weakly sculptured form of *T. altilira* are characteristic fossils.
- Keroher et al. (1966)

Synonymy: Quebrancha Member (of Caimito Formation); Quebrancha Limestone Member (of Caimito Formation); Quebrancha Limestone.

Location of the type section / Stratotype / Reference Section / Other localities: The type region is on the south limb of Quebrancha syncline; includes quarry of Panama Cement Co. Keroher et al. (1966)

Lithology: Described and mapped in detail by Thompson (1944, p. 17) for several miles around the Cemento Panama Plant. It is considered to be typical Caimito Formation (Woodring and Thompson (1949, p. 234); Jones (1950)). The Quebrancha limestone Member is the middle member of the Caimito Formation. Jones (1950). See Caimito Formation for more details.

Thickness: 110-135 m

Macro Fossils: The zones of abundant *Lepidocyclina candid*, *L. pancanalis*, and *L. vaughani* appear in this member and are found on the peninsula jutting into Zetek Bay, Barro Colorado Island, in the Panama Railroad cut at the east side of Bohío Peninsula, and at other points.

Overlying Unit: Upper Member of the Caimito Formation

Underlying Unit: Lower Member of the Caimito Formation

Remarks: The Term "Quebrancha Formation" is to be discarded and replaced by "Quebrancha Member of the Caimito Formation). See "Caimito Formation"

Unit: QUEBRANCHA MEMBER (of the Caimito Formation)

Age: - See "Caimito Formation"

Synonymy: Quebrancha Formation, Quebrancha Limestone Member (of Caimito Formation); Quebrancha Limestone.

Remarks: See "Caimito Formation"

Unit: *RÍO DUQUE SHALES

Epoch/Age/Author: Eocene **-** Woodring (1960)

Original Author and/or Origin of the Name: Thompson (1944). Fine-grained silty dark gray locally carbonaceous soft shales with thin sandstone beds. Thickness probably more than 600 meters. It is believed that Río Duque and Vamos Formations are identical and that age of both are either lower Miocene or uppermost Oligocene. According to Keroher et al. (1966), Río Duque is a small tributary of Río Agua Sucia immediately west of the Quebrancha syncline.

Relevant documents discussing the Unit:

- Wilson et al. (1957)
- Woodring (1960). Synonym of Gatuncillo Formation. Eocene. Río Duque (Quebrada Duque of Army Map Service Pequeni sheet) is a small tributary of Río Agua Sucia in Panama immediately west of the Quebrancha syncline. It is the unlabelled stream crossing the Transisthmian Highway close to locality 24 of the 1:75000 map.
- Keroher et al. (1966)

Synonymy: Gatuncillo Formation, Vamos Formation of Thompson (1944)

Unit: RÍO HATO FORMATION (of the Aguadulce Group)

Epoch/Age/Author: Holocene – Recent **-** Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)

Original Author and/or Origin of the Name: It makes its first appearance in Ministerio de Comercio e Industrias (1991) which includes it in the middle of the Aguadulce Group. It is described as "Conglomerate, sandstones, shales, tuffs, semi-consolidated sandstones, pumice" (APP-B3).

Relevant documents discussing the Unit: Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)'s map lists it as the bottom formation within the Aguadulce Group. The Boca de Chucara Formation having disappeared on this map.

Synonymy: Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)'s map lists it as the basal formation within the Aguadulce Group.
Overlying Unit: Las Lajas Formation (part of the Aguadulce Group)
Underlying Unit: Boca de Chucara Formation (part of the Aguadulce Group) in Ministerio de Comercio e Industrias (1991)'s map. It is unclear which formation underlies it in Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)'s map.
Remarks: See "Aguadulce Group". Occurs in Aguadulce Plain, Coclé province

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Unit: RIO INDIO MEMBER (of the Chagres Formation)
Epoch/Age/Author: Late Miocene (Tortonian, ~7.64 Ma) - Collins et al. (1996)
Remarks: See "Chagres Formation"

Unit: RÍO QUEMA FORMATION
Epoch/Age/Author: Cretaceous (late Campanian) to Eocene - Corral et al. (2011)
Original Author and/or Origin of the Name: A stratigraphic unit introduced by Corral et al. (2011) for the area of Cerro Quema in the central Azuero Peninsula (Figure 141)
Relevant documents discussing the Unit: Perelló et al. (2020).
Location of the type section / Stratotype / Reference Section / Other localities: Río Quema on the Azuero Peninsula (Figure 141)
Lithology: The Río Quema Formation consists of volcanic and volcaniclastic sediments interbedded with hemipelagic limestones, submarine dacite lava domes and crosscut by basaltic to andesitic dikes. The Río Quema Formation is interpreted as the infill sequence of the fore-arc Basin of the Cretaceous–Paleogene volcanic arc and is integrated within the five major units of the Azuero Peninsula as follows: 1) Azuero Igneous Basement, 2) Azuero Proto-arc Group, 3) Río Quema Formation, 4) arc-related intrusive rocks, and 5) Tonosí Formation (Figure 140).

The Río Quema Formation includes all sedimentary, volcaniclastic and extrusive volcanic units deposited in a fore-arc Basin, overlying both the Azuero Igneous Basement and locally the Azuero Proto-arc Group. The following units have been distinguished in the Cerro Quema district:

A Lower Unit, made up of andesitic lava flows (0.20-2m thick) and well bedded crystal-rich sandstone to siltstone turbidites interbedded with hemipelagic thin limestone beds. W-SW paleocurrents were deduced from cross bedding, ripples and tool marks.

A Limestone Unit, corresponding to a 100-150m thick light grey biomicritic hemipelagic limestone which is interlayered with well bedded cherts, thinly bedded turbidites and ash layers. The presence of planktonic foraminifera (*Globotruncana* sp., *Globotruncanita* sp., and *Globotruncanella* sp.) indicates a Late Cretaceous age. A late Campanian–early Maastrichtian age. Similar limestone beds have also been found in the Torio and Güera rivers, following the southernmost E-W trend fault zone of the Azuero Peninsula.

An Upper Unit, which crops out both in the northern and southern part of the Río Quema section. The northern part is composed of volcaniclastic sediments interlayered with massive to laminar andesitic lava flows (1 to 3m thick), andesitic hyaloclastites (0.1 to 0.5m thick), and massive dacites overlain by dacite lava flows and dacitic and resedimented hyaloclastites (the latter up to 3m thick). However, in the southern part, this unit is characterized by volcaniclastic turbidites, crystal rich sandstones (up to 1m thick), siltstones and thin pelagic limestone beds (up to 0.2m). Whereas massive lava flows and extrusive rocks prevail in the northern part of the section, volcaniclastic turbidites are dominant in the southern region. W-SW paleocurrents are deduced from cross bedding. Basaltic-andesitic dikes intrude part of the series but are more common in the northern part of the study area. Corral *et al*. (2011)
Thickness: ~1,700 m
Macro Fossils: See "Limestone Unit" under "Lithology".
Overlying Unit: Tonosí Formation
Underlying Unit: Proto-arc Group
Maps, Cross-Sections & Pictures:

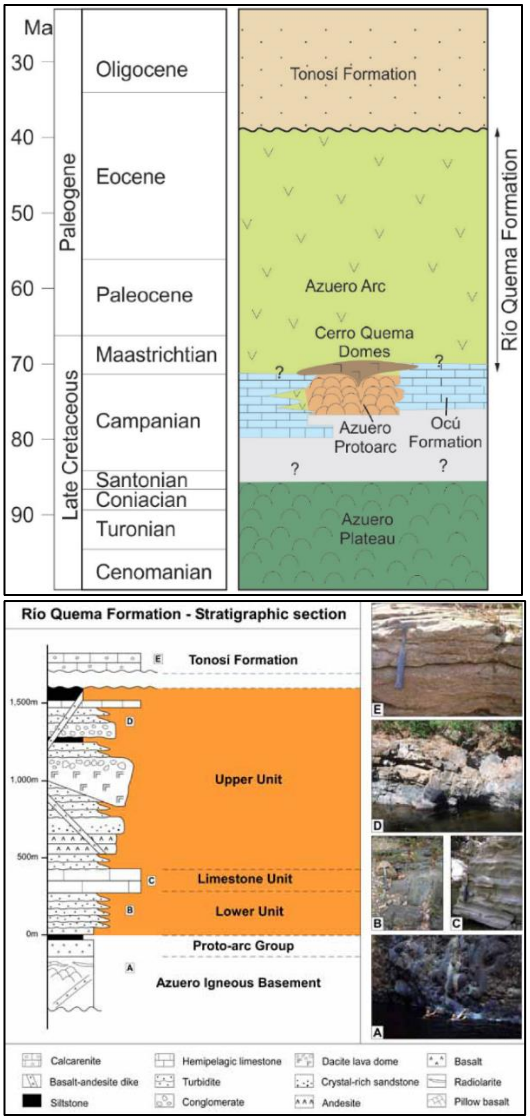


Figure 140. Top - Simplified stratigraphic column for the Azuero Peninsula showing the interval assigned to the Río Quema Formation. Perelló et al. (2020) *(Material reproduced with the permission of the editor)*. Bottom - Idealized stratigraphic section of the Río Quema Formation: **A)** Pillow basalts of the Azuero Igneous Basement at Río Joaquín. **B)** Volcaniclastic sediments of the Río Quema Formation lower unit at Río Quema. **C)** Hemipelagic limestones from the Río Quema Formation limestone unit south of Río Quema. **D)** Volcaniclastic and hemipelagic sediments crosscut by a basaltic-andesitic dike of the Río Quema Formation upper unit north of Río Quema. **E)** Fossiliferous calcarenite of the Tonosí Formation at Río Güerita. Corral et al. (2011).

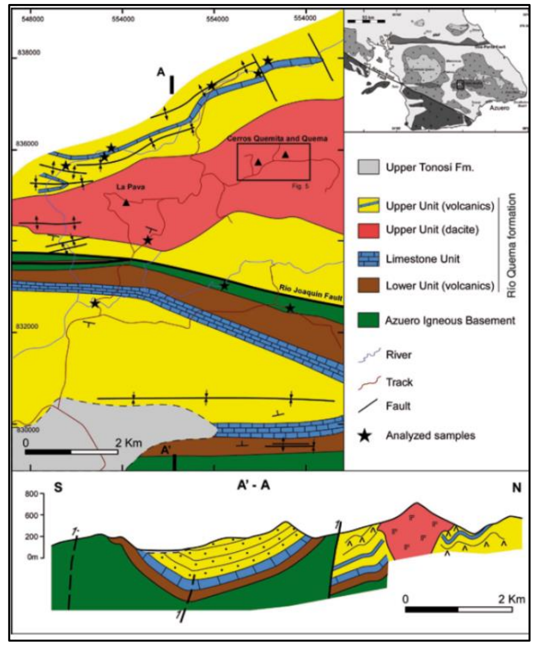


Figure 141. Geologic Map of the West Cerro Quema area. Corral *et al.* (2011).

Unit: *SABANITAS FORMATION
Epoch/Age/Author: Miocene - Jones (1950)
Remarks: See "Sabanitas Member" (of the Gatún Formation)

Unit: SABANITAS MEMBER (Lower Member of the Gatún Formation)
Epoch/Age/Author: Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Thompson (1947). The name "Sabanita Formation" appeared in a map explanation with an age designation of Pleistocene (?). Continental gravels, tuffs, and clays. Masks the contact of Gatún Formation with basement complex.
Relevant documents discussing the Unit:

- Jones (1950) altered the name from "Sabanita Formation" to "Sabanitas Formation". Considered middle Miocene(?) continental facies of basal part of Gatún Formation. Typically, a tuff-conglomerate unconformably overlying pre-Tertiary basement complex. Over wide exposures, weathering has altered it to a weathered ash and gravel. Unsorted and massive in type exposure. The best exposure showing its relation to the Basement Complex, is at Station 324 on the Boyd-Roosevelt Highway.
- Woodring (1960) considers it the lower Member of the Gatún Formation. Shallow-

water and nonmarine deposit at the base of the Gatún Formation.

- Keroher et al. (1966)

Synonymy: Sabanita. Now the Lower Member of the Gatún Formation
Location of the type section / Stratotype / Reference Section / Other localities: Type exposure: Along Boyd-Roosevelt Highway northeast of Sabanitas, vicinity of Gatún Lake. Keroher et al. (1966).
Lithology: See "Gatún Formation"
Thickness: 5 m
Remarks: Colón Province

Unit: SAN BLAS COMPLEX
Epoch/Age/Author: - Cretaceous (Base), top Middle Eocene (Top) **-** Coates et al. (2004)
Original Author and/or Origin of the Name: Bandy (1970); Bandy and Casey (1973)
Relevant documents discussing the Unit: Terry (1956); Esso Exploration and Production Panama (1970, 1971a, 1971b); Case (1974); Coates et al. (2004); Lissina (2005); Wegner et al. (2011); Buchs et al. (2010, 2011); Montes et al. (2012b); Barat et al. (2014).
Location of the type section / Stratotype / Reference Section / Other localities: The San Blas Complex crops out in the Massifs of San Blas–Darien, Majé, Bagre and Sapo, as well as in the San Miguel Gulf. Barat et al. (2014)
Lithology: The oldest reliably dated rocks in the Darien belong to a Campanian accretionary volcanic arc complex. Together with their magmatic arc equivalents, they form the basement complex of the Darien, herein described as the San Blas Complex (Figure 011). The San Blas Complex is composed of a Pre-Middle Eocene magmatic basement (Terry (1956); Case (1974)) overlain by volcano-clastic rocks (the Punta Sabana and Caobanera Formations; Esso Exploration and Production Panama (1970, 1971a, 1971b); Bandy and Casey (1973)) and Mesozoic sedimentary formations of the Changuinola Group, such as Morti Tuffs (Bandy and Casey (1973)) and the Ocú Formation (Ministerio de Comercio e Industrias (1991)). On the northeastern flank of the Chucunaque-Tuira Basin, in the San Blas and Darien Massifs, the San Blas Complex is a magmatic arc suite consisting of granodiorite, quartz diorite, basaltic andesite, dacite, and rhyolite. On the southwestern flank, in the region around the Gulf of San Miguel, it is represented by an accretionary lithofacies consisting of diabase and pillow basalt associated with radiolarian chert, named the Punta Sabana Volcanics. An assemblage of radiolarians was recovered from the interbedded chert that indicates deposition at abyssal depths during the Campanian. Coates et al. (2004). More recently, several studies have analyzed the geochemical and geochronological characteristics of the magmatic rocks (Lissina (2005); Wegner et al. (2011); Buchs et al. (2010, 2011); Montes et al. (2012b)), and these studies reported three distinctive volcanic–volcano-clastic groups: an oceanic plateau, and a proto-arc to a mature-arc.
Thickness: Very thick but not yet defined (Figure 011)
Macro Fossils: Nannofossils and foraminifera
Overlying Unit: The San Blas Complex is unconformably overlain by the Eocene-Oligocene Darien & Porcona Formations (Figure 011).
Underlying Unit: N/A (Figure 011).

Unit: *SAN CARLOS FORMATION
Epoch/Age/Author: Pleistocene(?) **-** Woodring (1960)
Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). At many places on the Pacific side of the Isthmus are remnants of a coastal plain of aggradation which has been uplifted 20 to 100 feet above high tide level and partly destroyed by marine action. A beautiful example is the San Carlos plain, lying between 30 and 50 miles west-southwest of Panama, and extending from a 100-foot white sea-cliff inland probably five miles to the base of a mountain mass. The sea-cliff about one mile east of San Carlos exposes the formation to perfection. In the maximum thickness of 100 feet [30m] there is included three divisions.
Relevant documents discussing the Unit:

- Woodring (1960). Poorly defined name for surficial deposits. Pleistocene (?).
- Keroher et al. (1966)

Remarks: Present on San Carlos Plain, Panama Province. Keroher et al. (1966).

Unit: *SAN PABLO FORMATION (or San Pablo phase of Barbacoas Formation)
Epoch/Age/Author: Oligocene(?) **-** Woodring (1960)
Original Author and/or Origin of the Name: Hill (1898). Brownish rock with fragments of decomposed light-blue eruptive material imbedded in it. Grades upward into Barbacoas Formation and is termed San Pablo phase of Barbacoas. The term Panamá Formation used to

include analogous deposits of Barbacoas, San Pablo, and Miraflores.

Relevant documents discussing the Unit:

- Wilson et al. (1957) has it listed as Pre-Eocene.
- Woodring (1960). Informal name for tuff at a now submerged locality in the Canal Zone. It was suppressed in Hill (1898, p. 206)'s publication in favor of "Panamá Formation". Oligocene (?)
- Keroher et al. (1966)

Synonymy: Panamá Formation

Location of the type section / Stratotype / Reference Section / Other localities: Described near village of San Pablo, west of Barbacoas. Now submerged locality in Canal Zone. Keroher et al. (1966).

Unit: SANTIAGO FORMATION

Epoch/Age/Author: Upper Oligocene to Middle Miocene (Figure 051) - Buchs et al. (2011)

Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). At the town of Santiago de Veraguas, where first discriminated, this is made up of thick layers of nonlaminated shale of a dull greenish gray color and a peculiar breccia and breccia-conglomerate. Although there are some thin layers of fine gravel and sand, the great mass of the formation is a shale, everywhere characterized by the same dull greenish or olive tint. The Santiago Formation forms the foundation of the entire Aguadulce-Santiago plain, over a large portion of which it is the surface formation. Here it always dips in some direction, but rarely at a high angle. On the lower two miles [3.2 kms] of the Torio River and at a promontory a short distance south of the mouth of the stream, it is exposed in beds of hard sandstone and shale over one thousand feet [300m] in thickness and dipping steeply in a general westerly direction.

Relevant documents discussing the Unit:

- Murata (1940);
- Olsson (1942b). Beds of sandstones and shales. Chart shows Santiago above Tonosí limestones. Upper Oligocene. *Ampullinopsis cf. spenceri* and *Turritella meroensis* have been found in strata that represent the Santiago Formation or its equivalent.
- Terry (1956); Woodring (1957, 1959);
- Woodring (1960). A poorly defined name for shale and other strata at Santiago, Veraguas Province, and in adjoining areas. A Late Cretaceous age was initially suggested. Later the name was used for marine Oligocene deposits at Santiago and in adjoining regions. More complete definition is desirable.
- Stern and Eyde (1963); Keroher et al. (1966); Woodring (1982); Ministerio de Comercio e Industrias (1991); Kolarsky et al. (1995a, 1995b); Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996); Krawinkel et al. (1999); Buchs et al. (2010 & 2011); Jud et al. (2017a); Rodríguez-Reyes et al. (2020a, 2020b).

Synonymy: Sometimes referred to as the "Macaracas Formation" (Kolarsky et al. (1995a, 1995b); Buchs et al. (2011); Rodríguez-Reyes et al. (2020b)). See definition of "Macaracas Formation".

Location of the type section / Stratotype / Reference Section / Other localities: At Santiago and adjoining areas, Veraguas Province (Keroher et al. (1966)

Lithology: N/A

Thickness: N/A

Macro Fossils: Kolarsky et al. (1995a, 1995b) reported samples of pollen, foraminifera, and nanofossils from the Santiago Formation in central Azuero and concluded that they support a late Oligocene to early Miocene age. Stern and Eyde (1963) reported that the Ocú silicified woods are associated with tuffs, which may be the source of the silica (Murata (1940)) that were mapped as Eocene-Oligocene by Terry (1956). At the surface of the Tonosí Formation, large quantities of petrified wood/trees can be found on catle ranch and other private lands. The fossils, known locally as chumicos, are strewn about in pastures and piled up in gullies in such abundance that the townspeople of Ocú and Chitre use them as decorative building stones. Pieces are angular and range in size from small hand specimens to stumps a foot or more in diameter (Stern & Eyde (1963)) (Figure 143). However, even though they lay at the surface of the Tonosí Formation, no trunks have ever been found *in-situ*. This led Jud et al. (2017a) to describe several specimens of silicified woods from the area of Ocú, which in turn led them to suggest that they originated from the younger Santiago Formation (eroded away in this area). This was confirmed by Rodríguez-Reyes (2019, 2020a, 2020b) who found similar medium to large size tree trunks *in-situ* within the Santiago Formation more the the northwest. Rodríguez-Reyes et al. (2020a) describe a new fossil-genus and species of Anacardiaceae tree from the largest fossil trunk discovered in Panama and probably, Central America (up to 2020). The trunk was collected on a private farm in Llano de La Cruz (latitude 08° 09' 4.7" N; longitude 80°

53’ 11.2” W) (Figure 142) and was lying within layers of sandy mudrock and sedimentary breccia, parallel to bedding. Fining upward sequences indicate fluvial environments as the main depositional system. The fossil silicified woods are interpreted as evidence for humid to perhumid megathermal climate in Panama during the late Paleogene-early Neogene (Jud et al. (2017a)). Rodríguez-Reyes et al. (2020b) collected fossil woods from two different locatities. Their sample STRI 44073 came from Los Cerritos, Los Pozos, Herrera (7° 46’ 43.5” N; 80° 35’ 53.3” W) and their sample STRI 45788 was collected on a private farm in Llano de La Cruz, Veraguas (08° 09’ 4.7” N; 80° 53’ 11.2” W). The two fossil wood types identified are new types for the “Ocú fossil forests” and adds Malvaceae to the list of families known from the Azuero Peninsula (e.g., Arecaceae, Humiriaceae, Salicaceae, Hernandiaceae, Lauraceae, Fabaceae, Moraceae, Euphorbiaceae, Anacardiaceae/Burseraceae, Simplocaceae, and Anacardiaceae). All of the genera identified from Azuero fossil assemblages grow in lowland rainforests of Central America, with the exception of *Beilschmiedia*, which occurs in tropical to temperate forests.

Overlying Unit: N/A

Underlying Unit: In the central and northern parts of the Azuero peninsula, near the towns of Santiago and Macaracas, the Santiago Fm. overlies the Tonosí Formation (Kolarsky et al. (1995a, 1995b); Krawinkel et al. (1999); Buchs et al. (2011)), which now includes the sediments formerly known as Pesé Formation. See definition of Pesé Formation.

Remarks: The age of the Santiago Formation has not been clearly determined due to its stratigraphic complexity, lack of good outcrops, and absence of radiometric elements for dating (Rodríguez-Reyes et al. (2020a)). Note that Ministerio de Comercio e Industrias (1991) shows the Santiago Formation as older than the Gatún Formation while Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996) shows it as younger.

Maps, Cross-Sections & Pictures:

Figure 142. The large Anacardiaceae tree in its original position in the Santiago Formation. The preserved trunk is ~20m in length and 2.5m wide. The dimensions suggest a probable height of ~35m. Rodríguez-Reyes (2020a). *(Material reproduced with the permission of the editor)*.

Figure 143. **A)** Facade of "La Posada" in the town of Ocú, showing the abundance and quality of the fossil woods in the area. **B)** Close-up of some woods on the façade. **C)** Fossil wood used as ornaments in a home garden in Chitré. Rodríguez-Reyes (2019).

Unit: *SENOSRI LIMESTONE or *SENSORI AGGLOMERATE AND LIMESTONE
Epoch/Age/Author: Oligocene - Woodring (1960)
Remarks: See "Sinosri Formation"

Unit: SHARK HOLE POINT FORMATION (part of the Bocas del Toro Group)
Epoch/Age/Author: Pliocene (Zanclean to lower Piacenzian; 5.3-3.6 Ma) **-** Coates et al. (2005)
Original Author and/or Origin of the Name: The Shark Hole Point Formation was named by Coates et al. (1992) for the promontory of the same name that lies 3 km east of Chong Point (Figure 043).
Relevant documents discussing the Unit: Jung (1989); Collins et al. (1999a & 1999b); Coates (1999); Collins (1993); Coates et al. (2005); Todd & Collins (2005); Beu (2010); Landau et al. (2012b); Schwarzhans et al. (2013).
Location of the type section / Stratotype / Reference Section / Other localities: The stratotype lies along the coast between Chong Point and Bruno Bluff (Figure 042; Figure 043). The Reference section (Section 15 in Coates (1999)) is along the south coast of the Valiente Peninsula.
Lithology: The formation consists of micaceous, clayey siltstone that is pervasively bioturbated and rich in large scaphopods. The uppermost part of the formation also contains abundant, thin, shelly beds and intraformational slumps with pillow folds and rip-up clasts (Coates et al. (2005)). Benthic foraminifera indicate that the paleobathymetry of this unit ranges from 100-200 m (Collins (1993)). This represents the first stage of the regressive phase of the Bocas del Toro Group transgressive/regressive cycle. Calcareous nannofossils and planktonic foraminifera are abundant in several horizons and suggest the age of the formation is early Pliocene (5.3-3.6 Ma).
Thickness: 340 m
Macro Fossils: Scaphopods, crabs
Overlying Unit: The Shark Hole Point Formation is overlain by an unnamed conglomeratic, cross bedded, coarser grained sequence of volcaniclastics containing large pieces of wood and plant fragments. This unnamed unit is exposed only along the southern coast of the Valiente Peninsula, east of Secretario (Figure 042; Figure 043). (Coates et al. (2005)).
Underlying Unit: The Shark Hole Point Formation conformably overlies the Nancy Point Formation.
Remarks: The stratigraphic order of the Tobabe, Nancy Point and Shark Hole Formations (three of the five formations which make up the Bocas del Toro Group) has been determined by physical superposition. The two remaining formations of the Bocas del Toro Group (Escudo de Veraguas and Cayo Agua) as well as the younger Pleistocene Swan Cay Formation are known only on islands and their position relative to the other units has been determined by biostratigraphic evidence (Figure 044)

Unit: *SINOSRI FORMATION
Epoch/Age/Author: Oligocene - Woodring (1960)
Original Author and/or Origin of the Name: MacDonald et al. (1919).
Relevant documents discussing the Unit:

- Sapper (1937). Chart shows middle Oligocene "Senosri limestone" below upper Oligocene Uscari Formation.

- Woodring (1960). Undefined name for deposit of Oligocene age in the Bocas del Toro area. Sapper (1937, pp. 131, 132, 134) used, without further definition, the spelling Senosri. The proper spelling is Sinosri.
- Keroher et al. (1966)

Synonymy: Senosri Limestone, Sensori Agglomerate and Limestone (the latter being a misspelling)
Lithology: Conglomerate shales, tuff limestone, tuff, sandstone silt. http://www.tierragrande.co/2009/08/ruta-geologica/
Remarks: Bocas del Toro Province. Keroher et al. (1966).

Unit: *SOSA HILL BASALT
Epoch/Age/Author: Lower Miocene - Woodring (1960)
Original Author and/or Origin of the Name: Jones (1950). Unconformable above La Boca Formation, and below Chagres alluvium, Chagres gravel, and Pacific muck. "Basalt" is used in this paper as field term applied to basic fine-grained igneous rocks including "andesite" and "basalt".
Relevant documents discussing the Unit:

- Woodring (1960). Poorly defined name. Miraflores basalt has precedence, should a name be necessary.
- Keroher et al. (1966)

Synonymy: Miraflores Basalt
Remarks: Occurs near Balboa, in Pacific area of Panama Canal Zone. Keroher *et al.* (1966).

Unit: *SWAN CAY FORMATION
Epoch/Age/Author: Pleistocene (Calabrian - 0.78-1.77 Ma) - Coates et al. (2005)
Remarks: See Swan Cay Member

Unit: SWAN CAY MEMBER (of the Urraca Formation)
Epoch/Age/Author: Pleistocene (Calabrian - 0.78-1.77 Ma) - Coates et al. (2005)
Original Author and/or Origin of the Name: The Swan Cay was named by Coates (1999) and given the status of "Formation" for the small island of the same name that lies 1.7 km off the north coast of Colon Island (Figure 042). Later, Klaus et al. (2012) changed its status to a Member of the Urraca Formation, named after a private island.
Relevant documents discussing the Unit: Collins et al. (1999a & 1999b); Coates et al. (2005); Landau et al. (2012d) ; Schwarzhans et al. (2016).
Synonymy: Swan Cay Formation. Coates (1999); Klaus et al. (2012)
Location of the type section / Stratotype / Reference Section / Other localities: The stratotype (Section 25 of Coates (1999)) is the section that runs from north (youngest) to south (oldest) across Swan Cay Island. No other sections of the Swan Cay Member have been observed.
Lithology: The Member has three components. **The lower 15 m** is exposed on the southerly low hill of the island and consists of silty sandstone and shelly calcarenitic siltstone, with coral rubble and red algal fragments and balls. **The middle 4 m** consists of calcarenitic clayey siltstone, with dense, fine shellhash horizons, and abundant large coral colonies in the lower part. **The upper 60 m** of the formation consists of massively thick-bedded, pale tan-white calcarenite. The upper 30 m are vuggy, sparry, and clean and include a 4-m-thick coral bed with large *Montastraea* colonies, other corals and mollusks. The lower 30 m consist of more silty calcarenite with common red algae and large foraminifera, shell hash, and micromollusks. This limestone also shows evidence of frequent microfracturing, many of which are healed with secondary calcite cement. Cave deposits, about 5 m above the base of the calcarenite, consist of silty, shelly, volcaniclastic sandstone, mixed with abundant volcanic cobbles and boulders, and calcareous reef rubble containing an abundant and diverse molluscan assemblage (Coates (1999) & Coates *et al.* (2005)).
Thickness: 79 m
Macro Fossils: Coral, Mollusks. The most abundant corals are *Acropora palmata, A. cervicornis, Diploria labyrinthiformis, Montastraea faveolata, Porites furcata, Agaricia (Undaria) agaracites, Meandrina meandrites,* and *Dichocoenia stokes*. Coates et al. (2005).
Overlying Unit: No contacts are observed but the stratigraphic relationship of the Pleistocene Swan Cay Member, within the Bocas del Toro Group, is based on biostratigraphic data (Figure 044). Coates (1999).
Underlying Unit: No contacts are observed but the stratigraphic relationship of the Pleistocene Swan Cay Member, within the Bocas del Toro Group, is based on biostratigraphic data (Figure 044). Coates (1999).
Remarks: The stratigraphic order of the Tobabe, Nancy Point and Shark Hole Formations (three of the formations which make up the Bocas del Toro

Group) has been determined by physical superposition. The remaining formations of the Bocas del Toro Group are known only on islands and their position relative to the other units has been determined by biostratigraphic evidence (Figure 044). Coates (1999). Organisms from a range of depths indicate that the deposit is reworked forereef debris formed at about 100 m (Collins et al. (1999a & 1999b)). Microfossils are similarly reworked. Abundant large and freshly preserved globigerinid planktonic foraminifera combined with paleomagnetic data strongly suggest that the deposit is early Pleistocene (0.78-1.77 Ma). Coates et al. (2005).

Unit: TAPALIZA FORMATION

Epoch/Age/Author: Middle Miocene - Coates *et al*. (2004)

Original Author and/or Origin of the Name:

- Schuchert (1935). Dark foraminiferal shales. Tapaliza is the name of a village on tributary of Río Pucro.
- The Tapaliza Formation was named for the Tapaliza River, a tributary of the Tuira River in the north of Darién around the Membrillo River (Esso Exploration and Production Panama (1970)) (Figure 144).

Relevant documents discussing the Unit:

- Olsson (1942b). Tapaliza [group] includes Arusa and Aguagua Formations. Chart shows Tapaliza above Capetí limestones and below Gatún Formation. Upper Oligocene and lower Miocene.
- Wilson et al. (1957)
- Woodring (1960); An undefined name of formation or group rank to include the Arusa and Aquaqua Members or Formations. Though used later by Sapper (1937, p. 451) and Olsson (1942b, pp. 234, 241), the name still is undefined.
- Keroher (1966); Coates et al. (2004); Montes et al. (2010);

Synonymy: In some publications it is wrongly spelled "Topaliza"

Location of the type section / Stratotype / Reference Section / Other localities: The stratotype (TT) is located as shown on Figure 144 and runs for about 4 km above the confluence with the Pucuro River. Reference sections (TR on Figure 145) lie along the Tuquesa River at Charco Chiva and along the Marraganti River, about 10 km above its junction with the Tuquesa River. Coates et al. (2004)

Lithology: In the north, around the Membrillo River, the Tapaliza Formation is dominantly conchoidally weathering foraminiferal mudstone and siltstone containing abundant mollusk-rich horizons, and minor 10-20 cm thick volcanic sandstone units, often with prominent calcareous 5-10 cm concretions. Occasional cobble horizons also occur.

Farther south, between the Tapaliza and Chico Rivers, the formation consists dominantly of thin, evenly bedded, coarse volcanic sandstone alternating with burrowed black shale. The base of the sandstone units is generally characterized by abundant flame structures and load casts. In the lower half of the sequence the sandstone is laminated, with low-angled cross-bedding, abundant carbonaceous material with frequent entire leaves, and concretions up to 1.5 m in diameter at some horizons. Interbedded sublenticularly laminated clayey siltstone contains channel lenses with shell hash and Pectén shell beds.

On the western flank of the Tuira Basin, around Yaviza, the Tapaliza Formation shows a different facies. Five to 10 cm thick rhythmically bedded turbidite units consist of alternating graded graywacke and blackish gray clayey siltstone. The siltstone units are rich in pteropods, foraminifera (especially *Orbulina*), and finely disseminated plant fragments.

The Río Tapaliza exposes dominant mudslides with concoidal weathering, fossiliferous and limolites, containing sections with abundant mollusks and less abundant volcanic sandstone, forming strata 10 to 20 cm thick. These strata often contain calcareous concretions 5-10 cm in diameter. Further south between the Río Tapaliza and the Río Chico, thin layers of coarse sandstone alternate with black shales with small cavities. In the lower part of the sequence the sandstone is laminated, with cross stratification, abundant carbonaceous material, and frequent whole leaves. The inter-stratification exposes thin layers of clayey silt and Pecten shells. On the west flank of the Tuira Basin, the formation exposes a different facies, turbidites with rhythmic stratification of 5 to 10 cm in width, in graded graywacke alternating with blackish gray clayey siltstones. Limolites rich in pteropods (mollusks), foraminifera (Orbulin), and fine dissemination of plant fragments. Coates et al. (2004).

The Tapaliza Formation lies in the upper part of the Middle Miocene. Its sediments were deposited at middle bathyal depths (500-1500 m) in the deeper part of the Basin (Membrillo River and Tuquesa River sections).

Thickness: The thickness of the Tapaliza Formation ranges from about 400m in the northwest to 1200m near Yaviza.

Macro Fossils: Plant material, Pecten shells, mollusks (see "Lithology")

Overlying Unit: The Tapaliza Formation is conformable with the overlying Tuira Formation; the contact is faulted on the Membrillo River.

Underlying Unit: The Tapaliza Formation is conformable with the underlying Clarita Formation; the contact is faulted on the Membrillo River.

Maps, Cross-Sections & Pictures:

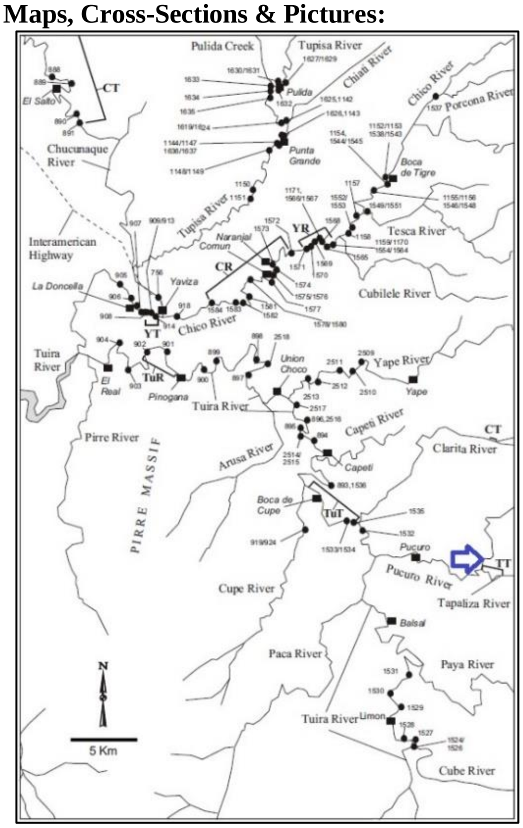


Figure 144. Locality of the Tapaliza Formation stratotype. Coates et al. (2004).

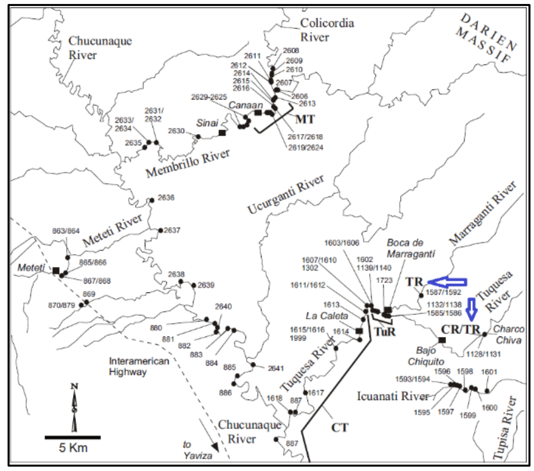


Figure 145. Locality of the Tapaliza Formation Reference Section. Coates et al. (2004).

Unit: *TIGRE LIMESTONE

Epoch/Age/Author: Oligocene Woodring (1960)

Original Author and/or Origin of the Name: MacDonald et al. (1919).

Relevant documents discussing the Unit:

- Wilmarth (1938).
- Woodring (1960). An undefined name of unspecified origin for limestone, assigned on unspecified grounds to the lower Oligocene. The name appeared in a table, showing that the limestone overlies the "Watsi and Mona shales". It was further specified that the limestone is locally subdivided into "the echinoid and the oyster Members" and that the limestone is generally characterized by *Orbitoides* [*Lepidocyclina*].
- Keroher et al. (1966)

Synonymy:

Location of the type section / Stratotype / Reference Section / Other localities: The type region, like that for the Mona shale, is in the Bocas del Toro area, in the foothills about 15 kilometers southwest of the mouth of Río Sixaola. The Tigre Creek is a local name for a small stream flowing into a northeastward-flowing tributary of Río San San. Woodring (1960).

Unit: TOBABE FORMATION (part of the Bocas del Toro Group)

Epoch/Age/Author: Upper Miocene (Messinian; 7.26-5.32 Ma) - Coates et al. (2003 & 2005)

Original Author and/or Origin of the Name: The formation was originally named by Coates

(1999) as "Tobabe" after the Guaymi village of Tobabe, located on the north coast of the Valiente Peninsula (Figure 043; Figure 042) near the Plantain Cays. In Coates et al. (2005), and few other authors after 2005, it is misspelled as "Tobobe".

Relevant documents discussing the Unit: Coates et al. (2003); Uhen et al. (2010); Todd & Collins (2005);

Synonymy: Tobabe sandstone, Tobobe (misspelling)

Location of the type section / Stratotype / Reference Section / Other localities: The stratotype (Section 12 of Coates (1999)) is on Small Plantain Cay (Figure 146); a small, unnamed island immediately to the west; and for about one km along the coast, between Tobabe Point and the village of Tobabe. Section 14 of Coates (1999) describes a lateral variation of the Tobabe Formation exposed on the Toro Cays, south of the entrance of Bluefields Bay, at the western end of the Valiente Peninsula (Figure 043; Figure 042).

Lithology: The Tobabe sandstone is the oldest unit of the Bocas del Toro Group (Figure 043). At the stratotype (Section 12 of Coates (1999)) the basal unit of the Tobabe sandstone is a pebble and cobble conglomerate, about 15 m thick, with a variety of sedimentary and volcanic subangular clasts. It is unfossiliferous in its basal portion, but contains scattered, thick-shelled mollusks and occasional echinoids in the upper part, which grades insensibly into the overlying quartz sandstone that forms the rest of the formation. The sandstone is relatively clean, indurated, massive and pervasively bioturbated, although thin but persistent horizons of pebble conglomerate occur and larger volcanic cobbles are scattered throughout.

The Tobabe Formation cropping out on the Toro Cays (Section 14 of Coates (1999)), is about 30 m thick. The lower 20 m consists of extensively burrowed, coarse, quartz and lithic volcanic sandstone with abundant and elaborate *thalassinoid* burrow systems, alternating with beds of 1m thick basalt and sandstone conglomerate, and occasional thin siltstone and muddy sandstone units containing scattered *turritellids* and other mollusks. The upper 10 m of the Tobabe Formation on the Toro Cays is composed of massive, shelly, volcaniclastic, relatively clean bioclastic sandstone, with strongly crosscutting, laminated channels. Spectacularly large, shell-filled burrows about 10-15 cm in diameter are very characteristic, as is pervasive burrow mottling, and in other horizons, vertical 1-3 cm burrow tubes. Thick-shelled mollusks, including pectens, erect bryozoans and spatangoid echinoids, are common.

Thickness: 30 m

Macro Fossils: Crabs, Mollusks, echinoids. Well-preserved burrows are present with particularly good examples of *Ophiomorpha* and *thalassinoid* burrows. The unit is distinguished by very abundant, large, thin-shelled *Amusium*, numerous large sand dollars and spatangoid echinoids. Other mollusks are present as low-diversity, poorly preserved molds. Occasional specimens of wood bored by *Teredo*, and worms, including serpulids and vermetids, are also present. A whale vertebra was also found in a sandy pebble conglomerate in the Tobabe Formation on Small Plantain Cay in the Bocas del Toro archipelago. Coates (1999) & Uhen et al. (2010).

Overlying Unit: It passes conformably up into the overlying Nancy Point Formation

Underlying Unit: The Tobabe Formation sits nonconformably upon the Miocene basement of basalt lavas, flow breccias, and volcaniclastic sediments.

Remarks: The stratigraphic order of the Tobabe, Nancy Point and Shark Hole Formations (three of the five formations which make up the Bocas del Toro Group) has been determined by physical superposition. The two remaining formations of the Bocas del Toro Group (Escudo de Veraguas and Cayo Agua) as well as the younger Pleistocene Swan Cay Formation are known only on islands and their position relative to the other units has been determined by biostratigraphic evidence (Figure 044). Coates (1999)

Maps, Cross-Sections & Pictures:

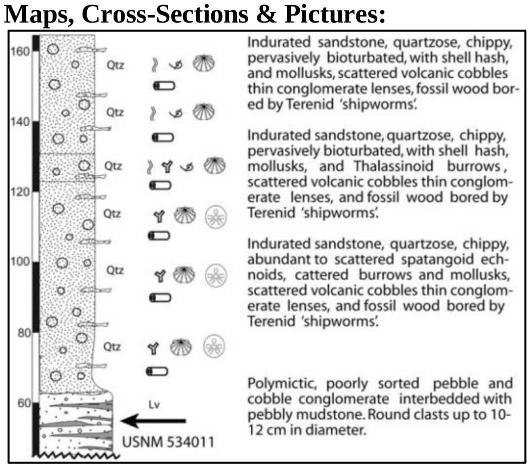


Figure 146. Section of the Tobabe Formation from Uhen et al. (2010). Small Plantain Cay to the Valiente Peninsula, Bocas del Toro (Figure 043;

Figure 042) (9°7’41.00”N, 81°48’36.25”W to ~9°7’11.45”N, 81°49’50.68”W)

Unit: TONOSÍ FORMATION

Epoch/Age/Author: Upper Eocene to Lower Miocene (Figure 051) - Buchs et al. (2011)

Original Author and/or Origin of the Name: Sapper (1937). Named on correlation chart. Occurs above Búcaro Formation and below unnamed upper Oligocene unit. **Note:** Vaughan (1918) talks about “Eocene of Tonosí”

Relevant documents discussing the Unit:

- Miller et al. (1939);
- Olsson (1942b). Name Tonosí limestone appears on correlation chart (p. 234). Occurs below upper Oligocene Santiago Formation and above unnamed lower Oligocene unit.
- Miller (1947); Terry (1956);
- Woodring (1960). An undefined name for strata of Oligocene age in Tonosí area. This age is defined by Larger foraminifera and corals.
- Stern & Eyde (1963); Keroher et al. (1966); Woodring (1973); Kolarsky (1992); Kolarsky et al. (1995a, 1995b); Krawinkel et al. (1999); Baumgartner-Mora et al. (2008); Buchs et al. (2010 & 2011); Corral et al. (2011); Herrera et al. (2012 & 2014b); Ramirez (2013); Vasquez & Pimiento (2014); Ramirez et al. (2016); Jud et al. (2017a); Perez-Consuegra et al. (2018).

Synonymy: The Pesé Formation (included in the Tonosí Formation in Buchs et al. (2008, 2011)). See definition of Pesé Formation.

Location of the type section / Stratotype / Reference Section / Other localities: Los Santos Province. Keroher et al. (1966)

Lithology: The Tonosí Formation consists of widespread marine and non-marine sedimentary rocks (Figure 150) thought to be of Middle Eocene-early Miocene age (Terry (1956); Kolarsky (1992); Kolarsky et al. (1995a, 1995b); Buchs et al. (2011)). It is exposed over most of the Azuero Peninsula (Buchs et al. (2011)) and it is conformed by a basal trangressive sequence of ~40 to 400 m-thick **(Lower Unit)** comprised of conglomerates and sandstones partly intercalated with minor coal seams and reefal limestone and is considered Middle Eocene to Upper Oligocene (Figure 149; Figure 145; Figure 146). The **Upper Unit** is a ~500 to 800 m-thick deepening upward section of mainly turbiditic sediments (interbedded sandstone, siltstone, shale and calcarenites) and is considered Upper Oligocene to Lower Miocene (Kolarsky et al. (1995a, 1995b); Krawinkel et al. (1999)).

At Punta Bucaró, the Lower unit crops out as a 560 m-thick section of basal conglomerate and minor sandstones; with no limestones present (Figure 147; Figure 148). It is assumed to directly overlie basement, although at this locality the base of the section is not exposed, and the lowermost beds are assumed to be faulted against basaltic basement (Kolarsky et al. (1995a, 1995b)).

Conglomerate beds range from massively bedded to thinly bedded and exhibit no thinning or finning upward trends. Thinly bedded conglomerate is more common than massive conglomerate, with beds of sand and gravel commonly 4 to 5 cm thick. Beds define both planar parallel stratification and tabular foresets. In decreasing abundance, conglomerate clasts include basalt, sandstone and shale fragments similar in lithology to Ocú Formation, and shell fragments (Kolarsky et al. (1995a, 1995b)).

Minor sandstone and siltstone beds make up less than 5% of the section. They are commonly 5 to 200 cm thick, poorly sorted, fine to coarse grained, and rarely pebbly. Sedimentary structures in sandstone beds include normal grading and planar cross stratification and through cross-stratification (Kolarsky et al. (1995a, 1995b))

Dominance of stratified conglomerate over massive conglomerate and the complete absence of mudstone interbeds suggest deposition of the Lower Tonosí Formation by traction currents of sheet flow in a high-energy shallow water environment. The presence of rare fossil-rich beds and lenses in conglomerate and sandstone is interpreted as the product of storm reworking and supports a shallow-water environment of deposition (Kolarsky et al. (1995a, 1995b)).

Thickness: 1200m

Macro Fossils: Nautiloids (*Aturia peruviana & Aturia panamensis*)[3](Miller et al. (1939); Miller (1947)), sharks and rays (*Odontaspis* sp., †*Cretolamna appendiculata*, Carcharnifomes, *Aetobatus* sp.). The sharks and rays material came from the three following localities: Agua Buena (7°26’58.85”N 80°20’58.40”W), Playa Búcaro

[3] Miller (1947) states that a paleontologist friend of his told him that he had seen some small aturias from beds of Lower Miocene (or possibly Upper Oligocene) age near David, in western Panama.

(7°20’53.28”N 80°21’7.88”W) and Escuela-Iglesia Búcaro (7°20’50.61”N 80°21’13.47”W). (Vasquez & Pimiento (2014)). Fossil fruits and seeds reported by Herrera et al. (2012) indicate the possible presence of nearby lowland rainforests in the Búcaro area; in agreement with the description of mangrove swamp palynomorphs found in the Gatuncillo Formation by Graham (1985). This macro and micro flora would be the first record of vegetation that colonized land in the Isthmus of Panama.

The first specimen of Humiriaceous fossil wood was collected by John E. Ebinger in 1961 (Stern and Eyde (1963)), 3.2 kms northwest of the town of Ocú on the Azuero Penuinsula. Herrera et al. (2014b) revisited Ocú and collected abundant large, silicified wood fragments. The wood specimens are not found in situ but instead appeared scattered in pastures, without evidence of the parental rock (lat. 7°55.476’N, long. 80°47.959’W) (see “Note” below). Near Ocú they found siltstones from a small quarry (lat. 7°54.790’N, long. 80°47.085’W). This new locality yielded impressions of elliptical fruits resembling Humiriaceae and fragments of carbonized wood. Fossil invertebrates from the siltstones indicate a late Eocene age for these sediments. Recent mapping of the north-central part of the Azuero Peninsula suggests that sediments exposed near the town of Ocú and surrounding areas belong to the late Eocene–late Oligocene Tonosí Formation (Buchs et al. (2011)). Based on their observations near Ocú and the recent geological mapping, Herrera et al. (2014b) tentatively consider the fossil wood [of *Humiriaceoxylon ocuensis*] of Stern and Eyde (1963) to be Late Eocene (ca. 37.2–33.9 Ma) in age. Perez-Consuegra et al. (2018) describes permineralized and carbonized fossil endocarps and seeds of *Humiriaceae* from Oligocene and Early Miocene sections of the Tonosí Formation in western Azuero Peninsula, near the town of Torio, province of Veraguas. In the lower part of one of the sections, they also recognize vertebrate remains, echinoderms, mollusks, burrows, corals, algae, Talassinoids, shells and leaves. At the mouth of Río Pedregal (548410/800564 UTM WGS84) paralic facies including well-rounded basaltic conglomerates encroach unconformably on accreted seamount rocks and on deformed packages of the Covachón Formation. These conglomerates contain large oysters (*Spondylus* sp.) and a detrital matrix with abundant larger benthic Foraminifera (Buchs et al. (2011)).

Note: At the surface of the Tonosí Formation near the towns of Ocú and Chitre, large quantities of petrified wood/trees can be found on catle ranch and other private lands. The fossils, known locally as chumicos, are strewn about in pastures and piled up in gullies in such abundance that the townspeople of Ocú and Chitre use them as decorative building stones. Pieces are angular and range in size from small hand specimens to stumps a foot or more in diameter (Stern & Eyde (1963)) (Figure 143). However, even though they lay at the surface of the Tonosí Formation, no trunks have ever been found *in-situ*. This led Jud et al. (2017a) to describe several specimens of silicified woods from the area of Ocú, which in turn led them to suggest that they originated from the younger Santiago Formation (eroded away in this area). This was confirmed by Rodríguez-Reyes (2019, 2020a) who found similar medium to large size tree trunks *in-situ* within the Santiago Formation more the the northwest (See “Santiago Formation”).

Overlying Unit: N/A

Underlying Unit: Depending on the region (Figure 051) the Tonosí Fromation is underlained either by the Azuero Arc Group, Covachón Formation or Ocú Formation.

Remarks: As per Baumgartner-Mora et al. (2008), the formation’s age spans from 40 to 35 Ma. Studies on foraminifera and paleobotanical reconstructions performed by Herrera et al. (2012) suggest that the sediments of the Tonosí Formation were deposited in a shallow marine environment. Additionally, these sediments have a strong terrestrial influence, possibly produced by the emergence of the Isthmus of Panama, which began during the Middle-Upper Eocene. Consequently, the Tonosí Formation represents one of the oldest sedimentary sequences of the Isthmus of Panama (Herrera et al. (2012)).

Maps, Cross-Sections & Pictures:

Figure 147 (up). Outcrop of the Lower Tonosí Formation at Bucaró beach. Basal conglomeratic

sandstones and coarse sandstones in planar parallel stratification. Ramirez (2013).

Figure 148 (down). Upper Tonosí - Gray, well-sorted, fossiliferous litharenites. Ramirez (2013).

Figure 149. Hemipelagic basal Tonosí Formation close to Cacao (511700/810125 UTM WGS84). Buchs (2008).

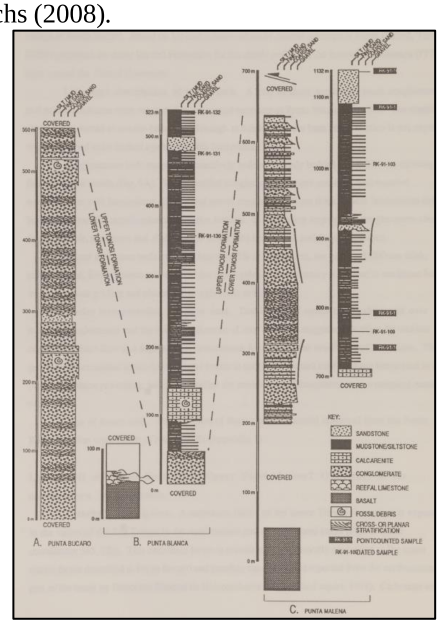


Figure 150. Stratigraphic sections of the Tonosí Formation on the Azuero Peninsula by Kolarsky (1992). **A)** Two measured sections at Punta Blanca on the southern coast of the Azuero Peninsula: the section to the left shows Middle Eocene reefal limestone unconformably overlying basaltic basement and the section to the right shows basal conglomerate and turbiditic section overlying a covered interval assumed to be basaltic basement similar to that seen at the section on the left; **B)** Measured section at Punta Búcaro on the southeast coast of the Azuero Peninsula; **C)** Measured section at Punta Malena on the west coast of the Azuero Peninsula.

Unit: *TOREO LIMESTONE

Epoch/Age/Author: Eocene (?) - Woodring (1960)

Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). This limestone is well exposed on the Torio River [Río Toreo], a few miles from the coast, in many irregular patches of light gray limestone, some of which are of small extent and others quite important. It is here always well stratified, being moderately thin-bedded and dipping steeply in one or another direction. It is a hard, light gray, massive limestone. It is sometimes nearly pure and is then sub-crystalline. More often it is very impure, but its outcrop always reveals its calcareous character. In places it abounds in fossils (mostly shells of marine brachiapod or lamellibranchiate species) which are so cemented into the rock that they can not be separated from it.

Relevant documents discussing the Unit:

- Olsson (1942b). Upper Eocene Torio Limestone is unconformable below Montijo Formation.
- Woodring (1960). Upper Eocene Torio Limestone is unconformable below Montijo Formation. A Late Jurassic or Early Cretaceous age was initially suggested. However, an Eocene age was later suggested.
- Keroher et al. (1966)

Synonymy: Torio Limestone, as written in Hershey (1901)'s report

Remarks: On west side of Azuero Peninsula. Along Río Toreo, Veraguas Province. Keroher et al. (1966).

Unit: TORO MEMBER (of the Chagres Formation)

Epoch/Age/Author: Late Miocene (Tortonian to Messinian**) -** Collins et al. (1996)

Original Author and/or Origin of the Name: MacDonald (1915). Sandy fragmental limestone at Toro Point, on the Caribbean coast of the Canal Zone and elsewhere west of the Canal is named the Toro limestone. Toro Point was specified as the type locality. The age was shown as Pleistocene or Pliocene in figure 2.

Relevant documents discussing the Unit:

- Vaughan (1918);
- Schuchert (1935, p. 560, map explanation) and Olsson (1942b, p. 247) use the designation of "Toro Formation".
- Thompson (1943). The names Toro limestone and Caribbean limestone have been used to describe deposits of shell breccia or cemented coquina that overlie Gatún sandstone in region between Lemon Bay and Chagres River. The Toro Formation has been assigned to upper Miocene.
- Woodring & Thompson (1949). Rank reduced to Member status in the Chagres sandstone. Chiefly a lime-cemented coquina made up of barnacle and shell fragments; lenses of medium- to coarse-grained sandstone interbedded with the calcareous beds. Variable thickness; maximum 125 feet [38m]. Overlies Gatún Formation. Late Miocene
- Woodring (1955). Late Pliocene
- Woodring (1957).
- Woodring (1960). The Toro limestone is a thin basal Member of the Chagres sandstone. It unconformably overlaps part of the Miocene Gatún Formation. The maximum thickness is 125 feet [38m]. The limestone contains *Sthenorytis toroensis*, *Pecten gatunensis macdonaldi* and other mollusks not yet recorded. The fossils, mostly mollusks, indicate an early Pliocene age.
- Keroher et al. (1966); Woodring (1982); Collins et al. (1996).

Synonymy: Toro Limestone, Toros Limestone, Caribbean limestone, Toro Formation.

Location of the type section / Stratotype / Reference Section / Other localities: Toro Point, Canal Zone (Keroher et al, 1966).

Lithology: See Chagres Formation for a description of the lithology and final age definition.

Thickness: 60 m (Collins et al. (1996))

Macro Fossils: See Chagres Formation

Overlying Unit: See Chagres Formation

Underlying Unit: See Chagres Formation

Unit: *TRANQUILLA SHALE FORMATION

Epoch/Age/Author: Upper Eocene - Woodring (1957)

Original Author and/or Origin of the Name: Coryell et al. (1937b). The name “Tranquilla” was suggested by the geologist Mr. Robert Terry [who would later write Terry (1956)], who carefully studied this region and who discovered the formation in the upper Chagres Valley.

Relevant documents discussing the Unit:

- Vaughan (1926);
- Coryell et al. (1937b). Name proposed for basal Tertiary beds that have been included in Bohío Formation. Bohío is restricted to include only Oligocene sediments which overlie Tranquilla. Greenish-gray shale that contains well-preserved foraminiferal fauna. On basis of fauna, regarded as Jackson (late Eocene).
- Thompson, T. F. (1944)
- Woodring & Thompson (1949). The name Tranquilla was discarded because the type area is now covered by the waters of Madden Lake (now Alajuela Lake), and no longer accessible.
- Woodring (1957) and Woodring (1960) and Keroher (1966). The name was suppressed in favor of Gatuncillo Formation.

Synonymy: Gatuncillo Shale, Gatuncillo Formation (current name). Woodring (1957)

Location of the type section / Stratotype / Reference Section / Other localities: The type locality is 79° 13' [33”] West, 10° 15' North (Figure 151) in upper Chagres River Valley. Location now under the man-made lake Alajuela.

Lithology: The Tranquilla shale is a greenish gray shale which changes easily to a waxy mud in wet outcrops. It contains, in addition to small fragments of feldspar, indigo-blue particles that are believed to be organic in origin. The most distinguishing characteristic of this shale is the finely preserved foraminiferal fauna. The samples yield a great abundance of typical Upper Eocene foraminifera. Coryell et al. (1937b).

Macro Fossils: Foraminifera [Vaughan (1926) studied *Lepidocyclina Chaperi*.]

Overlying Unit: An unconformity is present at the top of the Eocene beds in the Chagres Valley and the formation is overlain by the Oligocene Bohío Formation.

Underlying Unit: It immediately overlies the andesitic Cretaceous basement in the upper Chagres Valley

Remarks: Judged from the nature and abundance of its fauna, the shale is believed to have been deposited in shallow water. It forms the base of the Paleogene column in the Chagres Valley and is the oldest sedimentary formation which can be observed in Panama from the border of Costa Rica to the Province of Darien.

Note that Vaughan (1926) describes a limestone in the upper Chagres river and assigns it an Upper Eocene age due to its content in *Lepidocyclina chaperi*. However, no coordinate is mentioned in his article.

Maps, Cross-Sections & Pictures:

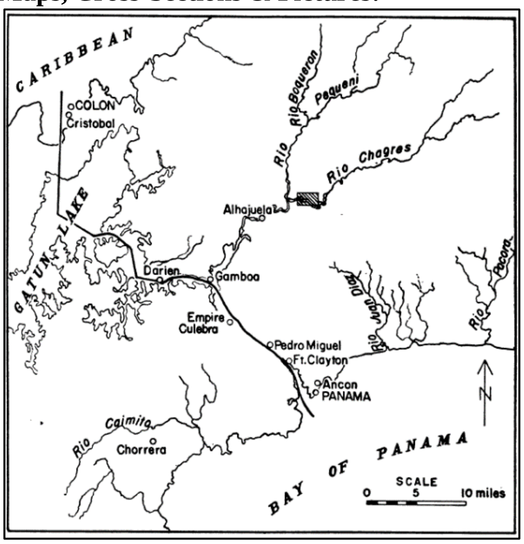


Figure 151. The shaded area on the Río Chagres includes the type locality of the Tranquilla shale and other good outcrops. Coryell et al. (1937b).

Unit: TUIRA FORMATION

Epoch/Age/Author: Upper Miocene (Tortonian) **-** Coates et al. (2004)

Original Author and/or Origin of the Name:

- Sapper (1937). (correlation chart). Underlies Pucro sandstone. Equivalent to the lower Gatún Formation of the Darien area. Middle Miocene.
- The Tuira Formation was named in the Esso Exploration and Production Inc., Annual Report, (1970) without reference to a type section.

Relevant documents discussing the Unit:

- Terry (1956, p.50). Though the name presumably was supplied by Terry, in his own publication he used the designation "lower Gatún".
- Wilson et al. (1957).
- Woodring (1960). Not properly defined. Miocene.
- Gertman (1969); Coates, Anthony G. et al. (2004); Todd & Collins (2005); Beu (2010); Landau et al. (2010); Barat et al. (2014); Gurocak-Orhun et al. (2017);

Synonymy:

Location of the type section / Stratotype / Reference Section / Other localities: The stratotype (TuT) of the Tuira Formation, defined in Coates et al. (2004), lies along the Tuira River, from the Clarita River northwestward to its junction with the Cupe River (Figure 152). Reference sections (TuR) are located on the Tuquesa River (Figure 152), and on the Tuira River, 6 km east of El Real to Pinogana. (Figure 153). Darien area.

Lithology: The Tuira Formation (Figure 154) is largely marine, consisting of thin and regularly bedded alternations of blue gray graywacke and arkosic sandstone with dark green to black, silty claystone and siltstone. The Tuira Formation belongs to the lower part of the upper Miocene (11 to 9.5 Ma.) on the basis of its age-diagnostic calcareous nannofossils and planktic foraminifera. Gurocak-Orhun et al. (2017).

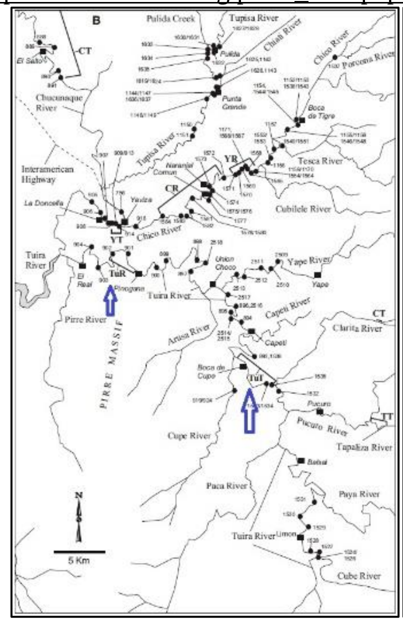
- Sediments were deposited at inner neritic (0–30 m) to middle bathyal (500–1500 m) depths.
- Paleoenvironments varied from middle to upper bathyal in the center of the Chucunaque-Tuira (C-T) Basin to shallower, neritic depths on its margins. The seaward Sambu Basin was as deep as the center of the C-T Basin. These paleoenvironments were mostly deep-water, low-oxygen facies, similar to those of the Eastern Pacific oxygen minimum zone and California borderland Basins.
- In the center of the C-T Basin and Sambu Basin, paleobathymetries of the Tuira Formation and its overlying and underlying formations show a progressive shallowing in the late Miocene from the middle bathyal, Tapaliza and Membrillo/Tuira Formations to the upper bathyal Chucunaque Formation, roughly 675 m, due to the uplift of the Isthmus of Panama.

Thickness: The thickness of the Tuira Formation ranges from 500m in the northwest to about 1000m around Yaviza.

Macro Fossils: Crabs, Abundant plant debris, scattered small mollusks, particularly pectinids, nuculanids, Notocorbula, sponges and abundant benthic foraminifera are typical. Many units have pervasive bioturbation or thalassinoid burrow systems. Occasional pebble breccia, shell beds, and stringers of rip-up clasts also occur. Locally, around the region of the Chico River, shelly volcanic sandstone and pebble conglomerate, and shell beds with large, thick-shelled mollusks, are more common.

Overlying Unit: The upper contact of the Tuira Formation in the Chucunaque-Tuira Basin is apparently conformable and marked by an abrupt

transition from sandstone to the more calcareous shelly facies of the Yaviza Formation.
Underlying Unit: The Tapaliza Formation across the Chucunaque-Tuira Basin. The lower contact is not exposed but is apparently conformable.
Remarks: Under https://www.mindat.org/paleo_strat.php?id=22296 the Tuira Formation is listed as belonging to the "Lara Group", however no information could be found about this group in the literature. Other formations included in this Group are unknown.
Maps, Cross-Sections & Pictures:



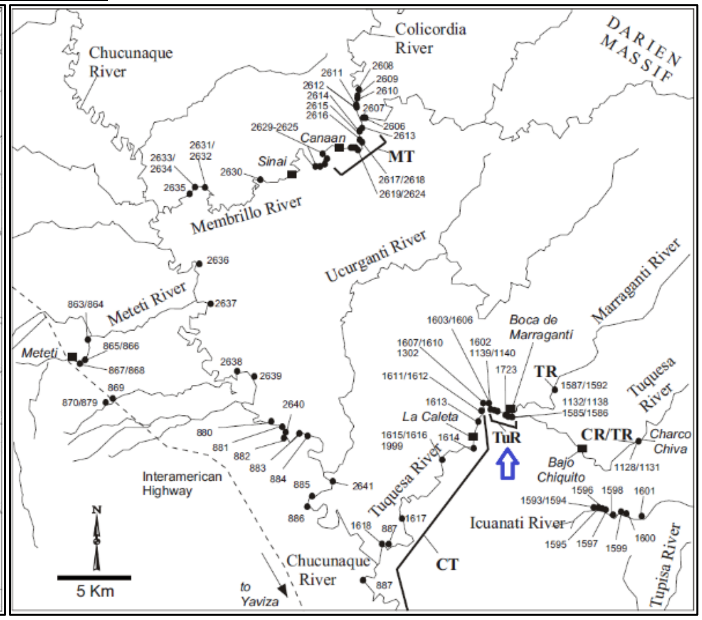


Figure 152 (left): Stratotype (TuT) & the first Reference Section (TuR) of the Tuira Formation. Coates *et al.* (2004).
Figure 153 (right): Locality of the second Reference Section of the Tuira Formation Coates *et al*. (2004).

Figure 154. Gray marls of Tortonian age from the Sambu Basin, Tuira Formation (8.04163°, −78.32661°, WGS84). Barat (2013) and Barat *et al*. (2014).

Unit: URRACA FORMATION
Epoch/Age/Author: Mid-Pleistocene (Calabrian: 1.2-0.78 Ma) - Klaus et al. (2012)
Original Author and/or Origin of the Name: The name first appeared in the literature in Klaus et al. (2012).
Relevant documents discussing the Unit: Coates (1999); Collins et al. (1999a & 1999b); Coates et al. (2005); Kiessling et al. (2011)
Location of the type section / Stratotype / Reference Section / Other localities: Isla Colon (Figure 042)
Lithology: The Urraca Formation comprises three Members (Base to Top):
The Mimitimbi Member is exposed along the banks of the Mimitimbi River on the northeastern coast of Colon Island (Figure 042). The unit is marked by abundant corals (Figure 155) and skeletal debris admixed with carbonate and siliciclastic mud. The unit consists of alternating coral-rich beds and muddy siliciclastic beds at its base and transitions up-section to a series of shallowing-upward burrowed-crossbedded units of carbonate sand.
The Hill Point Member occurs along the southeast coast of Colon Island as well as along the north coast as a series of pinnacle-barrier reefs (Figure 042). These shallow reef units correlate

with deeper fore-reef deposits found on Swan Cay north of Colon Island.

Swan Cay Member (79m): The Member has three components. **The lower 15 m** is exposed on the southerly low hill of the island and consists of silty sandstone and shelly calcarenitic siltstone, with coral rubble and red algal fragments and balls. **The middle 4 m** consists of calcarenitic clayey siltstone, with dense, fine shellhash horizons, and abundant large coral colonies in the lower part. **The upper 60 m** of the formation consists of massively thick-bedded, pale tan-white calcarenite. The upper 30 m are vuggy, sparry, and clean and include a 4-m-thick coral bed with large *Montastraea* colonies, other corals and mollusks. The lower 30 m consist of more silty calcarenite with common red algae and large foraminifera, shell hash, and micromollusks. This limestone also shows evidence of frequent microfracturing, many of which are healed with secondary calcite cement. Cave deposits, about 5 m above the base of the calcarenite, consist of silty, shelly, volcaniclastic sandstone, mixed with abundant volcanic cobbles and boulders, and calcareous reef rubble containing an abundant and diverse molluscan assemblage. Coates (1999) & Coates et al. (2005).

Based on stratigraphic relationships, the Mimitimbi Member is slightly older than the Hill Point Member.

Macro Fossils: The Swan Cay Member contains coral and mollusks. The most abundant corals are *Acropora palmata, A. cervicornis, Diploria labyrinthiformis, Montastraea faveolata, Porites furcata, Agaricia (Undaria) agaracites, Meandrina meandrites,* and *Dichocoenia stokes* (Coates et al. (2005)). Organisms from a range of depths indicate that the Swan Cay Member deposit is a reworked forereef debris formed at about 100 m (Collins et al. (1999a & 1999b)). Microfossils are similarly reworked. The corals from the Mimitimbi Member include *Madracis pharensis, Dichocoenia stellaris, Stephanocoenia spongiformis, Mycetophyllia danaana* and *Scolymia cubensis* (Figure 155). Klaus et al. (2012).

Overlying Unit: N/A

Underlying Unit: The Ground Creek Member and La Gruta Member of the Isla Colon Formation

Remarks:

Maps, Cross-Sections & Pictures:

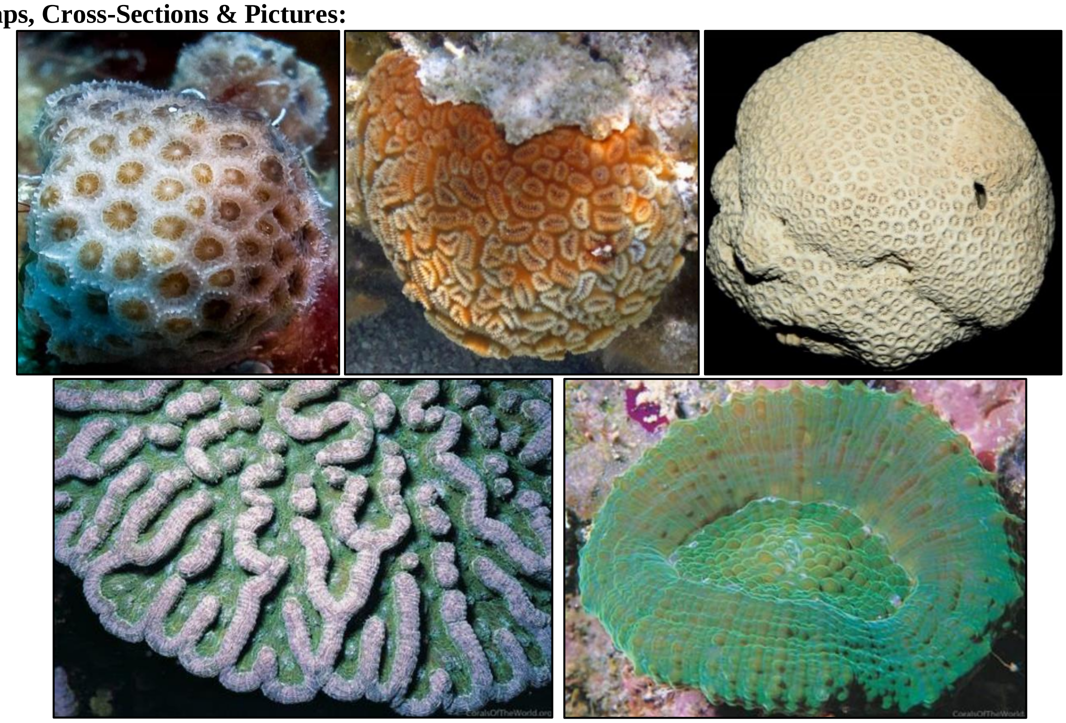


Figure 155. Modern day equivalent of common Neogene coral species from the Urraca Formation (Mimitimbi Member) that Klaus et al. (2012) recovered from the Bocas del Toro region of Panama. Top (left to right) - *Madracis pharensis, Dichocoenia stellaris, Stephanocoenia spongiformis.* Bottom (left to right) - *Mycetophyllia danaana, Scolymia cubensis.* From www.coralsoftheworld.org, www.wikipedia.org, and www.ebay.com

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Unit: *USCARI FORMATION
Epoch/Age/Author: Late Oligocene and Early Miocene - Woodring WP (1960)
Original Author and/or Origin of the Name: Olsson, A. A. (1922).
Relevant documents discussing the Unit:

- Woodring WP (1957): Olsson, A. A. (1922)'s Gatún rests unconformably on the Uscari Formation (or better Uscari shale), which consists almost entirely of moderately deep-water fine-grained rocks (Olsson, 1922, p. 10). Light oil issues from fractures in strongly deformed strata of the Uscari in the type region along Uscari Creek (Bocas del Toro). The Uscari is of late Oligocene and early Miocene age and corresponds in age to the Caimito Formation of Madden Basin.
- Woodring (1960). The Uscari shale (type locality in the adjoining part of Costa Rica) crops out in the Bocas del Toro area. Though the Uscari is known to be of Late Oligocene and Early Miocene age, faunal data for the Panama part of the area is meager, with the exception of a list of subsurface smaller foraminifera from Columbus Island [Isla Colon] (Terry, 1956, pp. 41-42).

Synonymy: Uscari Shale.
Remarks: Bocas del Toro Province. The Uscari Formation/Shale is not mentioned in Keroher et al. (1966) and should be discarded in Panama. The Uscari Formation is mentioned in Coates et al. (2005) but as a formation in Costa Rica.

Unit: VALIENTE FORMATION
Epoch/Age/Author: Lower to Upper Miocene (Burdigalian to Tortonian; 18.2 to 11 Ma) - Coates et al. (2003 & 2005)
Original Author and/or Origin of the Name: The Valiente Formation is named by Collins et al. (1999a & 1999b) for the Valiente Peninsula (Figure 043; Figure 042) on which the formation crops out extensively. Klaus et al. (2012).
Relevant documents discussing the Unit: Landau et al. (2012b); Coates et al. (2003 & 2005); Klaus et al. (2012)
Synonymy: Punta Valiente
Location of the type section / Stratotype / Reference Section / Other localities: In the **Southern Region** of Bocas del Toro, the Valiente Formation crops out extensively on the Valiente Peninsula (Figure 043, Figure 042, Figure 156) and nearby Deer and Popa islands (Figure 042). In the **Northern Region** a spectacular exposure along the northwestern coast of Bastimentos Island (Figure 042) of columnar basalt and flow breccia are assigned to the Valiente Formation solely on their great similarity in lithology. The exposures range from Toro Point to the eastern side of Dreffe Beach and occur also at the western end of Long Beach. These basalt units probably form the basement of the entire Bocas del Toro Archipelago. Coates et al. (2005).
Lithology: The Valiente Formation is of complex and highly variable lithology because it represents the suite of facies, marine and terrestrial, igneous and sedimentary, that is associated with an active emergent volcanic island arc. It includes (Klaus et al. (2012):
(1) columnar basalt-lava and flow-breccia lithofacies,
(2) pyroclastic tuff (airborne volcanic ash deposits) lithofacies,
(3) coarse-grained volcaniclastic lithofacies (fluviatile/estuarine conglomerate),
(4) marine debris-flow and turbidite lithofacies,
(5) coral reef lithofacies (12 and 11 Ma; Klaus *et al*. (2012)

These facies intercalate and replace each other over very short distances, both laterally and vertically (for detailed descriptions of the facies, see Coates et al. (2003)). Figure 043 shows that the basalt lava and flow breccia facies form a core around which the other facies are distributed peripherally as terrestrial, coastal or marine slope deposits. Coates et al. (2005).

At Toro Point the coral reef lithofacies (5) consists of thick-bedded, rubbly, bioclastic, pale blue limestone that contains volcanic sand and silt grains in varying amounts. The limestone is ~37 m thick and has interbeds up to 6 m thick of volcanic-cobble conglomerate with well-rounded clasts and a graywacke matrix. Klaus et al. (2012).
Thickness: 135 m thick at the type section at Toro Point, Valiente Peninsula (Figure 043; Figure 042). Klaus et al. (2012)
Macro Fossils: Landau et al. (2012b) study the Cancellariidae gastropods from the Valiente Formation. Facies 5 consist of several species of *Montastraea* (including *M. imperatoris* and *M. canalis*), massive *Porites waylandi* and thin branching *Stylophora* (possibly *S. granulate*).
Overlying Unit: Tobabe Sandstone of the Bocas del Toro Group, Valiente Peninsula (Figure 043; Figure 042) or Cayo Agua Formation, Popa Island (Figure 042). An unconformity between the Valiente Formation and the Bocas del Toro Group can be clearly observed in the inner islands of the Plantain Cays and along the coast immediately to

the west. The underlying columnar basalt of the Valiente Formation can be seen on the north side of the Cays and the fossiliferous conglomerate and sandstone of the Tobabe Sandstone on the south side.
Underlying Unit: Punta Alegre Formation
Remarks: Planktonic microbiotas and radiometrically dated basalt in the sequence indicate that the Valiente Formation ranges in age from 16.5-11.5 million years old and includes marine deposits from near-shore to as deep as 1000 m, as well as several types of terrestrial deposits. Coates et al. (2003).
Maps, Cross-Sections & Pictures:

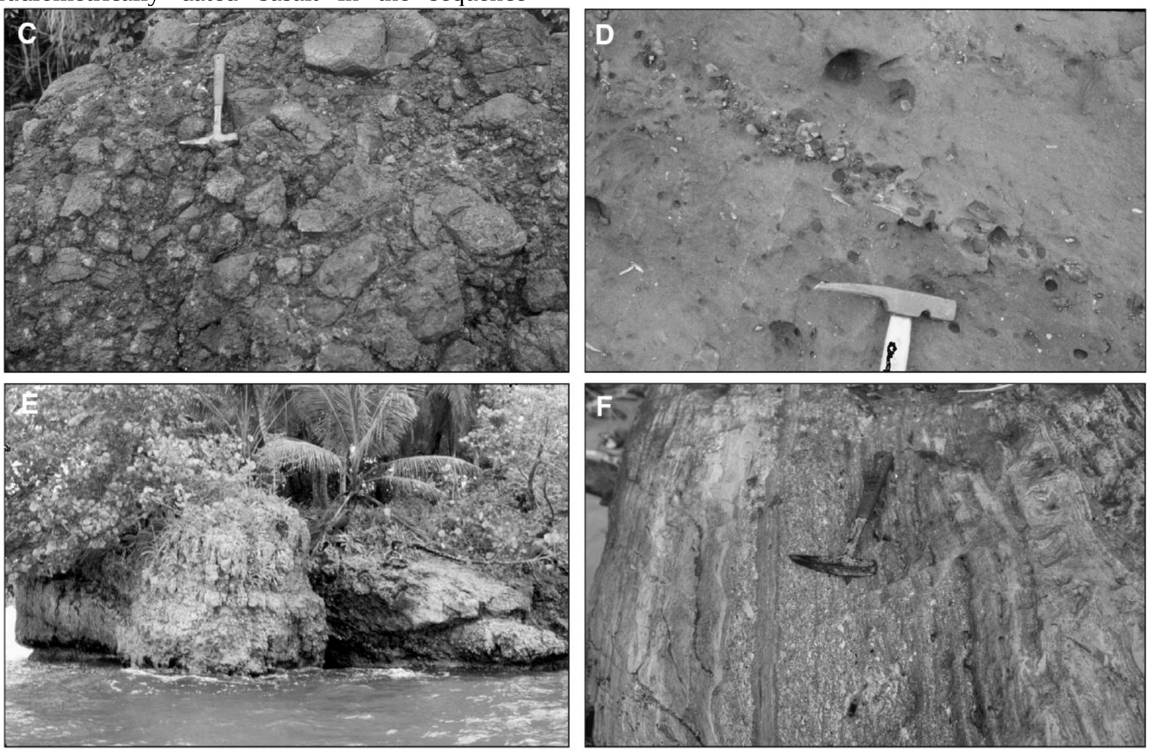

Figure 156. **(C)** Typical basaltic flow breccia in the stratotype of the Valiente Formation, along the coast, 900 m south of Toro Point, Valiente Peninsula (Figure 043; Figure 042), Bocas del Toro. **(D)** Coarse-grained volcaniclastic facies in the stratotype of the Valiente Formation, along the coast ;850 m south of Toro Point, Valiente Peninsula, Bocas del Toro. **(E)** Bedded reef-rubble limestone in the stratotype of the Valiente Formation at Toro Point, Valiente Peninsula, Bocas del Toro. **(F)** Overturned block of the turbidite lithofacies of the Valiente Formation, 1 km south of Toro Point, Valiente Peninsula, Bocas del Toro. In the photographs with a hammer for scale, the hammer head is 14 cm long and the handle is 34 cm long. Coates et al. (2003).

Unit: *VAMOS VAMOS BEDS
Epoch/Age/Author: Eocene or Oligocene - Woodring (1960)
Original Author and/or Origin of the Name: Hill (1898). He used the name “Vamos Á Vamos beds”.
Relevant documents discussing the Unit:

- Wilmarth (1938); Thompson (1944), Woodring (1957)
- Woodring (1960). “Vamos Á Vamos” beds are interpreted as marine deposits in the lower part of Bohío Formation. Name should be “Vamos Vamos”.
- Keroher et al. (1966)

Synonymy: Vamos Á Vamos beds; Part of Bohío Formation.
Remarks: Vamos Vamos is now a submerged locality on French Canal, Canal Zone. Site is off northeast coast of Barro Colorado Island. Keroher et al. (1966).

Unit: *VERAGUAS CRYSTALLINE SERIES
Epoch/Age/Author: Cretaceous(?) – (See “Remarks”) - Woodring (1960)
Original Author and/or Origin of the Name: Hershey (1901) (Figure 052). In the valley of the Río Santa Maria on the southern slope of the range (or Sierra Balcazar in the Cordillera de Veraguas),

the formation is mainly a rather coarsely crystalline plutonic rock of light yellowish gray color. With its abundant free quartz, it somewhat resembles a true granite on outcrop. The interior is hard and often horizontally jointed, giving it a quasistratiform appearance. This was identified as rhyolite, but the fragment examined was small, and although the rock has the composition of a soda-rhyolite, its occurrence as an intrusive, and its coarse granitic structure, would seem rather to entitle it to be termed an alkaline granite. The Veraguas crystallines (syenite and alkaline granite) belong to the same system of "pseudo granite or syenite" rocks mentioned by Hill as exposed in the plateau of Costa Rica, the Sierra San Bias, around the Sierra del Marta, on the South American mainland, and at several places in the Antilles. The age of these syenitic batholites is variously given as " mid-Tertiary " and "late-Tertiary." It is probable that it was the uplift of the Isthmian Territory due to the upthrust of the crystalline magmas of the Cordillera de Veraguas and the Sierra San Bias which ended the Tertiary sedimentation along the Panama Canal section, and hence it may be provisionally considered middle Miocene in age.

Relevant documents discussing the Unit:

- Woodring (1960). Volcanic and intrusive rocks in the range forming the Continental Divide in Veraguas Province. Cretaceous(?).
- Keroher et al (1966)

Remarks: Present in range forming continental divide in Veraguas Province. Woodring (1960).

Unit: *WEMIR AGGLOMERATE

Epoch/Age/Author: Miocene **-** Woodring (1960)

Original Author and/or Origin of the Name: Thompson (1943). Agglomerate is finer in texture than typical basaltic agglomerates in Pacific area; well bedded, with strata ranging from a few inches to several feet in thickness; commonly contains beds of soft shale of soapy fine-grained texture; contains water-sorted fragments and is believed to be phase of more massive land-laid deposits commonly present elsewhere. Age not stated.

Relevant documents discussing the Unit: Woodring (1960) and Keroher et al. (1966): A name, used for purposes of engineering geology, for fine grained agglomerate, in the Miraflores area, now included in the Pedro Miguel agglomerate Member of the Panamá Formation.

Remarks: Occurs in West Miraflores Hill area. Keroher et al. (1966).

Unit: YAVIZA FORMATION

Epoch/Age/Author: Upper Miocene (between 9.4 and 8.6 Ma) **-** Coates et al. (2004)

Original Author and/or Origin of the Name: The Yaviza Formation is defined and named for the town of Yaviza, the eastern terminus of the Pan-American Highway, by Coates et al. (2004).

Relevant documents discussing the Unit: No other could be found.

Location of the type section / Stratotype / Reference Section / Other localities: The stratotype of the Yaviza Formation lies on the northern bank of the Chucunaque River, downstream from the western edge of Yaviza (YT on Figure 157). A reference section is located on the Chico River below its junction with the Cubilele River (YR on Figure 157)

Lithology: The formation consists mainly of blue gray, massively bedded, pervasively bioturbated, shelly, lithic sandstone. The Yaviza Formation crops out in the central and eastern Chucunaque-Tuira Basin but thins westward and is not present in the Membrillo River section and beyond. The Yaviza Formation is an inner neritic deposit. Benthic foraminifera are generally absent from the Tuquesa River, Tupisa River, and Chico River sections or are very poorly preserved. The Yaviza Formation near Yaviza appears to be a slightly deeper, middle neritic facies. The inner neritic taxa are less common, and species that live mostly deeper than 30 m are very abundant. Farther south, near the Cube River, the Yaviza Formation is an outer neritic facies. The Yaviza Formation is placed in the middle part of the upper Miocene, based on the evidence from the upper Tuira River section. It falls within a 0.8 m.y. interval between 9.4 and 8.6 Ma.

Thickness: The thickness of the Yaviza Formation ranges from 140m in the northwest to about 300m around Yaviza.

Macro Fossils: Oyster beds, ledging calcified hard beds, and irregular large concretions are scattered throughout. Abundant whole mollusks, sometimes forming shell beds, and dense shell hash are also distinctive. The uppermost part of the formation is characterized by coquinoid limestone units and densely packed, hard, shelly sandstone with shells often concentrated in burrows. Some shell beds are oyster banks, and others have large bivalves.

Overlying Unit: Chucunaque Formation. The upper contact of the Yaviza Formation is not exposed and there is probably a hiatus above it of more than 1 m.y. in all sections, except the Membrillo River, where the base of the

Chucunaque Formation is thought to be older than the rest of the formation and the Yaviza Formation is absent.

Underlying Unit: Membrillo Formation. The Yaviza's lower contact is not observed.

Maps, Cross-Sections & Pictures:

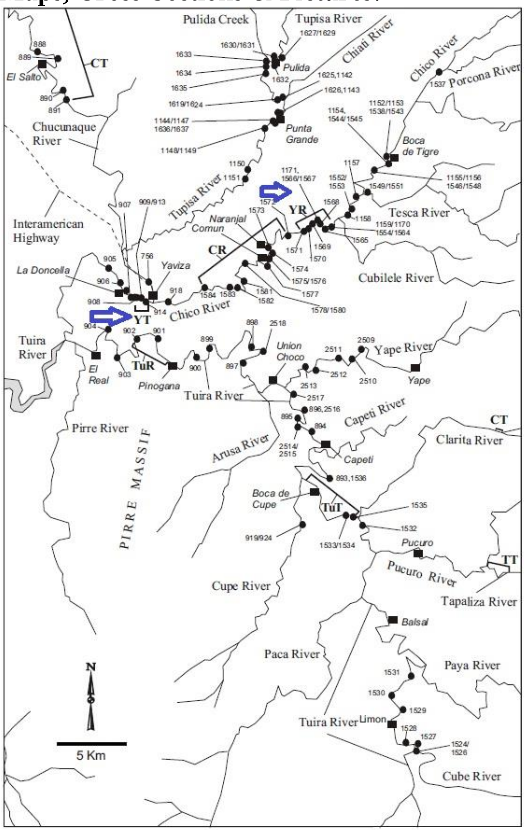

Figure 157. Stratotype (YT) and Reference Section (YR) of the Yaviza Formation. Coates et al. (2004).

Acknowledgments

The author wishes to thank Dr. Carlos Jaramillo, from the Smithsonian Institute in Panama and himself an author cited herein, for his thorough review of this Lexicon. His comments and pertinent observations helped at improving the content and conclusions of the document. I also want to thank Mr. Milton Solano, also from the Smithsonian Institute in Panama, for offering his knowledge of the historical geological maps in appendix.

Also, this research would not have been possible if it had not been for the incredible amount of publish material on the geology of Panama, either at local or regional level. Many geologists employed by the governemnt, the Smithsonian Institute, Oil & Mining companies and other organizations have contributed significantly to the understanding of the stratigraphy of Panama over the years. Many of them are mentioned in the text and the data that resulted from their own research is often summarized with regards to the formation(s) that they studied. Lastly, the enormous amount of paleontological information on Panama is due mainly because of the works undertaken in relation to the Panama Canal; especially the most recent work of the "Panama Paleontology Project (PPP)" involving the studies during the widening of the Canal from 2010 to 2016. I am therefore indebted to all the recent and past authors who have contributed to the geology, paleontology and stratigraphy of the country.

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Appendices

Appendix A. The geologic timescale for prehistoric land mammals in South America (SALMA) and North America (NALMA).

		SALMA Ages (Ma)	
Epoch	**SALMA**	**Top age**	**Base age**
Holocene		0.000	0.011
Late Pleistocene	Lujanian	0.011	0.800
Mid Pleistocene	Ensenadan	0.800	1.200
Early Pleistocene	Uquian	1.200	3.000
Late Pliocene	Chapadmalalan	3.000	4.000
Early Pliocene	Montehermosan	4.000	6.800
Late Miocene	Huayquerian	6.800	9.000
	Chasicoan	9.000	10.000
	Mayoan	10.000	11.800

	NALMA Ages (Ma)	
NALMA	**Top age**	**Base age**
Saintaugustinean	0.000	.004
Santarosean	.004	.12
Rancholabrean	.012	.300
Irvingtonian	.300	1.800
Blancan	1.800	4.900
Hemphillian	4.900	10.300
Clarendonian	10.300	13.600

Epoch	SALMA	SALMA Ages (Ma) Top age	SALMA Ages (Ma) Base age
Mid Miocene	Laventan	11.800	13.800
Mid Miocene	Colloncuran	13.800	15.500
Early Miocene	Friasian	15.500	16.300
Early Miocene	Santacrucian	16.300	17.500
Early Miocene	Colhuehuapian	17.500	21.000
Early Miocene / Late Oligocene	Deseadan	21.000	29.000
Early Oligocene / Late Eocene	Tinguirirican	29.000	36.000
Mid Eocene	Divisaderan	36.000	42.000
Early Eocene	Mustersan	42.000	48.000
Early Eocene	Casamayoran	48.000	54.000
Early Eocene / Late Paleocene	Riochican	54.000	57.000
Late Paleocene	Itaboraian	57.000	59.000
Mid Paleocene	Peligran	59.000	62.500
Early Paleocene	Tiupampan	62.005	64.500

	NALMA	NALMA Ages (Ma) Top age	NALMA Ages (Ma) Base age
	Barstovian	13.600	15.970
	Hemingfordian	15.970	20.430
Arikareean	Harrisonian	20.430	24.800
Arikareean	Monroecreekian	24.800	26.300
Arikareean	Geringian	26.300	30.800
	Whitneyan	30.800	33.300
	Orellan	33.300	33.900
	Chadronian	33.900	37.200
	Duchesnean	37.200	40.400
	Uintan	40.400	46.200
	Bridgerian	46.200	50.300
	Wasatchian	50.300	55.800
	Clarkforkian	55.800	56.800
	Tiffanian	56.800	61.700
	Torrejonian	61.700	63.300

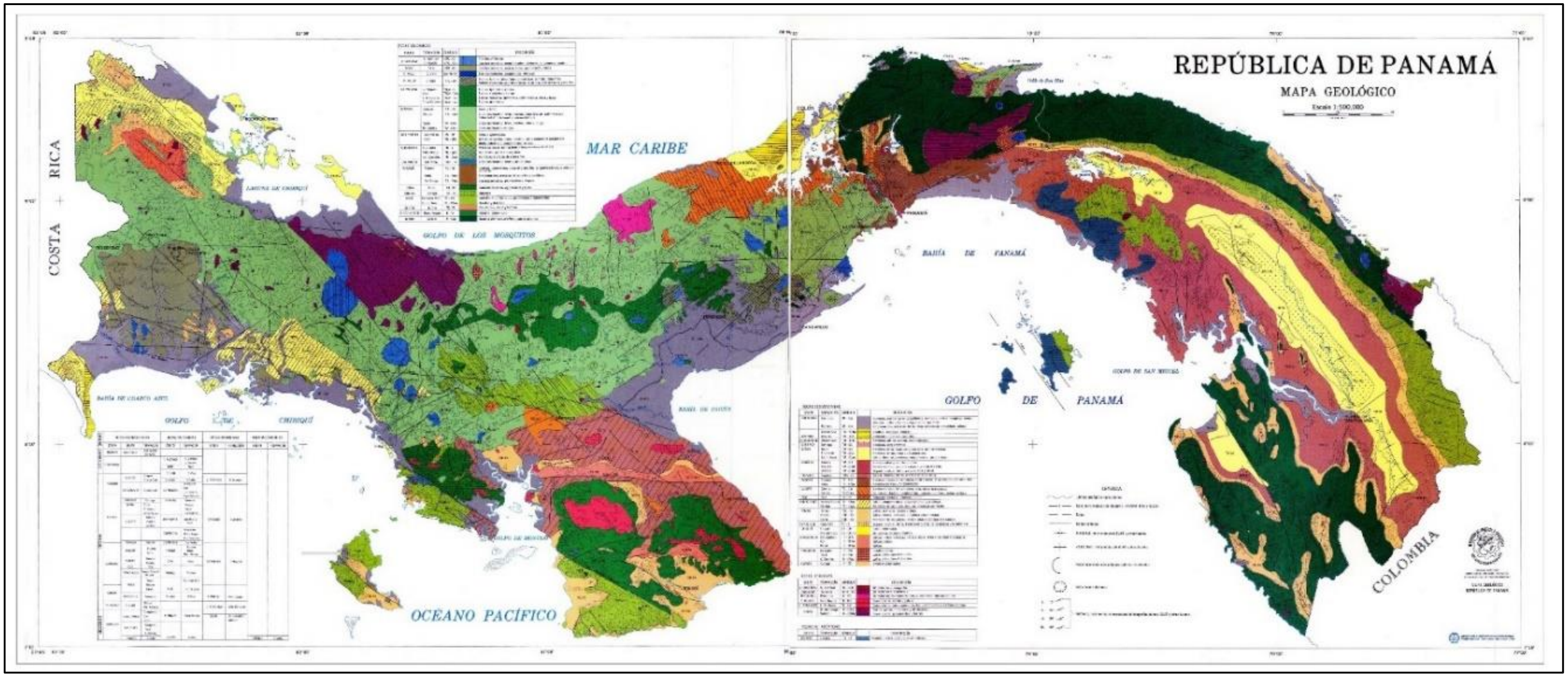
Epoch		SALMA	SALMA Ages (Ma) Top age	SALMA Ages (Ma) Base age	NALMA	NALMA Ages (Ma) Top age	NALMA Ages (Ma) Base age
					Torrejonian	63.300	66.000
Up. Cretaceous	Maast.				Lancian	66.000	70.000
	Camp.				Judithian	70.000	84.000
	Sant.				Aquilian	84.000	86.000

APP-A1: Compiled from the following sources:
SALMA – https://en.wikipedia.org/wiki/South_American_land_mammal_age
NALMA - https://en.wikipedia.org/wiki/North_American_land_mammal_age

Appendix B. Historic colored geolocical maps of Panama with their corresponding Stratigraphic Column.

EON	ERA	PERIOD	Epoch	SEDIMENTARY ROCKS Group	SEDIMENTARY ROCKS Formation	VOLCANIC ROCKS Group	VOLCANIC ROCKS Formation	INTRUSIVE ROCKS Group	INTRUSIVE ROCKS Formation	METAMORPHIC ROCKS Group	METAMORPHIC ROCKS Formation
PHANEROZOIC	CENOZOIC	QUATERNARY	RECENT / HOLOCENE	AGUADULCE	Las Lajas Rio Hato						
			PLEISTOCENE			C. SANTIAGO	C. Santiago C. Picacho				
						BARÚ	Barú				
						C. VIEJO	C. Viejo				
		NEOGENE	PLIOCENE	CHAGRES	Chagres Charco Azul	EL VALLE	El Valle	S. CRISTOBAL	S. Cristobal		
				CHUCUNAQUE	Chucunaque	LA YEGUADA	La Yeguada Bale C. El Encanto Playa Colorada	TABASARA	Guayabito		
			MIOCENE	SANTIAGO	Santiago	CANAZAS	Canazas Virigua Tucué Rio Culebra				
				GATUN	Gatun P. Valiente Gatun/Uscari						
				CULEBRA	Culebra Alajuela La Boca	SAN PEDRITO	San Pedrito Doro				
						CUCARACHA	Cucaracha Pedro Miguel Las Cascadas				
				TOPALIZA	Topaliza	LAS PERLAS	Las Perlas				
		PALEOGENE	OLIGOCENE	PANAMA	Panama Bohio	PANAMA	Panama Bohio Bas Obispo	PETAQUILLA	Petaquilla		
				CAIMITO	Caimito Caraba	SONA	Sona				
				PESÉ	Pesé	TRIBIQUE	Tribique				
				SENOS/USCA	Senosri/Uscari Galique						
				TONOSI	Tonosi Bucaro	MAJÉ	Complejo Majé				
			EOCENE	GATUNCILLO	David Gatuncillo	EL PIRO	Sur de Sona El Piro	V. RIQUITO	Valle Riquito		
			PALEOCENE	CHIGUIRI	Chiguiri Pta. Matanza			L. MONTUOSO	Loma Montuoso		
	MESOZOIC	CRETACEOUS	UPPER	CHANGUINOLA	Changuinola Ocu Piriati	P. VENADO	Playa Venado	COLON	Br. De Cuango/ Memoni		
				PARAGUITO	Paraguito Tiurti S. Sardina	QUEBRO	Quebro				
				CUANGO	Cuango					LOVAINA	Lovaina

APP-B1: The 1996 stratigraphic column of Instituto Geografico Nacional (IGN) "Tommy Guardia". See map in APP-B2.

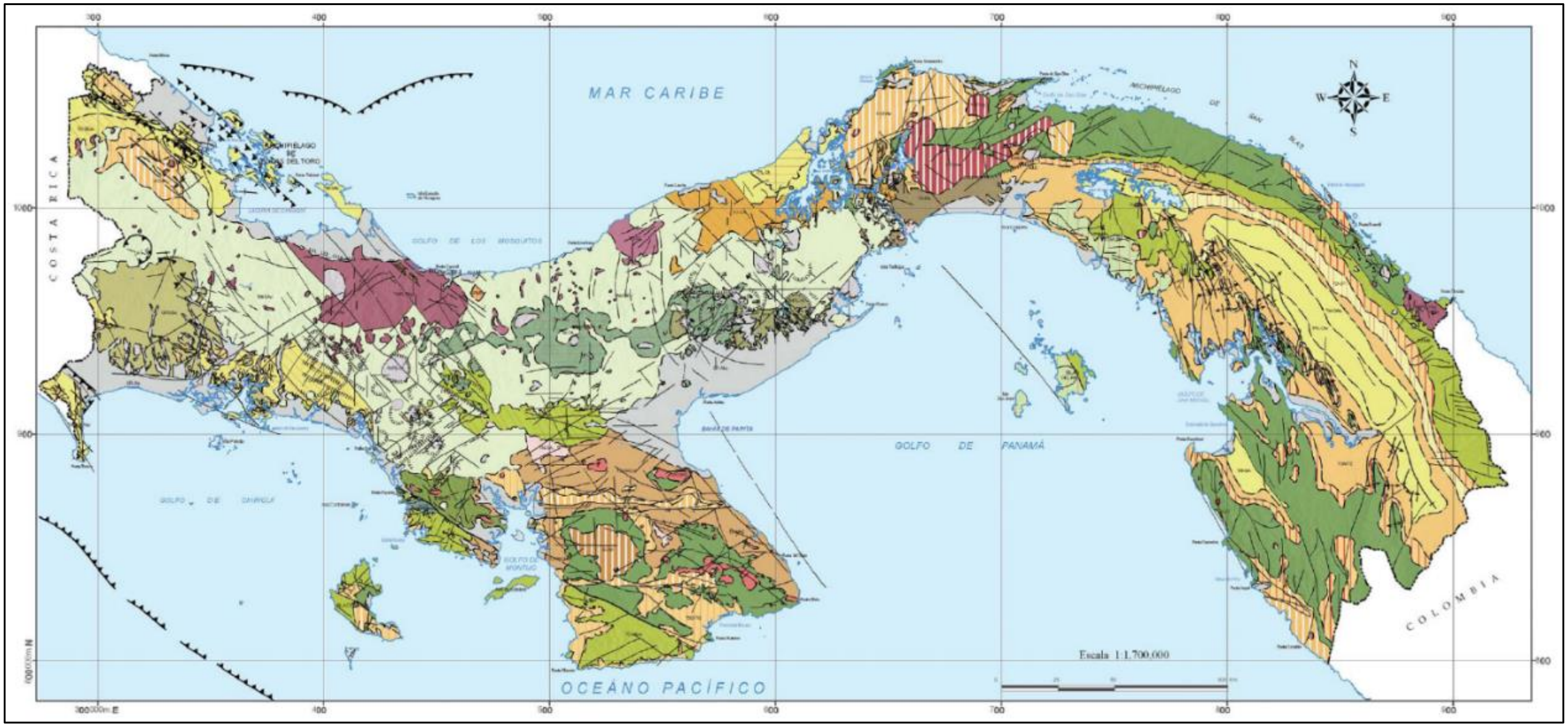


APP-B2: Geological map of Panama (Instituto Geografico Nacional (IGN) "Tommy Guardia" (1996)). See Legend in APP-B1.

GROUP	FORMATION	SYMBOL		DESCRIPTION - SEDIMENTARY FORMATIONS
Aguadulce	Las Lajas Rio Hato B. de Chucará	QR - Ala QR - Aha QR - Abch		Alluvium, consolidated sediments, sandstones, corals, mangroves, conglomerates, carbonaceous shales, deltaic type depositions Conglomerate, sandstones, shales, tuffs, semi-consolidated sandstones, pumice Alluvium, sand, carbonaceous shales, organic deposits with pyrite, deltaic type
	Chagres	TPL - Ch		Solid Sandstone (fine grain)
	Chucunaque	TPL - Chu		Sandstones, siltstones, clays, conglomerates
	Charco Azul	TMPL - Chaz		Clays, sandstones, siltstones
Gatùn	Pucro Gatùn Tuira Punta Valiente Gatùn-Uscari	TM - GApu TM - GA TM - GAtu TM - GAv TM - GAus		Limestone, sandstone, lodolite Shaly sandstones, tuffs, conglomerates, sandy clay Sandstones, lodolite, conglomerate Sandstones, shales, tuffs, conglomerates Shales, siltstones, sandstones, conglomerates, pyroclastics
	Santiago	TM - SA		Sandstones, conglomerates
La Boca	La Boca Alajuela	TM - LB TM - LBa		Argillaceous schists, shales, sandstone, tuff and limestone Tuffaceous sandstone, calcareous sandstone and calcareous shale
	Culebra	TM - CU		Calcareous sandstone and calcareous shale
	Topaliza	TOM - TZ		Limestones, siltstones, shales, tuffaceous sandstones and tuffs
	Capeti	TO - CP		Clayey sandstones, tuffs, limolite, lutolytic conglomerates and interstratified limestones
Caimito	Caimito Caraba	TO - CAI TO - CAlca		Tuffaceous sandstone, tuffaceous shale, tuff, limestone, foraminifera, Quebrancha Member - TOCAI gr., Dacitic agglomerate, conglomerate, limestone sandstone and fossiliferous limestone
Panamá	Panamá (Marine phase) Bohio	TO - PA TO - PAb		Tuffaceous sandstone, tuffaceous shale, foraminiferous limestone Conglomerates, sandstones, tuffs, basaltic dykes
Macaracas	Macaracas Pesé El Barro	TO - MAC TO - MACpe TO - MACba		Tuffs and tuffaceous sandstones Continental tuffs, sandstone, limestone Fossil reef limestones
Senosri-Uscari	Senosri-uscari galique	TO - SEus TO - SEga		Shales, conglomerates, tuffaceous limestones and clays Sandstone, shales, tuffs, siltstones, sandstone with fossils
	Gatuncillo	TE - G		Clayey shales, shales, quartz sandstone, foraminiferous and algae limestone
Tonosi	Darièn Tonosi David Búcaro	TE - TOda TEO - TO TE - TOd TE - TOb		Lodolites, tuffaceouss lodolites, tuff sandstones, graywackes, limestone, agglomerate, sub-lapilli, conglomerate, flint Shales, sandstones Sandstones, shales, limestones, lava and interbedded andesitic tuffs Sandy limestone, sandstone, conglomerates and breccia
Chiguiri	Chiguiri Punta Matanza	TPA - CHI TPA - CHImz		Deformed shales Graywacke, shales and siltstones
Changuinola	Changuinola Ocù Piriati	K-CHA K-CHAo K-CHAp		Limestones, shales, sandstones, ashes, tuffs, lava, interbedded andesite Limestones and tuffs Limestones
Paraguito	Paraguito Tiurti C. Sardina	K-PAR K-PARt K-PARs		Siltstones and tuffs Shales and siliceous siltstone Shales and siliceous siltstone
	Cuango	K-CG		Deformed siltstones

GROUP	FORMATION	SYMBOL		DESCRIPTION - VOLCANIC FORMATIONS
	C. Picacho	QPS - P		Basalts / Andesite, conglomerates, alluviums, colluviums, lodolites
	Barù	QPS - BA		Basalts / Andesites, ashes, agglomerated tuffs and lava
	Cerro Viejo	PI/PS - Cv		Basalts / Andesite, glassy vesicular post-ignimbritic basalts
	El Valle	TMPL - VA		Dacites, brechas, plugs, ignimbritic flows, pumices, fine tuffs Andesites / Basalts, tuffs and fine-grained subintrusives
La Yeguada	La Yeguada Bale C. El Encanto	TM - Y TM - Yba TM - Yen		Dacites, ignimbrites and tufas Dacites, rhodacites, rhyolites Dacites, rhodacites, ignimbrites, sub-intrusives, tuffs and lavas
	Playa Colorada	TM - PC		Dacites, ignimbrites
Cañazas	Virigua Tucuè Rio Culebra Cañazas	TM - CAvi TM - CATu TM - CArc TM - CA		Andesites, basalts, breccias, tuffs, blocks, sub-intrusives, dike-swarms, volcanic sediments Andesites / basalts, lava, breccia, tuff and plugs Andesites, basalts and tuffs Andesites, basalts and tuffs
San Pedrito	San Pedrito Boró	TM - SP TM - SPb		Tobas y aglomerados Andesitas, basaltos, arena, lutitas, sedimentos epiclasticos Madera silicificada, conglomerado, brechas
	Pedro Miguel Cucaracha Las Cascadas	TM - PM TM - C TM - CAS		Agglomerates, fine to coarse grains Andesites, tuffs, bentonitic clays, tuffaceous sandstone Agglomerates, fine-grained tuffs and andesites
	Las Perlas	TOM - LP		Andesites / basalts, lava and pyroclastics
Panamá	Panamá (f. volc.) Bas Obispo	TO- PA TO- PAbo		Andesites, agglomerate, fine-grained tuffs, conglomerate deposited by currents Basalts / Andesites, pyroclastics and blocks
Majé	Complejo Majé Sur de Soná	TO - MA TO - MAso		Andesites / basalts, pyroclastics and agglomerates Basalts and Diabases
	Soná	TEO - SO		Andesites / basalts, agglomerates and tuffs
	Tribique	TEO - TRI		Diabases
	El Piro	TE - PI		Pyroclastics, tuffs and vocanic bombs
Playa Venado	Caobanera Pta. Sabana Playa Venado	KT - VEca K - VEps K - VE		Volcanic agglomerates, brechas, conglomerates, interstratified fine-grained tuffs Pillow lavas, basalts and diabases interstratified with pyroclastic sediments Basalts, pillow lavas
	Dacitas Loma M	K - LMda		Dacites
	Quebro	K - QUE		Basalts picritic, picrites and Olivine gabbros
	San Cristóbal	TPL - CRI		Granodiorites and mangerits
Tabasará	Escopeta Rio Pito Guayabito	TMPL - TAe TMPL - TArp TMPL - TAgy		Granodiorites Granodiarites, Dacites Granodiorites and Monzonite
	Petaquilla	TO -PQ		Granodiorite, quartz monzonites, granodiorites, diorites, dacites
	Valle Riquito	TEO - RIQ		Quartzdiorites, norites and gabbros
	Loma Montuoso	K - LM		Quartzdiorites, quartzic gabbros, norites, granodiorites and quartz monzonites
Colón	Br. De Cuango Mamoni	K - COcg K - COma		Diorites, gabbros, monzonites and ultrabasics Quartzdiorites, granodiorites, diorites and syenite (Chagres)
	Armila	K - AR		Ultrabasic intrusives, serpentines
	Lovaina	K - LO		Green schistes (Chloritic - actinolytic)

APP-B3: Legend of the geological map of Panama seen in APP-B4. Translated from Ministerio de Comercio e Industrias (1991).



APP-B4: Geological map of Panama (Ministerio de Comercio e Industrias (1991)). See Legend in APP-B3. https://www.arcgis.com/home/webmap/viewer.html?useExisting=1&layers=343419d1aca4452585e47eb7f4d012de and downloaded from https://idoc.pub/documents/01-mapa-geologico-de-panama-1430310rpj4j

Appendix C. Geologic names of Panama discussed in this Lexicon.

AGUADULCE GROUP	LAS CASCADAS FORMATION
*AGUAGUA FORMATION (see "Aquaqua Member")	LAS LAJAS FORMATION (of the Aguadulce Group)
ALAJUELA FORMATION	LATE BASALT FORMATION (Informal name)
*ALHAJUELA FORMATION	*LIMON BOCAS FORMATION
ANCON HILL RHYOLITE or DACITE	*LIMONES SHALE
*ANOMIA zone	*MACARACAS FORMATION
AQUAQUA MEMBER (of Darien Formation) (formerly Aquaqua Formation)	*MAJAGUA FORMATION
ARMUELLES FORMATION (part of the Charco Azul Group)	*MARIATO FORMATION
*ARUSA FORMATION	*MATA CHIN FORMATION
*ARUZA MEMBER (of Tapaliza Formation)	MEMBRILLO FORMATION
ATLANTIC MUCK	MIMITIMBI MEMBER (of Urraca Formation)
*AZUERO FORMATION	*MINDI HILL BEDS
*BARBACOAS FORMATION	*MINITIMI LIMESTONE
BAS OBISPO FORMATION	*MIRAFLORES BASALT
*BASTIMENTOS SHALE	*MIRAFLORES PUMICE
*BOCA DE CHUCARA FORMATION (Part of the Aguadulce Group)	*MONA SHALE
*BOCAS FORMATION	*MONKEY HILL FORMATION
BOCAS DEL TORO GROUP	MONTE VERDE FORMATION
BOHÍO FORMATION	*MONTIJO CONGLOMERATE or FORMATION
*BRUJA ISLAND DIORITE or DOLERITE	*MOUNT HOPE FORMATION
*BÚCARO FORMATION	NANCY POINT FORMATION (part of the Bocas del Toro Group)
*BUCARÚ FORMATION	*OBISPO FORMATION
*BUJIO FORMATION	OCÚ FORMATION
BURICA FORMATION (part of the Charco Azul Group)	OLD BANK FORMATION
*BURICA SANDSTONE	PACIFIC MUCK
CAIMITO FORMATION	PANAMÁ FORMATION
*CAÑAZAS FORMATION	PANAMA CITY FORMATION (Informal name)
CAOBANERA FORMATION	*PANAMÁ TUFF
*CAPETÍ FORMATION	*PARITA FORMATION
*CARABA FACIES (of Caimito Formation)	PEDRO MIGUEL FORMATION (of the Gaillard Group)
CARABA FORMATION	*PEÑA BLANCA MARLS
*CARIBBEAN LIMESTONE	*PEÑITAS FORMATION or *PENITAS FORMATION (part of the Charco Azul Group)
*CASA LARGA MARLS	(*) PESÉ FORMATION
*CATIVA MARL (in Gatún Formation)	*PILIGUILLA CONGLOMERATE
CAYO AGUA FORMATION (part of the Bocas del Toro Group)	PIÑA SANDSTONE FACIES (or MEMBER) (of the Chagres Formation)
*CERRO GIGANTE BASALT	*POINT FARFAN DIORITE
*CHAGRES ALLUVIUM	PORCONA FORMATION
CHAGRES FORMATION	*PUCRO SANDSTONE MEMBER (of Gatún Formation)
CHARCO AZUL GROUP	PUNTA ALEGRE FORMATION
CHIGUIRI FORMATION	PUNTA MATANZA FORMATION

*CHILIBRILLO LIMESTONE MEMBER or FORMATION	*QUEBRANCHA FORMATION (Now "Quebrancha Member of the Caimito Formation")
*CHIVA CHIVA ANDESITE	QUEBRANCHA MEMBER (of the Caimito Formation)
*CHORRERA BASALT	*RÍO DUQUE SHALES
CHUCUNAQUE FORMATION	RÍO HATO FORMATION (of Aguadulce Group)
CLARITA FORMATION	RIO INDIO MEMBER (of the Chagres Formation)
*CONCH POINT SHALE	RÍO QUEMA FORMATION
COVACHÓN FORMATION	*SABANITAS FORMATION
CUCARACHA FORMATION	SABANITAS MEMBER (Lower Member of the Gatún Formation)
CULEBRA FORMATION	SAN BLAS COMPLEX
DARIEN FORMATION	*SAN CARLOS FORMATION
DAVID FORMATION	*SAN PABLO FORMATION (or San Pablo phase of Barbacoas Formation)
*EL BARRO FORMATION	SANTIAGO FORMATION
EMPERADOR LIMESTONE	*SENOSRI LIMESTONE or *SENSORI AGGLOMERATE AND LIMESTONE
*EMPIRE LIMESTONE	SHARK HOLE POINT FORMATION (part of the Bocas del Toro Group)
ESCUDO DE VERAGUAS FORMATION (part of the Bocas del Toro Group)	*SINOSRI FORMATION
FISH HOLE MEMBER (of Old Bank Formation)	*SOSA HILL BASALT
GAILLARD GROUP	*SWAN CAY FORMATION
GALIQUE FORMATION	SWAN CAY MEMBER (of the Urraca Formation)
*GAMBOA FORMATION	TAPALIZA FORMATION
GATÚN FORMATION	*TIGRE LIMESTONE
GATUNCILLO FORMATION	TOBABE FORMATION (part of the Bocas del Toro Group)
GROUND CREEK MEMBER (now part of the Isla Colon Formation)	TONOSÍ FORMATION
HILL POINT MEMBER (of Urraca Formation)	*TOREO LIMESTONE
ISLA COLON FORMATION (part of the Bocas del Toro Group)	TORO MEMBER (of the Chagres Formation)
*ISLA SOLARTE FORMATION	*TRANQUILLA SHALE FORMATION
*LA BOCA FORMATION (see newer definition of this name below)	TUIRA FORMATION
LA BOCA FORMATION (see older definition of this name above)	URRACA FORMATION
LA CHANCHA MEMBER (of Burica Formation)	*USCARI FORMATION
LA GRUTA MEMBER (now part of Isla Colon Formation)	VALIENTE FORMATION
LA PEÑITA FORMATION (part of the Charco Azul Group)	*VAMOS VAMOS BEDS
LA VACA MEMBER (of the La Peñita Formation)	*VERAGUAS CRYSTALLINE SERIES
*LARA GROUP	*WEMIR AGGLOMERATE
	YAVIZA FORMATION