UNIVERSIDADE FEDERAL DE MINAS GERAIS
Instituto de Geociências
Programa de Pós-Graduação em Geologia

Maria Clara Parreira Murta

VOLCANOSTRATIGRAPHY OF PYROCLASTIC DEPOSITS AND LAVA FLOWS, FERNANDO DE NORONHA, BRAZIL

Nº 241

Belo Horizonte
19/12/2022

Maria Clara Parreira Murta

VOLCANOSTRATIGRAPHY OF PYROCLASTIC DEPOSITS AND LAVA FLOWS, FERNANDO DE NORONHA, BRAZIL

Versão final

Dissertação apresentada ao Programa de Pós-Graduação em Geologia da Universidade Federal de Minas Gerais como requisito parcial para obtenção do título de mestre em Geologia.

Orientador: Prof. Antônio Gilberto Costa

Coorientador: Fábio Soares de Oliveira

Belo Horizonte
2022

M984v
2022

Murta, Maria Clara Parreira.

Volcanostratigraphy of pyroclastic deposits and lava flows, Fernando de Noronha, Brazil [manuscrito] / Maria Clara Parreira Murta. – 2022.

114 f., enc. il. (principalmente color.)

Orientador: Antônio Gilberto Costa. Coorientador: Fábio Soares de Oliveira.

Dissertação (mestrado) – Universidade Federal de Minas Gerais, Instituto de Geociências, 2022.

Área de concentração: Geologia Regional. Inclui bibliografias.

1. Vulcanismo – Fernando de Noronha, Arquipélago de (PE) – Teses. 2. Geologia estratigráfica – Teses. I. Costa, Antônio Gilberto. II. Oliveira, Fábio Soares de. III. Universidade Federal de Minas Gerais. Instituto de Geociências. IV. Título.

CDU: 551.21(813.4)

Ficha catalográfica elaborada por Elisabete Quatrini Vieira – CRB-6/2210 Biblioteca "Vitória Pedersoli", Instituto de Geociências da UFMG

UNIVERSIDADE FEDERAL DE MINAS GERAIS

PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA DO IGC-UFMG

FOLHA DE APROVAÇÃO

Volcanostratigraphy of Pyroclastic Deposits and Lava Flows, Fernando de Noronha, Brazil

MARIA CLARA PARREIRA MURTA

Dissertação submetida à Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em GEOLOGIA, como requisito para obtenção do grau de Mestre em GEOLOGIA, área de concentração GEOLOGIA REGIONAL, pelo Programa de Pós-graduação em Geologia do Instituto de Geociências da Universidade Federal de Minas Gerais.

Aprovada em 19 de dezembro de 2022, pela banca constituída pelos membros:

Prof. Antônio Gilberto Costa – Orientador
UFMG

Letícia F. Guimarães

Profa. Letícia Freitas Guimarães
UFBA

EVANDRO FERNANDES DE LIMA:21720142068 Assinado de forma digital por EVANDRO FERNANDES DE LIMA:21720142068 Dados: 2023.01.14 16:27:35 -03'00'

Prof. Evandro Fernandes de Lima
UFRGS

gov.br Documento assinado digitalmente ANDERSON COSTA DOS SANTOS

Prof. Anderson Costa dos Santos
UERJ

Belo Horizonte, 19 de dezembro de 2022.

To my family and to the Brazilian scientific community,

ACKNOWLEDGMENTS

My special acknowledgement to the ones I could not have undertaken this journey without, my beloved parents Clarice and Augusto. If I graduate as a master, it is thanks to them.

And I would like to extend my sincere thanks to my advisor Antônio Gilberto Costa and co-advisor Fábio Soares de Oliveira. Thank you for the opportunity to become a master under your guidance and to be part of the Project: “*Ocean Islands of the South Atlantic Ocean - Geology of the Fernando de Noronha Archipelago.”*

Special thanks to my fiancé, Thiago. Our love is a support in the face of challenges.

Words cannot express my gratitude to my brothers, Ieie and João. We have walked together. Always. I am also grateful to my friends. They have made me happier and smarter along my journey.

The Federal University of Minas Gerais molded me into a scientist, a citizen. I am deeply indebted to it and I will defend it forever. For this I also thank the “Pró-reitoria of Pós-graduação (PRPg)” and the Geology graduation program of the Geosciences Institute (IGC) of the UFMG.

I could not fail to mention my thanks to the funding agency Capes for have granted me a scholarship and assisted with financial resources for the development of my research. "This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001"; and the ICMBio - Instituto Chico Mendes de Conservação da Biodiversidade and the administration of Fernando de Noronha for allowing access to the territory and for carrying out research on the islands.

Lastly, I thank the universe for making me a rational little piece of the immensity. Because of that I am able to recognize and appreciate the power of the magmatic forces that shape our planet Earth.

RESUMO

Estabelecer relações estratigráficas precisas em sucessões vulcânicas antigas é um meio fundamental para entender a evolução, a dinâmica eruptiva e o comportamento passado dos vulcões. A metodologia de identificação, associação e interpretação de litofácies foi aplicada sistematicamente a fim de reconstruir a estratigrafia de áreas importantes do Arquipélago Fernando de Noronha, Oceano Atlântico Sul, Brasil. Este trabalho apresenta uma estratigrafia detalhada de parte das formações Remédios e Quixaba, permitindo a compreensão da distribuição lateral e vertical das fácies vulcânicas e da geometria 3D dos depósitos, e discussões sobre os mecanismos e estilos eruptivos. Através da descrição e associação de litofácies, três colunas estratigráficas foram construídas em escala 1:50 na Enseada da Caieira. Elas resultaram na distinção de quatro litofácies (todas piroclásticas) para a Formação de Remédios. As litofácies piroclásticas são tufo maciço (Tm), lapilli-tufo maciço (Ltm), lapilli-tufo maciço com blocos angulares, vesiculados de até 49 cm (Ltb), e brecha-tufo maciça (Btm). A associação das litofácies da Enseada da Caieira caracteriza os depósitos piroclásticos como ignimbritos não soldados de composição majoritariamente fonolítica com brechas co-ignimbríticas proximais, tendo sido originados a partir da deposição de correntes de densidade piroclástica. Para os fluxos de lava e depósitos piroclásticos da Formação Quixaba, foram construídas doze seções, distribuídas nas praias do Americano e Bode e na Ponta do Capim-Açu. A análise estratigráfica resultou na distinção de quatro litofácies piroclásticas, uma autoclástica e três coerentes. As litofácies piroclásticas presentes na Ponta do Capim-Açu são: lapilli-tufo maciço (Ltm), lapilli-tufo maciço com blocos vesiculados de até 28 cm (Ltb), brecha-tufo maciça (Btm), e lapilito com gradação normal (Lng) formado por agregados de cinzas (agregados de cinzas maciços, e variedades de lapili acrescionários). Por meio da associação das litofácies na Ponta do capim-Açu, os depósitos piroclásticos são caracterizados como *Scoria-and-ash flow* deposits e depósitos proximais de queda. As litofácies coerentes presentes na Ponta do Capim-Açu correspondem à olivina-nefelinito maciço (Onm), olivina-nefelinito vesicular (Onv), olivina-nefelinito escoriáceo (One) e melilita olivina-nefelinito maciço (Onmm). A associação das litofácies coerentes as caracteriza como fluxos de lava pahoehoe. Nas praias de Americano e Bode, a litofácie autoclástica corresponde à brechas monolíticas de olivina-nefelinito (Onb) e ocorre em associação com as litofácies Onv e Onm, caracterizando fluxos de lava 'A'a'. Durante o vulcanismo Quixaba, pulsos de atividade estromboliana levaram à formação de *Scoria-and-ash flow deposits* alternados com atividades efusivas de estilo Hawaiiano e à formação de extensos derrames Pahoehoe. Uma etapa posterior de atividade freatomagmática levou à formação de depósitos proximais de queda com agregados de cinzas.

Palavras-chave: Fernando de Noronha, Estratigrafia vulcânica, Análise de fácies

ABSTRACT

Establishing precise stratigraphic relationships in ancient volcanic successions is a fundamental means of understanding the evolution, eruptive dynamics, and past behavior of volcanoes. The methodology of lithofacies identification, association, and interpretation was applied systematically in order to reconstruct the stratigraphic framework of important areas of the Archipelago Fernando de Noronha, South Atlantic Ocean, Brazil. This work presents a detailed stratigraphy of part of the Remédios and Quixaba Formations, allowing the understanding of the lateral and vertical distribution of volcanic facies and the 3D geometry of the deposits, and discussions on the erupting mechanisms and styles. Through lithofacies description and association for volcaniclastic deposits, three stratigraphic columns were constructed in scale 1:50 at Caieira Beach. They resulted in the distinction of four lithofacies (all pyroclastic) for the Remédios Formation. The pyroclastic lithofacies are of massive tuff (Tm), massive lapilli tuff (Ltm), massive lapilli tuff with angular, vesicular blocks of up to 49 cm (Ltb), and massive tuff breccia (Btm). The lithofacies association characterizes non-welded endured ignimbrites of phonolitic composition bearing proximal co-ignimbrite breccias, which were originated from the deposition of ground-hugging density currents. For the lava flows and volcaniclastic deposits of the Quixaba Formation, twelve sections were constructed, distributed at Americano and Bode Beaches and Capim-Açu-Edge. The stratigraphic analysis resulted in the distinction of four pyroclastic lithofacies, one autoclastic and three coherent. The pyroclastic lithofacies present at the Capim-Açu Edge are massive lapilli-tuff (Ltm), massive lapilli tuff with vesicular blocks of up to 28 cm (Ltb), massive tuff breccia (Btm), and normal grading lapillistone (Lng) formed by ash-aggregates (massive ash pellets, and varieties of accretionary lapilli and armored lapilli). The lithofacies association characterizes scoria and ash flow pyroclastic deposits and proximal fallout deposits. The coherent lithofacies present at the Capim-Açu Edge are massive olivine-phyric nephelinite (Onm), vesicular olivine-phyric nephelinite (Onv), scoriaceous olivine-phyric nephelinite (One) and massive olivine-phyric melilite nephelinite (Onmm). The lithofacies association characterizes pahoehoe lava flows. At the Americano and Bode Beaches, the autoclastic lithofacie is olivine-nephelinitic breccia (Onb) and occurs in association with the Onv and Onm, characterizing ‘A’a lava flows. During the Quixaba volcanism, pulses of Strombolian activity led to the formation of scoria and ash flow deposits alternated to effusive Hawaiian activities and the formation of extensive pahoehoe lava sheets. A later stage of phreatomagmatic activity was followed leading to the formation of proximal fallout deposits with ash-aggregates formed through wet aggregation.

Key Words: Fernando de Noronha, Volcano stratigraphy, Facies analysis

TABLE OF CONTENTS

Appendices

Mineral Chemistry of pyroclasts and lava flows of the Quixaba Formation, Fernando de Noronha Archipelago, Brazil

Characterization of Ash aggregates from the Upper pyroclastic deposit of Capim-Açu Edge, Quixaba Formation

1. Introduction

This dissertation presents a stratigraphic approach based on the association of volcanic facies and architecture of volcaniclastic deposits and lava flows in the Fernando de Noronha Archipelago, located in the Brazilian equatorial margin. It contains findings and new data related to the volcanostratigraphy, petrography and depositional processes of the studied volcanic rocks.

As part of the Project: *Ocean Islands of the South Atlantic Ocean - Geology of the Fernando de Noronha Archipelago*, the results of this dissertation integrate the state of the art of geological knowledge, specifically related to physical volcanology, of Fernando de Noronha, which finds itself in an initial phase of development.

1.1 Objective

This dissertation aims, in a pioneering way, to construct a detailed stratigraphic framework involving the description and association of lithofacies for different geological units present in the Fernando de Noronha Archipelago. The chosen units involve volcaniclastic and coherent volcanic rocks representative of both formations: Remédios and Quixaba. In addition, this dissertation aims to create a morphological subdivision characterized by distinctive assemblages of facies, facies geometries, and depositional processes, which correspond to the architectural element of the volcanostratigraphy. Lastly, it aims to propose eruptive styles.

1.2 Dissertation Structure and Organization

This dissertation is organized in three parts: The first part is a recapitulation on the evolution of scientific knowledge about the geology of Fernando de Noronha, encompassing studies from the time of the navigations (from 1773 on) to modern studies from 1955 to 2020. Afterward, it presents the main study topic of the dissertation, which involves a stratigraphic approach based on the association of volcanic facies and architecture of volcanic rocks for representative deposits of the Remédios and Quixaba formations. Lastly, within the appendices it presents a detailed study of the mineral chemistry and microtexture of the studied coherent and volcaniclastic deposits from the Quixaba Formation.

THE EVOLUTION OF GEOLOGICAL KNOWLEDGE ABOUT VOLCANIC ACTIVITIES IN THE FERNANDO DE NORONHA ARCHIPELAGO - BRAZIL

Maria Clara Parreira Murta, Antônio Gilberto Costa, Fábio Soares de Oliveira

Universidade Federal de Minas Gerais - UFMG, Geosciences Institute, Campus Pampulha, Av Antônio Carlos, 6623, ZipCode: 31270-901, Belo Horizonte, MG, Brazil.

ABSTRACT

Our survey on the evolution of knowledge about the volcanic activities of Fernando de Noronha begins in the 18th century. The volcanic origin of the archipelago was attested by Darwin (1845) and by the naturalists of the expeditions: Challenger (1878), Imperial Service of Brazil (1889) and the British Museum (1890). In the 20th century, Almeida (1955) classified the volcanic and subvolcanic rocks into three formations, in order of age: Remédios (phonolites, trachytes, alkali-basalt, essexite porphyry, pyroclastic deposits cut by a variety of lamprophyric dikes); Quixaba (ankaratrite flow interbedded with thin melilite-rich flow and pyroclastic deposits, locally cut by nephelinite dikes); São José (basanite flow rich in xenoliths of dunite, lhertzolite, harzburgite and pyroxenite). Ulbrich (1993) proposed a revision of terms adopted by Almeida (1955) and relocated the São José basanites as belonging to the culmination of the Quixaba volcanism. Perlingeiro et al. (2013) confirmed the relative ages of the Remédios and Quixaba Formations according to Almeida (1955) and the absolute ages according to Cordani (1970). The São José Formation (9.2±0.5 to 9.0±0.1Ma) was proved to be concomitant with the Remédios Formation. Two distinct chemical series were recognized in the Remédios Formation: Na-enriched and another mildly potassic (Ulbrich et al. (1994), and the Quixaba rocks as being less evolved undersaturated sodic types (Ulbrich and Lopes, 2015). The magmatism associated with the Fernando de Noronha Fracture Zone was stated by Almeida et al. (1986), (1988), (1996) and Costa et al. (2002). While Perlingeiro et al. (2013), Lopes et al. (2014) and Lopes and Ulbrich (2015) discuss the existence of small-scale convection, temperature elevations and intermittent melting in an enriched mantle, respectively, as possibilities for the generation of magma, Fodor et al (1998), Almeida (2006) and more recently Mohiak (2020), associate the volcanism with the presence of a mantle plume.

Keywords: Marine Expeditions, Geology, Volcanism.

1. Introduction

The Archipelago Fernando de Noronha is what is left of a high and vast volcano, of long and complex history, whose base rests 4,000 meters deep on the ocean floor […] arranged in an alignment of islands and seamounts (Almeida, 1955) between parallels 3°53'20" and 3°48'05" in the South Atlantic Ocean (Figure 1).

The first records on the geology of the islands were left by some naturalists, such as Thomas Davies of the British Museum expedition, who proposed a chronology of the volcanic events, separating them into periods of activity. However, the most complete surveys in this area of knowledge took place from the middle of the 20th century. As a reference for works currently under development in the Archipelago, and with a focus on its geology, it is reasonable to bring to light a quick summary of these contributions involving information from the time of naturalists to that of modern scientists. With this retrospective, we also seek to highlight the impacts and meanings of new paradigms and concepts, such as the discovery of plate tectonics, for the Fernando de Noronha Archipelago, punctuating scientific works of great relevance about the geology of this extinct volcano.

From the 1950s on, with the pioneering of Almeida (1955), who carried a very complete study of the geology of Fernando de Noronha, great advances have been made in the areas of petrography, geochemistry, geochronology and on the understanding of the geotectonic of the archipelago. Especially for the effusive rocks and lamprophyric bodies, these studies have advanced substantially, nevertheless the same cannot be said for their associated pyroclastic deposits. Therefore, is the aim of this work gather and present the State of the Art of geological studies on Fernando de Noronha, to demonstrate the importance of our ongoing research and related to mapping and detailing volcanic terrains in the archipelago represented by pyroclastic deposits.

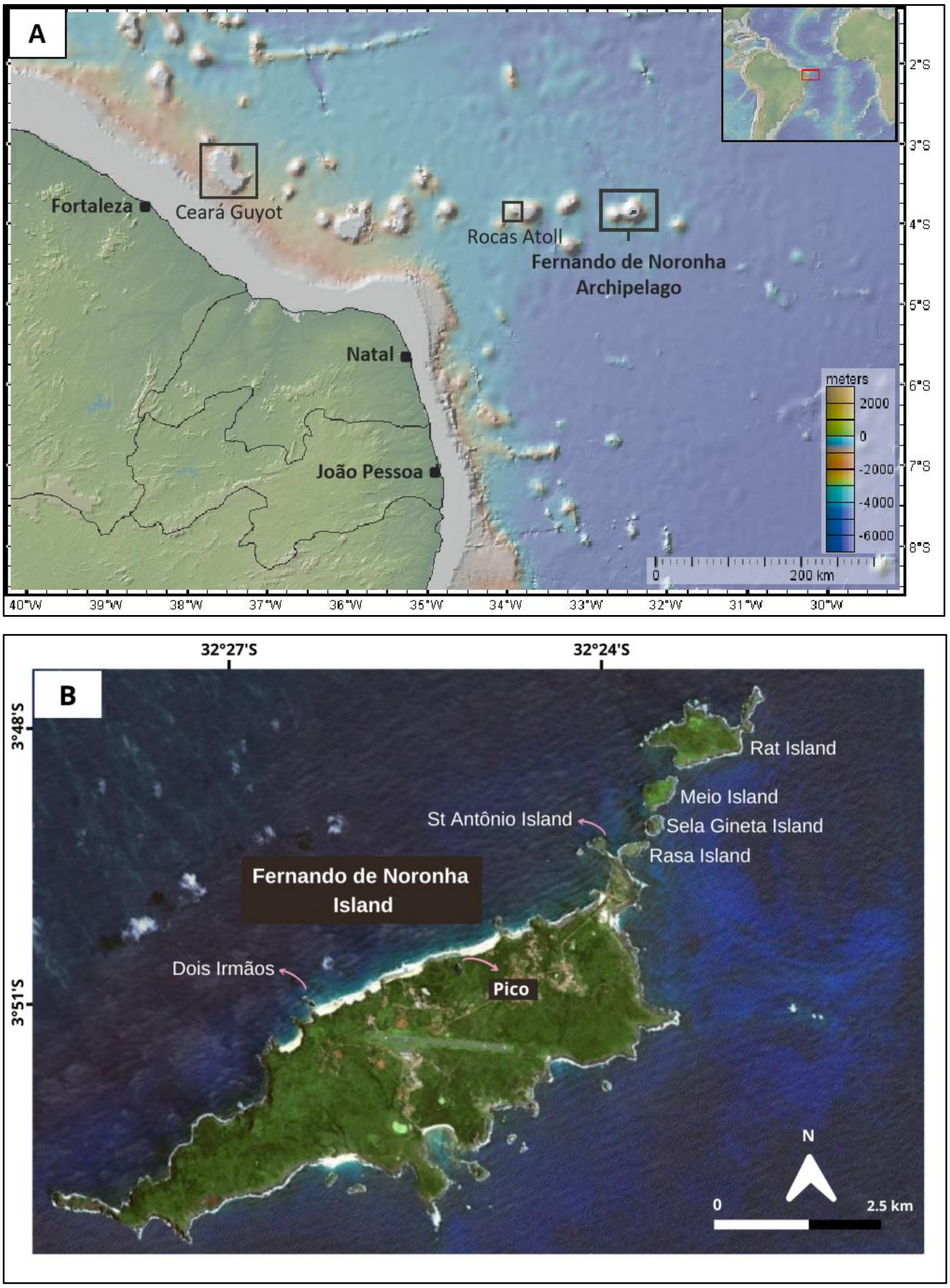


Fig. 1. A) Location of the Fernando de Noronha Archipelago, Rocas Atoll and Ceará Guyot along the alignment of islands and seamounts, and the location of the Brazilian state capitals from GeoMapApp. B) Fernando de Noronha Archipelago satellite image obtained from Google Earth Pro. The arrows indicate the location of Pico (The Peak) and Dois Irmãos (The Twins) as shown in figure 3.

2. Material and Methods

The work consisted in a survey of important scientific publications on the geology of Fernando de Noronha, from the 18th to the 21st century. The present analysis of the evolution of knowledge about the geology of Fernando de Noronha took into account: 1 - the vision of naturalists; 2 – evolutionary models, involving works from the middle of the 20th century, with congruent to conflicting visions about the magma sources and the geotectonic framework of the Fernando de Noronha volcano; followed by 3 – works concerned with the lithostratigraphy and description of the rocks, practically involving only details on effusive volcanic materials; and 4 – works related to geochronology, which ended up being decisive for revisions of previous definitions.

3. The State of Art

3.1 Fernando de Noronha in the View of the Naturalists of the 18th and 19th centuries

The first references to the Fernando de Noronha Archipelago date back to the end of the 15th century, nevertheless here some produced from the beginning of the 18th century will be described, which show relations with its geology.

Due to the abandonment by the Portuguese authorities, the Archipelago, which had already been used as a support point by the French in the campaign of occupation of Maranhão (a state in the northeast of Brazil) in the early 17th century, was revisited in 1734 and occupied in 1736. Due to this presence, the region was well mapped and its records can be observed in a cartographic document dated of September 1737 (Costa, 2013) (Figure 02A).

Within the document, next to the representation of Fernando de Noronha Island, it reads: *Isle de Fernand de Noronha nomée I. Dauphine au 1734 par um Navigatr. François.*

If it devided by a diagonal, the bottom right corner presents a map (Figure 2A) (*PLAN DE L'ISLE DE FERNAND DE NORONHA située sur les Cotes du Bresil à l'E.N.E de Rio Grande*) drawn by an officer of the Company of the Indies in 1734; next to a cut (*ET LA COUPE DE CETTE ISLE*) marked on the map by the AB line (with approx. 5.8 km), and whose plan intersects the northeastern portion of the main island, and brings a cross section representation of sandbanks, the arrangement of the seabed and the existing dangers along the line; and a figure representing this part of the main island, which from the surface to the bottom (with a maximum depth wrongly indicated of 65m) takes on contours that allow it to be identified as part of a volcanic structure (Figure 2B).

Costa (2013) highlights the presence of a map *(CARTE DE LA PARTIE DE L'OCEAN VERS L'EQUATEUR ENTRE LES COTES D'AFRIQUE ET D'AMERIQUE*), which brings the representation of the territory of Portuguese America, part of the African territory and part of the Atlantic Ocean, in the top right side of Figure 2A. In the superior portion of the document (detail in the Figure 2C) there is a cross section representation (*CUPE DU FONDS DE LA MER BETWEEN L'AFRIQUE AND L'AMERIQUE*), between Cape Tagrin, in Africa and Rio Grande in Brazil, with indications of islands, bottoms, reefs and other "dangers" between the two continents.

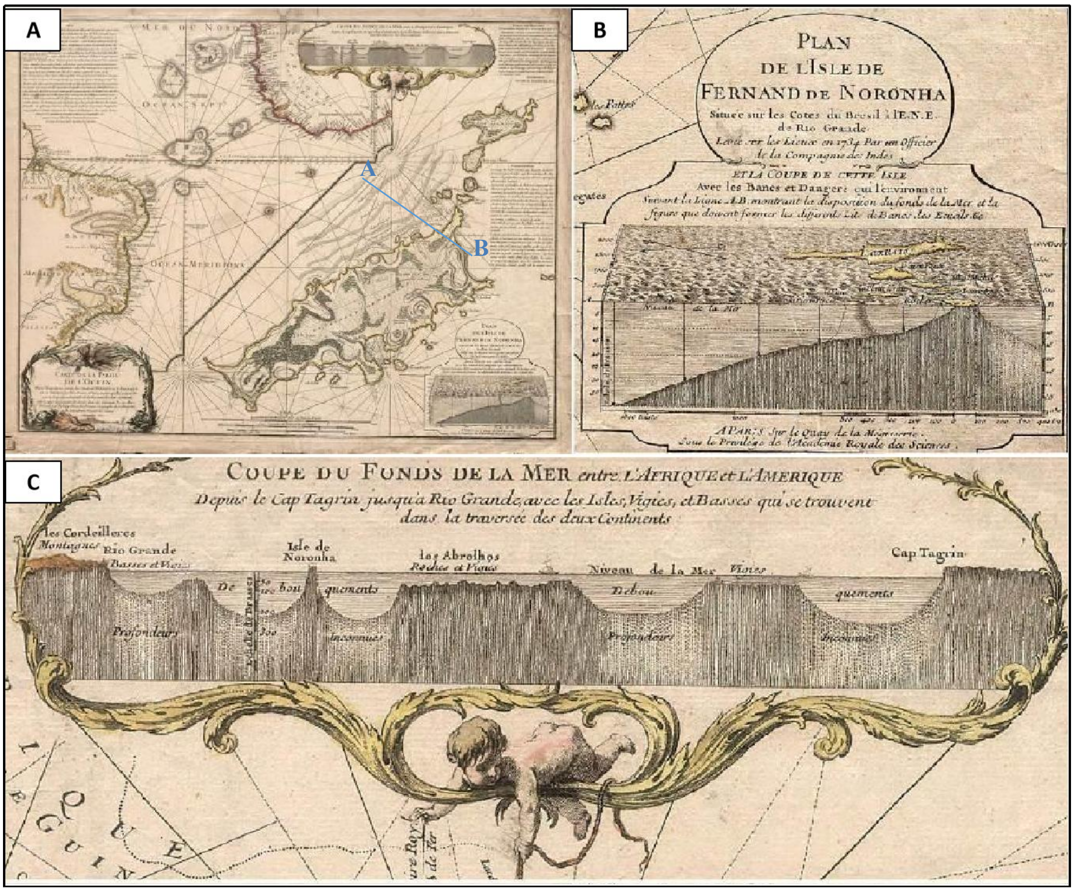


Fig. 2. *CARTE DE LA PARTIE DE L'OCEAN Vers l'Equateur entre lês Cotes D'AFRIQUE et D'AMERIQUE*. Figure 2A: Complete document: Map of the northeast coast of Portuguese America to the African coast; map of the Fernando de Noronha Archipelago and the cross sections; Figure 2B: AB cross section of the northeast portion of the Fernando de Noronha main island in detail. Figure 2C: Cross section of the South Atlantic Ocean between America and Africa coast, at low latitudes. [Navy Map Collection - 49.0 x 64.5 cm].

The main purpose of this document was to ensure safety for travel between the two continents, providing a general idea of the depth variations at the bottom of the sea, between Africa and South America. It also informed about the large mountain ranges located in the coastline of both continents and separated by the sea. Regarding this matter, the report to the Royal Academy of France in 1737 was the following:
"Ces chaines de montagnes se continuent pour lordre dans le fond de la Mer et formet les differents suites d'Isles, de Vigies de Récifs, de Bancs etc, qui suivent à peuprés la direction de ces chaines, et sont comme un prolongment. Un connoissaince détailliée de ces suites d'Isles et de Bancs, nous mettroit en etát de déterminer la liaison des montagnes d'un continent avec celles d'un autre qui en est separé par la Mer at par la de nous formes une idée de la surface entiere de notre Globe."

Although the main island was for a first time represented in the shape of a volcano by the French, it was up to Darwin to leave some record about this origin. The naturalist, pioneer of scientific observations on geology in several regions of the world, landed in Noronha, during the trip of H. M. S. Beagle. He arrived in Fernando de Noronha in 1832 and remained there only for a few hours.

He left registered in the 1845 edition of the Journal of Researches into the Natural History and Geology of the countries the following observation: "*As far as I was enabled to observe, during the few hours we stayed at this place, the constitution of the island is volcanic, but probably not of a recent date"*(p. 11).

The most striking feature of Fernando de Noronha in the eyes of Darwin was the Pico, described as "the conical hill", extremely steep, with approx. 1,000 feet (304 meters) high. The author classified it as a phonolite divided into regular columns.
[...] *when visualizing an isolated rock mass like that, it is possible to be led to think that it was pushed up in a semi-fluid state [...]"* (p.11).

Darwin cited some of Mount St. Helena pinnacles (Washington, USA) as similar to the Pico. According to the naturalist, both features would have been formed by the injection of molten rock in stratified layers, which formed the molds for these gigantic obelisks.

In the second half of the 19th century, between 1872 and 1876, the British Challenger expedition, guided by the naturalists John Murray and Charles Wyville, arrived in Fernando de Noronha on September 1th, 1873. The Pico was, once again, one of the first features noticed in the island: *"there was a very singular-looking mountain,* *The Peak […]"* (Fig. 3). *"To the extreme left (from the ship) there is a chain of small islands, one of them with a fine, bold outline called St. Michael's Rock, and another much larger, flat and rather bare, Rat Island. The view to the right is closed in by two very peculiar conical detached rocks, called " The Twins"* (p. 101)

The "*St. Michael's Rock"* corresponds to the *"*Ilha Sela Gineta" and the "Rat Island" keeps the same name today. "The Twins" correspond to the remarkable rocks structured in colunar joints, "Os Dois Irmãos". The observations on the geological structures of the islands were left to Mr. Buchanan, and were quoted in the Journal by the authors:

"The highest island, St. Michael's Mount, forms one of the prominent peaks which are characteristic of the group. It is very steep and formed entirely of phonolite, which occurs columnar at the base and massive toward the top; […] In this the glassy feldspar crystals are arranged with great regularity, with their broadest faces in a plane perpendicular to the length of the column. […] The crystals of hornblende, though in a less degree, project sometimes to the extent of a quarter of an inch, so much more decomposable is the crypto-crystalline matrix than the crystals occurring porphyritically in it. This rock possesses in an eminent degree the characteristic property from which it derives its name when struck with a hammer, it literally rings like a bell." (p. 107).

Rat Island was described as the largest of the secondary islands, composed on the western side of massive basaltic rock, and on the eastern of sandstone. He interpreted the sandstone as probably overlying the basalt, as in its structure, bearing the marks of having been deposited in drifts, and the calcareous sand consisting of shell debris. On the way to and from Rat Island they had to pass along the western side of Booby Island (Ilha do Meio): "*The wave-worn cliffs showed that the island was entirely formed of the above-mentioned calcareous sandstone; no igneous rock was visible, and, as the peculiar wind-blown stratification-marks are continued below the level of the sea, it is probable that the land here is sinking, or, at all events, has sunk."* (p. 108).

In this expedition, concepts on modern oceanography emerged, and was the first specifically organized to collect a wide variety of South Atlantic ocean data, including chemical and ocean temperature data, currents, marine life and ocean floor geology.

Fig. 3. Drawing of the Fernando de Noronha coast to the southwest of Santo Antônio Bay. In prominence there is the Morro do Pico (The Peak) and "The Twins" in the background, former name of "Dois irmãos". Source: Journal The Atlantic by Mr. Wyville Thomson (1878), page 15.

Three years after the Challenger Expedition have docked in Noronha, John Casper Branner, in 1876, visited the Archipelago as a member of the Imperial Geological Service of Brazil and produced a record about the geology of the islands, published in 1889 in the American Journal of Science (1880-1910)

John Casper Branner recognized the importance of the Challenger Expedition deep sea soundings discoveries on the ocean's bottom. According to his notes, it was formerly supposed that Fernando de Noronha was simply the original northeastern extreme of South American continent, separated from Cape St. Roque (Rio Grande do Norte state) by a shallow channel. The deep-sea sounding has shown, however, that Fernando de Noronha group is an isolated one, and that the channels separating it from the Rocas, from St. Paul's Rock and from the Brazilian mainland, are profound ones. Hence, Branner firmly attested that the archipelago rises abruptly from the ocean's floor.

As part of his work, John Casper Branner formulated an accurate map of the island (Figure 4) and Dr. George H. Williams, oversaw the petrographic descriptions. Six volcanic lithotypes were registered: amphibole-trachyte traversed by dykes of hornblend-augite trachyte; hyalotrachyte, phonolite, basalt, nepheline-basalt, augitite, limburgite, volcanic bombs and tuff; and one sedimentary, the calcareous sandstone.

In 1887, during the activities of a British Museum expedition, petrographic and volcanological observations were made by Thomas Davies, F.G.S. and reported by H.N. Ridley, M.A., and F.L.S (1890, p. 91):

"From the notes it will be seen that the islands are, as has been constantly affirmed, of volcanic origin, and further that we can trace two distinct periods in their history, the phonolitic and the basaltic periods: phonolite was ejected in the form of phonolitic lavas and tuffs, and that there were periods of cessation of action between the eruptions, during which some hot spring deposited beds of silica. After this had happened, and perhaps at a much later date, and after much denudation had taken place, craters in the north-west and south-east portions of the island ejected scorias, pumices, tuffs, and basalt, which covered a great portion of the phonolitic rocks and altered them where it came in contact with them."

The notes produced during the British Museum expedition and published in 1890, together with those produced by Branner (1880) on the geology of Fernando de Noronha were the most detailed ones until the end of the century. Their studies generated descriptions of bodies of phonolite and basalt, dykes, tuffs and pumices, as well as coral reefs and sedimentary rocks outcropping all over the territory.

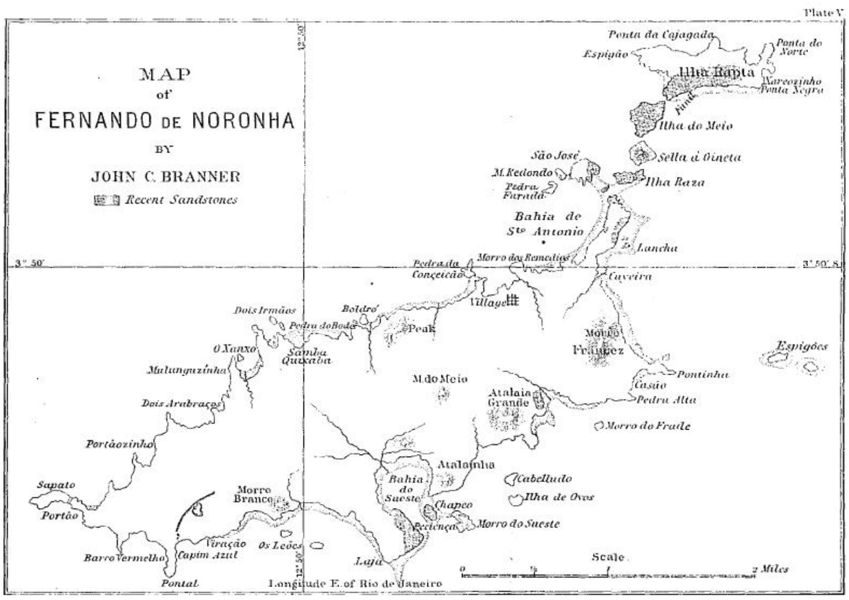


Fig. 4. Map of the Fernando de Noronha Archipelago by John C. Branner, 1889 – Plate V. American Journal of Science (1880-1910); Feb 1889; 37, 218; American Periodical.

3.2 Evolution of geological knowledge between the 20th and 21st centuries

3.2.1 Geotectonics and Magmatism

Forgotten for a while, the Archipelago reawakened interests for its strategic location at the end of the first half of the 20th century. Almeida (1955) recognized volcanic episodes succeeded by sedimentary cycles, all separated by erosive phases, proposed a lithostratigraphy for the rocks and gathered within his work an enormous contribution on the stratigraphy, petrography and geomorphology of Fernando de Noronha, which has served as the basis for all further studies.

The alignment of the seamounts and islands in the South Atlantic was identified by the examination of bathymetric charts by the Ministry of the Brazilian Navy in 1955. This arrangement was then mentioned as an alignment of volcanoes in a fracture zone, which extends into the interior of the continent with register on the Morro do Caruru, between Aguiraz and Mecejana, approximately 20 km southeast of Fortaleza (CE). Together with the cartographic observations, the phonolite samples on the coast of Ceará, collected by the Engineer Ernesto Pouchain and ceded by the Engineer Evaristo P. Souza, endorsed this statement regarding the extent of the fracture zone, since the samples collected in the interior of the continent were somewhat similar to the phonolites mapped in Fernando de Noronha (Almeida, 1955).

From numerous similar notes regarding the correlation between volcanic alignments and fracture zones for other areas, B. G. Escher (1952) in Almeida (1955) states that the efforts that originated such fractures would be of a nature to cause liquefaction of "latent magmas", initiating volcanic processes.

In Almeida (1986) is reinforced the generation of the alkaline rocks of Mecejana (CE) as being related to the alignment of seamounts of which Fernando de Noronha and the Atol das Rocas are part (Figure 5). "[...] *The Fernando de Noronha chain, which corresponds directly to the homonymous oceanic fracture zone and extends to the continental margin (Gorini & Carvalho 1984) would have in Mecejana volcanism a possible reflection of its presence in the emerging coastal area of Ceará. [...] Although E-W structural orientations are not observed in the coastal region, this seems to be an example, among several others cited in the world and referred to by Sykes (1978), of the* *appearance of alkaline volcanism in the continent, near the end of an oceanic strike-slip fault."* (Almeida, 1986, p.342)

Almeida et al. (1988, 1996 and 2002) support the statement about the formation of this alignment related to the fracture zone, with a volcanism originated from east to west, thus Fernando de Noronha the most recent manifestation. In addition, observations by Costa et al. (2002) from orbital images and field data confirm the extension, on the edge of the continent, of the Fernando de Noronha fracture zone.

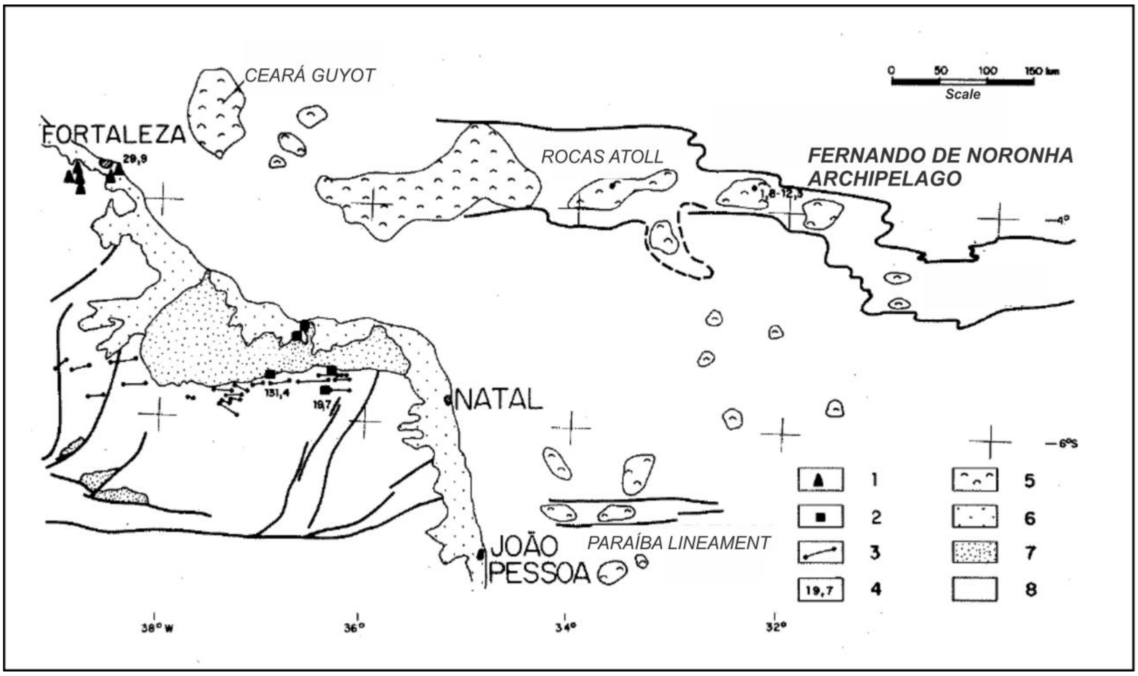


Fig. 5. Fracture Zone of Fernando de Noronha and the adjacent Mecejana Volcanism (modified from Schobbenhaus et al. 1981). I. Mecejana volcanism; 2. Macau volcanism; 3. Rio Ceará-Mirim volcanism; 4. K-Ar ages(Ma); 5. High lands of the basement; 6. Ccenozoic cover; 7. Mesozoic sediments; 8.Basement. References: ALMEIDA, F.F.M. de. 1986. Regional distribution and tectonic relationships of post-Paleozoic magmatism in Brazil. Journal. Bras. Geoc.; t6(4).

Fodor et al. (1998) addresses the existence of a plume derived from a hot spot, which would have functioned as a source of the tertiary alkaline basalts of the Brazilian northeast coast in Rio Grande do Norte and Pernambuco (30 to 13 Ma) and of the alkaline rocks of Fernando de Noronha (12 to 2 Ma). In general, the lava flows of these regions share isotopic and trace element compositions with those of Fernando de Noronha, therefore, would be derived from the same mantle plume. Some small differences between trace elements observed in Fernando de Noronha (e.g., more Zr, Nb and minus Th) compared to northeastern basalts, according to Fodor et al. (1998), would probably be due to the heterogeneity of the mantle plume and the contributions of delaminated subcontinental lithosphere melts underlying Fernando de Noronha.

In 2006, as well as Fodor et al. (1998), Almeida discusses the presence of hot spots, which would have been the magma sources of volcanism in the fracture zone. However, according to Almeida, studies carried by Ernesto (2005), in reconstitution of the position of South America to 130, 80 and 50 Ma ago, including spatial and paleomagnetic data, and assuming that the hot spots are fixed in the deep mantle, even if the area of influence of the supposed plume of Fernando de Noronha had ±1000 km of radius, there would be no possibility of relationship of the volcanism of this archipelago with the alkaline province of the northeast Brazil, as previously proposed.

According to Anderson (2000) in Almeida (2006), local temperature elevations below the lithospheric crust are possible and may originate melted fractions capable of forming hot spots on the upper mantle. Courtillot et. al (2003) exposes the possibility of the existence of plumes linked to the asthenosphere as passive replicas of the forms of lithospheric disruption and calls them the *Andersonian type*. Thus, after compilation and analysis of these previous studies and of other publications, Almeida (2006) considers the appearance of a fixed hot spot in the upper mantle in the middle Eocene in the region of Fortaleza, along the thinned and fractured edge of the continental crust in contact with the ocean, originated by a thermal anomaly in the asthenosphere induced by lithospheric kinematics. This finding was based on the existence of lithospheric fractures in the Fernando de Noronha fracture zone that enters the continent to Fortaleza, as magma channelers to the surface, during the drift of the plate towards west.

Perlingeiro et al. (2013) suggest that the magmatism associated with the proposed Fernando plume would perhaps be better explained by small-scale, plate-driven convection in the upper mantle, as suggested by King (2007) and Knesel et al.

(2011). According to Perlingeiro et al. (2013), this hypothesis is consistent with the presence of high seismic shear-wave velocities (interpreted as the downwelling limb of such an edge-driven convection cell) in the upper mantle beneath the eastern margin of the South American craton (King and Ritsema, 2000) and the lack of seismic evidence for a deeply sourced, plume upwelling (e.g., Montelli et al., 2006, and references therein). Moreover, small-scale convection triggered at the edge of the South American continent also provides a straightforward mechanism for introduction of an enriched-mantle component apparently derived from the Brazilian subcontinental lithosphere in the offshore volcanic rocks (e.g., Gerlach et al., 1987). The authors analyzed geochronological and stratigraphic data of the rocks along the Fernando de Noronha alignment and added an alternative genesis to the hot spot hypothesis.

According to Lopes et al. (2014) the volcanism in Fernando de Noronha is related to a stationary heat source and Lopes et al. (2015) states that the islands represent the activity of a protracted volcanic episode, fueled by intermittent melting of an enriched mantle, not related to asthenospheric plume activity.

Mohriak (2020) summarizes the characteristics of the volcanic islands along the eastern Brazilian margin and points to a source of magma for Fernando de Noronha as probably related to a hot spot track developed above a mantle plume (Steinberger 2000; Teixeira et al. 2003; Ulbrich et al. 2004; Almeida 2006). The author does not go into detail about the plume position or location in the earth's mantle.

3.2.2 Lithostratigraphy

Almeida (1955) joined in a geological map (1:15,000) (Figure 6) the occurrence of more than 20 different lithotypes mapped in the archipelago, which he grouped into three different formations, from the oldest to the youngest: Remédios Formation, Quixaba Formation and São José Formation.

The Remédios Formation was designated as a complex set of tuffs and volcanic breccia intruded by discordant bodies of phonolites and trachytes, a great variety of dykes and less regular bodies of ultra-basic and alkaline rocks, among which those of lamprophyric facies stand out. The pyroclastic rocks of Remédios Formation are the oldest exposed in the archipelago, classified as agglomerate, pyroclastic breccia, tuff breccia, lapilli tuff and tuff. Described as of comagmatic origin and accessory materials of intravolcanic origin, the fragments of pyroclastic rocks were classified, mainly, as phonolites, trachytes, glenmuirite and essexite porphyry, besides other lithotypes that were not found mineralogical equivalents among the eruptives exposed *in situ*. The tuffs were described as formed by fragments totally consolidated at the moment of ejection, as well as the bombs. According to Almeida (1955), these pyroclastic rocks were formed, mainly, on the "mise en place" of the phonolites and trachytes.

A few dikes and eleven independent phonolites in the form of domes, sometimes aphyric or porphyritic, exposed essentially in the central region of the main island, were mapped. When unaltered, they were described macroscopically as almost entirely aphanitic, colored in greenish gray, and distinguished from each other less by mineralogical variations than structural diversities. The relative regularity of the joint systems seemed to the author to indicate slow quenching, under appreciable cover, rather than a process of consolidation at the surface, in which an extreme fracturing would be a rule. The possibility that the phonolites in a molten state had reached the surface, however, was not discarded by the author.

Fig. 6. Geological map of the Fernando de Noronha Archipelago, Brazil by Almeida, 1955.

The trachytes in the archipelago were described as light greenish gray rocks, and almost free of dark phaneritic minerals. Six occurrences in the form of thick vertical dikes were mapped.

Almeida (1955) also identified kali-gauteites in the form of porphyritic dykes and several lamprophyric rocks, such as furchite, camptonite and melamochiquite. The melamonchiquites, are the most abundant among the dikes in Fernando de

Noronha and present in all association of dikes. Narrow dikes of tannbuschite, augitites, sannaite, limburgites and olivine teschenites were described and essexite porphyries. A single occurrence of olivine nephelinite was found included in the tuffs of Remédios Formation. The author also mentions the existence of glenmuirites, alochetites and alkali-basalts.

Homonymous to the village of Quixaba, the Quixaba Formation is composed of two varieties of ankaratritic lava flows (with and without pseudomorphs of melilite) sometimes interbedded with pyroclastic deposits, occurrences of nephelinite dykes and ankaratrite dykes. Regarding the pyroclastic deposits, these were described as consisting of tuffs, lapilli tuffs, tuff breccias and agglomerates, formed by essential particles and previously consolidated ankaratritic rock particles. The tuffs and lapilli tuffs are formed, mainly, by splashes of lava of lapilli and ash particles, and may contain crystals of olivine and rarely pyroxene, of intrateluric origin; The blocks and bombs of ankaratrite are up to 1 to 2 palms of diameter. A high cliff formed by decomposed coffee-brown tuffs showing clear stratification located about 450 meters east of Ponta do Capim-Açu were observed by Almeida.

The São José Formation were described as being formed by nepheline basanites structured in columnar jointing, with mantle xenoliths. The São José, Cuscuz, and de Fora islands are the only occurrences mapped. The NNE dip of the Quixaba ankaratrite flows located at the extreme northeastern portion of the main island, led Almeida (1955) to consider them as overlaid by the São José basanites, thus the latter, the youngest.

Ulbrich (1993) presents some modifications in the stratigraphy proposed by Almeida (1955) and presents a classification scheme for the rocks of Fernando de Noronha (Table 1). She sought to adapt the variety of names adopted by Almeida (1955) with simplified nomenclature, according to the IUGS classification, adopted in publications such as Gunn & Watkins (1976); Cornen, (1986) and Weaver (1990), in order to simplify and clarify the reader.

The basanites were grouped into the São José Formation by Almeida (1955) however, according to Ulbrich (1993) they probably represent the culmination of the Quixaba volcanism. She described the xenoliths within the basanites as dunites, lhertzolites and harzburgites, and possibly pyroxenites, with variable sizes from 1-2 mm to 30-40 cm.

The lamprophyres were separated into two groups: tephritic or melanocratic lamprophyres and typical lamprophyres, the former a suite characterized by a continuous increase in the modal content of amphibole.

Table 1: Stratigraphy and Rock Types in Fernando de Noronha, according to Ulbrich, 1993.

Stratigraphic Attribution (1)	Ulbrich (1993)(a)	Varietal and other names used in the literature	K-Ar Ages (2) (Ma)
Quixaba Formation	São José basanite *flow* [(b)]		
	Baía do Sancho basanite *pipes*		
	Ankaratrite *dikes*	Tanbushites (1)	
	Nephelinite *dikes*		
	Ankaratrite *flows*	Ankaramites* (3,5)	3.3 to 1.8
		Limburgites (3)	
		Nepheline basalts* (6)	
		Nephelinites (6)	
		Basanites* (6)	
Remédios Formation	Tephrite, basanite *dikes*	Pyroxene fourchite (1)	8.8
		Olivine teschenites (1)	
	Typical lamprophyres *dikes*	Camptonites (1)	
	Amphibole-rich tephrite, tephritic lamprophyre *dikes*	Fourchites (1)	
		Nosean sannaites (1)	
		Melanocratic mochiquites (1)	
	Trachyte *plugs, dikes*	Alkali trachytes (1)	10.7
	Trachyandesite *plugs, dikes*	Kali-gauteites (1)	
		Tristanites (3)	
		Benmoreites (4)	
	Phonolite *domes*		11.1 to 8.0
	Essexite porphyry *sill*		9.7 to 9.2
	Alkali basalt *plug*	Havaiites (3)	12.3
	Lapilli tuffs, breccias, agglomerates		

Pyroclastic rocks and ankaratrite flows are the oldest registered events of the Remédios and Quixaba formations, respectively; the rest of the stratigraphic sequence is unclear and only tentative; (b) Almeida (1955) considers these rocks as part of the younger São José Formation, but they may actually belong to the Quixaba volcanism as a culminating phase (which must also be the case for the Baía do Sancho basanites. References: (1) Almeida (1955); (2) Cordani (1970); (3) Gun & Watkins (1976); (4)

*Corner (1986); (5) Shwab & Bloch (1985); (6) Weaver (1990). *Improper names, see Ulbrich (1993). Source: modified from Ulbrich (1993).*

Rolim et al. (2019) was the first work to conduct a study specifically on the pyroclastic deposits of Fernando de Noronha. The study was based on description of lithofacies and association for different geological units.

3.3.3 Geochemistry and Magmatic Evolution

Gunn and Watkins (1976), one of the pioneers in the geochemical studies on the rocks of Fernando de Noronha, presented results of chemical analyses on samples from the Archipelago and related them to results from samples from Cabo Verde. In summary, the author discusses the petrogenetic characteristics based on investigations of crystal fractionation and processes involved from primary magma of basanitic composition (limburgite); Weaver (1990) discusses the geochemical aspects of the highly unsaturated basaltic suites in the South Atlantic Ocean: Fernando de Noronha and Trindade, and establishes parallels with tolleitic volcanic geological sites such as Hawaii, through those of moderate alkalinity such as Ascenção, Santa Helena, Gough, Tristan da Cunha to the highly alkaline Cabo Verde.

Volcanic and hypabyssal rocks of Fernando de Noronha vary in composition with time (Gerlach et al 1987:142): *"the earliest samples belong mainly to an alkaline magma series [...] the basalts and alkali-trachytes [...] and the youngest lavas are more alkaline, highly Si-undersaturated rocks, such as nefelinites, ankaratrites and melilitites."* The two series are largely distinguishable by differences in isotopic composition. Alkali-basalts and trachytes (Remédios Formation) generally display more radiogenic Sr-isotopic compositions and less radiogenic Pb- and Nd-isotopic compositions relative to the more alkaline Si-undersaturated rocks (Quixaba Formation). The authors state that the geochemical characteristics of the youngest lavas, the Quixaba ankaratrites and melilitites, are consistent with mixing of magmas derived from two geochemically distinct sources.

Ulbrich et al. (1994) recognized two distinct chemical series in the Remédios Formation: Na-enriched, unsaturated with tephritic (basanite), tephritic phonolite-phonolite trend (and coarse-grained equivalents, such as the essexite porphyry), and another mildly potassic with alkali basalt-trachyandesite-trachyte with silica saturation ranging from unsaturated (nepheline in the norm) to slightly saturated (quartz in the norm). As for the parental magmas, according to the authors, they are probably limburgitic or tephritic basanitic (sodic series) and alkali basaltic (potassic series), the former being enriched with incompatible elements compared to the latter.

Petrographic and field data led the authors to suggest that several chemically similar parental magmas may have existed for each of the proposed rock series. According to Lopes (2002), the evolution of the liquids went through fractional crystallization processes and in the potassic series evidence of magma mixing processes were observed.

No clear correlation was found by Ulbrich et al. (1994) between the melanocratic or tephritic lamprophyres (with amphibole phenocrysts) and the more evolved typical lamprophyres, suggesting that at least two independent lamprophyric liquids may have existed, derived from one or several tephytic-basanitic parental magmas. Limburgites were positioned chemically within the trend of the sodic Remédios series, and the essexite porphyry were related to the limburgites (and tephrites), on the one hand, and to the more evolved phonolites on the other. The porphyritic and aphyric phonolites would have crystallized from commom magmas and the differences in chemistry among the two would be explained by feldspar, pyroxene and titanite fractionation. Lopes (1997) carried petrographic and chemical studies specifically on the phonolites.

Maringolo (1995) characterized 36 mafic and ultramafic dikes based on petrographic and chemical features (from both the Remédios and Quixaba Formations) and the structural relations between mafic and felsic dikes from the Remédios Formation are found in Ulbrich et al. (1998).

The occurrence of xenoliths and xenocrysts within the rocks of the Remédios Formation, were discussed by Maringolo (1995), Ulbrich et al. (1994b) and Ulbrich and Lopes (1996). Ulbrich and Lopes (2000) carried a specific study on the petrography and chemistry of the xenoliths from the pyroclastic rocks of the above mentioned formation.

As for the Quixaba volcanism, Ulbrich (1994) suggested that mainly generated A-type ankaratrite, which are different from the more localized B-type ankaratrites, and that the two types probably represents two chemically distinct parental magmas, generated from different mantle sources. The Ni- and Cr-enriched ankaratrite dikes, attributed to the Quixaba event, would be the result of olivine and clinopyroxene accumulation processes. On the other hand, the nepheline dikes (showing no modal olivine) were suggested to be derived from the ankaratrite magma by removal of olivine.

Lopes (2002) used the term melanephelinites, instead of ankaratrites, to refer to the rocks of Quixaba Formation. She discusses the interbedding of olivine melanephelinite flows with melilite-bearing rocks, sometimes with similar chemical composition, as being related to different CO_2 fugacity of the volatile-rich liquids in the different melanephelinite flows. The Sr and Nd isotopic studies of the author revealed a single source for these rocks, differently from what was suggested by Ulbrich (1994). As per Lopes and Ulbrich (2006) the high incompatible element content of the melanephelinites and the differences between the ratios of these elements in the various lithological types point to an origin from distinct parental magmas, originating from distinct mantle sources, or by different degrees of melting of the same source. The SiO_2(% by weight) content is highlighted as an indicator of the chemical differences between melanephelinites, as well as the composition of melilites, being variable in each type.

The São José basanite flow, carrying abundant mantle xenoliths, possibly represents a primary magma, akin in chemical features to the Baía do Sancho basanite pipe (Ulbrich 1994), (such similarity already mentioned previously by Ulbrich (1993)), and would be derived from very similar mantle sources as the A-type ankaratrites. Lopes (2002) also associates the Basanites of São José and Cuscuz islands to the Quixaba event.

According to Rivalenti 2000, the protogranular xenoliths of São José Formation are interpreted as representative of the uppermost part of the mantle column. Also, the porphyroclastic xenoliths of Fernando de Noronha bear evidence of reactive porous flow at upward-decreasing melt/rock ratio, inducing both modal variations (orthopyroxene dissolution and clinopyroxene and olivine crystallization) and marked incompatible element enrichment. According to the author, at Fernando de Noronha, the isotopic signature of the metasomatic component is similar to that of the 8 Ma old lavas of the Remédios Formation, suggesting that this is the age of metasomatism.

Kogarko et al. (2001) classified the xenoliths of São José Formation into two groups: a) spinel lhertzolite and harzburgites (predominantly) and b) pyroxene-rich rock and wehrlites (less common). Both groups, according to the authors, show evidence of metasomatism characterized by the presence of carbonate, apatite, and secondary assemblages of olivine, pyroxene, spinel, carbonate, glass, and very fine-grained sulfides. They suggested a connection between carbonatitic metasomatic processes in the lithosphere and the origin of Ca-rich and silica-unsaturated carbonatitic magmas in the Canary Islands, Cabo Verde and Fernando de Noronha.

Other important authors on the petrography and geochemistry of Fernando de Noronha are pointed by Lopes (2002): Maringolo and Ulbrich (1997), Lopes and Ulbrich (1997), Lopes and Ulbrich (1998), Ulbrich and Lopes (1999) Lopes and Ulbrich (2001).

Unlike the aforementioned authors, the studies of Kogarko et al. (2006) temporally related the Remédios and São José Formations: "*Basanites of the São José Formation and alkaline differentiates (trachytes and phonolites) were formed at the early stages of the evolution of the Fernando de Noronha hot spot, whereas the primitive alkaline magnesian melts erupted at the final stages (represented by the Quixaba Formation). The same sequence was established in the hot spot of Trindade Island in the southern Atlantic.*" (p.88)

In 2011, new data were presented by Horota and Wildner on the lithochemical and petrological characterization of the two volcanic events (Remédios and Quixaba).

Lopes et al. (2014) conducted new studies related to the mineral chemistry of the rocks of Fernando de Noronha. They analyzed mineral specimens and xenocrysts from dikes and phonolithes of the Remédios Formation. The reaction edges of these crystals observed in some lamprophyres, tephryphonolites and phonolites were interpreted as an evidence of disequilibrium and an indication of crystal-magma mixing. The presence of centimeter-sized fragments of plutonic cumulates, according to the authors, clearly points to the existence of deeper magma chambers connected by fractures, which are passages of magmas that have crystallized as dikes and plugs. Regarding melilite crystallization, from the Quixaba flows, they confirm the finding of Lopes (2002) about this process being strongly influenced by increasing CO_2 fugacity in the magma, while a decrease would favor olivine nucleation. The São José basanites were recognized as belonging to the homonymous Formation, a minor unit, and not anymore as a final stage of Quixaba volcanism.

In 2015, Lopes and Ulbrich published new geochemical data from the rocks of Fernando de Noronha that reinforced several previous findings. The authors support the generation of the Remédios Formation series from two distinct parental magmas, as per Lopes (2002). They also highlight the importance of the role of magma mixing in the formation of the rocks of the Remédios event, evident in the disequilibrium textures as observed by Ulbrich et al. (2014). As for the rocks of the Quixaba Formation, they conclude as being less evolved types, derived from primitive magmas, which did not differentiate, or did so only slightly (for basanites). Concerning the São José Formation, they point to a direct eruptive mechanism, which connected the surface with the original molten protolith, as attested by the abundance of mantle xenoliths.

3.3.4 Geochronology

Some of works presented turned out to be determinant in revising definitions regarding the stratigraphy of Fernando de Noronha. Until the 1970s, the chronology of the magmatic manifestations and sedimentary processes of the Archipelago had been studied by Fernando Flávio Marques de Almeida and published in 1955. Almeida based, essentially, on the principles of classic stratigraphy and on sea level variations through the study of sedimentary rocks and geomorphological observations, and related them to glacial periods of known age. The first radiometric dating of samples from Fernando de Noronha belongs to Cordani (1970).

Cordani (1970) performed 28 K-Ar analyses in 23 samples from the Fernando de Noronha. From the Remédios Formation, six phonolitic rocks, three essexite porphyries, and five other rocks included in the formation were dated. Most of the phonolitic intrusions of the Remédios Formation yielded ages close to 9.00 Ma; the alkali basalt located at Enseada do Abreu, yielded an age of 12.32 ± 0.37 Ma and represents the oldest among the samples of this Formation. Six samples from ankaratritic flows of the Quixaba Formation were analyzed. The oldest age verified was 6.64 ± 0.20 Ma and the youngest was 1.81 ± 0.13 Ma from Rata Island. The other results of the Quixaba volcanism indicated evidence of higher volcanic activity around 3.00 Ma.

Discordant results were presented by the three nepheline basanite samples from the São José Formation: 9.49 ±0.33 - 9.38±0.94 Ma (independent determinations of fragments from the same sample); 8.13±0.36 Ma; and 21.9 ±0.8 Ma in a sample containing olivine xenoliths and olivine phenocrysts in the matrix. The latter was considered by Cordani as contaminated, given the high value found. He considered the possibility that the degassing of the material of the xenoliths was not complete during the lava ascent, and that the two other samples of the same nepheline basanite were also affected by a certain amount of excess argon, present in xenolitic material.“*[...] if this possibility is the truth, the hypothesis that nepheline basanites are really the youngest rocks of the archipelago, as formulated by Almeida (1955), cannot be excluded [...]”* (Cordani, 1970, p.38).

More than forty years after the publication of Cordani, Perlingeiro et al. (2013) revealed data from the same samples previously dated by Cordani (1970). The main objective of this study was to evaluate the presence or absence of excess Ar and to endorse the geochronological database of the archipelago. The $^{40}Ar/^{39}Ar$ data indicated that the Remédios formation lasted circa 3 Ma, between 12.5±0.1 and 9.4±0.2 Ma. The São José Formation returned plateau ages between 9.00±0.10 and 9.50±0.40 Ma, therefore of similar age to the Remédios Formation. The Quixaba Formation data indicated ages between 6.20±0.10 and 1.30±0.10 Ma. According to the authors, the ^{40}Ar / ^{39}Ar results revealed that Quixaba magmatism lasted approx. 5 Ma, from 6.20 ± 0.10 to 1.30 ± 0.10 Ma, and that the Fernando de Noronha volcanism lasted even more than previously determined.

4. Discussion

Currently uncertainties remain about the mechanisms involved with the genesis of the magmatism that originated the alkaline rocks of the Fernando de Noronha alignment. This alignment comprises rock bodies that can be observed from the homonymous archipelago to the continental part of northeastern Brazil along a fracture zone. The past action of a plume in a hot spot context to explain this magmatism has been reinforced by several researchers, in particular due to the existence of alignments of island and seamounts very similar to what is observed today in regions of active plumes in the Pacific Ocean.

This is the case of Fodor et al. (1998), one of the first to consider the existence of a mantle plume as a source of the alkaline rocks of northeastern Brazil and Fernando de Noronha, and of Kogarko et al. (2006). Almeida, for the first time, in 2006, considered in his model for the Noronha magmatism the existence of a plume as a magma-generator. According to this author volcanic chains emerged in fracture zones reactivated in the Middle Eocene, extending to the continental margin, through which magma overflowed from fixed hot spots in the upper mantle during the westward drift of the lithospheric plate caused by the spreading of oceanic crust. However, unlike Fodor (1998), Almeida (2006), based on the studies of Courtillot (2003) and Ernesto (2005), considered the possibility of a plume located in the upper mantle.

Despite the divergences regarding the position and nature of the plume, the uniformity of the aforementioned publications is clear as to the existence of a plume as the generator of the alkaline rocks of Fernando de Noronha and the alkaline rocks of northeastern Brazil located in the alignment of the Fernando de Noronha Fracture Zone.

Knesel et al., (2011) and Perlingeiro et al., (2013) diverge from some of these publications that preceded them, regarding the existence of a plume as a generator of these rocks. The authors established correlations with alkaline rocks southeast of the Fernando de Noronha alignment, previously attributed to the passage of the Fernando de Noronha plume, located around Pico do Cambuji, approximately 50 km southeast of Macau (RN). Based on new geochemical and geochronological data, these studies revealed that ages of the youngest continental alkalines (8.9±0.5 and 7.1±0.3 Ma in Knesel et al. (2011)), show that volcanic activity in northeastern Brazil was not ended before the start of offshore volcanism on the island of Fernando de Noronha. Thus, the same plume acting under the drifting plate could not have been the source of the volcanic events that occurred in Fernando de Noronha and in northeastern Brazil, since both areas were active contemporaneously for at least 5 Ma. Collectively, the results from the works of both authors shed doubt over the plume origin for some, if not all, of the continental alkaline volcanism in northeastern Brazil. In summary, the authors suggested the existence of small-scale convections in the upper mantle as responsible for the emergence of hot spots and the intraplate alkaline volcanic events.

Later, Lopes et al. (2014) and Lopes and Ulbrich (2015) follow this line of reasoning and reject the mantle plume as the generator of the magmatism in Fernando de Noronha. In sum, the large interval of time during Remédios and Quixaba magmatic events and differences in the geochemistry between the formations, seems to indicate, according to Ulbrich et al. (2015) that the islands represent the activity of a protracted volcanic episode, fueled by intermittent melting of an enriched mantle, not related to asthenospheric plume activity.

Regarding the stratigraphy of the Fernando de Noronha Volcano, the rocks were grouped, from the oldest to the youngest, in three formations: Remédios, Quixaba and São José, according to description and characterization by Almeida (1955). Towards the end of the second half of the 20th century, some studies contributed to revisions of this proposed sequence. In the set of proposed revisions, Ulbrich (1993) relocated some bodies between formations, e.g. the tanbushite dikes of the Remédios Formation to the Quixaba Formation and renamed them as ankaratite dikes. She also proposed a change in the terminology alkali-basalt from the Remédios Formation to trachybasalt, and proposed a reclassification of the rocks according to IUGS recommendations.

Ulbrich et al. (1994), Maringolo (1995), Lopes (1997), Ulbrich and Lopes (2002), Lopes and Ulbrich (2006), among others, followed the sratigraphic sequence proposed by Almeida (1955) for the rocks of Remédios and the Quixaba Formations. The basanites at São José, Cuscuz and De Fora islands, allocated in the São José Formation by Almeida (1955), were not considered as a stratigraphic unity by the aforementioned authors and were attributed to the culmination of the Quixaba magmatism, due mainly to their geochemical and petrographic similarities with the basanitic pipes of the Baía do Sancho, and the occurrence of narrow basanite levels interbedded with the Quixaba ankaratites.

Kogarko et al., (2006) proposed that the Remédios and São José Formations were contemporaneous, and both generated in the early stages of the Fernando de Noronha hot spot. This proposal proved to be congruent with the more recent geochonological data of Perlingeiro et al. (2013), which resolved the remaining uncertainties about the ages of the São José Formation since the first results of Cordani (1970). The state of the art for the known stratigraphic sequence of Noronha, therefore, rests on the following geochronological order: Remédios Formation contemporary to the São José Formation and the Quixaba Formation the youngest.

The differences between the geochemistry of both Formations, Quixaba and Remédios, were mentioned by all the authors who dedicated their studies on the understanding of the evolution of the magmas composition with time. The Remédios Formation shows a chemical variety not seen in the other formations (also xenoliths of various textures and compositions and xenocrysts in many rocks), hence processes as crystal fractionation plus “contamination” of different liquids (Ulbrich 1994), magma mixing (Ulbrich, 1994; Maringolo, 1995; Lopes, 2002; Lopes et al. 2014;

Lopes and Ulbrich, 2015), assimilation of mineral fragments from wall rocks as well as from lower parts of deep magma chambers (Maringolo, 1995), were considered to have occurred during the magma evolution.

Concerning the Quixaba Formation, it was suggested mixing of magmas derived from distinct sources (Gerlach et al., 1987); and the existence of two distinct parental magmas, generated from different magma sources. (Ulbrich et al., 1994). Lopes (2002), after carrying isotopic studies, revealed a single source for these rocks. Later, in 2006, Ulbrich suggests distinct mantle sources, or different degrees of melting of the same source. Lopes et al., (2014) brings concise statements about this matter as well as about parental magmas, chemical evolution, and processes of differentiation mainly about the Remédios and Quixaba Formations.

5. Conclusions

As a basis for the ongoing studies by the authors of this paper, which has pyroclastic rocks as an emphasis, and taking into account previous works, it can be considered: 1) the magmatic events that occurred at Fernando de Noronha can be understood as intraplate volcanism generated by the presence of a hot spot or by temperature elevations and melting of an enriched mantle not related to asthenospheric plume activity (divergences still remain); 2) The rocks are grouped in three formations: Remédios Formation (12.50± 0.10 Ma to 9.40±0.20 Ma) formed by phonolites and trachytes in the form of domes and dikes, alkali-basalt, essexite porphyry, pyroclastic deposits cut by a variety of lamprophyric dikes. The São José Formation (9.00±0.10 and 9.50±0.40 Ma), contemporaneous with the Remédios Formation, formed by basanite flow rich in xenoliths of dunite, lhertzolite, harzburgite and pyroxenites. The youngest, Quixaba Formation (6.20 ± 0.10 to 1.30 ± 0.10 Ma), formed by ankaratrite flow interbedded with thin and melilite-rich flow and pyroclastic deposits, locally cut by nephelinite dikes; 3) The subvolcanic intrusions of the older Remédios Formation are classified into two different alkaline series, a sodic (undersaturated: basanites, tephrites, essexites, tephriphonolites, phonolites) with a parental magma probably of limburgitic or tephritic basanitic composition, and a potassic (mildly undersaturated to silicic, with alkali basalts, basaltic trachyandesites,trachyandesites, trachytes) and lamprophyres, derived from an alkali basaltic parental magma. The primitive Quixaba rocks are mostly melanephelinites: with melilite, with pyroxene and with abundance of olivines, and subordinate basanites. They are primitive undersaturated sodic types.

Acknowledgements

The authors wish to acknowledge LABTECRochas-IGC-UFMG and CNPq for their financial support during our research. This paper contains results of the M.Sc. dissertation of the first author at the UFMG, with scholarship from CAPES. Special thanks to the administration of the Fernando de Noronha Territory and to the Chico Mendes Institute for Biodiversity Conservation for facilities and authorizations for research in the territory.

References

Almeida, F.F.M. de., 1955. Geologia e petrologia do Arquipélago de Fernando de Noronha, DNPM/DGM, Rio de Janeiro.

Almeida, F.F.M. de., 1986. Distribuição regional e relações tectônicas do magmatismo pós-paleozóico no Brasil. Revista Brasileira de Geociências, 16(4):325-349.

Almeida, F.F.M. de, Carneiro, C.D.R., Dehira, L.K., Machado, D.L.J., 1988. Magmatismo pós-paleozóico no nordeste oriental brasileiro. Revista Brasileira de Geociências, 18 (4):451-462.

Almeida, F.F.M. de, Carneiro C.D.R., Mizusaki A.M.P., 1996. Correlação do magmatismo das bacias da margem continental brasileira com o das áreas emersas adjacentes. Revista Brasileira de Geociências, 26(3):125–138.

Almeida, F.F.M. de, Schobbenhaus, C., Queiroz, E.E., Winge, M., Berbert-Born, M., 2002. Arquipélago de Fernando de Noronha registro de monte vulcânico do Atlântico Sul. SIGEP 66: 361-368.

Almeida, F.F.M. de., 2006. Ilhas oceânicas brasileiras e suas relações com a tectônica atlântica. Terræ Didatica 2(1):3–18.

Branner, J.C., 1889. The geology of Fernando de Noronha. American Journal of Science 1880-1910, Feb 1889; 37, 218; American Periodicals:145-161.

Cordani, U.G., 1970. Idade do vulcanismo do Oceano Atlântico Sul. Boletim IAG USP 1:33-39. DOI: 10.11606/issn.2316-9001.v1i0p09-75

Costa, P.R.C., Antunes, A.F., Sá, E.F.J. de, Amaro, V.E., Matos R.M.D. de., 2002. O registro da deformação mesozóica relacionada à abertura da margem equatorial atlântica no litoral do Estado do Ceará (Nordeste do Brasil): evidências a partir da análise de imagens orbitais e de afloramentos. Congresso Brasileiro de Geologia, João Pessoa, 41:623.

Costa, A.G., 2013. Geological and Historical Cartographic Expedition to the Archipelago of Fernando de Noronha: an example of communication between historical cartography and geology. Simpósio Lusobrasileiro de Cartografia Histórica, 5, 2013, Petrópolis. <http://www.cartografia.org.br/vslbch/trabalhos-apresentados.html>

Darwin, C., M.A., F.R.S., 1845. Journal of researches into the natural history and geology of the countries visited during the voyage of H.M.S Beagle round the world. London, (second edition), 519 p.

Fodor, R.V., Mukasa, S.B., Sial, A.N., 1998. Isotopic and trace-element indications of lithospheric and astenospheric components in Tertiary alkalic basalts, northeastern Brazil. Lithos 43:197–217. DOI: 10.1016/S0024-4937(98)00012-7

Gerlach, D.C., Stormer Jr., J.C., Muller, P.A., 1987. Isotope geochemistry of Fernando de Noronha. Earth and Planetary Science Letters, 85:l29–144. DOI: 10.1016/0012-821X(87)90027-6

Gunn, B.M.; Watkins, N.D., 1978. Geochemistry of the Cape Verde Islands and Fernando de Noronha. GSA Bulletin, 87(8):1089-1100. DOI: 10.1130/0016-7606(1976)87<1089:GOTCVI>2.0.CO;2

Horota, R.K.,Wildner H. 2011. Caracterização geoquímica do Arquipélago de Fernando de Noronha. Congresso brasileiro de geoquímica, 13; Simpósio de geoquímica dos países do Mercosul, 3, Rio Grande do Sul: Anais CGQ02 T83:927-930.

King, S.D., 2007. Hotspots and edge-driven convection. Geology 35, 223–226. DOI: 10.1130/G23291A.1

Knesel, K.M., Souza, Z.S. de., Vasconcelos, P.M., Cohen, B.E., Silveira, F.V., 2011. 40Ar/39Ar geochronology reveals the youngest volcanism in mainland Brazil and no evidence for a plume trace on the continent. Earth and Planetary Science Letters 302(1-2), 38–50. DOI: 10.1016/j.epsl.2010.11.036

Kogarko, L.N., Kurat, G., Ntaflflos, T., 2001. Carbonate metasomatism of the oceanic mantle beneath Fernando de Noronha Island, Brazil. Contributions to Mineralogy and Petrology 140, 577–587. DOI: 10.1007/s004100000201

Kogarko, L.N., Lebedev, V.A., Levskii, L.K., 2007. Heterogeneity of isotope sources of alkaline magmatism in the hot spot of the southwestern Atlantic: Fernando de Noronha islands. Doklady Earth Sciences 412 (1), 85–88. DOI: 10.1134/S1028334X07010199

Le Maitre, R.W., 2002. Igneous rocks: a classifification and glossary of terms: recommendations of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks. Cambridge University Press, 236 p.

Lopes, R.P., 1997. Petrologia dos Fonólitos do Arquipélago de Fernando de Noronha, PE. Instituto de Geociências, University of São Paulo, São Paulo.

Lopes, R.P., 2002. O vulcanismo do Arquipélago de Fernando de Noronha, PE: química mineral e geoquímica. Instituto de Geociências, University of São Paulo, São Paulo.

Lopes, R.P., Ulbrich, M.N.C, 1997. Petrografia e química mineral de fonólitos do Arquipélago de Fernando de Noronha, PE. Anais Academia Brasileira de Ciências, 68:431.

Lopes, R.P., Ulbrich, M.N.C, 1998. Evolução geoquímica da suíte de fonólitos do Arquipélago de Fernando de Noronha, PE. Congresso Brasileiro de Geologia, 40, Belo Horizonte. Anais, SBG:464.

Lopes, R.P., Ulbrich, M.N.C., 1999. Petrografia e química mineral de fragmentos de rochas gábricas e dioríticas em depósitos piroclásticos de Fernando de Noronha, PE. Congresso de Geoquímica dos países de língua portuguesa, 5, Congresso Brasileiro de Goquímica, 7, Porto Seguro. Anais: 620-621

Lopes, R.P., Ulbrich, M.N.C., 2001. Olivina melilita melanefelinitos da Formação Quixaba, Arquipélago de Fernando de Noronha, PE, Brasil.

Lopes, R.P., Ulbrich, M.N.C., 2006. Rochas vulcânicas alcalinas da Formação Quixaba de Fernando de Noronha, PE: Química mineral e litogeoquímica. Revista Brasileira de Geociências 36(1): 35-48.

Lopes, R.P., Ulbrich, M.N.C., Ulbrich, H., 2014. The volcanic-subvolcanic rocks of the Fernando de Noronha Archipelago, Southern Atlantic Ocean: Mineral chemistry. Cent. Eur. J. Geosci. 6(4):422-456. DOI: 10.2478/s13533-012-0195-7

Lopes, R.P., Ulbrich, M.N.C., 2015. Geochemistry of the alkaline volcanic-subvolcanic rocks of the Fernando de Noronha Archipelago, southern Atlantic Ocean. Brazilian Journal of Geology. 45(2). DOI: 307-333. 10.1590/23174889201500020009

Maringolo, V., 1995. Estudo petrográfifico e químico de diques ultramáficos e máficos do Arquipélago de Fernando de Noronha, PE. Instituto de Geociências, University of São Paulo, São Paulo.

Maringolo, V., Ulbrich, M.N.C., 1997. Registros da evolução de diques máficos do Arquipélago de Fernando de Noronha na química dos clinopiroxênios e anfibólios. Congresso de geoquímica dos países de língua portuguesa, 4. Lisboa, Portugal, Actas, 83-85.

Mohriak, W., 2020. Genesis and evolution of the South Atlantic volcanic islands offshore Brazil. Springer Nature, Geo-Marine Letters 40: 1–33. DOI: 10.1007/s00367-019-00631-w

Perlingeiro, G., Vasconcelos, P.M.M., Knesel K. M., Thiede D.S., Cordani. U.G., 2013. 40Ar/39Ar geochronology of the Fernando de Noronha Archipelago and implications for the origin of alkaline volcanism in the NE Brazil. Journal of Volcanology and Geothermal Research 249:140–154. DOI: 10.1016/j.jvolgeores.2012.08.017

Rivalenti, G., Mazzucchelli, M., Girardi, V.A.V., Vannucci, R., Barbieri, M.A., Zanetti, A., Goldstein, S.L., 2000. Composition and processes of the mantle lithosphere in northeastern Brazil and Fernando de Noronha: evidence from mantle xenoliths. Contributions to Mineralogy and Petrology 138, 308–325. DOI: 10.1007/s004100050565

Rolim, J. M., Murta, M.C.P, Costa, A.G., Soares, F., 2019. Caracterização dos depósitos piroclásticos: uma contribuição para o entendimento da geologia do Arquipélago Fernando de Noronha. Simpósio de geologia do nordeste, 28, Aracaju, SBG. Anais, único:399.

Ridley, H.N., M.A., F.L.S. 1890. The Natural History of the Island of Fernando de Noronha based on the Colections made by the British Museum Expedition in 1887. The Journal of the Linnean Society, 27: 570 p.

Ulbrich, M.N.C., 1993. Petrography of alkaline volcanic–subvolcanic rocks from the Brazilian Fernando de Noronha Archipelago, Southern Atlantic Ocean. Boletim IG-

USP Série Científica, 24:77-94. DOI: 29. DOI: 10.11606/issn.2316-8986.v24i0p77-94

Ulbrich, M.N.C., Maringolo,V., Ruberti, E., 1994. The geocheminstry of alkaline volcanic-subvolcanic rocks from the Brazilian Fernando de Noronha Archipelago, South Atlantic Ocean. Geochimica Brasiliensis, 8(1):21-39.

Ulbrich, H.H.G.J., Ulbrich, M.N.C., Lopes, R. P., 1998. Diques máfico-ultramáficos e félsicos da Formação Remédios, Arquipélago de Fernando de Noronha, PE: contemporaneidade das intrusões. Congresso Brasileiro de Geologia, 40, Belo Horizonte. Anais, SBG:464.

Ulbrich, M.N.C., Lopes, R. P., 1996. Xenocristais de olivina com coroas e bordas de reação, em fonólito porfirítico de Fernando de Noronha. Congresso Brasileiro de Geologia, 39, Salvador. Anais, SBG 3:43-45.

Ulbrich, M.N.C., Lopes, R. P., 2000. Xenólitos de origem subvulcânica na Formação Remédios, Arquipélago de Fernando de Noronha: petrografia, textura e química mineral. Geochimica Brasiliensis, Rio de Janeiro, 14(1): 97-114.

Weaver, B.L., 1990. Geochemistry of highly-undersaturated ocean island basalt suites from the South Atlantic Ocean: Fernando de Noronha and Trindade islands. Contributions to Mineralogy and Petrology 105:502–515. DOI: 10.1007/BF00302491

Wyville, C.T, K.N.T., L.L.D., D.Sc., F.R.SS.L., E., F.L.S., F.G.S., 1878. The Voyage of The Challenger The Atlantic a preliminary account of the general results of the exploring voyage of H.M.S. "Challenger" during the year 1873 and the early part of the year 1876. New York 2:340p.

LITHOFACIES ASSOCIATION AND STRATIGRAPHY OF THE QUIXABA AND REMÉDIOS FORMATIONS, FERNANDO DE NORONHA ARCHIPELAGO, BRAZIL

Maria Clara Parreira Murta, Antônio Gilberto Costa, Fábio Soares de Oliveira

Universidade Federal de Minas Gerais - UFMG, Geosciences Institute, Campus Pampulha, Av Antônio Carlos, 6623, ZipCode: 31270-901, Belo Horizonte, MG, Brazil.

ABSTRACT

Establishing precise stratigraphic relationships in ancient volcanic successions is a fundamental means of understanding the evolution, eruptive dynamics, and past behavior of volcanoes. The methodology of lithofacies identification, association, and interpretation was applied systematically in order to reconstruct the stratigraphic framework of important areas of the Archipelago Fernando de Noronha, South Atlantic Ocean, Brazil. This work presents a detailed stratigraphy of part of the Remédios and Quixaba Formations, allowing the understanding of the lateral and vertical distribution of volcanic facies and the 3D geometry of the deposits, and discussions on the erupting mechanisms and styles. Through lithofacies description and association for volcaniclastic deposits, three stratigraphic columns were constructed in scale 1:50 at Caieira Beach. They resulted in the distinction of four lithofacies (all pyroclastic) for the Remédios Formation. The pyroclastic lithofacies are of massive tuff (Tm), massive lapilli tuff (Ltm), massive lapilli tuff with angular, vesicular blocks of up to 49 cm (Ltb), and massive tuff breccia (Btm). The lithofacies association characterizes non-welded endured ignimbrites of phonolitic composition bearing proximal co-ignimbrite breccias, which were originated from the deposition of ground-hugging density currents. For the lava flows and volcaniclastic deposits of the Quixaba Formation, twelve sections were constructed, distributed at Americano and Bode Beaches and Capim-Açu-Edge. The stratigraphic analysis resulted in the distinction of four pyroclastic lithofacies, one autoclastic and three coherent. The pyroclastic lithofacies present at the Capim-Açu Edge are massive lapilli-tuff (Ltm), massive lapilli tuff with vesicular blocks of up to 28 cm (Ltb), massive tuff breccia (Btm), and normal grading lapillistone (Lng) formed by ash-aggregates (massive ash pellets, and varieties of accretionary lapilli and armored lapilli). The lithofacies association characterizes scoria and ash flow pyroclastic deposits and proximal fallout deposits. The coherent lithofacies present at the Capim-Açu Edge are massive olivine-phyric nephelinite (Onm), vesicular olivine-phyric nephelinite (Onv), scoriaceous olivine-phyric nephelinite (One) and massive olivine-phyric melilite nephelinite (Onmm). The lithofacies association characterizes pahoehoe lava flows. At the Americano and Bode Beaches, the autoclastic lithofacie is olivine-nephelinitic breccia (Onb) and occurs in association with the Onv and Onm, characterizing 'A'a lava flows. During the Quixaba volcanism, pulses of Strombolian activity led to the formation of scoria and ash flow deposits alternated to effusive Hawaiian activities and the formation of extensive pahoehoe lava sheets. A later stage of phreatomagmatic activity was followed leading to the formation of proximal fallout deposits with ash-aggregates formed through wet aggregation.

Key Words: Volcano stratigraphy, Facies analysis, Pyroclastic flows

1. Introduction

Volcanic stratigraphy is a fundamental tool in the reconstruction of volcanological evolution and eruptive dynamics (Pasqualon et al., 2019; Martí et al., 2018; Pedrazzi et al., 2013; Groppelli and Martí, 2013; Cas and Write 1988), and is crucial in any attempt to identify, characterize and reconstruct stratigraphic successions encompassing volcanic events and eruptive occurrences in the geological record of a volcanic area (Martí et al 2018). Detailed volcanic stratigraphy, combined with data on juvenile texture, has permitted the reconstruction of the eruptive dynamics of particular eruptions (Pasqualon et al., 2019; Brown et al., 2014; Van Eaton and Wilson, 2013; Miyabuchi et al., 2006; Gurioli et al., 2005; Mellors and Sparks 1991), which is important for the comprehension of the geological evolution of a region and hazard assessment.

The geology of the Fernando de Noronha Archipelago (FNA) was first described through a petrological, geochemical, and geochronological approach by Almeida (1955) and followed by others (e.g. Cordani, 1970; Gerlach et al., 1987; Ulbrich, 1993; Lopes, 1997; Fodor et al., 1998; Lopes, 2002; Almeida, 2006; Lopes and Ulbrich, 2006; Perlingeiro et al., 2013; Lopes and Ulbrich, 2015). These and other studies have mostly concentrated on the effusive and subvolcanic rocks of the Archipelago. Ulbrich and Lopes 1999 presented an abstract on the petrography and mineral chemistry of fragments within pyroclastic rocks of Fernando de Noronha, and only recently, Rolim et al., 2019 presented a preliminary study on the characterization of pyroclastic rocks of FNA based on stratigraphic analyses.

Therefore, advances in the study of the pyroclastic rocks of FNA have not followed those on the effusive and subvolcanic rocks, which may have as cause some limitations which are imposed mainly on the stratigraphic analysis of the pyroclastic rocks: (1) the advanced state of erosion of the extinct volcano which has only a small volume of pyroclastic material outcropping in accessible areas (2) the stage of preservation of part of the pyroclastic deposits is precarious due to the relatively ancient age of the deposits and exposure in a humid equatorial environment; (3) the pyroclastic deposits from the Quixaba Formation occur on cliffs mostly inaccessible even by boat. As a result, the complete sequences are not accessible, which makes an integrated understanding of the different lithofacies in terms of source proximity and superposition relationships difficult; and (4) the location of the volcanic craters is unknown or only suspected.

Considering this scenario, a detailed stratigraphic framework involving the description of lithofacies and association for different geological units was conducted in this work. We present field and laboratory-based descriptions of pyroclastic deposits of the two main volcanic episodes in the Fernando de Noronha Archipelago (FNA), which are grouped in the Remédios Formation, of age between 12.5±0.1 and 9.0±0.1 (Cordani, 1970) and the Quixaba Formation, of age between 6.2± 0.1 and 1.3± 0.1 Ma (Perlingeiro et al. 2013), the latter in association with lava flows of the same formation. The detailed analysis of the stratigraphy of part of the deposits of the Remédios and Quixaba Formations allows the understanding of the lateral and vertical distribution of facies and the geometry of the deposits, generating discussions on the erupting mechanisms and eruptive styles.

2. Geological setting

The Fernando de Noronha Archipelago is what is left of a high and vast volcano, whose base rests 4,000 meters deep on the ocean floor and is arranged in an alignment of islands and seamounts (Almeida, 1955) between parallels 3°53'20" and 3°48'05" in the South Atlantic Ocean (Fig.1). Its base is elongated in the east-west direction with a length of approx. 75 kilometers (Almeida, 2006).

The Fernando de Noronha alignment comprises rock bodies that can be observed from the homonymous archipelago to the continental part of northeastern Brazil (Fig. 1) along a fracture zone (Almeita, 1986; Almeida et al., 1988; Almeida et al., 1996; Almeida et al., 2002). The past action of a plume in a hot spot context to explain this magmatism has been proposed by Fodor et al., 1998 and reinforced by several researchers (Kogarko et al., 2006; Almeida, 2006, Mohriak, 2020 and references therein). Perlingeiro et al. (2013) suggest that the magmatism associated with the proposed Fernando de Noronha plume would perhaps be better explained by small-scale, plate-driven convection in the upper mantle, as suggested by King (2007) and Knesel et al. (2011). This hypothesis is consistent with the presence of high seismic shear-wave velocities (interpreted as the downwelling limb of such an edge-driven convection cell) in the upper mantle beneath the eastern margin of the South American craton (Perlingeiro et al., 2013; King and Ritsema, 2000) and the lack of seismic evidence for a deeply sourced plume upwelling (e.g., Montelli et al., 2006, and references therein). Moreover, small-scale convection triggered at the edge of the South American continent also provides a straightforward mechanism for the introduction of an enriched-mantle component derived from the Brazilian subcontinental lithosphere in the offshore volcanic rocks (e.g., Gerlach et al., 1987).

The rocks of the Fernando de Noronha Archipelago are divided into three formations: Remédios, São José and Quixaba (Almeida, 1955) (Fig.2). Nearly 3 M.a separates an older period of volcanism between 12.5±0.1 until 9.0±0.1 Ma, comprising the Remédios and São José formations (Perlingeiro et al., 2013) and a younger episode, the Quixaba Formation, between 6.2± 0.1 and 1.3± 0.1 Ma (Cordani 1970; Perlingeiro et al., 2013). The high alkalinity of the archipelago was stated by Gunn and Watkins, 1976; Gerlach et al 1987; Ulbrich et al., 1994, involving rocks representing effusive and explosive events.

The *Remédios Formation* was designated as a complex set of tuffs and volcanic breccia intruded by discordant bodies of phonolites and trachytes, which are widespread, a great variety of dykes and less regular bodies of ultra-basic and alkaline rocks, among which those of lamprophyric facies stand out (Fig. 2) (Almeida, 1955). Some of the lamprophyric rocks recognized by Almeida, 1955 were reclassified by Ulbrich, 1993 according to IUGS nomenclature. The *São José Formation* comprises nepheline basanites (Fig. 2) structured in columnar jointing, with mantle xenoliths (Almeida, 1955) of dunites, lherzolites and harzburgites, and possibly pyroxenites (Ulbrich, 1993) and wehrlites (less common) (Kogarko et al., 2001). The *Quixaba Formation* is composed of two varieties of ankaratritic lava flows (with and without pseudomorphs of melilite) sometimes interbedded with pyroclastic deposits, occurrences of nephelinite dykes, and ankaratrite dykes (Fig. 2) (Almeida, 1955). The pyroclastic deposits of the Quixaba Formation were described as tuffs, lapilli tuffs, tuff breccias, and agglomerates, formed by essential particles and previously consolidated ankaratritic rock particles. The term melanephelinites has been used to denominate the occurrences of the Quixaba ankaratrite flows by Lopes 2002; Ulbrich 2006; Ulbrich 2014, Ulbrich 2015, among others.

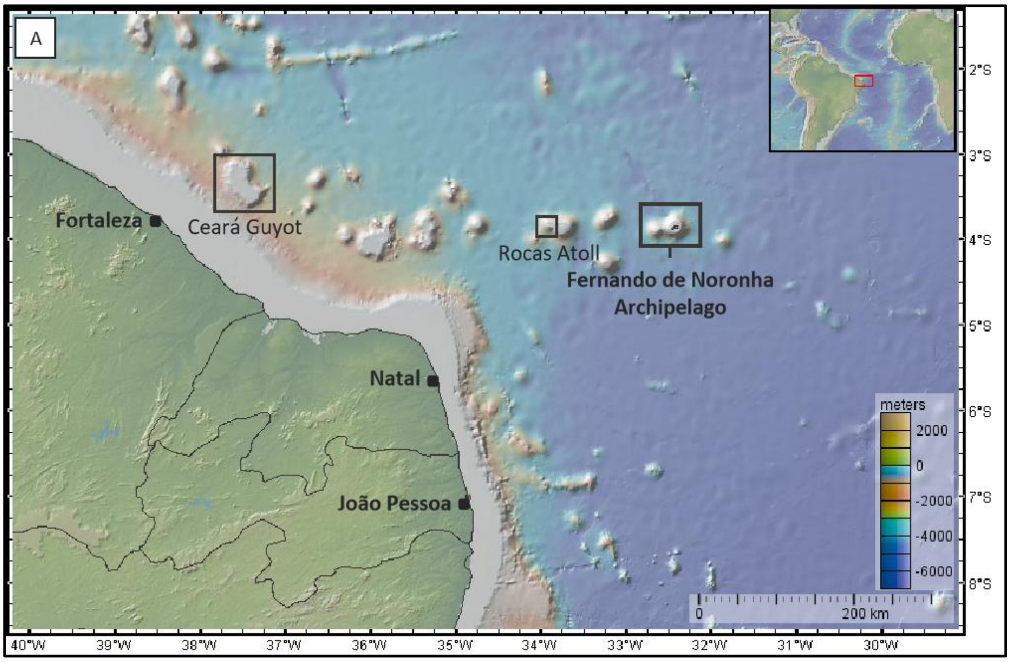


Fig. 7. Location of the Fernando de Noronha Archipelago in the South Atlantic Ocean (GeomapApp). Note the alignment of rock bodies, which includes the Fernando de Noronha Archipelago, Rocas Atoll, and Ceará Guyot, and can be observed from the homonymous archipelago to the continental part of northeastern Brazil.

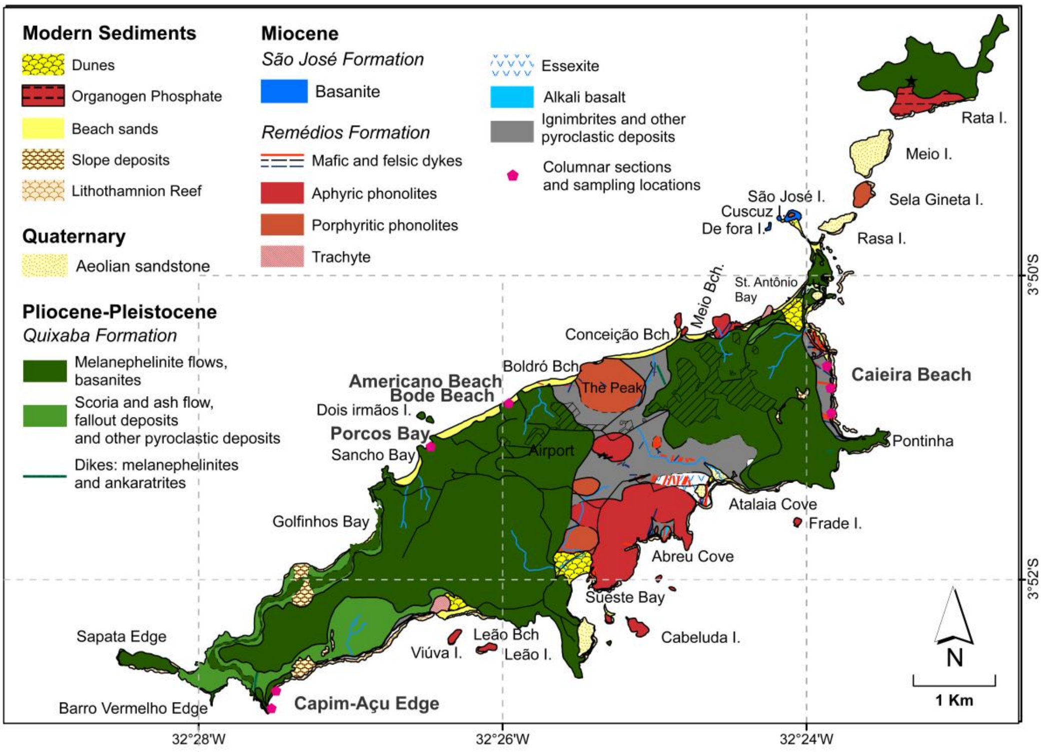


Fig. 8. Geological map of Fernando de Noronha Archipelago with columnar sections and sample localities represented by pink pentagons, modified from Almeida 1955.

3. Analytical procedures

Fieldwork and petrography were carried out for the general description of the pyroclastic deposits and lava flows. Conventional optical microscopy was applied for petrographic characterization using the petrographic microscope ZEISS Axioskop 40 under transmitted light. The software Hardledge was used for a systematic data organization and rock description. The software Zen 3.3 allowed thin sections image capture and measurements of vesicles and crystals.

For the stratigraphic analysis of the pyroclastic deposits from the Remédios Formation, 3 sections were built; and for the pyroclastic deposits from the Quixaba Formation interbedded with lava flows 12 sections were built. For each section, the deposits were represented in a vertical log succession combined with the description of the lithofacies and facies association. Part of the sections is in the supplementary material.

In this work, the description of lithofacies for the pyroclastic deposits follows the criteria adopted for sedimentary rocks created by Miall (1977), with the adaption of the grain size nomenclature to volcanic particles (e.g. ash, lapilli, bomb, and block), following the classification proposed by Schmid (1981) and applied by Pasqualon et al. 2019. For the lava flows and autoclastic rocks, the lithofacies description was based on the primary composition followed by the textures and rock structures (e.g. porphyritic, aphyric, massive, vesicular, fractured) as suggested by McPhie (1993).

4. Petrography

The pyroclastic rocks of the Remédios Formations outcrop in some areas of the main island as in Sueste Bay, Meio Beach, Abreu Cove, the central region where the airport is located, and Caieira Beach (Fig 2). Among these regions, the latter exhibit greater continuity of exposure and a less advanced state of alteration of the pyroclastic rocks, therefore it was the region where the studies of this Formation were conducted.

The pyroclastic deposits of the Quixaba Formation cover a large area of the main island, and can be observed mainly on the south coast cliffs from Sapata Edge, through Barro Vermelho Edge to Capim-Açu Edge (Fig. 2). However, only at Ponta do Capim-Açu can they be seen on foot.

4.1 **Remédios Formation - Caieira Beach**

Caieira Beach is located in the northeast region of the FNA (Fig. 2), occupying an area of approximately 0.12km². The pyroclastic rocks in Caieira Beach are of light greenish-gray and pale pink colors, composed of angular to sub-angular lithic and juvenile fragments. The lithics are constituted of phonolite (Fig. 3A-B), trachyte, tephrite, olivine-basalt, and essexite, which are moderately vesicular to massive, ranging in size from lapilli to block. Juvenile pyroclasts are commonly found as light gray and beige pumice lapilli, of variable shapes. The fragments are matrix-supported. The matrix is composed of ash, amounts of fine pumice lapilli of trachytic-phonolitic composition, fine lithic lapilli, and crystal fragments of ortho, clyno and alkali-pyroxene, hornblende, and feldspar, most commonly as ash-size components. The vesicles are elongated and partially filled by carbonate and zeolite.

Slight differences in the size of the fragments in different layers in addition to discontinuous lateral and vertical grain size variations give an irregular and indistinct stratification to the deposit. Overall, the internal organization of the ignimbrites is marked by poor sorting and a lack of continuous grading patterns.

4.2 **Quixaba Formation - Capim-Açu Edge**

The region of Capim-Açu Edge is located in the southwestern portion of the FNA, occupying an area of approximately 0.10km². In the low tide, at the extreme southwest of the Capim-Açu Edge, where there is a wide erosion feature in the shape of a tunnel carved by the seawater, it is possible to identify a sequence of lava flows interbedded with layers of pyroclastic deposits, along a relief of cliffs approximately 15m high. The petrographic descriptions were carried out at the first pyroclastic level.

From this point towards the northeast, about 250 meters from the tunnel, the pyroclastic deposits occur interbedded with lava flows on another cliff. Three distinct levels of pyroclastic deposits were identified in the northeast region:

i) Lower level: pyroclastic deposits overlaid by a lava flow.

ii) Intermediate level: melilite-bearing pyroclastic level on top of the lava flow.

iii) Upper level: brown coffee cliff with ash aggregates.

The pyroclastic rocks of the tunnel region and the lower level of the northeast region are mainly comprised of angular to subangular juvenile (Fig. 3C) and comagmatic fragments of olivine-phyric nephelinite (Fig. 3D). The juvenile constituents show variable sphericity and are moderate to highly vesicular, ranging in size from ash to block. The comagmatics are poorly vesiculated to massive. It is notable the ubiquitous presence of reddish-brown iddingsite replacing the olivine forsterite phenocrysts on a micro-scale (Fig 4C-D) and with the naked eye. Clinopyroxene occurs as microphenocrysts and in the matrix as laths of diopside (Fig. 4C). The matrix is also composed of nepheline and Fe-oxide. Melilite occurs as an accessory phase (<1%) in the matrix (Fig 4D).

Petrographically the intermediate level is distinguished from the lower level mainly by the melilite content, which increases to 15-20% (Fig. 4E). It is also notable, on a microscopic scale, the appearance of millimetric dark juvenile fragments of several forms with a fluidal aspect and a glassy matrix. (Fig. 4E).

The internal organization of the pyroclastic deposits of the lower and intermediate levels is marked by poor sorting, and grading patterns marked by grain size variations often laterally discontinuous.

The upper level is located on a high cliff, approximately 50 meters in altitude in the northeast region. The two basal layers studied are made of juvenile clasts, ranging in size from fine to coarse lapilli and bombs in less abundance. The layers are laterally continuous, well sorted, clast-supported, and variably graded. On a microscopic scale, it is seen that the apparent coherent aspect of the studied juvenile clasts is in reality of a fragmentary nature. They are made of five distinct types of ash aggregates: massive ash pellets, accretionary lapilli, complexly layered accretionary lapilli, olivine and melilite nuclei coated by fine ash, and olivine nuclei coated by multiple layers of fine ash. The ash aggregates are held together in a cryptocrystalline groundmass (Fig 4F). The ash aggregates are composed of olivine forsterite, canary yellow and colorless melilite, Mg-rich clinopyroxene as laths of microcrystals and microlites, Fe-oxide grains, and nepheline.

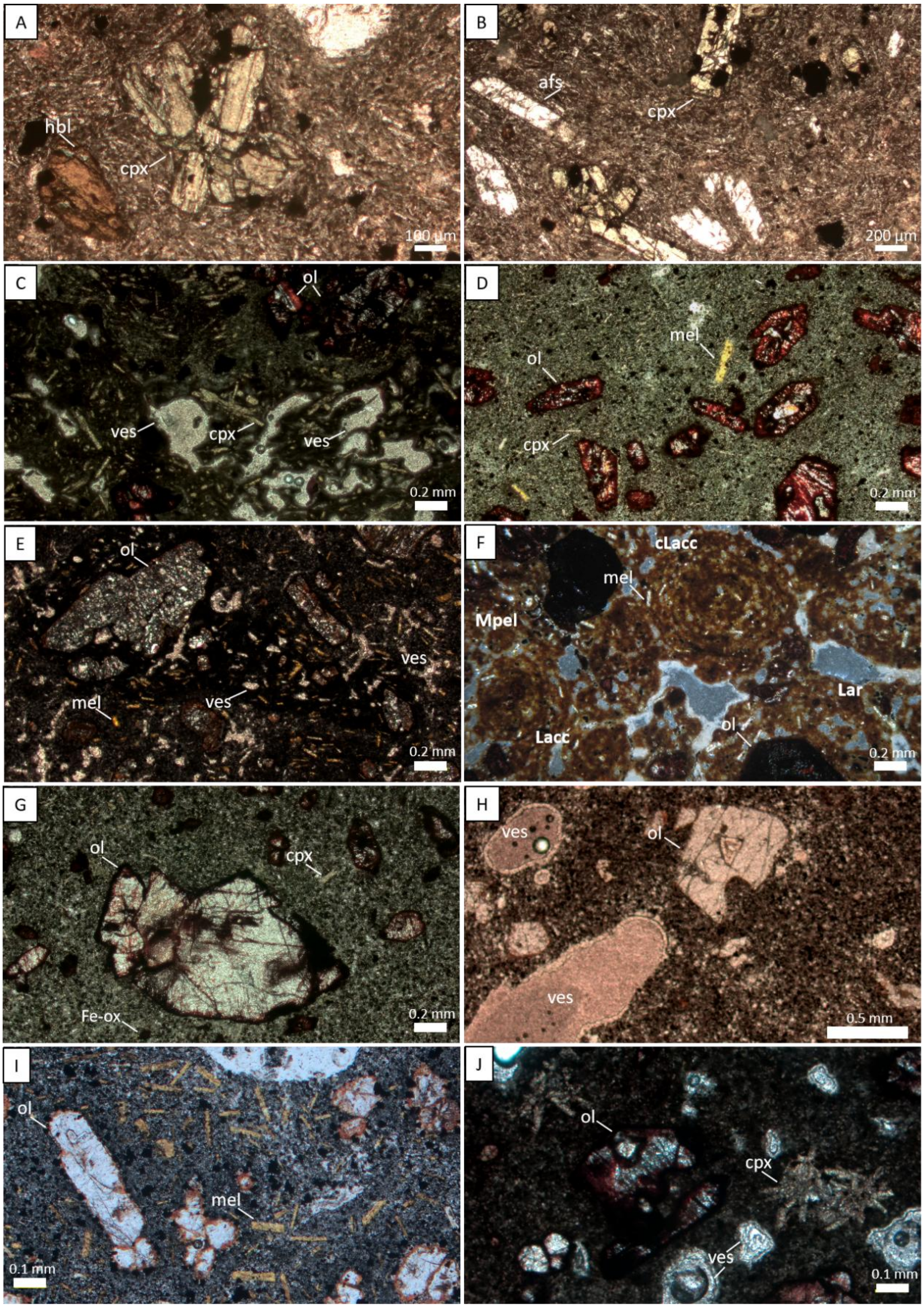


Fig. 9. Thin sections of pyroclastic rocks and nephelinitic lava flows from Remédios and Quixaba Formations. A) and B) Phonolite lithic fragment from Caieira Beach - glomeroporphyritic texture defined by clusters of pale green clinopyroxene, isolated white alkali feldspar phenocrysts, medium brown hornblende phenocryst, nepheline microphenocryst, and oxide grains. The groundmass is mainly composed of alkali feldspar defining a trachytic texture; C) A scoria fragment from the lower level of

the Capim-Açu Edge: diopside glomeroporphyritic clusters and reddish-brown forsterite phenocrysts altered to iddingsite in a vesicle-rich groundmass. The groundmass is mainly composed of Fe-oxide grains, laths of diopside, and microcrystalline nepheline; D) A lithic fragment from the lower level of the Capim-Açu Edge (tunnel region): melilite-bearing olivine phyric nephelinite. Note the canary yellow color of melilite crystals and the ubiquitous presence of reddish-brown iddignsite replacing the forsterite phenocrysts. E) A scoria fragment from the intermediate level of the Capim-Açu Edge: solidified juvenile rock fragment with olivine phenocrysts and melilite microphenocrysts in a vesicle-rich dark glassy matrix. Note the fluidal form of the glassy fragment; F) A juvenile lapilli from the upper level of the Capim-Açu Edge: complexly layered accretionary lapilli (cLacc), layered accretionay lapilli (Lacc), layered armored lapilli (Lar) with olivine nucleus, massive ash pellet (Mpel), and melilite crystals; G) Massive olivine-phyric nephelinite lava flow (Onm) from the Capim-Açu Edge (tunnel region). Note the seriate texture of the forsterite crystals and the alteration to iddignsite; H) Scoriaceous olivine-phyric nephelinite (One) which occurs between the lower pyroclastic level from the Capim-Açu Edge (northeast region); I) Massive olivine-phyric melilite nephelinite (Onmm) which occurs as centimetric levels interleaved with the olivine-phyric nephelinite lava flow in the Capim-Açu Edge (northeast region); J) Vesicular olivine-phyric nephelinite (Onv) from the Americano Beach. Note the glomeroporphyritic clusters of diopside and reddish-brown forsterite altered to iddingsite in a vesicle-rich fine matrix. Ol: olivine, cpx: clinopyroxene, Fe-ox: Fe oxide, mel: melilite, ves: vesicle.

It was possible to study and analyse the first 6 meters of the lava flows that lie above the lower pyroclastic levels along the cliffs in the Capim-Açu Edge. The lava flows occur in a tabular shape and in irregular contact with the pyroclastic deposits below. The flows are vesicular-rich at the base, in which the vesicles exhibit a flattened oval shape with a decrease and change to a more round shape and become sparse towards the top. Three thin levels of massive melilite-bearing olivine-phyric nephelinite occur interleaved with the lava flows. A scoriaceous and lenticular shaped lava flow of the same compositionoccurs within the lower pyroclastic level, where the sections PCA-02 and PCA-03 were built.

The Americano and Bode Beaches are located approximately 1.1 and 1.4km, respectively, at a straight distance towards northeast from the Porcos Bay. The regions comprise coherent massive to vesicular flows and less coherent, fragmented levels. The latter show grain-supported framework, composed of angular to rounded fragments of same composition.

Petrographically the lava flows in the Capim-Açu Edge, Americano and Bode Beaches are classified as olivine-phyric nephelinite (Fig. 4G-H). Olivine forsterite occur as glomeroporphyritic clusters and in a seriate texture (Fig. 4I-J). The matrix is composed essentially of diopside, Fe-oxide grains and nepheline. The vesicles are spheroidal or long tubular (Fig. 4H). Amygdalas filled by carbonate material are widespread in the vesicular level.

5. Lithofacies

Facies is a term applied to a body of rock characterized by a particular combination of lithology, physical and biological structures that bestow an aspect different from the bodies of rock above, below and laterally adjacent (Walker and James, 1992). Facies description was applied for the pyroclastic deposits and lava flows for the Remédios and Quixaba Formations, considering lithology and physical morphology aspects - structures, grain size and textural patterns - for the purpose of grouping them later in a Facies Association.

5.1 **Lithofacies Description**

The description of lithofacies followed the systematic adopted by Pasqualon et al 2019, Sohn and Chough (1992) and Rossetti et al. (2014). The lithofacies were grouped into tables according to each location. The tables contain the description of lithofacies and interpretations associated with the depositional processes.

For the Remédios Formation the description of the lithofacies was performed in the Enseada das Caieiras. For the Quixaba Formation the description was performed in the Capim-Açu Edge and Americano and Bode Beaches.

5.1.1 Remédios Formation - Caieira Beach

Four lithofacies were recognized during the construction of the Caieira Beach stratigraphic framework. The lithofacies are all pyroclastic: massive tuff (Tm), massive lapilli-tuff (Ltm), massive lapilli-tuff with blocks and massive tuff-breccia (Btm). Lithofacies are described and interpreted in Table 2 and illustrated in Fig. 4, 7 and 8.

Table 2: Caieira Beach facies description and interpretation.

Facies	Figures	Description	Interpretation
Tm	7B	Massive grayish brown tuff composed of ash and subordinate angular fine lapilli of up to 1 cm. This lithofacie occurs very discretely as a set between the Ltb lithofacie. It was preferentially eroded compared to the others.	Fallout from an overriding expanding cloud of ash derived from the flow.
Ltm	4C, 4D	Massive light gray lapilli-tuff composed of lapilli-size lithic fragments of up to 5 cm diameter and juvenile pumice lapilli. Some trails of coarse lapilli occur along the fine matrix.	Dense pyroclastic density currents which travel as a gravity controlled high particle concentration gas-solid dispersion.
Ltmb	4A, 4B, 4E, 7B, 7C, 8D	Light gray massive lapilli-tuff with angular, vesicular blocks of up to 49 cm. The blocks are mostly of phonolitic composition, dark gray, sometimes oxidized turning into reddish colors. Their distribution is restricted to some centimeter horizons, which draw trains of lithics along the lapilli-tuff, and scattered in the matrix.	Dense pyroclastic density currents which travel as a gravity controlled high particle concentration gas-solid dispersion.
Btm	4C, 4E, 4F, 7A, 8B, 8C	Massive light gray matrix-supported tuff-breccia composed of massive, angular, dark, and sometimes oxidized lithic blocks of variable sphericity. The block-size fragments vary from 64mm to up to 52 cm in diameter. The breccia fraction occurs as laterally discontinuous portions and isolated zones in a lapilli-tuff matrix. The fragments seldom show imbrication and grain-supported framework.	Deposition of the densest components of the flow.

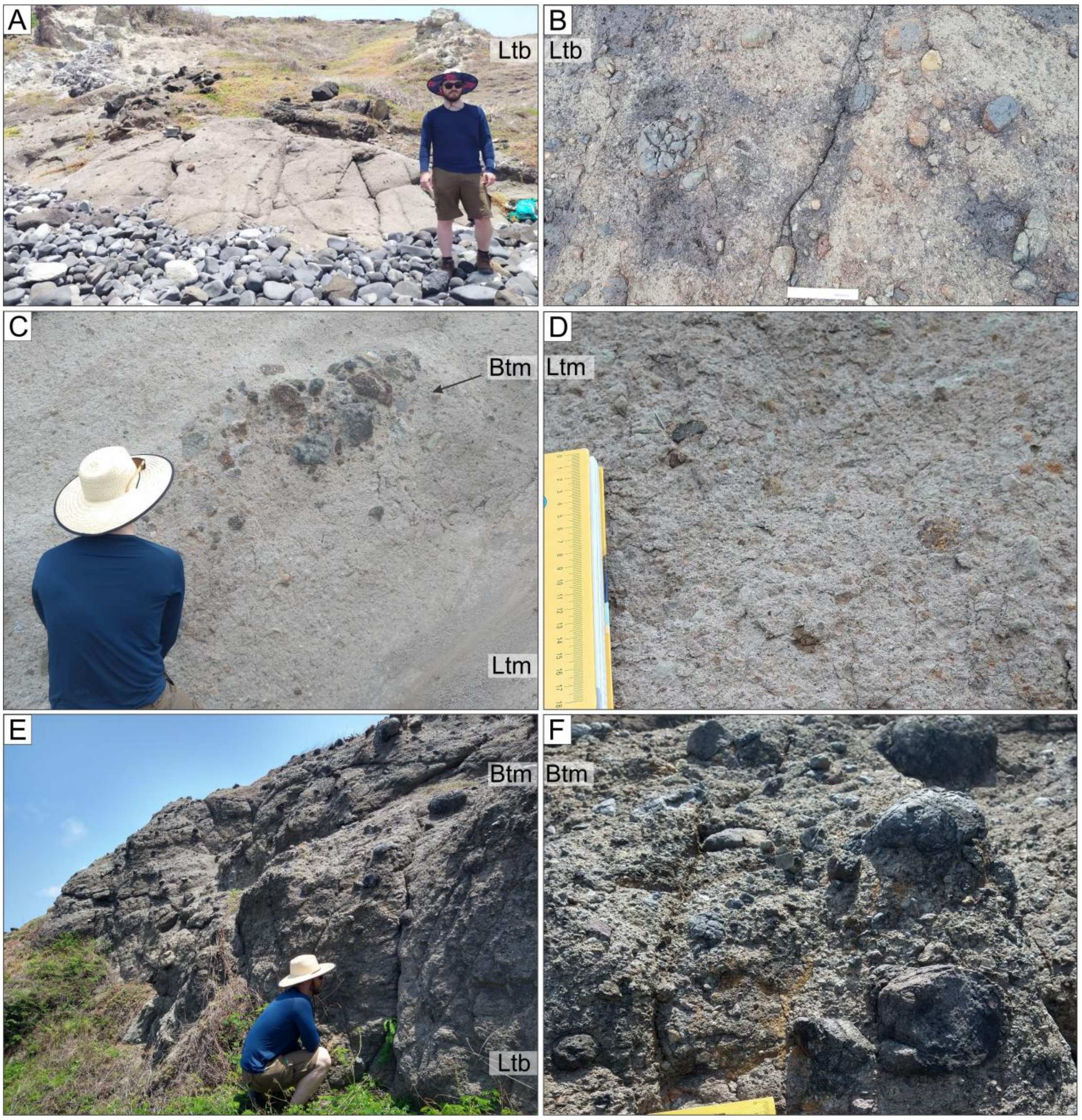


Fig. 10. Identified lithofacies in Caieira Beach. A) Lapilli-tuff with scattered lithic blocks (Ltb) forming the substrate of the beach; B) Detail of the Ltb lithofacie in which it is possible to observe the greenish tone of alteration of the rock and the arrangement of lithic fragments of varying sphericity and roundness; C) Discontinuous tuff-breccia (Btm) level containing oxidized lithic fragments assuming reddish oxidation colors, and massive lapilli-tuff (Ltm); D) Detail of the massive lapilli-tuff (Ltm) lithofacie. Note the beige matrix formed mainly by juvenile pumice; E) Btm lithofacie overlying the Ltb lithofacie. Note the orientation of the lithic blocks, which occur imbricated in the fine matrix that forms the Btm lithofacie; F) Imbrication of lithics in a matrix-supported tuff-breccia (Btm).

5.1.2 Quixaba Formation - Capim-Açu Edge

Nine lithofacies were recognized during the construction of the Capim-Açu Edge stratigraphic framework, divided into five volcaniclastics (all pyroclastics) and four coherent. Four of the pyroclastic lithofacies are massive, composed mainly of lapilli (Ltm; Lm) and block-size fragments (Lbm; Btm) with a minor amount of volcanic ashes. The lithofacie Lng shows planar stratification marked by grain-size variations. The coherent lithofacies are massive to vesicular olivine-phyric nephelinite (Onm; Onv) and olivine-phyric melilite nephelinite (Onmm), with occasional scoriaceous (One) and amygdaloidal (One.a) zones. Lithofacies are described and interpreted in Table 3 and illustrated in Fig. 5, 10, 11, and 12.

Table 3. Capim-Açu Edge facies description and interpretation.

Facies	Figures	Description	Interpretation
Ltm	5E, 11C	Massive oxidized lapilli-tuff composed of vesicular, angular fragments of up to 4 cm with variable sphericity. The Ltm occurs restricted and adjacent to the Lbm lithofacie. Most of the fine ash particles are altered to palagonite. Olivine macrocrysts of up to 4mm are visible within the fragments.	Ash and fine lapilli in a grain dispersive pressure from the high particle concentration grain/mass flow.
Lbm	5B, 5E, 5F, 10C, 10E, 11C, 11E	Massive oxidized dark gray lapillistone with angular and vesicular blocks of up to 28cm with low sphericity. The blocks are scattered among the lapilli particles and represent 30% of this facie. Olivine macrocrysts of up to 4mm are visible within the fragments.	Juvenile scoria and comagmatic lithic fragments of erupting magma and from wall rocks in a grain dispersive pressure from the high particle concentration flow moving on unstable slopes as granular/mass flow.
Btm	5D, 10C, 11C.	Massive dark gray tuff-breccia composed mainly of angular, vesicular, and amygdaloidal bombs of olivine-phyric nephelinite in a lapilli framework with subordinate ash particles. Some bombs are rounded and preserve curved shapes. Lithic block-size fragments vary from 64 mm to up to 1m in diameter with some sub-rounded outlier blocks of up to 2m in diameter. The breccia fraction represents (70-80%).	Juvenile scoria and comagmatic lithic fragments of erupting magma and from wall rocks in a grain dispersive pressure from the high particle concentration flow moving on unstable slopes as granular/mass flow.
Lng	12B	Normal grading grayish brown lapillistone composed of rounded to sub-rounded olivine-phyric melilite nephelinite. The fragments (1.3 to 6.0 cm diameter) are made of ash aggregates: massive ash pellets, internally layered accretionary lapilli, and armored lapilli.	Fallout from a complex, turbulent cloud system.
Onm	5C, 10A, 11D	Massive olivine-phyric nephelinite - Dark gray coherent volcanic rock with euhedral olivine phenocrysts (5-10%) (partially altered to iddingsite) in a seriate texture ranging from 0.2mm to 6.0mm, and as glomeroporphyritic clusters in a microcrystalline matrix.	Solidified nephelinitic lava with olivine as a preserved primary crystal cargo. Rapid cooling.
Onv	5C, 10A, 11D	Vesicular olivine-phyric nephelinite - Dark gray coherent volcanic rock with euhedral to subhedral olivine phenocrysts (5-10%) (partially altered to iddingsite) in a seriate texture ranging from 0.2mm to 6.0mm and as glomeroporphyritic clusters in a microcrystalline matrix. Vesicles are mainly	Growth and rise of gas bubbles in a cooling nephelinitic lava and concurrent crystallization from top and bottom. Rapid cooling with olivine as a preserved primary crystal cargo.

		elongated and in arborescent forms, sometimes rounded and connected by microfractures, varying in size from 0.1mm to >3.0cm.	
One	5A, 5B, 10A, 10D, 11D	Scoriaceous olivine-phyric nephelinite - Dark gray coherent volcanic rock with euhedral to subhedral olivine phenocrysts (5-10%) (partially altered to iddingsite) in a seriate texture ranging from 0.2mm to 6.0mm and as glomeroporphyritic clusters in a microcrystalline matrix. Vesicles are mainly elongated and in arborescent forms, sometimes rounded and connected by microfractures, varying in size from 0.1mm to >3.6cm. The vesicles are up to 60% of the rock volume. Amygdalas **(One.a)** with carbonatic and zeolitic materials occur in restricted levels.	Buoyant bubble rise and concurrent crystallization of the nephelinitic lava from top and bottom. (volatile supersaturation). Rapid cooling with olivine as a preserved primary crystal cargo.
Onmm	5A	Massive olivine-phyric melilite nephelinite - Dark gray coherent volcanic rock with euhedral to subhedral olivine phenocrysts (5-10%) (partially altered to iddingsite) in a seriate texture ranging from 0.2mm to 6.0mm, and as glomeroporphyritic clusters, and euhedral melilite crystals partially replaced by Al-rich clay mineral in a microcrystalline matrix.	Solidified nephelinitic lava with olivine as a preserved primary crystal cargo, and melilite as a phenocryst phase. Rapid cooling.

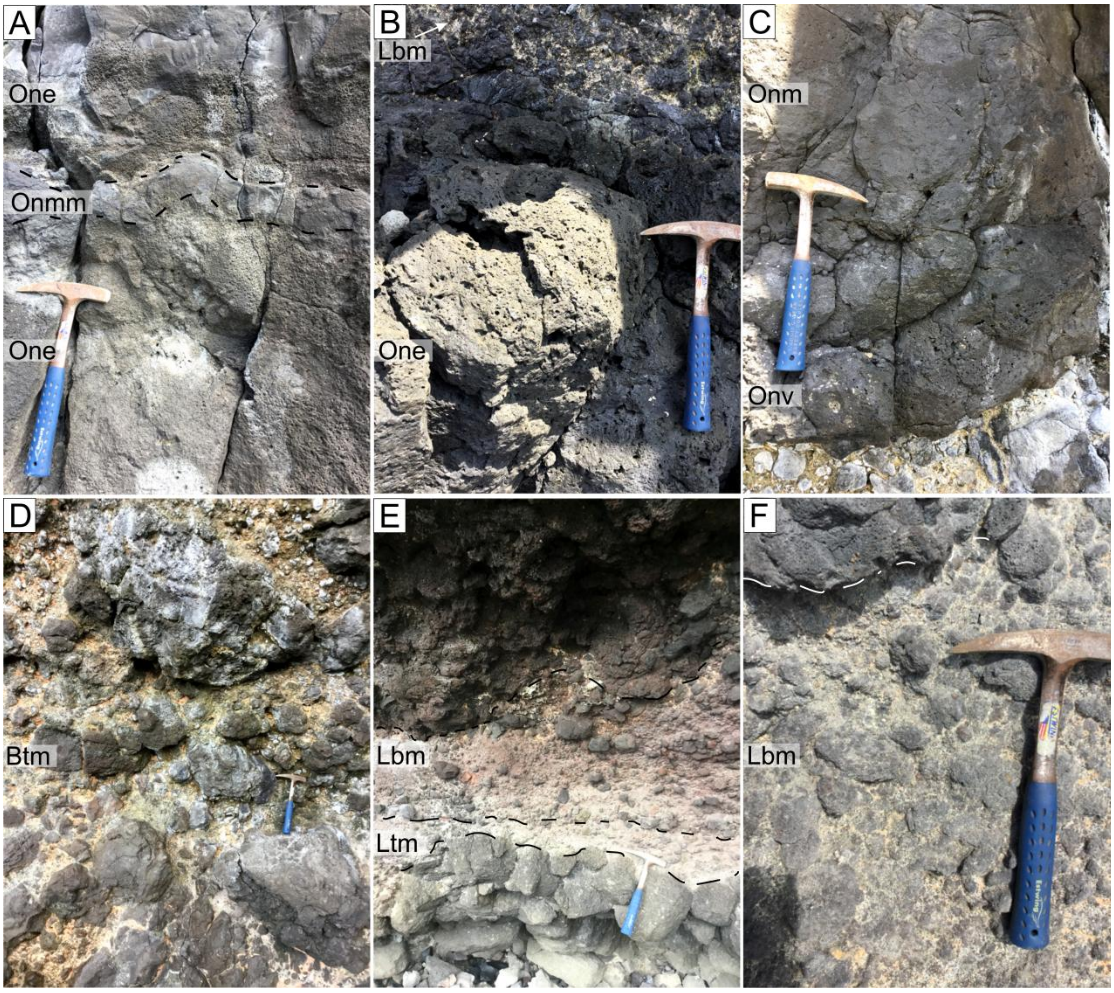


Fig. 11. Lithofacies identified in the Capim-Açu Edge. A) Thin level of massive olivine-phyric melilite nephelinite (Onmm) between portions of scoriaceous olivine-phyric nephelinite (One); B) Onv overlaid by lapilli-tuff with blocks (Lbm); C) Vesicular olivine-phyric nephelinite (onv) grading upwards to the massive central portion (Onm) of the flow; D) Massive tuff-breccia (Btm); Thin level of massive lapilli-tuff (Ltm) grading upwards to massive lapilli-tuff with scattered block-size fragments defining reverse grading; F) Lapilli-tuff with bombs in a more regular frequency and distribution.

5.1.4 Quixaba Formation - Americano and Bode Beaches

Three lithofacies were recognized during the construction of the Americano and Bode Beach stratigraphic framework, divided into one autoclastic and two coherent. The autoclastic lithofacie is made of vesicular, angular to rounded fragments of olivine-phyric nephelinitic composition (Onb); the coherent lithofacies are massive to vesicular olivine-phyric nephelinite (Onm; Onv) (Fig.6). Lithofacies are described and interpreted in Table 4 and illustrated in Fig. 6 and 9.

Table 4: Americano Beach and Bode facies description and interpretation.

Facies	Figures	Description	Interpretation
Onb	6A, 6B, 6C, 9A, 9D, 9E	Dark gray monolithic breccia composed of vesicular angular to subrounded olivine-phyric nephelinite blocks and lapilli-size fragments in a scoriaceous framework. The vesicularity reaches up to 30%.	Spontaneous fragmentation of parts of the nephelinitic lava which are locally more subject to higher strain rates and/or rapid cooling with (apparent) viscosity increase.
Onm	6F, 9C	Massive olivine-phyric nephelinite - Dark gray coherent volcanic rock with euhedral olivine phenocrysts (5-10%) (partially altered to iddingsite) in a seriate texture ranging from <0.5mm to 4.6mm and as glomeroporphyritic clusters in a microcrystalline matrix.	Solidified nephelinitic lava with olivine as a preserved primary crystal cargo and melilite as a phenocryst phase. Rapid cooling.
Onv	6D, 6E, 6F	Vesicular olivine-phyric nephelinite. Dark gray coherent volcanic rock with euhedral to subhedral olivine phenocrysts (5-10%) (partially altered to iddingsite) in a seriate texture ranging from 0.02mm to 3.4mm and as glomeroporphyritic clusters in a microcrystalline matrix. Clinopyroxene also occurs as phenocrysts (<1%) in a glomeroporphyritic texture. Vesicles are mainly elongated and in arborescent forms and sometimes are connected by microfractures. This lithofacie occurs within the Onb levels as angular fragments/lava blocks.	Buoyant bubble rise and concurrent crystallization of the nephelinitic lava from top and bottom. Rapid cooling with olivine as a preserved primary crystal cargo.

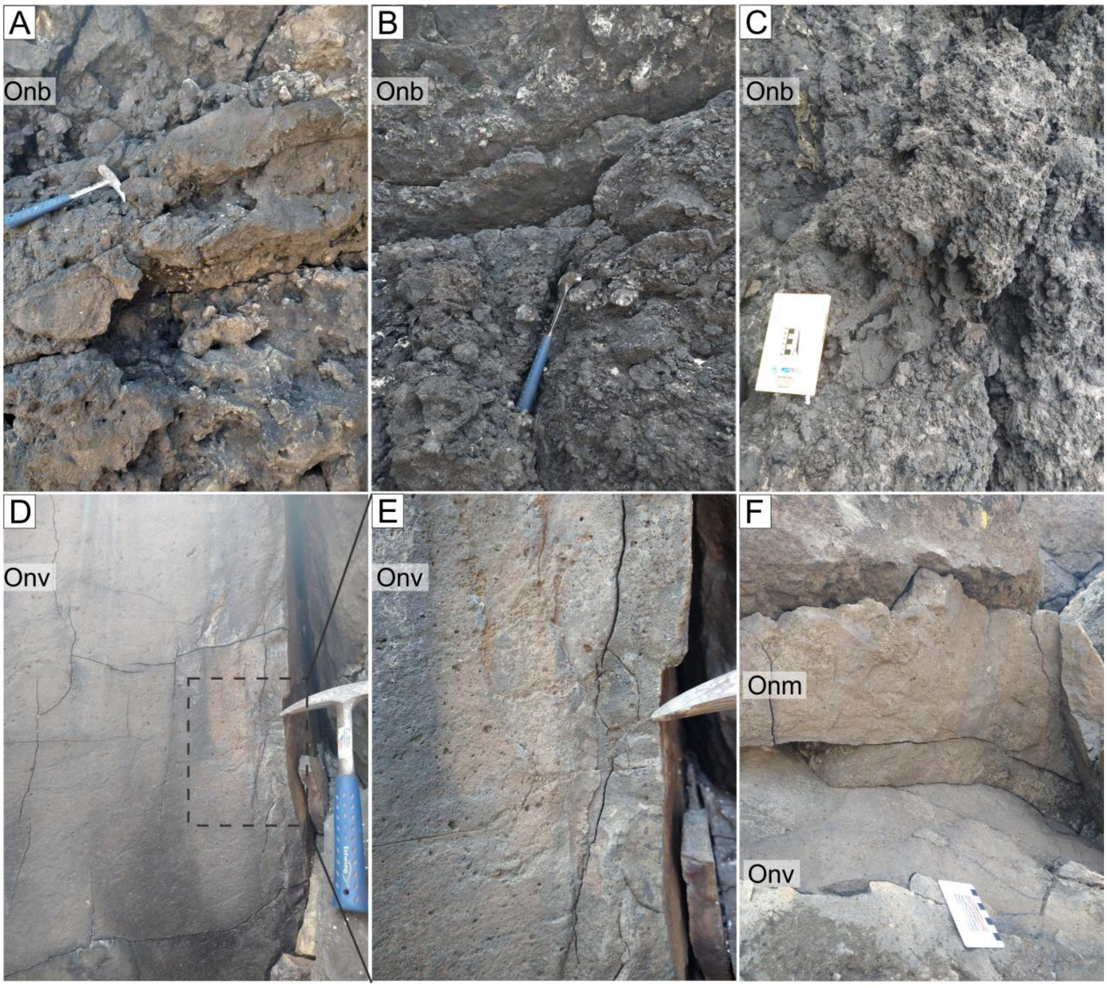


Fig. 12. Lithofacies identified in the Americano and Bode Beaches. A) Monolithic breccia of olivine-phyric nephelinite (Onb) containing massive slabs held together by the solid central mass of the flow in a cavernous texture.; B) and C) Onb containing angular and rounded fragments, located at the lower portions; D) Vesicular olivine-phyric nephelinite (Onv); F) Detail of the Onv showing sparse round vesicles; F) Subtle contact between the massive olivine-phyric nephelinite (Onm) and Vesicular olivine-phyric nephelinite (Onv).

5.2 Lithofacies Association

The studied areas comprise 5 genetic facies associations: (1) Ignimbrites; (2) Pahoehoe lava flows; (3) 'A'a lava flows; (4) Scoria and ash flow deposits; (5) Proximal fallout deposits.

5.2.1 Pyroclastic flow deposit - Ignimbrites

Non-welded, endured ignimbrite lithofacies association occur along the substrate and slope of the entire length of Caieira Beach. It shows a continuous extension of approx. 1.25 kilometers and a visible thickness of approximately 30 meters. This facies association consists of massive pyroclastic tuff-breccia (Btm) of up to 1.95m thick with dark lithic fragments of up to 49 cm in diameter sometimes showing imbrication (Fig. 7A), massive tuff (Tm) of up to 12 cm thick, massive lapilli-tuff (Ltm) of up to 1.20 meters thick; massive lapilli-tuff of up to 3 meters thick with blocks of up to 35 cm in diameter (Ltb) frequently restricted to some centimeter horizons, which draw trails of lithics along the matrix (Fig. 7B-C);

The lithofacies occur vertically alternated showing reverse grading, marked by Ltb and Btm facies (Fig. 7), multiple inverse grading, marked by Ltb and Btm facies (Fig. 8), and symmetric grading- inverse to normal, marked by Ltm, Btm and Ltb (PEC 02 *in* supplementary material). The distribution of the massive tuff lithofacie is restricted to centimeter bands (Fig. 7B) of approximately 2 meters in length, which have remained preserved. It occurs in abrupt contact with the Ltb lithofacie. An apparent increase in the amount of block-sized lithics occurs towards the north of Caieira Beach.

5.2.2 'A'a lava flows

This facies association was identified at Americano and Bode Beaches, occupying an exposed area of approx. 2,65 m². The lava sheets are up to 6 meters with the massive portions (Onm) varying from 1.0 to 0.25 meters and grading upward and downward into clinkery fragmental olivine-phyric nephelinite (Onb - flow breccia), which reaches up to 4.10 meters (Fig. 9A-B). The fragments are mainly angular, albeit rounded fragments also occur (mainly at the base of the flow) (Fig. 9D-E), and sometimes they are elongated as massive plates/slabs among the smaller fragments, all held together by the solid central mass of the flow in a cavernous texture. The thickness of the fragmented portion (Onb) varies considerably along the outcrop. This facies is almost absent at the southeast end of Americano Beach, being visible only at the top of the massive coherent lava sheet. The contacts between the Onv and Onb facies are not always easily distinguishable.

5.2.3 Pahoehoe lava flows

Pahoehoe facies association is composed of thick lava sheets that reach at least 15 meters in height, and extend laterally for at least 1.5km in the Capim-Açu Edge region (Fig. 10A-11A). The descriptions, however, are of restricted accessible levels, as mentioned in the items above. The base of the flows is vesicular to scoriaceous (Onv, One), 0.16 to 0.90 meters thick, grading to an extensively fractured massive core, 2.0 to 4.5 meters thick (Fig. 10B-11B). When a pyroclastic level is present overlying the lava flow (Fig. 11, section PCA 10) it is possible to identify the reappearance of the vesicles at the top of the flow, 0.40 to 0.95 meters thick (Fig. 11D). Sometimes the vesiculate portion occurs as isolated pockets of 0.10 to 0.65 meters thick. The vesicles are mainly flattened and oval at the base, and spherical at the pockets and at the top of the flow.

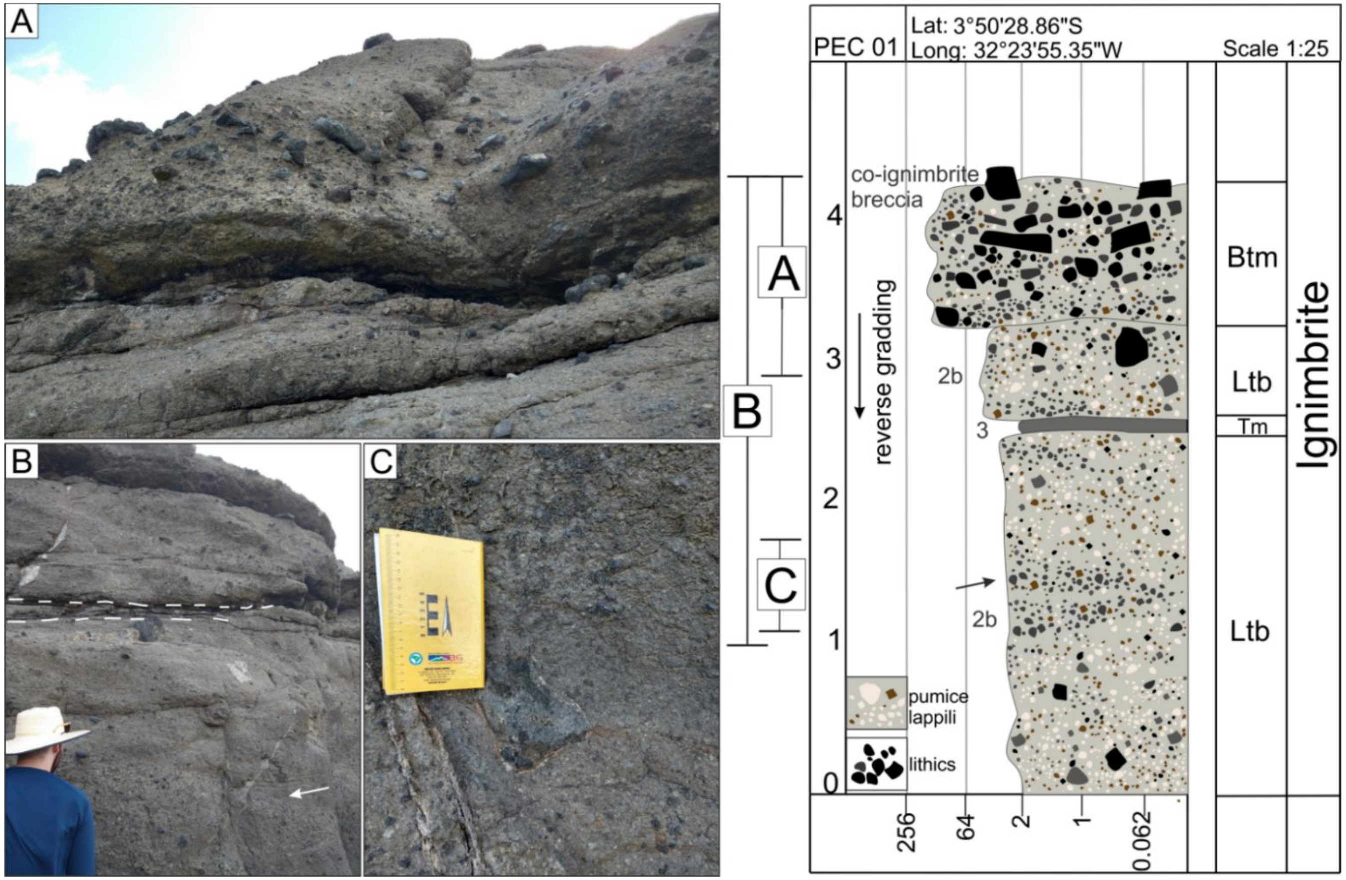


Fig. 13. Ignimbrite lithofacies association defined by the association of the lithofacies Btm, Ltb, and Tm (PEC-01). A) Tuff-breccia (Btm) on the top of the flow showing imbrication of dark gray lithics of phonolitic composition; B) Massive tuff layer (dashed line) between lapilli-tuff layers with scattered blocks. Note the lapilli size lithics trail in the fine matrix of the ignimbrite (indicated by the arrows). C) Detail of the ignimbrite matrix, which is rich in dark gray lapilli-sized lithics. Note the angular block, whose appearance is similar to that of the other blocks that occur throughout the entire ignimbrite deposits at Caieira Beach. The numbers on the left of the column represent the altitude.

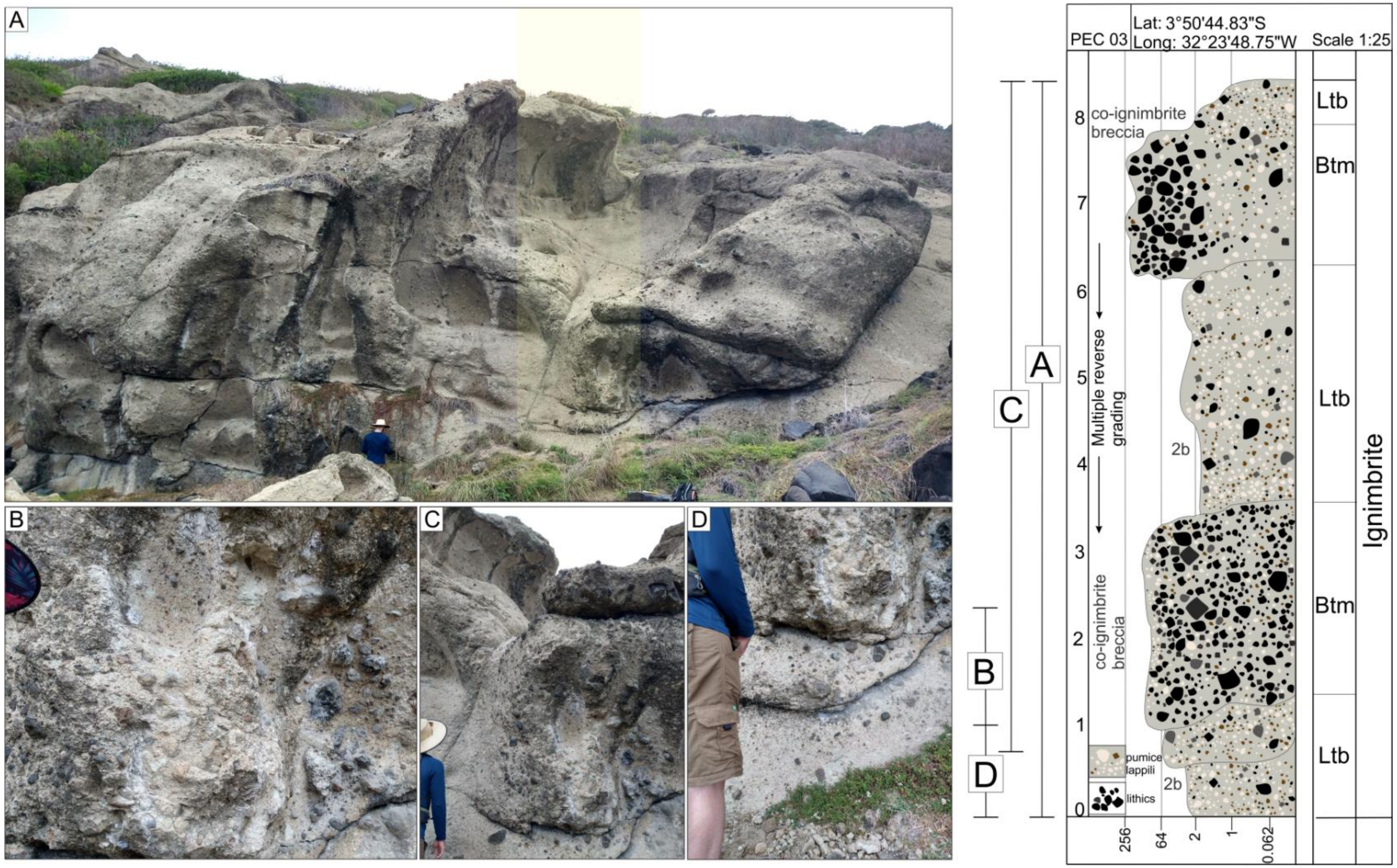


Fig. 14. Ignimbrite lithofacies association defined by the association of the lithofacies Btm and Ltb (PEC 03). A) View of the outcrop and section position (yellow rectangle); B) Detail of the Tuff-breccia (Btm). Note the massive and matrix-supported appearance; C) Detail of the lower and upper levels of Tuff-breccia (Btm) (indicated by the arrows), which show restricted lateral continuity. Note the clast-supported appearance of the upper Btm in contrast to the lower Btm; D) Layers of lapilli-tuff with blocks (Ltb) dispersed in a fine matrix overlaid by the first tuff-breccia layer.

5.2.4 Pyroclastic flow deposits - Scoria and ash flow

This facies association occur interbedded with the olivine-phyric nephelinite lava flows. It appears in the Ponta do Capim Açu at the Tunnel region and 250 meters towards the northeast. At the former, it shows a flat upper surface overlaid by the lava flow, a tabular geometry of up to 2m in thickness with a 14.0m lateral extension (aspect ratio: 1:7), which abruptly grates to a thickness of up to 7.5m (at the tunnel) in a maximum observed lateral extent of 20m (aspect ratio: 1:4) (Fig 11A). At the latter, it also shows a flat upper surface overlaid by the lava flow, a tabular geometry of up to 1.4m in thickness (Fig 10A) with a total of approx. 40m in extent (aspect ratio: 1:29). Locally a discontinuous lenticular shaped-level of scoriaceous olivine-phyric nephelinite of up to 70cm in thickness occurs within the pyroclastic level limits (Fig. 10B-D).

The facies association consists of massive lapilli-tuff (Ltm) of up to 22 cm in thickness, with considerable amounts of fine ash altered to clay minerals (Fig. 11C); massive lapillistone of up to 1m in thickness with blocks (Lbm) randomly distributed and of up to approx. 13 cm in diameter (Fig.10C-E, 11C-E); massive pyroclastic tuff breccia (Btm) of up to 2m in thickness with fragments of up to 25 cm in diameter and some occasional and outlier large semi-rounded, non-vesicular, dense cognate lithic fragments of 30x25cm, 46x27cm, 80x40cm and 1,80x1,00m (Fig 10C, 11C). All lithofacies are monolithologic, composed of olivine-phyric nephelinite. The lithofacies occur vertically alternated showing symmetric grading - inverse to normal (PCA 01 *in* supplementary material), symmetric grading - normal to inverse(PCA 08 *in* supplementary material), and mainly reverse grading as seen in PCA 02, PCA 04, PCA 09 and PCA 11 sections (*in* supplementary material) and PCA 03 (Fig.10).

5.2.5 Proximal fallout deposits - Ash aggregates

This facies association occurs on a cliff, approx. 50 meters of altitude in an exposed area of ca. 1,280 square meters, approx. 370 meters northeast of the Tunnel at the Capim-Açu Edge. It is described here as the *Upper pyroclastic level* (Fig 12A).

The first basal layer (B1), 1,24 meters thick, is composed of spherical (equant) to spheroidal (subequant) coarse lapilli fragments and bombs of up to 8.0 cm in diameter (Fig 12B). The B2 layer, ca. 2,0 meters thick, is composed of spherical (equant) to spheroidal (subequant) lapilli fragments mainly varying from 1.5 cm to 3.3 cm in diameter with a maximum found of 6.0 cm (Fig. 12B). Both layers are in a clast-supported loose framework, showing planar stratification marked by gain-size variation (Fig. 12B). The fragments are made of massive ash pellets, complexly layered accretionary lapilli, layered accretionary lapilli, complexly layered armored lapilli, and layered armored lapilli. The five types of ash aggregates are present in both layers B1 and B2.

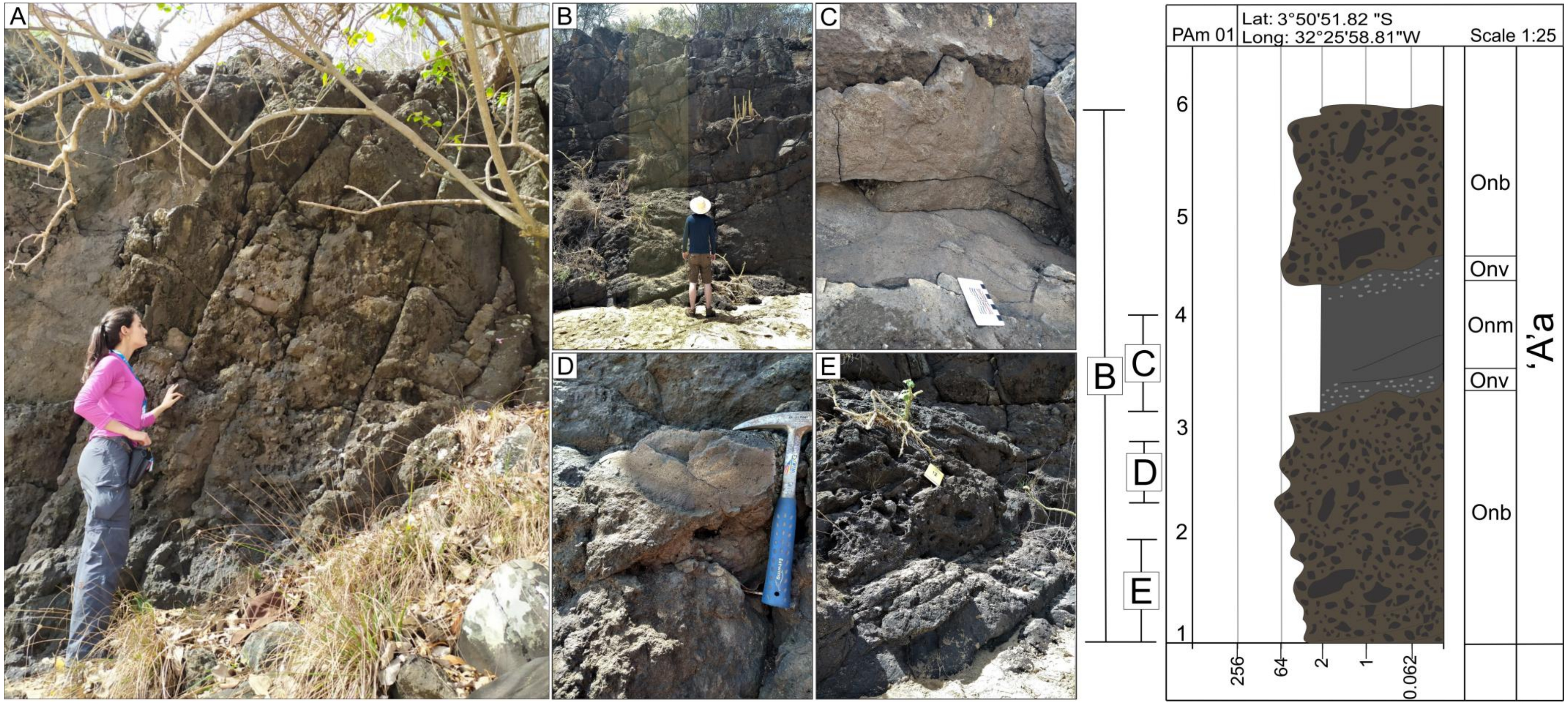


Fig. 15. 'A'a lithofacies association. A) 4 meters away from the section position - General aspect of the brecciated portion (Onb) of the A'a' lava flow. Note the sharp contact with the massive core (Onm) on the top of the flow; B) Location of the section PAm 01; C) Detail of the massive core of the flow; D) Detail of the brecciated portion (Onb) in which it is possible to notice the presence of massive round fragments; E) Basal breccia. The umbers on the left of the column represent the altitude.

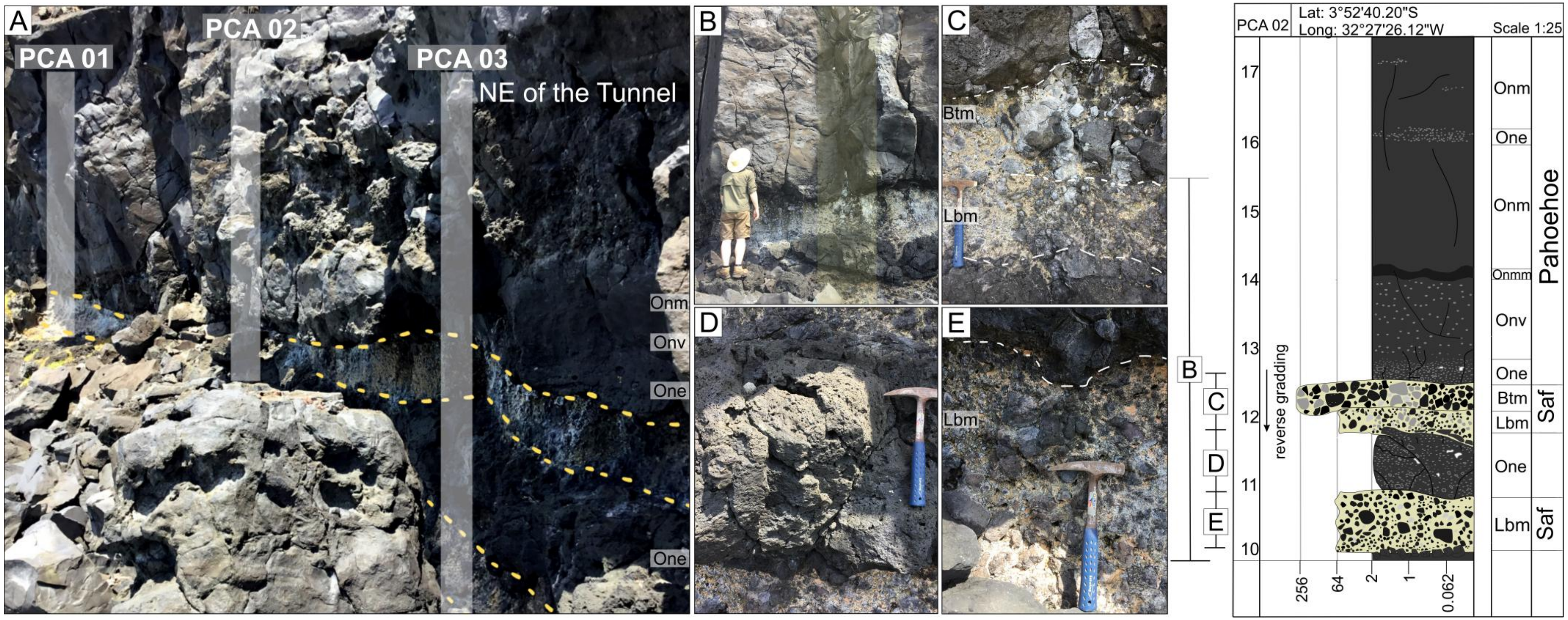


Fig. 16. Pahoehoe and Scoria and ash flow deposits (Saf) lithofacies associations. A) Location of the sections PCA 01-03 in the northeast region of the Capim-Açu Edge; A) Complete section PCA 02 located at the northeast portion of the Capim-Açu Edge; B) Scoria and ash flow deposits showing reverse grading from massive lapilli-tuff with angular and vesicular blocks (Lbm) to massive dark gray tuff-breccia (Btm); C) Scoriaceous lava between pyroclastic levels; D) Massive lapilli-tuff with angular and vesicular blocks (Lbm) at the base of the section. The numbers on the left of the column represent the altitude.

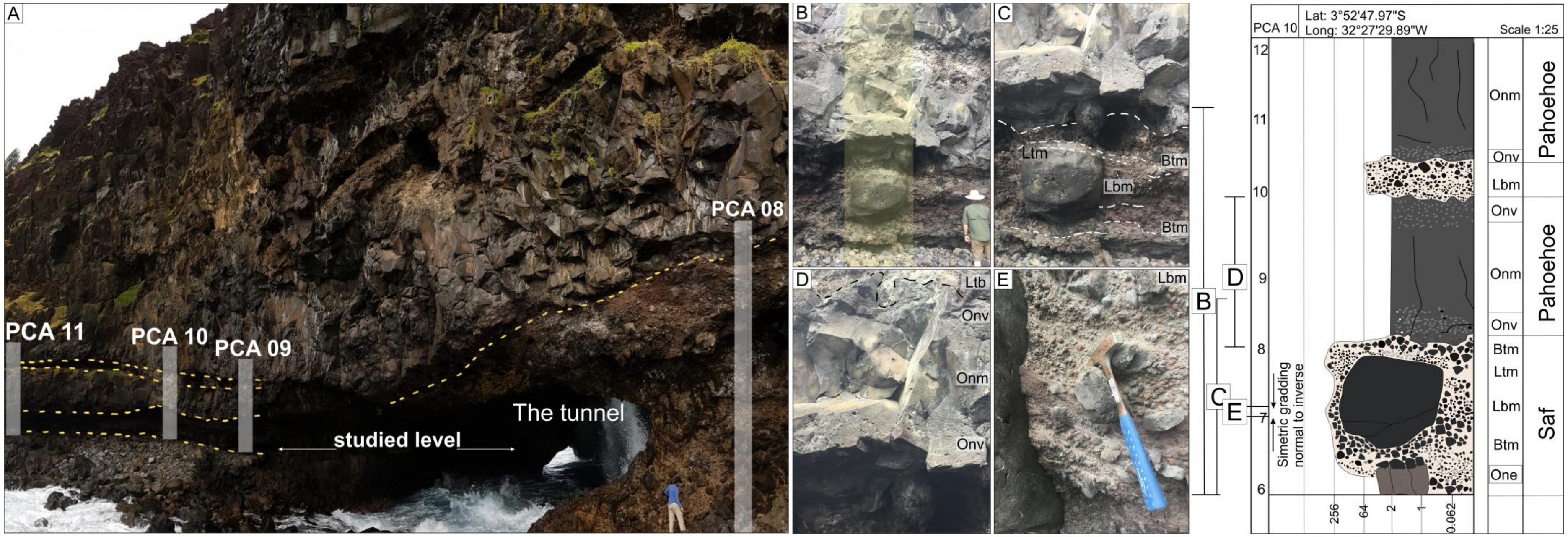


Fig. 17. Pahoehoe and Scoria-and-ash flow deposits (Saf) lithofacies associations. A) Location of the sections PCA 08-11 in the tunnel region of the Capim-Açu Edge; B) Complete section PCA 10; C) Scoria and ash flow deposits showing symmetric grading - normal to inverse formed by the Btm, Lbm and Ltm lithofacies; D) Pahoehoe lava flow formed by massive olivine-phyric nephelinite (Onm) grading upward and downward to vesicular olivine-phyric nephelinite (Onv); E) Detail of the poor sort of the Lbm lithofacies.

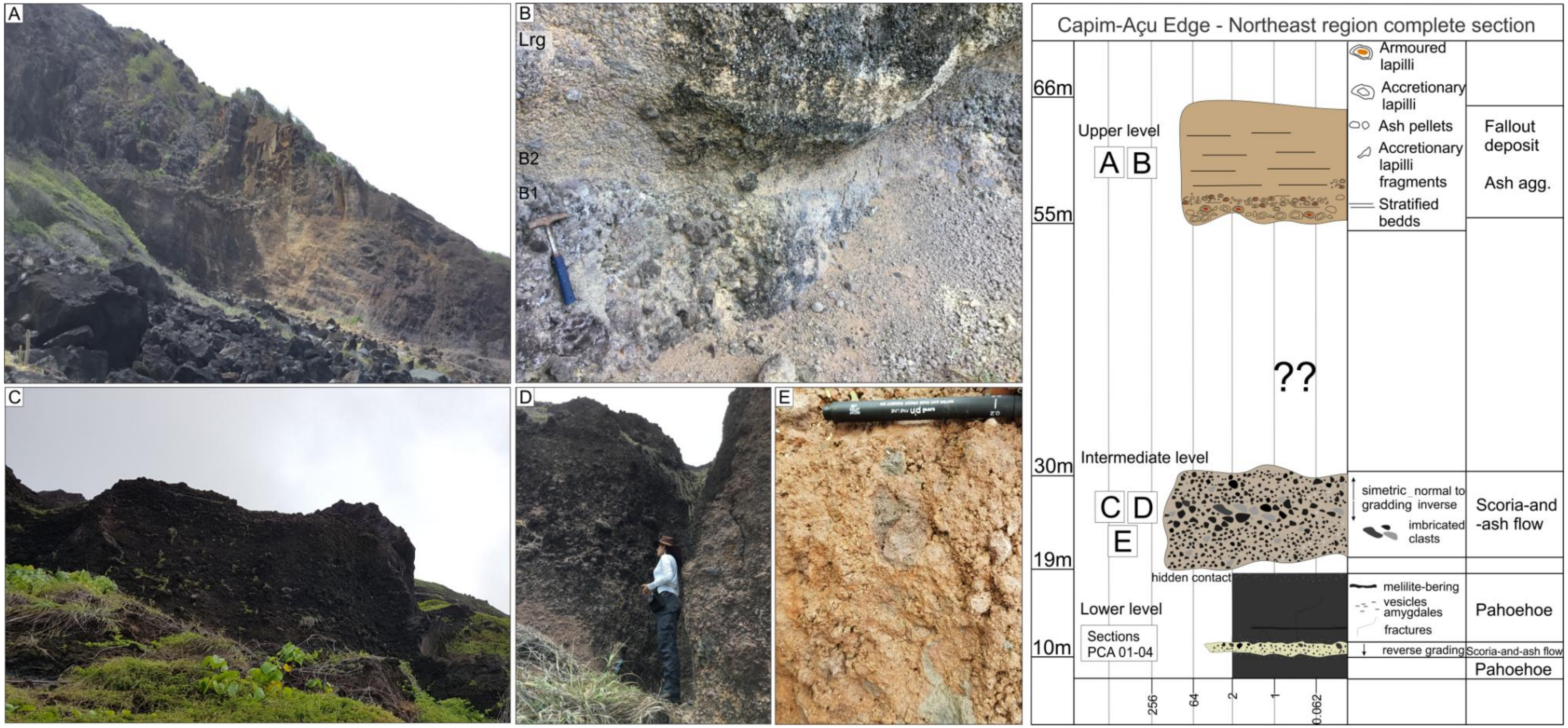


Fig. 18. Summary section of the Capim-Açu Edge contains the pyroclastic deposits from the lower level interbedded with lava flows and the pyroclastic deposits from the intermediate and upper levels. A) Upper level: note the stratified structure marked by grain-size variation. To the right of the person who is the scale and in dark gray color is the coarse base layer which was sampled; B) Sampling location of both studied layers. Note the juvenile coarse lapilli layer at the base and the medium to fine juvenile lapilli layer overlaying the former in an abrupt contact; C) Intermediate pyroclastic level; D) Simetric grading - normal to inverse with imbricated clasts seen especially in the breccia fraction. E) Extensive altered and oxidized state of the deposit, whose matrix is dominated by secondary clay minerals. Note the presence of light brown and gray lapilli scoria fragments.

6. Interpretations and Discussions

Based on facies bedform, componentry, and morphological analyses a distinctive assemblage of architectural elements was constructed (Table 4). Further, interpretations and discussions were conducted on the lithofacies association. Afterward, eruption styles were inferred from representative phonolitic and olivine nephelinitic successions in Fernando de Noronha Archipelago.

6.1 **Lithofacies Association**

6.1.1 Lava flows

The identification and systematic documentation of the occurrence of limited 'A'a lava flows in a predominantly pahoehoe flow region belonging to the Quixaba Formation in the Fernando de Noronha archipelago is important in constraining the emplacement dynamics of lava flows that can aid in a better understanding of alkaline lavas architecture and in building a volcanic stratigraphy of highly dissected ancient ocean volcanic islands such as the Fernando de Noronha Archipelago. The presence of diverse lava morphologies within the ancient olivine-nephelinites could also reflect a spectrum of volcanic processes operating simultaneously in various parts of the flow region that could lead to a good comprehension of the eruption conditions and the stratigraphic evolution of the ancient volcano.

A'a' lava flows

The 'A'a facies association is characterized by a fragmental and spinose surface and markedly irregular and distorted vesicles with massive and fragmented cores (McDonald, 1953). A'a' lava flows can be formed due to some physical processes according to McDonald, (1953) and Rowland and Walker (1990): turbulence and internal shearing from violent stirring by fountain action at the vents; turbulence in pouring over a steep slope (>5°); or merely from prolonged flowage to great distance from the vent. These processes promote loss of dissolved gas and an advance in the degree of crystallization, hence the lava viscosity increases correspondingly. Furthermore, because of the high volumetric flow rate (>5–10 m^3/s), the lava continues to move even after its viscosity and yield strength have increased greatly, eventually reaching the point at which surface disruptions can no longer be healed by flowing of the underlying lava. The lava then forms a rubble surface.

A spinose character is seen on the surface of the fragments in the Onb lithofacie which is the main evidence for the classification of this type of lava in the Americano and Bode Beaches. In addition, the stratigraphic organization of the lithofacies recognized - massive cores of olivine-phyric nephelinite (Onm) grading up and downwards to irregular vesiculated portions (Onv) in contact with olivine-phyric breccias (Onb) - corroborates the architecture of this type of lava. Evidence of rounding was identified in several fragments at the base of the flow which may be related to mutual abrasion due to the movement of the flow.

Pahoehoe lava flows

The presence of a smooth surface, spherical shape vesicles in the uppermost parts of a unit, as well as vesicles in the lower parts enclosing/delimiting a massive core with irregular jointing characterize pahoehoe lava flows (Self et al. 1998, Reidal et al. 2013, Cashman and Kauahikaua, 2015). Pahoehoe flows are emplaced by inflation - the injection of additional liquid lava into the molten core of the flow, underneath a solidified crust (Self et al., 1976, Hon et al., 1994, Self et al. 1998; Hoblitt et al., 2012). During inflation, upper and lower flow surfaces cool conductively to form upper and lower flow crusts (Cashman and Kauahikaua, 2015) as documented in several terrestrial and submarine environments. The low slopes (<2°) inhibit channelization and promote coalescence of lava into sheets with a uniformly distributed liquid lava core that produces the remarkably constant thickness of the flows (Hon et al., 1994); and low volumetric rates (5-10 m^3/s) are usually attributed to the formation of pahoehoe lava type (Rowland and Walker, 1990; Belousov and Belousova, 2018; Soldati et al., 2018).

The pattern of the vesicles recognized at the top and bottom of the nephelinitic lava flows from FNA as well as its tabular geometry are coherent with pahoehoe lava flow characteristics. A pattern such as the one described for the pahoehoe lava flows of the Quixaba Formation has been recognized and interpreted in Aubele et al. 1988, which indicates bubble growth and rise following the exsolution of gases from the lavas after they have been emplaced. The low viscosity that the lavas of ultrabasic composition commonly present, as is the case of the composition of the lavas of the Quixaba Formation, is an important physical characteristic that would allow them to flow under the process of inflation, leading to the formation of thick lava sheets from initially thin fluid pahoehoe flowing on flat terrain at a low discharge rate.

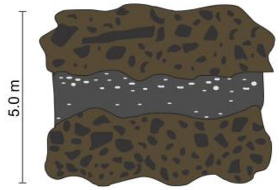
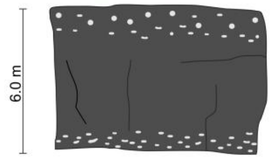
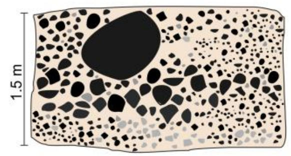
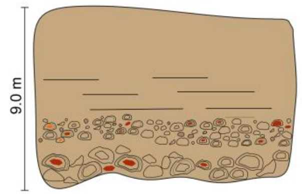
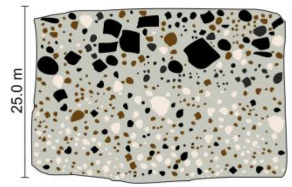
6.1.2 Pyroclastic Deposits

Pyroclastic volcanic rocks often provide the most important parameters for establishing the stratigraphic framework in volcanic areas (Fisher and Schmincke 1984). Important approaches concerning the reconstruction of the eruptive characteristics of pyroclastic deposits in FNA presented in this work have led to a wide understanding of the volcanic events during the magmatic activity that originated part of the pyroclastic rocks of the Remédios and Quixaba Formations.

Pyroclastic flow - Ignimbrite

Ignimbrites are the deposits left by surface flows of pyroclastic debris that travel as a high particle concentration gas-solid dispersion and are gravity controlled (Cas and Wright 1988). Most non-welded pyroclastic flow deposits are poorly sorted and massive (Sparks et al. 1973; Sparks (1976), but may show subtle grading, alignment bedding, or imbrication of oriented particles (Fisher & Schmincke 1984). Lapilli and block-size pyroclasts are supported in an ash matrix and may be weakly graded (McPhie et al 1993). These features match the main characteristics of the ignimbrites present in Caieira Beach, which we interpret as the products of dense pyroclastic density currents.

Table 5: Lithofacies association, description, and interpretation of the studied rocks of the Quixaba and Remédios Formations.

Facies Association	Lithofacies	Facies Architecture and Geometry	Description	Interpretation
'A'a	Onm, Onv, Onb		Sheet flows with massive to vesicular cores varying from 0.25 to 1.0m thick gradding up and downward into breccia zones reaching up to 4.10m thick.	High volumetric flow rate (>5–10 m³/s) of effusive activity. Loss of dissolved gas and an advance of the degree of crystalization causing an increase in the lava viscosity promoting surface disruptions.
Pahoehoe	Onm, Onv, One		Sheet flows with massive and fracturated cores varying from 2.0 to 4.5m thick. The base and top of the flow is vesiculated ranging from 0.16 to 0.95m thick. The vesicles are oval and flattened at the base and become spherical and sparse towards the top.	Low volumetric rates of effusive activity on slightly sloping topography. Bubble growth and rise following the exsolution of gases from the lavas.
Scoria-and-ash flow deposit	Ltm, Lm, Lbm, Btm		Tabular and discontinuous monolithologic layers of lappili tuff, lappilistone and tuff brecia displayed in inverse grading and simetric gradding: normal to inverse and inverse to normal. Cognate lithic blocks of up to 0.8m in diameter occur widespread.	Pulses of explosive activity with avalanches of ejecta on outer unstable slopes.
Ash aggregates Fall deposit	Lng		Planar basal layers of normal gradding lappilistone ranging from 1.24 to 2.0m thick, composed of massive ash pellets, accretionary lappili and armoured lappili.	Collapsing eruption column due to increasing vent diameter and/or decrease in magmatic gas content.
Ignimbrite Flow deposit	Tm, Ltm, Ltb Btm		Massive tuff, lapilli-tuff, lapilli-tuff with scattered lithic blocks and massive pyroclastic tuff breccia displayed predominatly in inverse grading. Composed of light pumice clasts and dark gray lithic fragments, sometimes showing imbrication.	Magmatic fragmentation of the upper vent rocks and conduit walls due to the release of high gas pressure. Surface flows of gravity controlled pyroclastic debris.

The concentration of lithic clasts in the Btm lithofacie marks the fragmentation of the conduit walls and vent as a result of the release of the exsolved gas phase, triggering explosive eruptions. In addition, the several compositions found in the lithics: tephrite, olivine-basalt, and essexite may be related to accidental lithics, which were picked up from the ground during flowage, and excavated rock materials during the eruption. Therefore, this major introduction of lithic clasts causes a mixing with the juvenile pyroclastic components from the erupting magma.

The Btm lithofacie represents co-ignimbrite breccias, which are near-vent facies emplaced by flow processes. This type of deposit, according to Cas and Wright 1988 may grade into matrix-supported breccias and coarse ignimbrite containing large lithics, the latter represented in this work as the Ltb lithofacie.

Pyroclastic flow - Scoria and ash deposits

Evidence for a flow origin includes extremely poorly sort, the presence of inversely graded layers, frequent lateral grain-size variation, and discontinuous trains of large fragments (Fisher & Schmincke (1984), Sparks et al. (1973), Sparks (1976). These features were identified in the deposits of the Capim-Açu Edge.

The scoria fragments are generated and transported as avalanches of ejecta on outer unstable slopes (McGetchin et al. 1974; Cas and Wright, 1988) moving as granular flows (Yamamoto et al. 2005; Lowe 1979; Wilson et al. 1982). Grain flow of the loose granular material during downslope movement produces reverse grading (Cas and Wright, 1988), as observed alongside the entire lower sequence of the Capim-Açu Edge. The non-vesicular dense semi-rounded fragments - 80x40cm and 1,80x1,00m present in the Btm facies are interpreted as cognate lithic fragments incorporated in the pyroclastic flow.

Pyroclastic flows surmount the landscapes when spreading outwards from the source and can form valley-pond deposits with a nearly horizontal upper surface locally attaining depths exceeding 10 meters (Walker et al 1980). The thickening of the pyroclastic deposit in the Tunnel of the Capim-Açu Edge may represent a depression in the paleotopography filled by coarse-grained material from the pyroclastic flow - the valley ponded part (PCA-08: Btm, Lbm). The thickness abruptly decreases preserving a lateral continuity with the thin adjacent layer (1.4m thick) due to an overspill of the valley margin (sections PCA 09 to 11 *in supplementary material*).

Pyroclastic fall deposits - Ash aggregates

Clast-supported, well-sorted, size-graded layers are characteristics of pyroclastic fall deposits (Cas & Wright, 1988; Fisher and Shmincke, 1984). Particle aggregates, such as accretionary and armored lapilli, are a well-known product of phreatomagmatic eruptions (Moore et al., 1966; Lorenz, 1974; Self, 1983), and occasionally form when meteoric moisture wets ash in eruption plumes (Folch et al., 2010). Aggregation can be triggered immediately after eruption due to the incorporation of surface water at the vent (Tomita et al., 1985), or many hours afterward (100s to 1000s kilometers downwind) by entrainment of tropospheric moisture in the plume (Durant et al., 2009). The clusters are bound together by cohesive forces related to electrostatic attraction (Schumacher, 1994; James et al., 2002, 2003) and/or liquid water (Gilbert and Lane, 1994; Schumacher and Schmincke, 1995; Telling and Dufek, 2012) followed by cementation (Van Eaton, 2013).

Co-deposition of several aggregate types, massive ash pellets, complexly layered and layered accretionary lapilli, suggests that some of the simple massive pellets falling out of a high plume experienced additional growth during re-entrainment and/or passage through stratified cloud levels (Reimer, 1983 in Van Eaton et al 2013). Armored lapilli develops because the ash cloud contains abundant cohesive ash that sticks to solid particles (crystals and crystal fragments) within it (Fisher and Shmincke, 1984). The presence of distinct aggregate types concurrently present in both levels B1 and B2 indicates that these processes of accretion took place during the formation of the fallout deposit.

6.2 **Eruptive Styles**

The volcanic episodes of the Remédios and Quixaba Formations are not directly linked to the location of the respective craters, as their positions are unknown or only suspected and the morphology of outcrops was heavily changed by erosion. To infer the eruptive styles we assessed the deposit types and architecture from the lithofacies association, and componentry through petrographic characterization. We further sought to correlate them with previously studied deposits of similar composition and occurrence.

6.2.1 Remédios Formation

The ignimbrites of Caieira Beach represent markedly explosive magmatic events, which originated ground-hugging density currents that moved through the volcanic terrain driven by gravity. Almeida 1955 points out to an explosive volcanic activity in the Archipelago, now represented by the pyroclastic rocks of the Remédios Formation (herein ignimbrites), which may have preceded the intrusion of domes and plugs of trachytes and phonolites, as part of a continuous volcanic episode. Interpretations in Almeida (1955), however, are limited in the understanding of the formation of the essential components of ignimbrites, that is the juvenile lithics and pumice. The non-cognate lithics, markedly in the Btm lithofacie, were formed previously to the eruptions that originated the juvenile particles from the erupting magma that generated the ignimbrites. Therefore, the origin of the non-cognate lithics are related to country rocks that have been explosively ejected during eruption (accessory lithics) and clasts picked up locally by the pyroclastic flows (accidental lithics).

The large volume of accessory lithic clasts in the ignimbrites suggests that a considerable volume of rock material was excavated during major eruptions. This could mean that the erupted volumes of magma and crustal rock debris were high enough to have caused calderas to form or further incrementally subside during explosive phonolitic eruptions in Fernando de Noronha. In addition, following the deposition of ignimbrites, we have records of the crystallization of mostly phonolitic domes and plugs, which may be associated with one or more forming ignimbrite eruptions. Afterward, we have a hiatus of volcanic activity in the geological record of the archipelago, which would have as cause the emptying of the magma chamber and cessation of the eruptions.

Nevertheless, there is no indication of what volumes of the erupted ignimbrites are buried under the lavas of the Quixaba Formation and submerged, and since there is no clear landform morphology linked to caldera-forming eruptions (as linear fissure vents along ring faults and/or other types of caldera faults) in Fernando de Noronha related to the Remédios Formation, we can not go further in our conclusions.

A precise eruptive-style proposition for the formation of the ignimbrites would be based on the distinction of ignimbrites deriving from collapses of eruption columns issuing from single, point source vents, from those derived from ring-faults during caldera collapses as in (Giordano and Cas, 2021). It requires primarily the individualization of each ignimbrite outflow unit, i.e. emplaced without significant breaks in their sedimentation, in extra-caldera settings, and forming individual cooling units, irrespective of internal lithofacies architecture. Afterward, determine the aspect ratios, and calculate their volume, thicknesses, and areal extent, which are essential physical features to characterize the various eruptions styles.

We were able to identify the existence of two flow units within the ignimbrites of Caieira Beach, which are separated by the massive tuff lithofacie, Tm (deposited from an overriding expanding cloud of ash derived from the flow). However, the area and thickness of both units cannot be obtained given the extensive erosion of the deposit, therefore we were not able to propose an eruptive style.

6.2.2 Quixaba Formation

The olivine nephelinitic magmatic activities that produced the rocks of the Quixaba Formation have changed significantly over time, which is confirmed by the variety of products generated. We see a shift in volcanic activity in the various outcropping rock types of this formation: coherent lava flows in the form of pahoehoe lavas; autoclastic flows in the form of 'a'a lavas identified in the Americano and Bode Beaches; pyroclastic rocks originated from density pyroclastic currents represented by the scoria and ash flow deposits in the Capim-Açu Edge; and pyroclastic fallout deposits markedly stratified with massive ash pellets, accretionary and armored lapilli in the Capim-Açu Edge.

Capim-Açu Edge is the region of the Archipelago where the several types of rocks, deposits, and an alternation of eruptive styles can best be observed and verified. The successive alternation between nephelinitic lava flows and pyroclastic rocks of the same composition in abrupt contacts shows how the conditions in the volcanic conduit have changed repeatedly, evidencing the expressiveness of the volatile content and efficiency of gas segregation within the magma, leading to the formation of different rock types.

At the same vent, eruptive activity at basaltic volcanoes shifts frequently between Strombolian and Hawaiian and vice versa (Spampinato et al., 2012). Jaupart and Vergniolle, 1988 address that some controls on these styles of activity are shallow seated, with changes in magma ascent rate and segregation efficiency of the gas phase controlling dynamics and transitions. In this line of reasoning, Taddeucci et al 2015 attribute the shifting of styles due to processes such as magma-gas segregation dynamic in the volcanic plumbing system; increase in magma and gas supply rate; change in the rheological properties of magma at shallow levels, as an increase of bulk magma viscosity, which usually promotes efficient fragmentation and the formation of ash. In the light of these statements and from our field observations and laboratory analyses, the alternating between the effusive activity that generated the pahoehoe lava flows and the explosive activities that led to magma fragmentation and generation of pyroclasts, especially seen in the rock bodies and deposits of the Capim-Açu Edge, reflects these shifting in pre- and eruptive processes/styles.

Strombolian eruptions are those in which discrete explosions separated by periods of less than a second to several hours occur in magma columns near the surface (Fisher and Schmincke, 1984). Ejecta consists of bombs, scoriaceous lapilli, and ash. The presence of lithic fragments likely related to wall-rock lithic debris is evidence of Strombolian-style activity (Taddeucci et al 2015). In addition, the absence of fluidal textures such as achneliths, Pele's hair and tears, which are found in pyroclasts formed during fountaining episodes is considered another evidence for the Strombolian style of activity (Fisher and Schmincke, 1984; Taddeucci et al 2015; Houghton et al 2016). The studied pyroclastic deposits of the lower level of the Quixaba Formation seen in Capim-Açu Edge display a majority of juvenile pyroclasts of nephelinitic composition ranging from ash to block sizes, cognate lithic fragments of the same composition and rare melilite-bearing accidental lithic fragments. The intermediate level also displays a majority of juvenile pyroclasts of several sizes including juvenile fragments with olivine phenocrysts in a dark glassy matrix rich in vesicles and amygdales; and minor lithic fragments. Within both levels, particles and features that match the fluidal behavior of products from Hawaiian eruptions were not distinguished. We, therefore, attribute Strombolian activity to the generation of scoria and ash flow deposits of Ponta do Capim-Açu Edge. This style of activity repeatedly switched to the Hawaiian style with effusive phases as marked by the levels of lava flows interleaved with the pyroclastic flow deposits.

Strombolian and Hawaiian styles of activity are not always easily distinguished from one another based on the observations of their eruptive products. To be functional, any unambiguous classification of these eruptive styles also requires the inclusion of some measure of event duration (Houghton et al 2016). When it comes to ancient deposits as all of those present in FNA we suggest, in addition to the application of the lithofacies association study as presented here, the application of quantitative morphological analysis on juvenile pyroclasts in order to understand fragmentation mechanisms and infer eruptive styles with a statistical basis, as in Figueiredo et al., 2022.

7. Conclusions

Fernando de Noronha is a volcanic archipelago located in the South Atlantic Ocean, which is the easternmost territory of the Fernando de Noronha alignment of islands and seamounts along the Fernando de Noronha fracture zone. Volcanic activity started to form the emerged part of the archipelago in the mid-Miocene, lasting until the Pleistocene, generating lava flows, domes, intrusions, and pyroclastic rocks of strongly alkaline and SiO_2 undersaturated nature. The Remédios Formation (Miocene) groups the products of the earliest known volcanic activity of FNA, represented mainly by ignimbrites, domes of phonolites and trachyte. The Quixaba Formation contains the records of the last episodes of ultrabasic alkaline volcanic activities, which generated ‘A’a lava flows, extensive pahoehoe lava plateaus alternated with pyroclastic flow deposits, and fallout sequences.

The stratigraphic study of specific areas of the Archipelago through field observations complemented with laboratory-based pyroclastic and lava flow descriptions allowed the understanding of the distribution of facies, the geometry of the deposits, its architectural elements providing the means to infer deposition processes and eruptive styles. From the lithofacies association of the exposed ignimbrites of the Remédios Formation in the Caieira Beach and the lava flows, scoria and ash flow, and fallout deposits of the Quixaba Formation in the area of Capim-Açu Edge, Americano and Bode Beaches, remarkably, the volcanism in the FNA went through different stages. Therefore, it is possible to draw a sequence of events that occurred in time:

i) Explosive magmatic eruptions of phonolitic composition, which originated ground-hugging density currents represented by the lithic-rich non-welded ignimbrites;
ii) Volcanic and subvolcanic manifestations generated mainly domes and plugs of phonolitic and trachytic composition;
iii) A hiatus in the geological record of about 7 Ma, characterized as a period of quiescence and erosion;
iv) Effusive Hawaiian eruptions with the emplacement of olivine nephelinitic pahoehoe and minor volume of ‘A’a lava flows. Alternated to the effusive eruptions, strombolian pulses led to mass ejections of juvenile ash, lapilli, bombs, and cognate lithic fragments, forming the scoria and ash pyroclastic flow deposits.
v) Stage of dominant water-magma interaction and the formation of a water-rich volcanic cloud, which led to the formation of planar-stratified bedforms, fall-dominated with mixed deposition of ash aggregates in the shape of massive ash pellets, complexly layered accretionary lapilli, layered accretionary lapilli, complexly layered armored lapilli and armored lapilli, formed through wet aggregation.

Acknowledgements

The authors wish to acknowledge LABTEC Rochas-IGC-UFMG and CNPq for their financial support during our research. This paper contains results of the M.Sc. dissertation of the first author based at UFMG, with scholarship from CAPES. Special acknowledgments to the administration of the Fernando de Noronha Territory and to the Chico Mendes Institute for Biodiversity Conservation for research authorization in the territory.

References

Almeida, F.F.M., 1955. Geologia e petrologia do Arquipélago de Fernando de Noronha. (Monografia 13). DNPM, Divisão de Geol. Mineral.

Almeida, F.F.M. de., 1986. Distribuição regional e relações tectônicas do magmatismo pós-paleozóico no Brasil. Revista Brasileira de Geociências, 16(4), 325-349.

Almeida, F.F.M. de, Carneiro, C.D.R., Dehira, L.K., Machado, D.L.J., 1988. Magmatismo pós-paleozóico no nordeste oriental brasileiro. Revista Brasileira de Geociências, 18 (4), 451-462.

Almeida, F.F.M. de, Schobbenhaus, C., Queiroz, E.E., Winge, M., Berbert-Born, M., 2002. Arquipélago de Fernando de Noronha registro de monte vulcânico do Atlântico Sul. SIGEP 66, 361-368.

Almeida, F.F.M. de., 2006. Ilhas oceânicas brasileiras e suas relações com a tectônica atlântica. Terræ Didatica 2(1), 3–18.

Aubele, J.C., Crumpler, L.S., Elston, W.E., 1988. Vesicle zonation and vertical structure of basalt flows. Journal of Volcanology and Geothermal Research, 35:349 - 374 349.

Belousov, A., Belousova, M., 2018. Dynamics and viscosity of ‘a’a and pahoehoe lava flows of the 2012–2013 eruption of Tolbachik volcano, Kamchatka (Russia). Bull. Volcanol.80 (1):6.

Cas, R.A.F.,Wright, J.V., 1988. Volcanic Successions,Modern and Ancient: A Geological Approach to Processes, Products and Successions.

Cashman, K.V., Kauahikaua, J.P., 1997. Reevaluation of vesicle distributions in basaltic lava flows. Geology 25 (5):419–422.

Cordani, U.G., 1970. Idade do Vulcanismo no Oceano Atlântico Sul. Bol. IGA, 1, 9-75.

Durant, A.J., Rose, W.I., 2009. Sedimentological constraints on hydrometeor-enhanced particle deposition: 1992 eruptions of Crater Peak, Alaska. Journal of Volcanology and Geothermal Research 186, 40–59.

Figueiredo, C. A., Bongiolo, E. M., Jutzeler, M., Gomes, O. D. F. M., & Neumann, R., 2022. Alkalic pyroclast morphology informs on fragmentation mechanisms, Trindade Island, Brazil. Journal of Volcanology and Geothermal Research, 428, 107575.

Fisher, R.V., Schmincke, H.U., 1984. Pyroclastic Rocks, 472 pp. Springer, Berlin, doi 10 (978-3).

Fodor, R.V., Mukasa, S.B., Sial, A.N., 1998. Isotopic and trace-element indications of lithospheric and astenospheric components in Tertiary alkalic basalts, northeastern Brazil. Lithos 43, 197–217. https://doi.org/10.1016/S0024-4937(98)00012-7.

Folch, A., Costa, A., Durant, A., Macedonio., A., 2010. A model for wet aggregation of ash particles in volcanic plumes and clouds: 2. Model application. Chemistry and

Physics of Minerals and Rocks/Volcanology 115, B9. DOI: https://doi.org/10.1029/2009JB007176.

Gerlach, D.C., Stormer Jr, J.C., Muller, P.A., 1987. Isotope geochemistry of Fernando de Noronha. Earth and Planetary Science Letters, 85, l29–144. https://doi.org/10.1016/0012-821X(87)90027-6.

Gilbert, J.S., Lane, S.J., 1994. The origin of accretionary lapilli. Bulletin of Volcanology 56, 398–411.

Giordano, G. Cas, R.A.F., 2021. Classification of ignimbrites and their eruptions, Earth-Science Reviews, 220, 103697. https://doi.org/10.1016/j.earscirev.2021.103697.

Groppelli, G., Martí, J., 2013. Volcanic Stratigraphy - State of the art. Ciências da Terra, 18, 99-104.

Gunn, B.M., Watkins, N.D., 1978. Geochemistry of the Cape Verde Islands and Fernando de Noronha. GSA Bulletin, 87(8):1089-1100. DOI: http://doi.org/10.1130/0016-7606(1976)87<1089:GOTCVI>2.0.CO;2

Gurioli, L., Houghton, B.F., Cashman, K.V., Cioni, R., 2005. Complex changes in eruption dynamics during the 79 AD eruption of Vesuvius. Bull. Volcanol. 67, 144–159.

Hoblitt, R.P., Orr., T.R., Heliker, C., Denlinger, R.P., Hon, K., Cervelli, P.F., 2012. Inflation rates, rifts, and bands in a pāhoehoe sheet flow. Geosphere 8 (1):179–195. DOI: https://doi.org/10.1130/GES00656.1

Hon, K., Kauahikaua, J., Denlinger, R., Mackay, K., 1994. Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii. Geol. Soc. Am. Bull. 106 (3):351–370.

Houghton, B.F., Taddeucci, J., Andronico, D., Gonnermann, H.M., Pistolesi, M, Patrick, M.R., Orr, T.R.,T.R. Swanson, T.R., Edmonds, M., Gaudin, D., Carey, R.J., Scarlato, P., 2016. Stronger or longer: Discriminating between Hawaiian and Strombolian eruption styles. Geology, 44 (2): 163–166. doi: https://doi.org/10.1130/G37423.1

James, M.R., Gilbert, J.S., Lane, S.J., 2002. Experimental investigation of volcanic particle aggregation in the absence of a liquid phase. Journal of Geophysical Research 107, http://dx.doi.org/10.1029/2001jb000950.

James, M.R., Lane, S.J., Gilbert, J.S., 2003. Density, construction, and drag coefficient of electrostatic volcanic ash aggregates. Journal of Geophysical Research 108, 2435. http://dx.doi.org/10.1029/2002jb002011.

Jaupart, C., & Vergniolle, S., 1988. Laboratory models of Hawaiian and Strombolian eruptions. Nature, 331(6151), 58-60.

Kogarko, L.N., Kurat, G., Ntaflflos, T., 2001. Carbonate metasomatism of the oceanic mantle beneath Fernando de Noronha Island, Brazil. Contributions to Mineralogy and Petrology 140, 577–587. DOI: http://doi.org/10.1007/s004100000201

Lopes, R.P., Ulbrich, M.N.C, 1998. Evolução geoquímica da suíte de fonólitos do Arquipélago de Fernando de Noronha, PE. Congresso Brasileiro de Geologia, 40, Belo Horizonte. Anais, SBG, 464.

Lopes, R.P., 2002. O vulcanismo do Arquipélago de Fernando de Noronha, PE: química mineral e geoquímica. Instituto de Geociências, University of São Paulo, São Paulo.

Lopes, R.P., Ulbrich, M.N.C., 2006. Rochas vulcânicas alcalinas da Formação Quixaba de Fernando de Noronha, PE: Química mineral e litogeoquímica. Revista Brasileira de Geociências 36(1), 35-48.

Lopes, R.P., Ulbrich, M.N.C., Ulbrich, H., 2014. The volcanic-subvolcanic rocks of the Fernando de Noronha Archipelago, Southern Atlantic Ocean: Mineral chemistry. Cent. Eur. J. Geosci. 6(4), 422-456.https://doi.org/10.2478/s13533-012-0195-7.

Lopes, R.P., Ulbrich, M.N.C., 2015. Geochemistry of the alkaline volcanic-subvolcanic rocks of the Fernando de Noronha Archipelago, southern Atlantic Ocean. Brazilian Journal of Geology. 45(2). https://doi.org/10.1590/23174889201500020009.

Lowe, D. R. 1979. Sediment gravity flows: their classification and some problems of application to natural flows and deposits. In Geology of continental slopes. Vol. 27, pp. 75-82. SEPM Special publication.

Macdonald, G.A., 1953. Pahoehoe, aa, and block lava. Am. J. Sci. 251 (3):169–191.

Martí, J., Groppelli, J., Silveira, A.B., 2018. Volcanic stratigraphy: A review. Journal of Volcanology and Geothermal Research, 357, 68-91. https://doi.org/10.1016/j.jvolgeores.2018.04.006.

McGetchin, T.R., Settle, M., Chouet, B.A., 1974. Cinder cone growth modeled after northeast crater, Mount Etna, Sicily. J. Geophys. Res. 79 (23), 3257–3272.

McPhie, J., 1993. Volcanic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks.

Miall, A.D., 1977. Lithofacies Types and Vertical Profile Models in Braided River Deposits: A Summary.

Miyabuchi, Y., Watanabe, K., Egawa, Y., 2006. Bomb-rich basaltic pyroclastic flow deposit from Nakadake, Aso Volcano, southwestern Japan. Journal of Volcanology and Geothermal Research, 155, 1–2, 90-103. https://doi.org/10.1016/j.jvolgeores.2006.02.007.

Mellors, R.A., Sparks, R.S.J., 1991. Spatter-rich pyroclastic flow deposits on Santorini, Greece. Bull. Volcanol. 53, 327-342.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., 2006. A catalogue of deep mantle plumes: new results from finite-frequency tomography. Geochemical, Geophyshics, Geosystems 7, Q11007. http://dx.doi.org/10.1029/2006GC001248.

Moore, J.G., 1967. Base surge in recent volcanic eruptions. Bull Volcanol 30, 337–363. https://doi.org/10.1007/BF0259767.

Pasqualon, N.G., Lima, E.F. de., Scherer, C.M.S., Rossetti L.M.M., Luz F.R., 2019. Lithofacies association and stratigraphy of the Paredão Volcano, Trindade Island, Brazil. Journal of Volcanology and Geothermal Research, 380, 48-63. https://doi.org/10.1016/j.jvolgeores.2019.05.011.

Pedrazzi, D., Martí, J., Geyer, A., 2013. Stratigraphy, sedimentology and eruptive mechanisms in the tuff cone of El Golfo (Lanzarote, Canary Islands). Bull Volcanol 75, 740. https://doi.org/10.1007/s00445-013-0740-3.

Perlingeiro, G., Vasconcelos, P.M., Knesel, K.M., Thiede, D.S., Cordani, U.G., 2013. 40Ar/39Ar geochronology of the Fernando de Noronha Archipelago and implications. Journal of Volcanology and Geothermal Research, 249, 140-154. https://doi.org/10.1016/j.jvolgeores.2012.08.017

Reimer, T.O., 1983. Accretionary lapilli in volcanic ash falls: physical factors governing their formation. In: Peryt, T.M. (Ed.), Coated Grains. Springer, Berlin, pp. 56–68.

Rolim, J. M., Murta, M.C.P, Costa, A.G., Soares, F., 2019. Caracterização dos depósitos piroclásticos: uma contribuição para o entendimento da geologia do Arquipélago Fernando de Noronha. Simpósio de geologia do nordeste, 28, Aracaju, SBG. Anais, único, 399.

Rowland, S.K., Walker, G.P., 1990. Pahoehoe and aa in Hawaii: volumetric flow rate controls the lava structure. Bull. Volcanol. 52 (8):615–628.

Schmid, R., 1981. Descriptive nomenclature and classification of pyroclastic deposits and fragments. Geol. Rundsch. 70 (2):794–799.

Self, S., 1983. Large-scale phreatomagmatic silicic volcanism: A case study from New Zealand, Journal of Volcanology and Geothermal Research, 17, Issues 1–4: 433-469. https://doi.org/10.1016/0377-0273(83)90079-3.

Self, S., 1976. The recent volcanology of Terceira, Azores. J. Geol. Soc. 132 (6):645–666.

Self, S., Keszthelyi, L., Thordarson, Th., 1998. The importance of Pahoehoe. Annual Review of Earth and Planetary Sciences, 26:1, 81-110.

Schumacher, R., 1994. A reappraisal of Mount St. Helens ash clusters-depositional model from experimental observation. Journal of Volcanology and Geothermal Research 59, 253–260.

Soldati, A., Sehlke, A., Chigna, G.,Whittington, A., 2016. Field and experimental constraints on the rheology of arc basaltic lavas: the January 2014 Eruption of Pacaya (Guatemala). Bull. Volcanol. 78 (6):43.

Spampinato, L., Oppenheimer, C., Cannata, C., Montalto, P., Salerno, G.G., and Calvari, S., 2012, On the time-scale of thermal cycles associated with open-vent degassing: Bulletin of Volcanology,74:1281–1292, DOI: https://doi.org/10.1007/s00445 -012 -0592-2.

Sparks, R.S.J., Walker, G.P.L., 1973. The ground surge deposit: a third type of pyroclastic rock. Nat. Phys. Sci. 241 (107), 62.

Taddeucci, J., Edmonds, M., Houghton, B., James, M. R., & Vergniolle, S., 2015. Hawaiian and Strombolian eruptions. The encyclopedia of volcanoes, 485-503. Academic Press.

Telling, J., Dufek, J., 2012. An experimental evaluation of ash aggregation in explosive volcanic eruptions. Journal of Volcanology and Geothermal Research 209, 1–8.

Tomita, K., Kanai, T., Kobayashi, T., Oba, N., 1985. Accretionary lapilli formed by the eruption of Sakurajima volcano. The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists, 80(2), 49-54.

Ulbrich, M.N.C., 1993. Petrography of alkaline volcanic–subvolcanic rocks from the Brazilian Fernando de Noronha Archipelago, Southern Atlantic Ocean. Boletim IG-

USP Série Científica, 24, 77-94. https://doi.org/10.11606/issn.2316-8986.v24i0p77-94

Ulbrich, M.N.C., Lopes, R. P., 1999. Petrografia e química mineral de fragmentos de rochas gabróicas e dioríticas em depósitos piroclásticos de Fernando de Noronha, PE.. V Congresso de geoquímica dos países de língua portuguesa e VII Congresso brasileiro de geoquímica, Porto Segura, Brasil. Anais, 620-621.

Ulbrich, M.N.C., Maringolo,V., Ruberti, E., 1994. The geocheminstry of alkaline volcanic-subvolcanic rocks from the Brazilian Fernando de Noronha Archipelago, South Atlantic Ocean. Geochimica Brasiliensis, 8(1):21-39.

Ulbrich, M.N.C., 1993. Petrography of alkaline volcanic–subvolcanic rocks from the Brazilian Fernando de Noronha Archipelago, Southern Atlantic Ocean. Boletim IG-USP Série Científica, 24:77-94. DOI: http://doi.org/10.11606/issn.2316-8986.v24i0p77-94

Van Eaton, A.R., Wilson, C.J.N., 2013. The nature, origins and distribution of ash aggregates in a large-scale wet eruption deposit: Oruanui, New Zealand. Journal of Volcanology and Geothermal Research, 250, 129-154. https://doi.org/10.1016/j.jvolgeores.2012.10.016.

Wilson, C. J. N., Walker, G. P. L. 1982. Ignimbrite depositional facies: the anatomy of a pyroclastic flow. J. geof. Soc. London, Vol. 139, pp. 581-592.

Walker, G.P.L. 1980. The Taupo pumice: Product of the most powerful known (ultraplinian) eruption?, Journal of Volcanology and Geothermal Research, 8:69-94, https://doi.org/10.1016/0377-0273(80)90008-6.

Yamamoto, T., Takada, A., Ishizuka, Y., Miyaji, N., & Tajima, Y. 2005. Basaltic pyroclastic flows of Fuji volcano, Japan: characteristics of the deposits and their origin. Bulletin of volcanology, 67(7):622-633.

APPENDICE - Mineral Chemistry of pyroclasts and lava flows of the Quixaba Formation, Fernando de Noronha Archipelago, Brazil

1. Introduction

Major element composition of olivine, pyroxene, nepheline, oxide and melilite crystals within pyroclastic deposits and lava flows is presented in this section. The focus were given on the Quixaba Formation, specifically in the lower and intermediate levels of Capim-Açu Edge and Americano Beach (see item *4.2 Petrography of Quixaba Formation* in *Lithofacies Association and Stratigraphy of the Quixaba and Remédios Formations, Fernando de Noronha Archipelago, Brazi*l for stratigraphic reference*)*.

2. Analytical procedures

Electron microprobe analyses were performed using the Jeol-Model JXA 8900RL WD/ED Combined Microanalyzer for crystal chemical composition. The analyses were carried out at the Microscopy Center of the Federal University of Minas Gerais, Brazil. Afterward, the major element electron micropobe analyses were entered in calculation spreadsheets from GabbroSoft 2011. The systematic for the clinopyroxene classification followed the methodology of Marimoto 1988. The molecular percentages of minerals were plotted in diagrams using the Triquick software.

3. Mineral Chemistry

The composition of olivine grains within the analyzed pyroclasts (*n=13*) exhibit similar composition to the olivine grains within the analyzed lava flows (*n=9*). The Mg# [=Mg/(Mg+Mn+Fe)x100 for olivines renge from 80.06 to 88.70. Lower contents with respect to Mg# were found in highly altered olivine grains: 69.09 to 77.66. Particularly for these grains with Mg# as low as 78, the contents of Al_2O_3 and

K_2O increase significantly. Two out of thirteen olivine grains analyzed are from dark glass fragments found in the interior of a pyroclast from the intermediate level of the Capim-Açu Edge. Both of them exhibit Mg# within the same range found for the other grains from lower and intermediate levels (Fig. 1, Table 1 and 2)

The pyroxene crystals analyzed within the pyroclasts *(n=8)* and lava flows *(n=13)* are in the following modes of occurrence: i) fine-grains in the matrix, ii) glomeroporphyritic clusters, iii) isolated phenocrysts iv) arranged in a corona texture around a phenocrystal of olivine. The latter is a specific occurrence found only in a lava flow sample. The fine grains in the matrix and the glomeroporphyritic clusters exhibit similar composition, identified as diopside, with an average composition in terms of molecular percentage of: $Wo_{52}En_{36}Fe_{12}$. For the isolated phenocrysts we have found an enstatite series phases within the pyroclasts, with a significant compositional variation regarding the core and rim, respectively: $Wo_{01}En_{74}Fe_{25}$ and $Wo_{01}En_{85}Fe_{14}$, and a ferrosilite series phase in a lava flow from Capim-Açu Edge: $Wo_{0}En_{24}Fe_{86}$ (Fig. 2, Table 3 and 4).

Nepheline microcrysts and microlites were identified in the matrix of the analyzed pyroclasts and lava flows. The NaO wt% contents range from 6.4 to 14.3, and the K_2O wt% contents range from 6.99 to 9.45 (Table 5 and 6).

The laths of melilite are in reality pseudomorphs replaced by an Al-rich clay mineral. Overall, the silica aluminum ratio is between 1.5 to 2.0 but can reach up to 4.5. The FeO content is markedly present, whereas the alteration led to a more substantial loss of CaO and MgO.

The majority of oxide grains analyzed exhibit compositions close to the hematite (Fig. 3). One grain present in an olivine-phyric lava flow from the Capim-Açu Edge yield a rutile composition (Fig. 3, Table 7 and 8).

The amygdales are filled with carbonate material with $\%CaCO_3$ ranging from 97.8 to 93.6 and $\%MgCO_3$ ranging from 2.2 to 6.4 (Table 9).

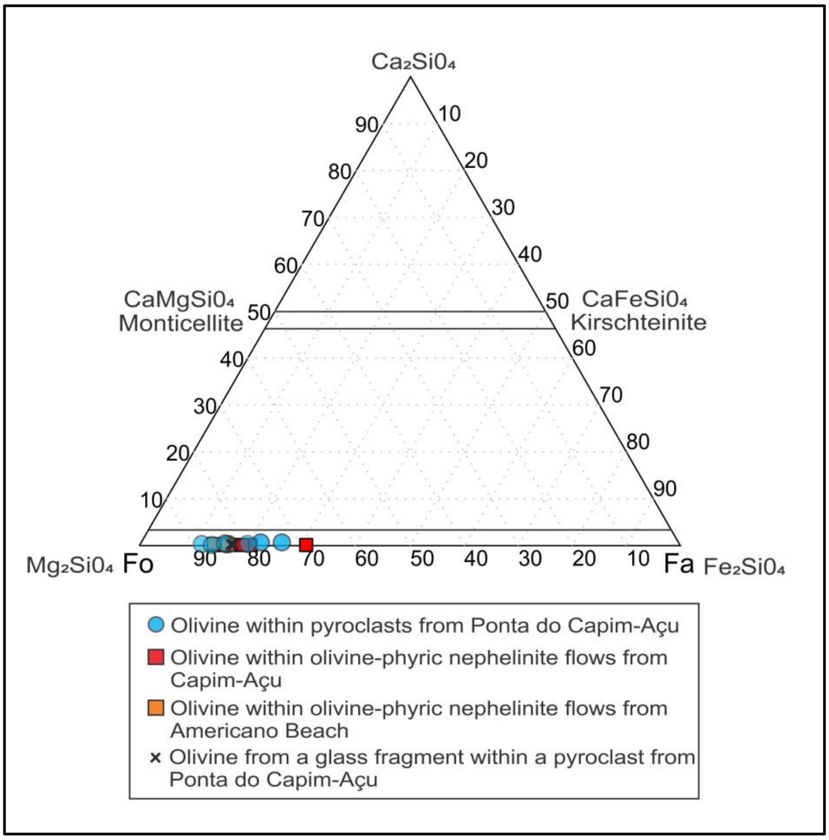


Fig. 1. Composition of the analyzed olivines plotted in the system Ca_2SiO_4 - Mg_2SiO_4 - Fe_2SiO_4. The diagram were extracted from Klein and Dutrow, 2012.

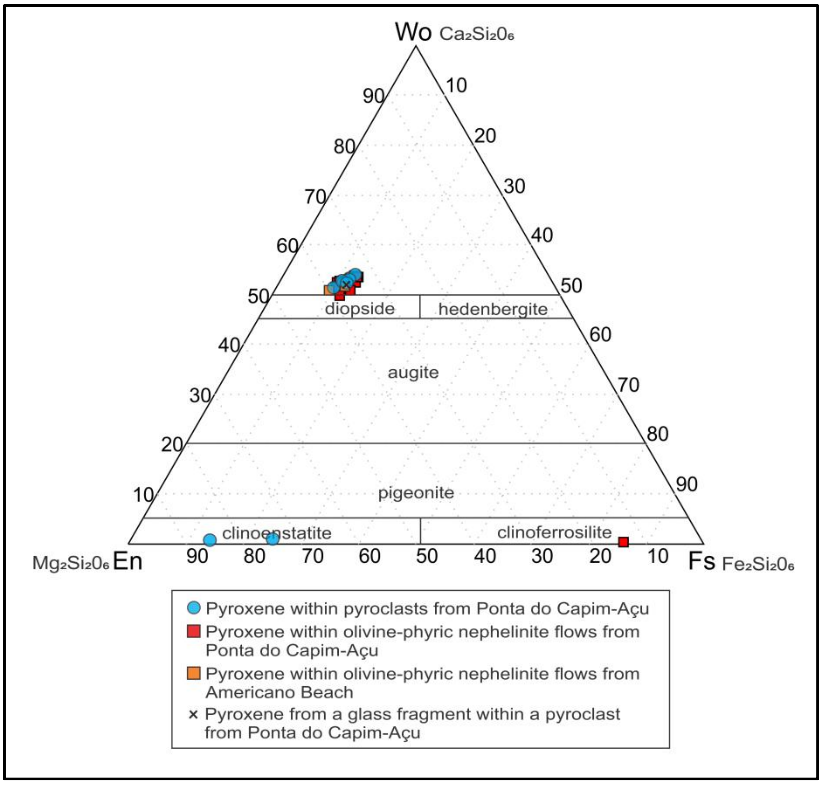


Fig. 2. Composition of the analyzed pyroxenes plotted in the system $Ca_2Si_2O_6$ - $Mg_2Si_2O_6$ - $Fe_2Si_2O_6$. The diagram were extracted from Marimoto 1988.

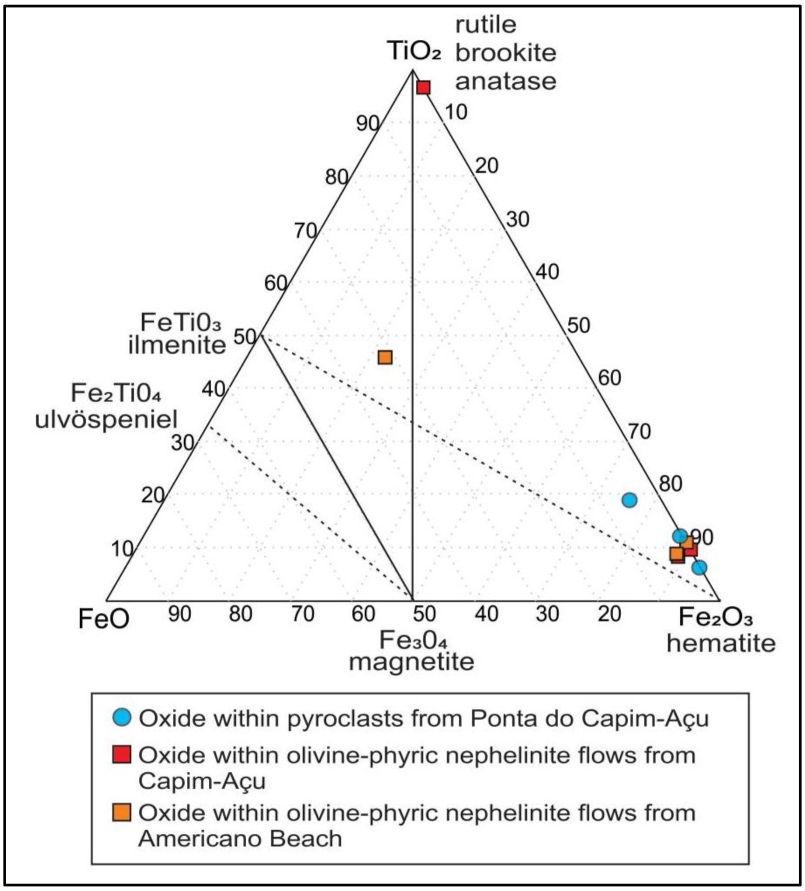


Fig. 3. Composition of the analyzed oxide grains plotted in the system FeO-Fe_2O_3-TiO_2. The dashed lines indicate complete solid solution between the end-members. The continuous lines indicate coexistence in relatively low temperatures. The diagram were extracted from Klein and Dutrow, 2012.

Table 1: Electron microprobe analyses of olivines in pyroclasts, Capim-Açu Edge, Quixaba Formation.

Electron Micropobe analyses of olivines in pyroclasts from Capim Açu Edge, Fernando de Noronha Archipelago, Brazil

Sample	M2102109-1	M2102109-2	M2102109-3	M2102109-4	M2102110-1	M2102110-2	M2102110-3	M2102110-4	M2102110-5	M2102111-1	M2102111-2	M2102111-3	M2102111-4
Location	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA
Rock type	On	On	On	On	Omn	Omn	Omn	Omn-d	Omn-d	On	On	On	On
Mineral	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol
Target	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core	Core
SiO_2	39.668	39.632	38.694	39.034	38.759	40.248	40.110	40.924	41.164	42.529	41.305	40.765	41.506
TiO_2	0.058	0.098	0.050	0.014	0.000	0.010	0.053	0.044	0.014	0.036	0.000	0.000	0.039
Al_2O_3	0.028	1.692	4.166	2.690	0.029	0.053	0.050	0.057	0.076	0.065	0.015	0.030	0.009
Cr_2O_3	0.034	0.038	0.000	0.031	0.046	0.053	0.000	0.064	0.032	0.000	0.000	0.021	0.005
FeO	14.875	16.607	19.961	17.480	14.453	14.069	14.041	15.472	15.568	12.043	10.676	15.249	10.537
MnO	0.290	0.356	0.252	0.252	0.174	0.115	0.157	0.215	0.290	0.071	0.324	0.262	0.225
MgO	43.462	38.214	31.872	34.588	42.303	42.950	42.329	42.525	43.044	44.113	48.177	44.641	47.373
NiO													
CaO	0.685	0.851	0.637	0.573	0.208	0.204	0.199	0.311	0.283	0.296	0.049	0.053	0.156
Na2O	0.047	0.060	0.142	0.027	0.031	0.020	0.046	0.017	0.035	0.038	0.000	0.024	0.001
K2O	0.000	0.063	0.245	0.138	0.008	0.013	0.000	0.010	0.015	0.034	0.019	0.011	0.002
Total	99.15	97.61	96.02	94.83	96.01	97.74	96.99	99.64	100.52	99.23	100.57	101.06	99.85

On: olivine phyric nephelinite
Omn: olivine phyric melilite nephelinite | -d: dark juvenile fragments
LF: Lithic fragment
Ol: Olivine
PCA: Capim Açu Edge
AB: Americano Beach

Table 2: Electron microprobe analyses of olivines in lava flows, Capim-Açu Edge and Americano Beach, Quixaba Formation.

Electron Micropobe analyses of olivines in lava flows from Capim Açu-Edge and Americano Beach, Fernando de Noronha Archipelago, Brazil

Sample	M2102108-1	M2102108-2	M2102108-3	M2102108-4	M2102108-5	M2102108-6	M2102112	M2102114-1	M2102114-2
Location									
Rock type	On	On	On	On	Omn	Omn	On	On	On
Mineral	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol	Ol
Target	Core	Core	Core	Core	Core	Core	Core	Core	Core
	PCA	PCA	PCA	PCA	PCA	PCA	PCA	AB	AB
SiO_2	39.388	39.548	36.455	37.479	38.386	39.013	40.670	40.767	41.300
TiO_2	0.026	0.016	0.020	0.023	0.169	0.081	0.030	0.025	0.030
Al_2O_3	0.056	0.042	2.539	0.878	3.442	1.342	0.019	0.116	0.025
Cr_2O_3	0.042	0.033	0.011	0.004	0.034	0.000	0.052	0.024	0.000
FeO	14.211	14.047	23.067	15.219	15.731	15.670	13.411	15.097	12.573
MnO	0.212	0.086	0.245	0.069	0.267	0.257	0.149	0.213	0.159
MgO	45.964	43.079	29.121	39.510	34.627	38.244	44.655	43.452	44.699
NiO									
CaO	0.234	0.153	0.487	0.337	0.961	0.696	0.187	0.545	0.218
Na2O	0.000	0.031	0.095	0.009	0.066	0.067	0.033	0.015	0.013
K2O	0.009	0.005	0.250	0.090	0.252	0.108	0.000	0.005	0.000
Total	100.14	97.04	92.29	93.62	93.94	95.48	99.21	100.26	99.02

On: olivine phyric nephelinite
Omn: olivine phyric melilite nephelinite
Ol: Olivine
PCA: Capim Açu Edge
AB: Americano Beach

Table 3: Electron microprobe analyses of pyroxenes in pyroclasts, Capim-Açu Edge, Quixaba Formation.

Electron Micropobe analyses of pyroxenes in pyroclasts from Capim Açu Edge, Fernando de Noronha Archipelago, Brazil

Sample	M2102109-1	M2102109-2	M2102109-3	M2102109-4	M2102109-5	M2102109-6	M2102110	M2102111-1	M2102111-2	M2102111-3
Location	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA
Rock type	On	On	On	On	On	On	On	On	On	On
Mineral	Di	Di	En	En	Di	Di	Di	Di	Di	Di
Target		Core	Core	Rim	Core	Rim	Core	Core	Core	Core
SiO_2	45.082	45.696	39.304	40.024	41.531	45.429	47.944	46.264	53.331	46.834
TiO_2	3.546	3.669	0.045	0.041	5.293	3.739	3.928	3.462	1.097	3.310
Al_2O_3	5.546	5.878	3.937	0.029	8.918	6.131	5.550	6.235	1.294	6.089
Cr_2O_3	0.005	0.053	0.016	0.014	0.013	0.000	0.020	0.000	0.052	0.036
FeO	7.102	7.249	21.420	14.310	7.392	6.833	6.953	7.046	6.182	6.474
MnO	0.115	0.068	0.379	0.271	0.097	0.122	0.174	0.070	0.124	0.117
MgO	11.829	11.869	33.695	45.022	11.062	12.470	12.109	12.176	13.587	12.520
CaO	25.157	24.987	0.674	0.544	24.842	24.878	24.483	25.031	25.245	25.224
Na2O	0.282	0.373	0.091	0.000	0.366	0.425	0.490	0.370	0.479	0.307
K2O	0.000	0.027	0.266	0.000	0.025	0.015	0.021	0.000	0.000	0.019
Total	98.66	99.87	99.83	100.26	99.54	100.04	101.672	100.65	101.39	100.930
Fe2O3										
FeO										
New Total										

On: olivine phyric nephelinite
Di: Diopside
En: Enstatite
PCA: Capim Açu Edge
AB: Americano Beach

Table 4: Electron microprobe analyses of pyroxenes in lava flows, Capim-Açu Edge and Americano Beach, Quixaba Formation.

Electron Micropobe analyses of pyroxenes in lava flows from Capim Açu Edge and Americano Beach, Fernando de Noronha Archipelago, Brazil

Sample	M2102108-1	M2102108-2	M2102108-3	M2102108-4	M2102108-5	M2102112-1	M2102112-2	M2102112-3	M2102112-4	M2102112-5	M2102112-6	M2102114-1	M2102114-2
Location	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	PCA	AB	AB
Rock type	On	On	On	On	On	On	On	On	On	On	On	On	On
Mineral	Di	Di	Di	Fs	Di	Di	Di	Di	Di	Di	Di	Di	Di
Target	Core	Core	Core	Core	Core	Core	Core	Core	Core	Rim	Rim	Core	Core
SiO_2	46.515	39.818	40.955	0.314	46.421	45.865	44.164	44.480	45.783	47.967	43.619	46.912	52.030
TiO_2	2.939	4.826	4.805	5.681	3.016	2.387	4.219	3.815	3.205	2.439	4.337	3.050	1.544
Al_2O_3	5.228	7.994	8.815	8.375	5.254	5.173	9.330	8.464	7.506	5.956	9.327	6.595	1.900
Cr_2O_3	0.003	0.000	0.066	14.960	0.009	0.071	0.026	0.127	0.165	0.111	0.113	0.046	0.014
FeO	5.974	7.162	7.582	59.734	6.200	6.113	7.346	7.725	7.475	6.932	7.366	6.876	5.643
MnO	0.072	0.164	0.096	1.091	0.027	0.118	0.051	0.089	0.161	0.178	0.064	0.039	0.167
MgO	12.992	11.166	10.880	4.410	12.562	12.911	10.991	11.406	11.864	13.034	10.849	12.293	13.908
CaO	25.246	24.610	24.404	0.201	25.039	24.102	23.973	24.186	23.274	23.466	24.022	24.238	24.708
Na2O	0.348	0.500	0.477	0.038	0.335	0.276	0.447	0.470	0.508	0.376	0.398	0.347	0.416
K2O	0.017	0.006	0.019	0.056	0.000	0.019	0.001	0.017	0.002	0.000	0.000	0.011	0.011
Total	99.33	96.25	98.10	94.86	98.86	97.04	100.55	100.78	99.94	100.46	100.10	100.41	100.34
Fe2O3													
FeO													
New Total													

On: olivine phyric nephelinite
Di: Diopside
Fs: Ferrossilite
PCA: Capim Açu Edge
AB: Americano Beach

Table 5: Electron microprobe analyses of nepheline in pyroclasts, Capim-Açu Edge, Quixaba Formation.

Electron Micropobe analyses of nepheline in pyroclasts from Capim Açu Edge, Fernando de Noronha Archipelago, Brazil

Sample	M2102109-PCA03I -C2 - 3	M2102111-PCA 10II - C6 - 5
Location	PCA	PCA
Rock type	On	On
Mineral	Ne	Ne
SiO_2	43.046	42.850
TiO_2	0.161	0.176
Al_2O_3	33.392	33.596
Cr_2O_3	0.000	0.000
FeO	1.318	1.344
MnO	0.000	0.000
MgO	0.265	0.114
CaO	0.209	0.555
Na2O	14.292	13.097
K2O	7.993	9.451
Total	100.68	101.18

On: olivine phyric nephelinite
Ne: Nepheline
PCA: Capim Açu Edge

Table 6: Electron microprobe analyses of nepheline in lava flows, Capim-Açu Edge and Americano Beach, Quixaba Formation.

Electron Micropobe analyses of nepheline in lava flows from Capim Açu Edge and Americano Beach, Fernando de Noronha Archipelago, Brazil

Sample	M2102108-PCA02I -C4 - 1	M2102112-PCA 10IV - C6 -	M2102112-PCA 10IV - C6 - 2	M2102114-PAM 01III- C2 - 4
Location	PCA	PCA	PCA	AB
Rock type	On	On	On	On
Mineral	Ne	Ne	Ne	Ne
SiO_2	44.687	42.893	43.207	44.718
TiO_2	0.127	0.130	0.151	0.069
Al_2O_3	35.638	34.676	35.220	35.047
Cr_2O_3	0.025	0.046	0.044	0.053
FeO	1.074	1.419	1.486	1.288
MnO	0.000	0.020	0.000	0.000
MgO	0.294	0.051	0.023	0.162
CaO	0.130	0.275	0.247	0.785
Na2O	9.406	13.148	13.525	6.354
K2O	7.371	9.082	9.080	6.999
Total	98.75	101.74	102.98	95.48

On: olivine phyric nephelinite
Ne: Nepheline
PCA: Capim Açu Edge

Table 7: Electron microprobe analyses of oxides in pyroclasts, Capim-Açu Edge, Quixaba Formation.

Electron Micropobe analyses of Fe-oxide in pyroclasts from Capim Açu Edge, Fernando de Noronha Archipelago, Brazil

Sample	M2102110-PCA05A - C2 - 4	M2102111-PCA 10II - C1 - 2	M2102111-PCA 10II - C6 - 1
Location	PCA	PCA	PCA
Rock type	On	On	On
Mineral	Ox	Ox	Ox
SiO_2	0.132	0.062	0.098
TiO_2	7.943	11.236	5.619
Al_2O_3	0.118	0.367	1.727
Cr_2O_3	2.249		
FeO	77.322	72.169	74.489
MnO	1.094	0.796	1.083
MgO	1.919	6.073	2.756
CaO	0.221	0.216	0.256
Na2O	0.030	0.032	0.066
K2O	0.010	0.029	0.083
Total	91.04	91.09	91.22

On: olivine phyric nephelinite
Ox: oxide
PCA: Capim Açu Edge

Table 8: Electron microprobe analyses of oxides in lava flows, Capim-Açu Edge, Quixaba Formation.

Electron Micropobe analyses of Fe-oxide in lava flows from Capim Açu

Sample	M2102108	M2102112-1	M2102112-2	M2102114-1	M2102114-2	M2102114-3
Location	PCA	PCA	PCA	PCA	PCA	PCA
Rock type	On	On	On	On	On	On
Mineral	Ox	Ox	Ox	Ox	Ox	Ox
SiO_2	0.079	0.146	0.042	0.137	0.108	0.000
TiO_2	17.432	9.227	54.982	38.858	8.065	10.236
Al_2O_3	3.144	0.239	0.000	1.960	1.684	0.629
Cr_2O_3						
FeO	67.721	75.625	0.433	43.701	74.763	72.361
MnO	1.023	1.251	0.018	0.183	0.157	0.778
MgO	5.452	4.450	0.000	4.483	2.504	5.533
CaO	0.194	0.401	39.575	0.124	0.178	0.367
Na2O	0.085	0.000	0.885	0.007	0.005	0.000
K2O	0.004	0.020	0.059	0.033	0.030	0.028
Total	91.04	91.36	95.99	89.97	90.15	90.842

On: olivine phyric nephelinite
Ox: oxide
PCA: Capim Açu Edge

Table 9: Electron microprobe analyses of carbonate in amygdales of lava flows, Capim-Açu Edge, Quixaba Formation.

Electron Micropobe analyses of carbonate within vesicles in lava flows from Capim Açu Edge and Americano Beach, Fernando de Noronha Archipelago, Brazil

Sample	M2102112-1	M2102112-2	M2102112-3	M2102112-4
Location	PCA	PCA	PCA	PCA
Rock type	On-ves	On-ves	On-ves	On-ves
Mineral	Cb - Cal	Cb - Cal	Cb - Cal	Cb - Cal
SiO_2	0.108	0.213	0.065	0.107
TiO_2	0.013	0.000	0.015	0.000
Al_2O_3	0.000	0.047	0.000	0.000
Cr_2O_3	0.020	0.000	0.048	0.000
FeO	0.007	0.000	0.000	0.015
MnO	0.032	0.000	0.000	0.029
MgO	1.353	0.813	0.833	2.443
CaO	60.262	59.365	60.302	59.089
Na2O	0.012	0.000	0.047	0.015
K2O	0.004	0.000	0.004	0.008
Total	61.81	60.44	61.31	61.71

Ves: vesicule
On: olivine phyric nephelinite
Cb - cal: carbonate - calcite
PCA: Capim Açu Edge

References

Morimoto, N. (1988). Nomenclature of pyroxenes. Mineralogy and Petrology, 39(1), 55-76.

Klein C, Dutrow B (2012) Manual of mineral science, 23rd edn. New York: Wiley.

APPENDICE - Characterization of Ash aggregates from the Upper pyroclastic deposit of Capim-Açu Edge, Quixaba Formation

1. Introduction

This topic describes and illustrates the componentry, morphological, textural, and structural aspects of the upper pyroclastic level present at Capim-Açu Edge (Fig. 1), southwest of the Fernando de Noronha main island.

The upper pyroclastic level belongs to the Quixaba Formation, as described in *"Lithofacies Association and Stratigraphy of the Quixaba and Remédios Formations, Fernando de Noronha Archipelago, Brazil"* and is the representative of the most recent record of pyroclastic rocks among those found in the Archipelago. Scientific works about these volcanic rocks have never been presented before, being this a pioneer study. The descriptions in Almeida, 1955 are restricted to a distance macroscopic description of the outcrop, therefore this work brings hitherto unpublished data on the pyroclastic deposit containing accretionary particles in Fernando de Noronha Archipelago.

2. Analytical methods

Fieldwork and petrography were carried out for the general description of the upper pyroclastic deposit. Conventional optical microscopy was applied for petrographic characterization using the petrographic microscope ZEISS Axioskop 40 under transmitted light at the Federal University of Minas Gerais, Brazil. The Zen 3.3 software allowed thin sections image capture and measurements of vesicles and crystals.

Scanning Electron Microscope images were obtained for a detailed and accurate description of the morphology of ash-sized fragments using STEM FEG Quanta 200 FEI. The Pegasus integrated detector EDS (energy dispersive X-ray spectrometer) and EBSD (electron backscattered diffraction) were used for crystal and ultra-fine particle composition. The analyses were carried out at the Microscopy Center of the Federal University of Minas Gerais, Brazil.

3. Deposit description

The upper level consists of a preserved portion of a stratified volcanic sequence formed by a proximal fallout deposit (Fig. 1A). The layers, rich in juvenile clasts, are made of fine to coarse lapilli, and minor bombs, being laterally continuous, well sorted, clast-supported, and variably graded (Fig. 1B).

The layers selected for a detailed study are located at the base of the sequence (Fig. 1C), being the only ones with secure access due to the rugged and steep terrain. The first basal layer (B1) is 1.24 meters thick, composed of juvenile spherical (equant) to spheroidal (subequant) coarse lapilli fragments and bombs of up to 8.0 cm in diameter (Fig. 1D). The B2 layer is ca. 2.0 meters thick, composed of juvenile spherical (equant) to spheroidal (subequant) medium to fine lapilli fragments mainly varying from 1.5 cm to 3.3 cm in diameter with a maximum found of 6.0 cm (Fig.1D). Layer B2 overlays layer B1 in abrupt contact and follows the same conformation and shape as the lower layer. Both layers are in a clast-supported loose framework, with grain-to-grain contacts (Fig.1E), showing a stratified structure marked by gain-size variation.

The surfaces of the juvenile fragments are generally continuous, devoid of fractures, and rounded. Their interior shows a concentric structure evidenced by a vesicular pattern forming concentric circles and asymmetrical semicircles (with respect to the center (Fig. 2A and B). Typically, the fragments' interior presents sections with massive portions occurring mostly in the center while the rims tend to be more vesicular, albeit the opposite may also occur (Fig. 2C). Under the naked eye, the fragments have usually a micro porphyritic texture with microphenocrysts of olivine included in an aphanitic groundmass (Fig.2D). Occasionally, the texture is aphyric being entirely constituted by a very fine-grained primary igneous material.

3.1 Nomenclature

Here the term ‘ash aggregates’ is used to encompass all types of juvenile clasts formed by aggregation of ash particles, regardless of their internal structure, shape, and size, as in Van Eaton et al. (2013). As the descriptions progress, specific nomenclature is used to discriminate between each of the aggregate types, primarily, on the basis of their physical characteristics as internal structure and constituent grain size distributions.

The specific usage of the term ash pellets is employed here to refer to internally structureless aggregates whereas the term accretionary lapilli is employed to refer to ash aggregates with a concentrically layered internal structure in rough equivalence to the core-type vs. rim-type classification of Schumacher and Schmincke (1991) for the accretionary lapilli from Laacher See Volcano, Germany.

The term armored lapilli is referred to melilite nuclei coated by fine ash, and olivine nuclei coated by one or more complete or partial layers of accreted fine ash, being variants of accretionary lapilli, as described by White and Houghton (2000) *in* Encyclopedia of Volcanoes.

3.2 **Petrography**

The ash aggregates are formed of olivine, which usually occurs as euhedral phenocryst in a seriate texture, and glomeroporphyritic clusters (Fig. 3A, B, C). More rarely olivine phenocrysts show embayments and skeletal terminations (Fig. 3B); canary yellow and colorless melilite as euhedral tabular microphenocrysts (Fig. 3C, E, F); clinopyroxene as laths of microcrysts and microlites (Fig. 3C, D); oxide grains as cuboctahedron isolated microcrystals and clusters (Fig. 3E, F); and nepheline, which is hardly seen in a microscopic scale. The general appearance of the ash aggregates is characterized by an earthy aspect with brown colors due to the alteration of juvenile fine ash and volcanic glass. A ubiquitous presence of reddish-brown iddingsite occurs replacing the olivine phenocrysts.

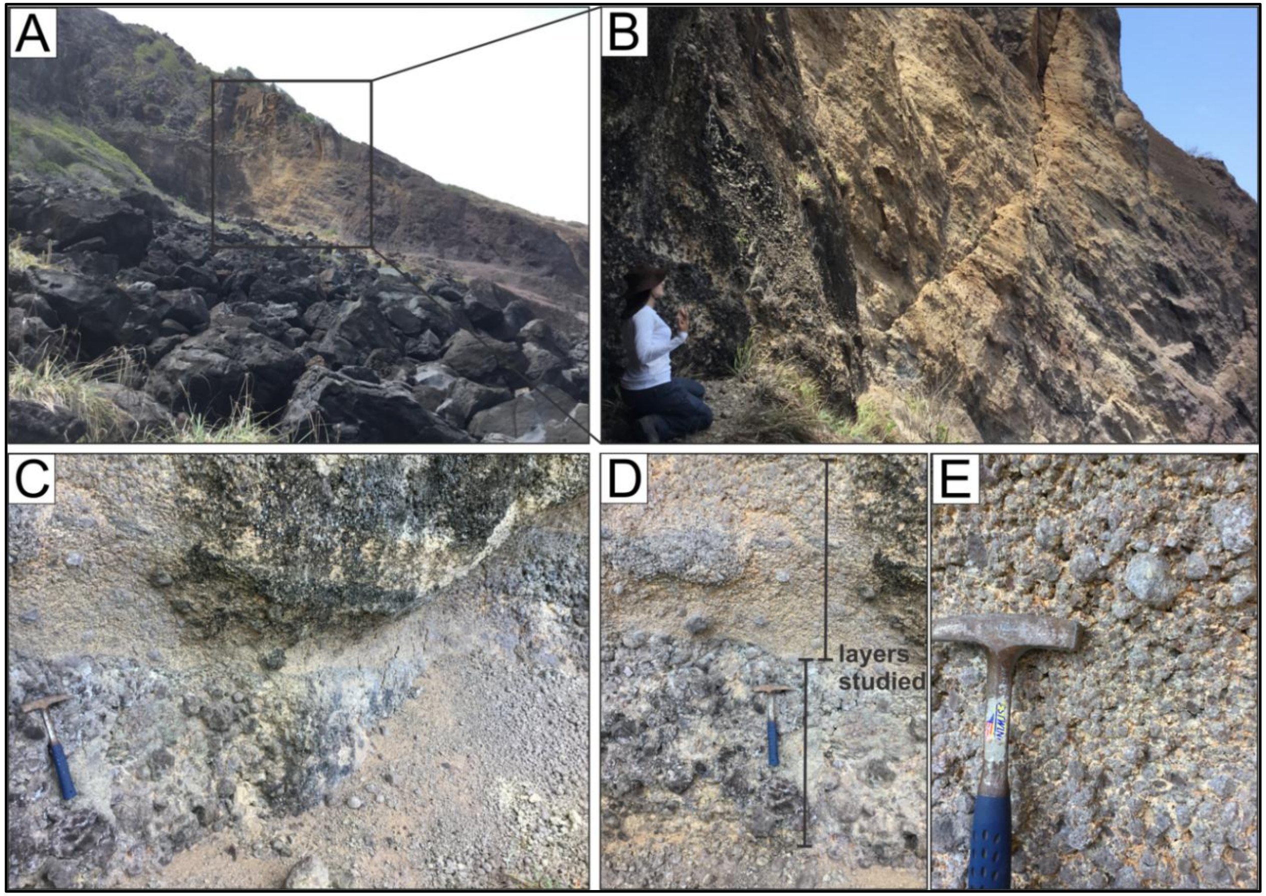


Fig. 1. Pyroclastic deposits of the studied stratified volcanic sequence. A) Preserved portion of the sequence located in a topographically high brown coffee cliff composed of layered fall deposits. B) Detail to the volcanic sequence: note the stratified structure marked by grain-size variation. To the right of the person who is the scale and in dark gray color is the coarse base layer which was sampled. C) Sampling location of both studied layers. Note the juvenile coarse lapilli layer at the base and the medium to fine juvenile lapilli layer overlaying the former in abrupt contact. D) Detail of the studied layers. Note the change in grain size. E) Detail of the rounded and semi-rounded lapilli clasts in the upper level in a loose framework. Note the presence of the orange clay mineral due to the alteration of the ash-size particles and the borders of the lapilli.

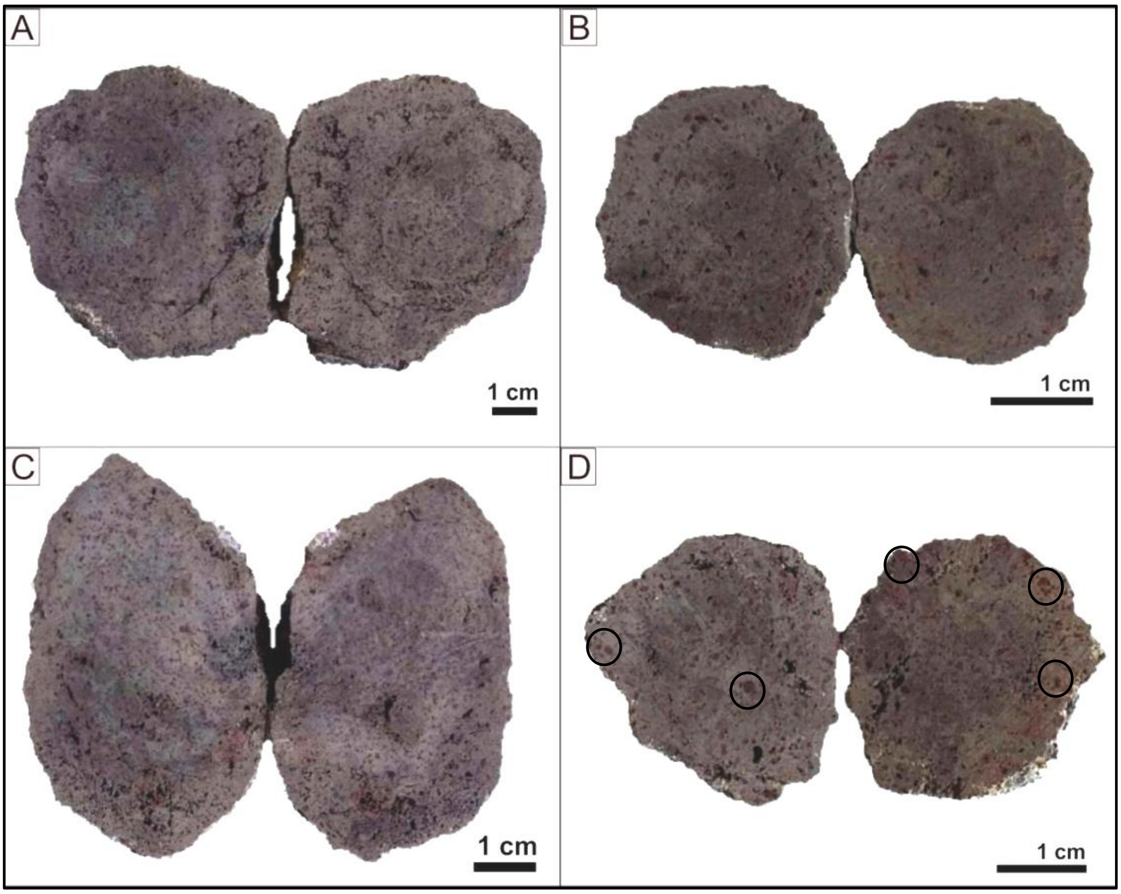


Fig 2. Fragments from the studied layers from the brown coffee volcanic sequence in the Capim-Açu Edge. A) Olivine-phyric melilite nephelinite spherical bomb from the base layer, showing a vesicular pattern forming concentric circles and asymmetrical semicircles (with respect to the center); B) Olivine-phyric melilite nephelinite spherical phase from the base layer, showing vesicles arranged drawing circular contours; C) and D) Olivine-phyric melilite nephelinite spheroidal bomb from the upper layer, showing a coherent aspect mostly in the center while the rims are more vesicular. The circles indicate olivine phenocrysts altered to iddingsite.

3.3 **Morphology and Structure**

The juvenile clasts are made of five types of ash aggregates: massive ash pellets (Mpel), accretionary lapilli (Lacc), complexly layered accretionary lapilli (cLacc), olivine and melilite nuclei coated by fine ash refered as layered armored lapilli (Lar), and complexly layered olivine nuclei coated by fine ash (cLar), held together in a cryptocrystalline groundmass. Due to the concavo-convex contacts, particularly noticed when the ash aggregates are spherically shaped, the fabric shows considerable vesicularity. The morphological classification of the ash-aggregates is summarized in Table 1.

The massive ash pellets occur as rounded aggregates, sometimes elongated, showing circular and oval shapes, preserving the syndepositional fluidal condition. They present an average size of 0.181 mm and a maximum measured size of 0.760 mm. In general, massive ash pellets have the smallest sizes among the ash aggregate types present and are the most abundant in both studied layers (Fig. 3A, B, C).

The accretionary lapillis host a massive ash pellet nucleus, usually centered and enveloped by one layer of ash (Fig. 3C). They present an average size of 0.291 mm and a maximum measured size of 0.550 mm.

The complexly layered accretionary lapillis generally present one nucleus of massive ash pellet (Fig. 3D), but they also occur lacking a distinct nucleus or show more than one unstructured nucleus of pellet (Fig. 3A, C and E). They present multiple (two to five) outer concentric laminations of ash, which sometimes truncate each other giving the appearance of rose petals. Laths of melilite and microcrysts of clinopyroxene frequently occur concentrically oriented following the approximately circular contour of the accretionary ash layers (Fig. 3A). The average size is 0.558 mm and the maximum measured size is 1.119 mm. In general, complexly layered accretionary lapillis have the largest sizes among the ash aggregate types present and show significant morphological variations.

The armored lapillis host a crystalline nucleus, usually centered and made of a single euhedral to subhedral olivine phenocryst (avg. 0.233 mm), which is partial to fully coated by ash aggregates (Fig. 3A, C and F). More rarely, the olivine crystals present delicate skeletal borders which, despite the fragmentary character of the rock, are fully preserved (Fig. 3B). The size of the nucleus is normally limited to half (avg. 55%) the of diameter of the aggregate but may reach up to 94% of the aggregate volume in the case of crystals coated by a thin rim. Besides the olivine crystalline core, 23% of the armored lapilli found and measured have a melilite crystalline core (Fig. 3F). This type of aggregate is on average 65% smaller than those with an olivine core and the size of the nucleus is also limited to half (avg. 49%) of the diameter of the clast, reaching up to 73% of the aggregate volume.

The complexly layered armored lapillis host a crystalline nucleus with up to 4 fragmented and/or whole olivine phenocrysts arranged in clusters. Laths of melilite and microcrysts of clinopyroxene frequently occur concentrically oriented following the approximately circular contour of the accretionary ash layers. They present multiple (2+) outer concentric laminations of ash as the complexly layered accretionary lapilli, with a maximum found of 5 layers that truncate one another (Fig. 3B, F). Similar to armored lapillis the crystalline nucleus is normally limited to half (avg. 49%) of the diameter of the aggregate. The measurement of the nucleus took into account the size of the largest olivine phenocrystal.

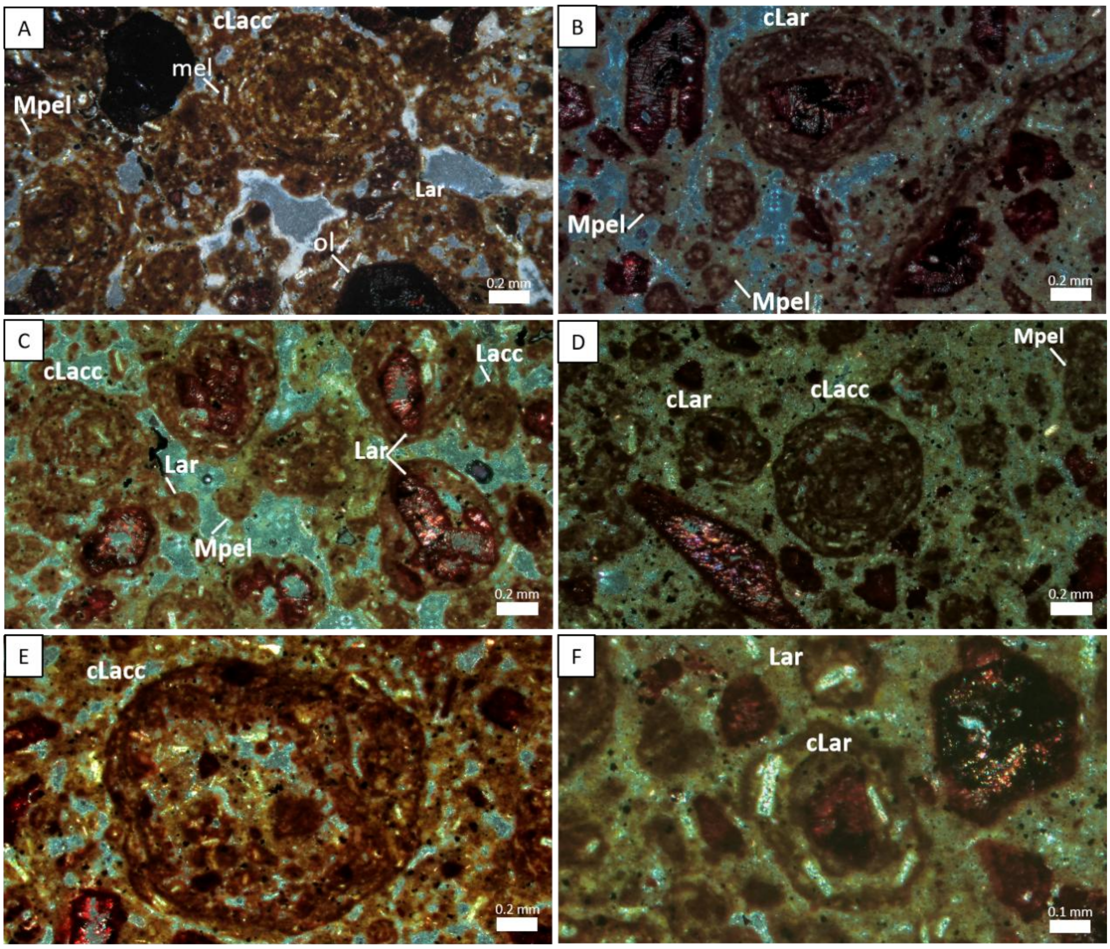


Fig 3. Thin sections of lapilli fragments made of ash aggregates from the Upper pyroclastic deposit, Capim-Açu Edge. A) Complexly layered accretionary lapilli with a nucleus of massive ash pellets, layered armored lapilli with a crystalline nucleus of euhedral olivine, and a massive ash pellet. Note the melilite crystals following the circular contour of the cLacc. The concavo-convex contacts of the spherically shaped ash aggregates gives it a considerable vesicularity; B) Complexly layered armored lapilli composed of a crystalline nucleus of olivine and three accretionary layers that truncate each other. Several massive ash pellets with rounded forms. Note the small sizes of the massive ash pellets in comparison with the more complex aggregate types. Olivine phenocrystal showing a poorly developed skeletal structure in the upper right corner of the image; C) Complexly layered accretionary lapilli with an unstructured nucleus of ash pellets, massive ash pellets, and three layered armored lapillis. One is formed by a phenocrystal of olivine fully coated by fine ash, and the others are formed by a crystalline nucleus of olivine phenocrysts arranged in clusters; D) Complexly layered accretionary

lapilli, complexly layered armored lapilli with a completely altered nucleus of olivine, and an elongated massive ash pellet; E) Complexly layered accretionary lapilli. Note the chaotic unstructured nucleus constituted of seveal ash pellets; F) Layered armored lapilli with a crystalline nucleus of melilite, a complexly layered armored lapilli with a crystalline nucleus of olivine and several melilite crystals concentrically oriented following the circular contour of the aggregate.

The petrographic and mineralogical studies using SEM-EDX microscopy on thin sections offer a so far unrevealed nature of the constituted elements of the ash aggregates. Olivine microphenocryts are wrapped into a dense microlitic structure with interstitial altered glass (Fig. 4A and B). The microlites are of micrometric size (<20μm) and exhibit prismatic shapes and embayments surfaces (Fig. 4E). A concentric morphology in the distribution of microlites around olivine microphenocrysts is noteworthy, as already attested by the optical images (Fig. 4A, B).

3.4 **Chemical Composition**

EDS analyses (energy dispersive X-ray spectrometer) and EBSD (electron backscattered diffraction) of minerals indicate that they correspond to $Fo_{(87)}$, diopside with an average composition in terms of molecular percentage of $Wo_{50}En_{38}Fe_{12}$, nepheline, and hematite. The interstitial material is constituted of an Al-rich silicate, which represents the pyroclasts' groundmass, and corresponds to an alteration of volcanic glass (Fig. 4A, C and E). An expected primary composition for melilite crystals was not identified. The EDS analysis results showed microlites with a silica aluminum ratio of 2.5:1.0 with high CaO, FeO, and MgO contents. Possibly this represents melilite pseudomorphs partially replaced by an Al-rich clay mineral.

Overall, the images show a generalized absence of vesicles, the existence of abundant constituents with preserved compositions: forsterite microphenocrysts (Fig. A, B and C), microlites of diopside (Fig. 4C and G), nepheline (Fig. 4G and H) and hematite (Fig. 4G), which denote the primary composition of the erupting magma, and the presence of Al-rich interstitial secondary material that holds together the crystals (Fig. 4E).

All five types of ash aggregates identified share the characteristic that their outermost edges have an earthy appearance as seen microscopically (Fig. 3), with a more advanced alteration appearance with respect to the interior of the layers. Also, when it comes to complexly layered types, each layer edge has a darker brown color (similar to a thin rim), which was even used to individualize the different layers. It is plausible to relate this altered aspect with the results from the EDS detector, which yield notably high contents of an Al-rich silicate (Fig. 4E and F).

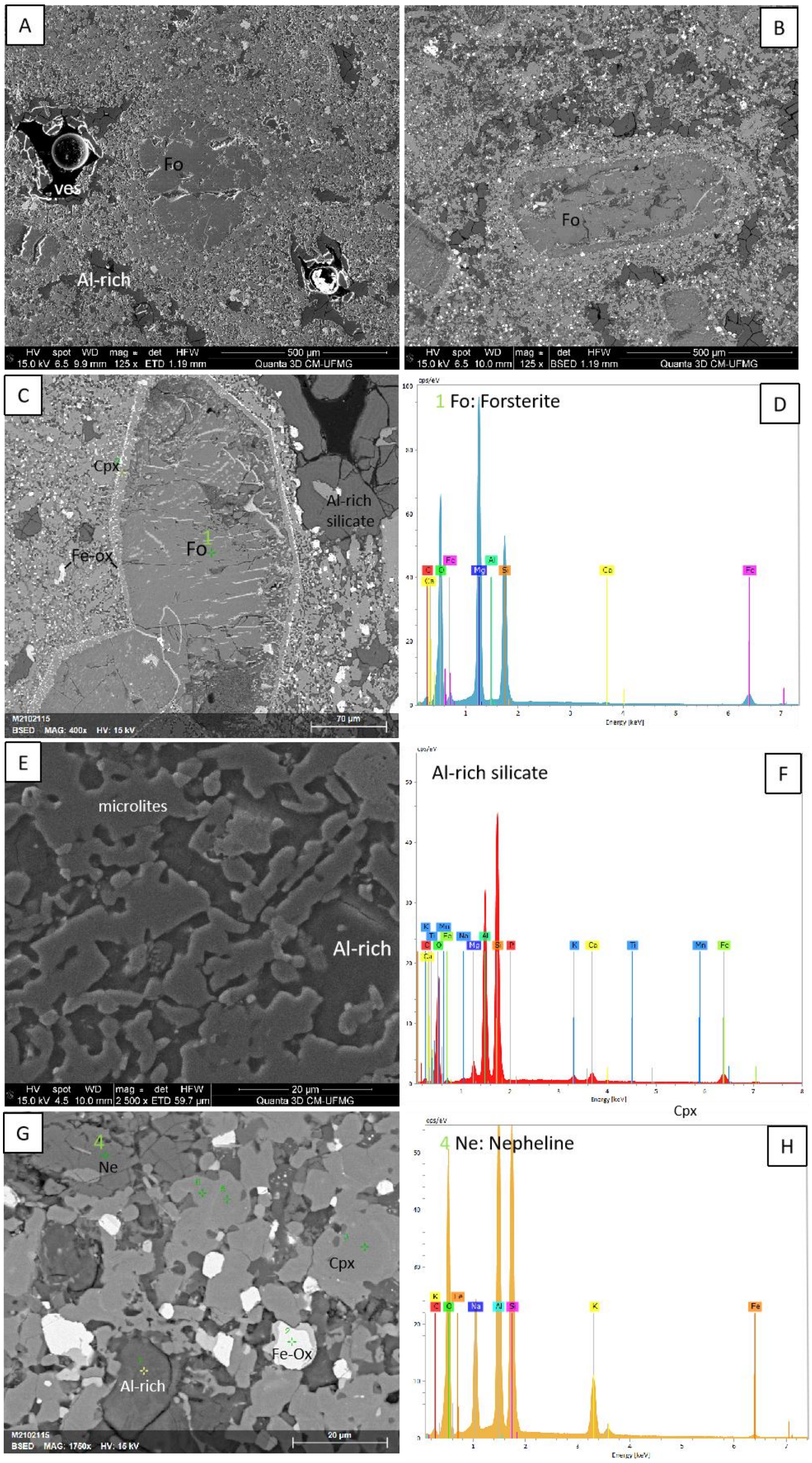


Fig. 4. SEM images of polished thin sections of ash aggregates from the upper pyroclastic deposit of Capim-Açu Edge. A) Forsterite microphenocrystal in a groundmass of microlites (pale gray), Al-rich silicate which corresponds to interstitial altered glass (dark gray), and vesicles (black void); B) Forsterite microphenocrystal wrapped into a dense microlitic structure with interstitial altered glass; C)

Cluster of two euhedral forsterite microphenocrysts with pale gray rims formed by Cpx and white Fe-oxides (hematite), following the euhedral contour of the forsterite; D) EDX spectrum obtained from the forsterite core in picture c), showing its Mg-rich chemical composition; E) General aspect of the microlites. Note the embayment texture of the microlites and the interstices filled with Al-rich altered glass (dark gray); F) EDX spectrum obtained from the interstitial Al-rich silicate in picture e); G) Constituent elements of the ash aggregates: Nepheline, Cpx (diopside), Fe-oxide (hematite) and interstitial altered glass (Al-rich silicate); H) EDX spectrum obtained from the nepheline microlite in picture g), showing its Na and K-rich chemical composition.

4. Interpretations

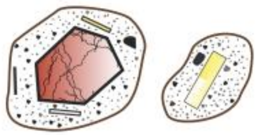
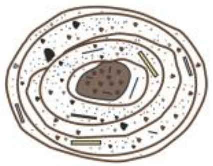
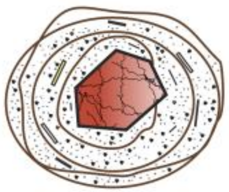
The spectrum of aggregate types in the upper pyroclastic deposit of Capim-Açu Edge is divisible into six categories (Table 1). Three of which are varieties of accretionary lapilli, two are varieties of armored lapilli and one correspond to massive ash pellet. The most striking feature of the layered ash aggregates is their concentric structuring with one or more ash layers having formed around one or more massive ash cores, or around olivine or melilite crystals.

In summary, the ash aggregates are clastic in origin as demonstrated by the optical and SEM-EDX microscopy images presented, and consist of microphenocrysts and microlites amalgamated by silicate glass. The armored variations show these constituents around one or more forsterite phenocrysts and a melilite microphenocrystal. The analysis by energy dispersive X-ray spectrometry methods shows the Al-rich silicate nature of the altered glass.

The formation of ash aggregates at Capim-Açu Edge comprised at least two successive stages. The first one generated the juvenile components that form the ash aggregates, i.e. phenocrysts, microphenocrysts and microlites. This was a stage related to magma fragmentation of a partially crystallized ultrabasic alkaline melt, as indicated by the occurrence and composition of the rock-forming minerals: forsterite, diopside, nepheline, melilite and hematite. In sequence, following the magma fragmentation, the ash particle accretion would have taken place to form the aggregates with spherical forms.

The accretionary textures are consistent with growth by a process of grain-by-grain accretion (Sastry et al., 2003) and the presence of concentric (multiple) layering signifies that the aggregate experienced (cyclic) passage through sub-saturated regions of ash-laden atmosphere (Van Eaton and Wilson, 2013).

Table 1: Categories of aggregate types identified in the Upper pyroclastic deposit from Capim- Açu Edge, with field descriptions, typical range of diameters, and inferred mechanism of formation.

Appearance	Name	Symbol	Description	General Interpretation
	Massive ash pellets	Mpel	Subspherical aggregates, often showing fluidal forms, that are internally massive. Usually clast-supported, with concavo-convexcontacts. Diameters 0.03 to 0.8mm. (type A[a], core type[b],ash pellets[c,d], AP1[e])	Growth by wet nucleation and rapid coalescence under saturated conditions. Freezing may occur during transport, followed by syn-depositional deformation from landing wet or melting.
	Layered accretionary lapilli	Lacc	Subspherical aggregates with a single concentric layer around a pellet. Diameters 0.1 to 0.55mm. (type B[a], core type[b], accretionary lapilli[c], coated pellets or accretionary lapilli[d], Ap2[e])	Massive ash pellets that developed outer layers by cycling through regions with varying grain size populations and/or sub-saturated conditions.
	Layered armored lapilli	Lar	Olivine or melilite phenocryst surounded by a single concentric layer of ash. Diameters 0.1 to 1.0mm.	Phenocysts that developed outer layers by cycling through regions with varying grain size populations and/or sub-saturated conditions.
	Complexly layered accretionary lapilli	cLacc	Multiple (3+) outer laminations of fine ash; truncations and lenses are common. Generally lack a distinct core or show more than one unstructed core of pellet. Diameters 0.1 to 1.1mm. (type B[a], rim type[b],accretionary lapilli[c,d], AP2[e])	Massive ash pellets or layered accretionary lapilli that were re-entrained through abrasive, grain size-stratified regimes under moist/ sub-saturated conditions.
	Complexly layered armored lapilli	cLar	Single olivine phenocryst or a clusters of (4-) olivines surounded by multiple outer (3+) laminations of fine ash; truncations and lenses are common. Diameters 0.3 to 1.1mm.	Olivine phenocrysts or layered armored lapilli that were re-entrained through abrasive, grain size-stratified regimes under moist/ sub-saturated conditions.

Corresponding terminology from the studies of a: Reimer (1983), b: Schumacher and Schmincke (1991), c: Thordarson (2004), d: Brown et al. (2010) and Brown et al. (2012), e: Van Eaton et al. 2013

References

Almeida, F.F.M., 1955. Geologia e petrologia do Arquipélago de Fernando de Noronha. (Monografia 13). DNPM, Divisão de Geol. Mineral.

Brown, R.J., Branney, M.J., Maher, C., Harris, P.D., 2010. Origin of accretionary lapilli within ground-hugging density currents: evidence from pyroclastic couplets on Tenerife. Geological Society of America Bulletin 122, 305–320.

Reimer, T.O., 1983. Accretionary lapilli in volcanic ash falls: physical factors governing their formation. In: Peryt, T.M. (Ed.), Coated Grains. Springer, Berlin, pp. 56–68.

Brown, R.J., Bonadonna, C., Durant, A.J., 2012. A review of volcanic ash aggregation. Physics and Chemistry of the Earth 45–46, 65–78.

Sastry, K.V.S., Dontula, P., Hosten, C., 2003. Investigation of the layering mechanism of agglomerate growth during drum pelletization. Powder Technology 130, 231–237.

Schumacher, R., Schmincke, H.-U., 1991. Internal structure and occurrence of accretionary lapilli — a case study at Laacher See volcano. Bulletin of Volcanology 53, 612–634.

Thordarson, T., 2004. Accretionary-lapilli-bearing pyroclastic rocks at ODP Leg 192 Site 1184: a record of subaerial phreatomagmatic eruptions on the Ontong Java Plateau. Geological Society London Special Publication 229, 275–306.

Van Eaton, A.R., Wilson, C.J.N., 2013. The nature, origins and distribution of ash aggregates in a large-scale wet eruption deposit: Oruanui, New Zealand. Journal of Volcanology and Geothermal Research, 250, 129-154. https://doi.org/10.1016/j.jvolgeores.2012.10.016.

White, J.D.L., Houghton, B.F., 2000. Surtseyan and related phreatomagmatic eruptions. In: Sigurdsson, H., Houghton, B.F., McNutt, S., Rymer, H., Stix, J. (Eds.), Encyclopedia of Volcanoes. Academic Press, San Diego, California, pp. 495–511.