UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS

EVOLUÇÃO DO VULCANISMO HISTÓRICO DE 1580 A.D. DA ILHA DE SÃO JORGE, ARQUIPÉLAGO DOS AÇORES

MARCOS DE MAGALHÃES MAY ROSSETTI

ORIENTADOR - Prof. Dr. Evandro Fernandes de Lima

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RESUMO

A erupção histórica de 1580 A.D. ocorreu ao sudoeste da Ilha de São Jorge, Açores recobrindo uma área total de 4 km². Este trabalho teve como objetivo caracterizar as diferentes morfologias de lava de 1580 A.D, juntamente com a definição de padrões petrográficos e geoquímicos. A erupção gerou quatro *flow fields*: Ribeira do Almeida, Queimada, Ribeira do Nabo I e Ribeira do Nabo II. A descrição detalhada das lavas permitiu identificar *spiny*, *sheet*, e *slabby pahoehoe* e derrames do tipo *'a´ā*. Próximo aos cones, derrames do tipo *'a´ā* são descritos. Com a constante erupção, estas lavas fluem em direção a costa formando deltas de lava ao entrar em contato com a água. Estes deltas geram um relevo sub-horizontal favorecendo a colocação de derrames do tipo *sheet pahoehoe.* A contínua alimentação interna favorece o espessamento dos derrames, podendo gerar o rompimento da superfície formando derrames *slabby pahoehoe.* Os estágios finais da erupção são marcados por derrames do tipo *'a´ā* canalizados lateralmente e sobre os derrames do tipo *sheet pahoehoe*. A variação na superfície dos derrames é controlada pelas taxas de efusão e pela topografia. Petrograficamente, todas as lavas da erupção de 1580 A.D. são olivina basaltos. Os dados geoquímicos indicam uma afinidade magmática alcalina com os termos menos diferenciados localizados na região de Ponta Queimada. Isto pode ser explicado por uma constante recarga de magma mais primitivo na câmara magmática. Os padrões de ETR normalizados sugerem que os basaltos estudados foram gerados a partir de um baixo grau de fusão de uma fonte profunda e enriquecida do tipo *OIB*. O estudo dos aspectos físicos dos derrames de 1580 juntamente com a petrografia e geoquímica permitiram compreender a história geológica deste evento.

Palavras-Chave: Arquipélago dos Açores. Lavas basálticas, Ocean Island Basalts;

ABSTRACT

The historic eruption of 1580 A.D. occurred in the southwestern of São Jorge Island, in the central Azores covering a total area of 4 km². This work provides a characterization of the distribution and morphology of the 1580 A.D. lava flows, integrated to petrography and geochemistry. The eruption formed four distinct flows fields: Ribeira do Almeida, Queimada, Ribeira do Nabo I and Ribeira do Nabo II. Detailed geological analysis allowed the identification of spiny, sheet and sllaby pahoehoe and ‘a´ā lava morphotypes. Near the vent, the flow fields are characterized by channelized ‘a´ā flows. With continuous eruption, these lavas flowed downwards forming fan-shaped lava deltas when entering the sea. Sheet pahoehoe flows overlay the ‘a´ā lavas and with continuous inflation the surface of the flows breaks generating slabby pahoehoe surface. The gradual increase in surface fragmentation form rubbly surfaces. In the late stages of the eruption channelized ‘a´ā flows were emplaced, depositing laterally and over the sheet pahoehoe flows. The variations in the lava surface are controlled by the effusion rates and the topography. Petrographically, all lava flows are olivine basalts. The chemistry of the basalts indicate an alkaline nature for the 1580 volcanism. The less-evolved compositions are found in Ribeira do Almeida and this fact can be related to continuous recharge of the magma chamber with more primitive melts. Normalized REE profiles show that the basalts were generated by low volumes of melt of an enriched OIB source. The study of the physical aspects of 1580 lava flows with petrography and geochemistry allowed understand the geologic history of this event.

Keywords - Azores archipelago; basalt lavas; Ocean Island Basalts; lava emplacement

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SOBRE A ESTRUTURA DA DISSERTAÇÃO

Esta dissertação de mestrado está estruturada na forma do *artigo "The Eruptive History of 1580 A.D. Eruption, São Jorge, Azores."* submetido a revista *Journal of Volcanology and Geothermal Research*. Sendo assim, sua organização compreende as seguintes partes principais:

PARTE I: Introdução sobre o tema e descrição do objeto da pesquisa de mestrado, onde estão sumarizados os objetivos e a filosofia de pesquisa desenvolvidos, o estado da arte sobre o tema de pesquisa.

PARTE II Apresenta o artigo científico submetido a periódicos com corpo editorial permanente e revisores independentes, escritos pelo autor durante o desenvolvimento de seu Mestrado.O artigo apresenta os resultado obtidos, discussão e conclusão.

PARTE I

1. INTRODUÇÃO

Erupções históricas normalmente apresentam excelente exposições de rochas vulcânicas, viabilizando o estudo das características físicas de lavas basálticas. O Arquipélago dos Açores possui 13 erupções históricas subaéreas documentadas, sendo duas delas em São Jorge, 1580 e 1808 A.D (Zbyszewski, 1963; Weston, 1963/64; Madeira, 1998).

A erupção de 1580 A.D teve início no dia 28 de abril na porção sudoeste da Ilha de São Jorge (38°38' - 38°41'N, 28°8' - 28°12'O),com uma duração de cerca de 4 meses afetando as vilas de Ribeira do Almeida, Queimada e Ribeira do Nabo (Fouquet, 1873; Weston, 1964). O vulcanismo cobriu uma área de aproximadamente 4 km² e é caracterizado por um evento havaian/estromboliano ao longo de uma zona de fissura E-W. Dados geológicos disponíveis para a Ilha de São Jorge são escassos e a maioria dos estudos tratam sobre datação isotópica e da interação do magmatismo e a tectônica(Madeira and Silveira, 2003; Hildenbrand, et al. 2008; Millet, *et al*., 2009; Mendes, *et al.* 2013).

A descrição da erupção de 1580 A.D. foi realizada ao longo de quatro campos de lavas (*flow fields*) tendo como objetivo a caracterização dos tipos de lava e a descrição de padrões petrológicos. Com isso, foi possível a compreensão da dinâmica deste evento ocorrido na Ilha de São Jorge.

1.1. Justificativa

Os aspectos físicos do vulcanismo são determinantes na geração de diferentes tipos de depósitos e auxiliam a compreender as taxas de efusão dos sistemas e os processos de acomodação das lavas no relevo. A descrição das superfícies de derrames e a sua estruturação e o agrupamento destas, permitem estabelecer a origem, os processos deposicionais e os ambientes de deposição dos sistemas vulcânicos.

No estudo da Ilha de São Jorge investigaram-se os diferentes tipos de derrames básicos colocados em condições de ambiente subaéreo. Tipos específicos de derrames neste ambiente representam membros finais definidos como *pahoehoe* e`*Ã`a* observando-se um conjunto de tipos transicionais entre estes extremos. Esta variedade de tipos de derrames básicos é descrita especialmente em ilhas vulcânicas como Havaí e Islândia onde a intensa atividade vulcânica é documentada. Para concretização desta proposta optou-se pela definição de uma área com exposições adequadas para a identificação dos tipos de derrames, faciologia dos depósitos e sucessão dos basaltos. O vulcanismo ocorrido na Ilha de São Jorge em 1580 deixou um registro que contempla estes requisitos.

1.2. Problemas

Na região do Arquipélago dos Açores investigações envolvendo a descrição de morfologias de derrames basálticos são escassos, o que torna a pesquisa na área relevante para a compreensão da complexidade do vulcanismo nesta ilha. Dados geológicos disponíveis para a Ilha de São Jorge tratam especialmente da interação do magmatismo e a tectônica, que contribuem na compreensão da dinâmica mantélica e cinemática de placas (Hildenbrand *et al.,* 2008).

Os tipos de derrames, a sucessão destes e as características geoquímicas dos basaltos não foram estudadas de forma integrada até o momento na investigação geológica da Ilha de São Jorge.

1.3. Objetivos

A presente proposta envolve a investigação física e petrológica das erupções que ocorreram no ano de 1580 na Ilha de São Jorge no Arquipélago dos Açores. As áreas selecionadas expõem uma expressiva heterogeneidade morfológica de rochas vulcânicas básicas, favorecendo o estudo de associações vulcânicas em escala de afloramento. O trabalho prioriza a identificação e caracterização dos tipos de derrames, suas litofácies e associações destas para estabelecer os processos e os ambientes de *emplacement* de erupções basálticas de 1580. Objetiva-se também o estudo petrográfico e caracterização geoquímica destas erupções.

2. Localização da área estudo

A Ilha de São Jorge faz parte do Arquipélago dos Açores, juntamente com mais oito ilhas. Elas estão posicionadas ao longo de uma faixa de direção N50°W localizadas ao nordeste do Oceano Atlântico (Fig. 1a e 1b) entre os 37º e os 40º de latitude Norte e os 25º e os 31º de longitude Oeste e são divididas em três grupos: o Grupo ocidental (Ilha das Flores e Corvo), localizado em uma zona estável da placa Norte-Americana, o Grupo central (Ilhas de São Jorge, Pico, Faial, Graciosa e Terceira) e o Grupo oriental (Ilhas de São Miguel e Santa Maria), ambos posicionados na Microplaca dos Açores (Lourenço *et al.,* 1998).

São Jorge possui uma morfologia alongada de direção WNW-ESE com uma porção subaérea de 55 km de comprimento e 7 km de largura (Fig. 1c). Estudos batimétricos sugerem que a Ilha de São Jorge possui cerca de 3000 m de elevação total (sendo 2000 m abaixo do nível do mar), correspondendo a uma parte emersa de uma cadeia vulcânica alongada (Lourenço *et al*., 1998).

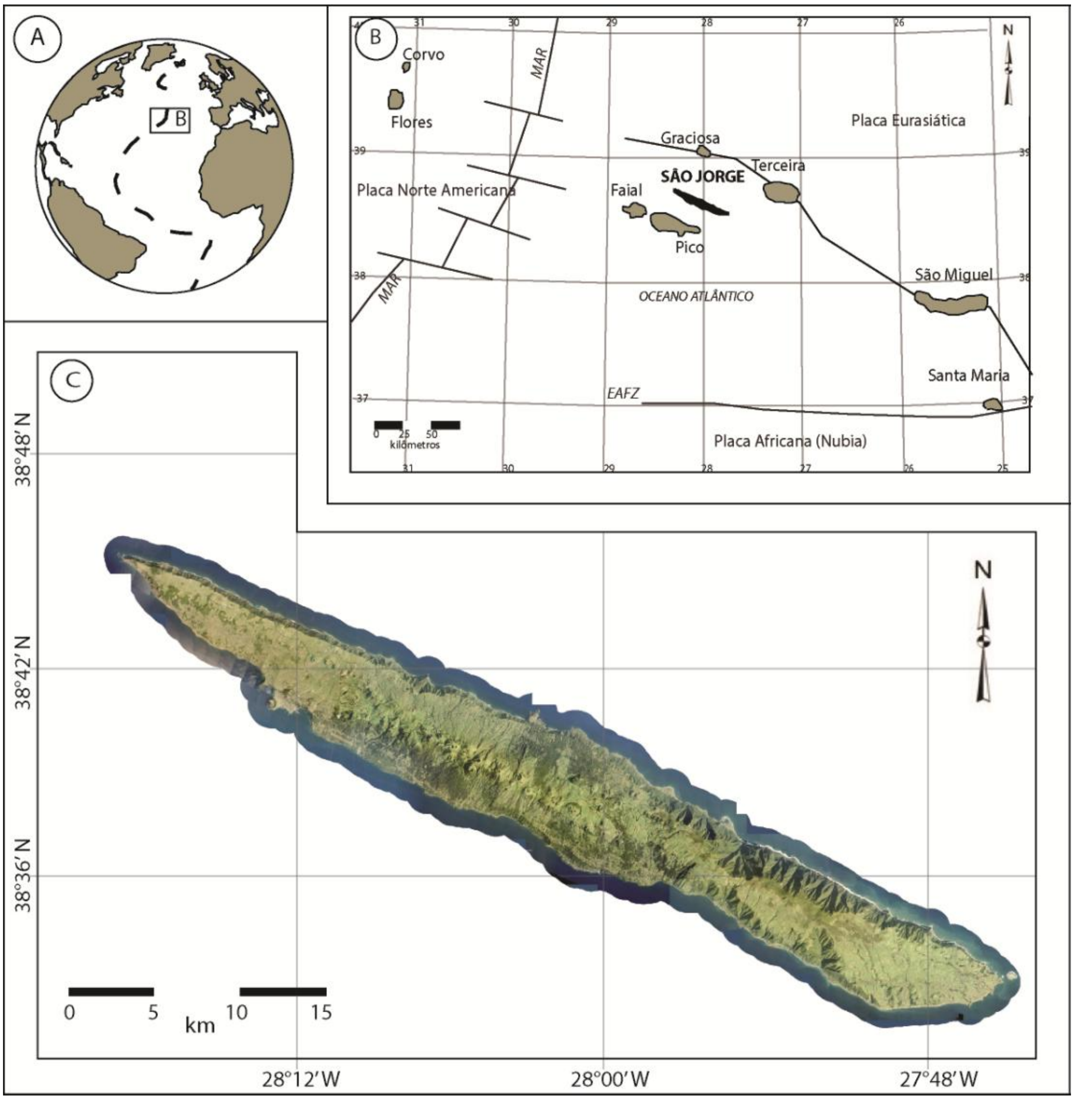


Figura 1 – a) e b) Localização do Arquipélago dos Açores formado por 9 ilhas oceânicas. Elas estão posicionadas ao longo de uma faixa de direção N50°W localizadas ao nordeste do Oceano Atlântico; c) Ilha de São Jorge com uma morfologia alongada de direção WNW-ESE com uma porção subaérea de 55 km de comprimento e 8 km de largura (Imagem base cartográfica IgeoE, 2000).

O Estudo da erupção de 1580 A.D. se concentrou no sudoeste da ilha de São Jorge. Quatro campos de lava foram descritos: Ribeira do Almeida, Queimada, Ribeira do Nabo I e Ribeira do Nabo II (Figura 2).

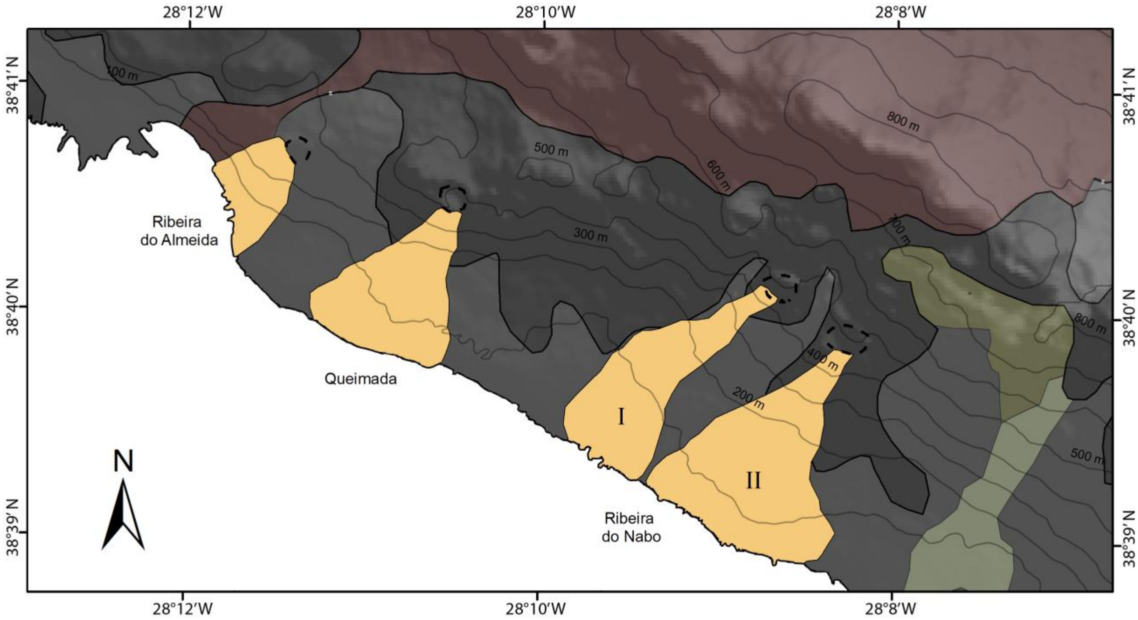


Figura 2 - Localização dos quatro campos de lava descritos na erupção de 1580 A.D.

3. CONTEXTO GEOLÓGICO

Para a contextualização geológica da área foi realizado o levantamento bibliográfico sobre a geologia do Arquipélago dos Açores, a geologia da Ilha de São Jorge, a caracterização e descrição de derrames básicos, os diferentes tipos morfológicos básicos e sistemas vulcânicos com situações geotectônicas análogas a Ilha de São Jorge (Havaí - Intraplaca e Islândia - Cordilheira Mesoatlântica).

3.1 Arquipélago dos Açores

O arquipélago dos Açores está localizado no Oceano Atlântico (37°- 40°N and 25°-31°O) próximo à junção tríplice entre as placas tectônicas Eurasiática, Norte-americana e Africana (Núbia), É cortado a oeste pela cadeia Mesoatlântica (CMA) e limitado ao sul pela Zona de fratura dos Açores Leste. O limite superior é formado por um complexo de lineamentos WNW-ESE, chamado de Rifte da Terceira, que vão da CMA até o limite ocidental da Falha de Glória (Argus *et al*., 1989). Sobre este platô foram geradas nove ilhas posicionadas ao longo de uma faixa de direção N50°W, que foram divididas em três grupos: Grupo ocidental (Ilha das Flores e Corvo), localizadas em uma zona estável da placa Norte-Americana; Grupo central (Ilhas de São Jorge, Pico, Faial, Graciosa e Terceira) e Grupo Oriental (Ilhas de São Miguel e Santa Maria), ambos incluídos na Microplaca dos Açores. (Lourenço *et al.,* 1998).

A formação da junção tríplice dos Açores foi discutida por diversos autores (McKenzie, 1972; Laughton & Whitmarsh, 1974; Searle, 1980; Ribeiro, 1982; Udlas *et al.*, 1986; Buforn *et al.*, 1988; Forjaz, 1988; Madeira & Ribeiro,1990). O modelo *Leaky transform* (Fig. 3) é uma hipótese assumida em diferentes trabalhos (McKenzie, 1972; Laughton & Whitmarsh, 1974, Searle, 1980; Ribeiro, 1982; Madeira & Ribeiro, 1990). Neste modelo assume-se que o segmento transtrativo oriental foi gerado a partir de uma falha transcorrente oblíqua com direção WNW- ESE, que liga o rifteamento da cadeia Mesoatlântica à Falha da Glória.

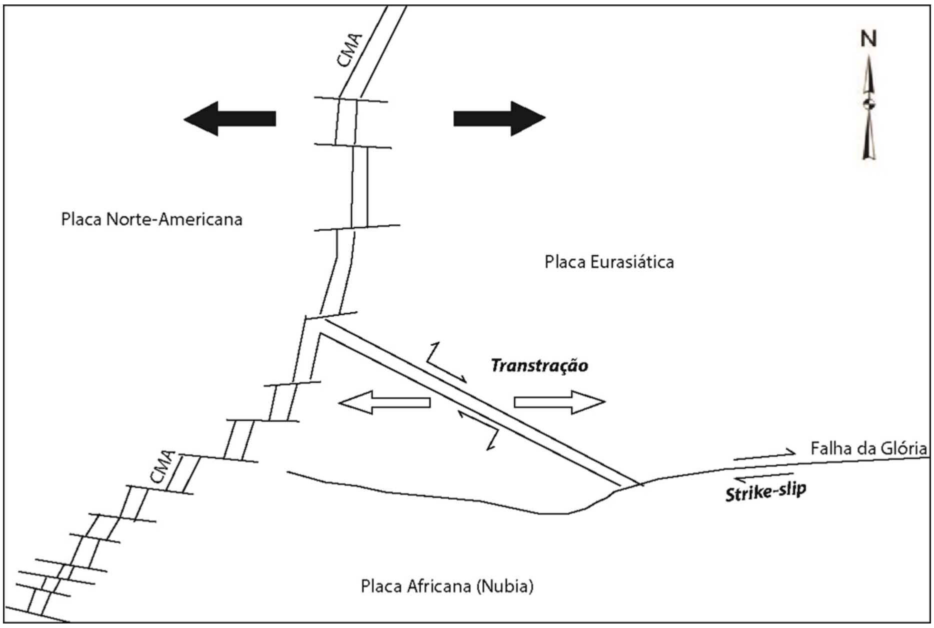


Figura 3 - Modelo *Leaky transform* que atribui a um regime geodinâmico do tipo transtrativo (modificado de Madeira & Ribeiro, 1990).

A origem do vulcanismo nos Açores tem sido atribuída à interação de pluma mantélica através de zonas de fraqueza na litosfera oceânica (Schilling, 1975; White *et al*., 1976; Searle, 1980; Luís *et al*., 1994; Lourenço *et al*., 1998; Cannat *et al*., 1999; Vogt & Jung, 2004). O platô dos Açores é geralmente interpretado como uma LIP (*Large Igneous Province*) devido a grande produção de magma nas zonas de fraqueza com idades de 20 a 7 Ma (Cannat *et al*., 1999; Gente *et al*., 2003).

3.2. Ilha de São Jorge

A Ilha de São Jorge encontra-se na microplaca açoriana e possui uma morfologia alongada de direção WNW-ESE. Estudos batimétricos (Lourenço *et al*., 1998) indicam que a Ilha de São Jorge assim como outras ilhas (Faial -Pico) correspondem a cadeias vulcânicas lineares (*LVR- Linear Volcanic Ridges*) (Fig. 4). Estas cadeias marcam o padrão estrutural regional, provavelmente construído por um vulcanismo fissural ao longo do sistema de falha (Lourenço *et al*., 1998).

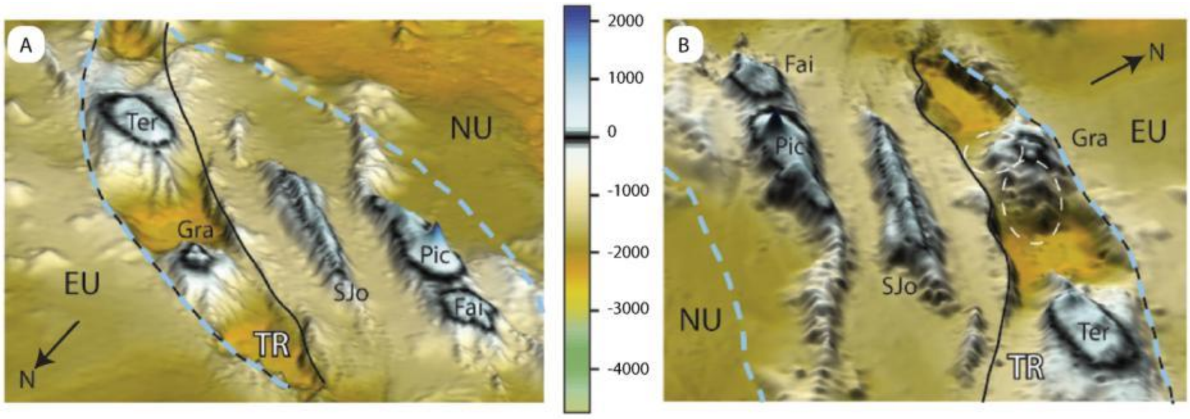


Figura 4 - Mapa batimétrico em 3D mostrando a morfologia alongada da Ilha de São Jorge, considerada uma cadeia vulcânica linear (*LVR*), profundidade em metros. (Extraído de Sibrant *et al.*, 2014)

A importância na investigação das *LVR* é destacada pela possibilidade de compreender a interação entre fenômenos magmáticos e tectônicos, que elucidam aspectos referentes a dinâmica mantélica, natureza da atividade vulcânica e cinemática de placas (Hildenbrand *et al.,* 2008). Alguns mecanismos são propostos para explicar tais morfologias alongadas: (1) A construção de sucessivos edifícios vulcânicos através do movimento de placas sobre *hotspots* (Morgan, 1972; O'Connor *et al*., 1998); (2) a episódica geração de magmas, relacionados com plumas, ao longo de zonas de fraqueza na litosfera oceânica (Maia *et al*., 2001; O'Connor *et al*., 2002) e (3) o desenvolvimento de estruturas vulcânicas lineares e/ou *en-echelon* controlada pela quebra litosférica durante uma deformação transtrativa (Winterer & Sandwell, 1987).

Hildenbrand *et al*. (2008) sugerem a partir de dados de K/Ar, que a construção da Ilha de São Jorge ocorreu nos últimos 1,3 milhão de anos (Fig. 5), que geraram três complexos vulcânicos denominados por Forjaz & Fernandes (1975): Serra do

Topo, Rosais e Manadas (Fig.4). O sistema vulcânico mais antigo é o Serra do Topo que corresponde à porção oriental da ilha onde afloram depósitos estrombolianos e efusivas basálticas (hawaiitos) e mugearíticas (Madeira, 1998). O sistema vulcânico Rosais é constituído por basaltos hawaiíticos e tem sua exposição na parte ocidental e nos *cliffs* centrais. Cones estrombolianos distribuídos ao longo do eixo WNW-ESE representam as atividades vulcânicas mais recentes (Madeira, 1998), agrupadas no sistema vulcânico Manadas. Um aspecto importante desta unidade foi o ingresso de algumas lavas provenientes destes cones no ambiente litorâneo formando "deltas de lavas" com uma distribuição paralela ao eixo WNW-ESE, mas alguns também oblíquos a esta direção. O vulcanismo recente é caracterizado por três eventos vulcânicos históricos: erupção de 1580 e 1808 (vulcanismo efusivo e piroclástico), e a erupção submarina de 1964 (Madeira, 1998).

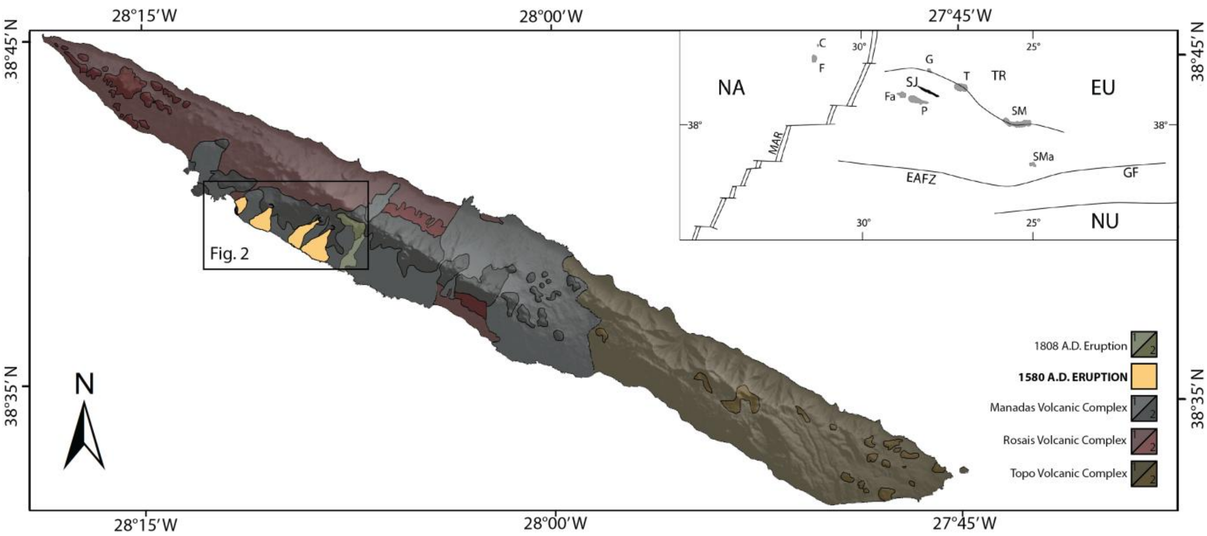


Figura 5 - Três complexos vulcânicos definidos por Forjaz & Fernandes, (1975): Serra do Topo, Rosais e Manadas. (Modificado de Mendes *et al.*, 2013).

3.3.Tipos de derrames básicos

Macdonald (1953) identificou em basaltos três tipos de derrames com base nas feições de superfície e na estruturação interna, denominando-os *pahoehoe, `Ã`a* e lava em bloco*,* este último comum em sistemas intermediários a ácidos. Derrames *pahoehoe* são básicos e identificados por suas superfícies lisas, onduladas ou em corda e por uma estruturação interna dividida em crosta superior, núcleo e crosta inferior (Macdonald, 1953; Aubele *et al*., 1988, Self *et al*., 1996). A dinâmica dos derrames *pahoehoe* (Fig. 6a) envolve inicialmente um avanço na forma de lobos com pequena espessura, onde a crosta superior é rapidamente formada, podendo ser posteriormente inflado se a superfície de base possuir baixa inclinação (Hon *et al*., 1994).

Os derrames *`Ã`a* (Fig. 6b) são geralmente basálticos a andesibasálticos caracterizados por topo e base escoriáceos, com vesículas esparsas e estiradas e por reentrâncias das zonas escoriáceas na porção central maciça em função do avanço do derrame (Macdonald, 1953; Kilburn, 1990). Derrames deste tipo são formados quando a lava é transportada em canais abertos, em geral associada a altas taxas de erupção (Macdonald, 1953; Pinkerton & Sparks, 1976), ou associadas a grandes taxas de deformação durante o fluxo (*shear rates*), causadas por relevos abruptos (Hon *et al.*, 2003). Sob estas condições a crosta externa do derrame tende a romper e fragmentar continuamente, sendo estes fragmentos transportados para as porções basais em um movimento análogo ao de uma esteira de trator (*caterpillar efect*).

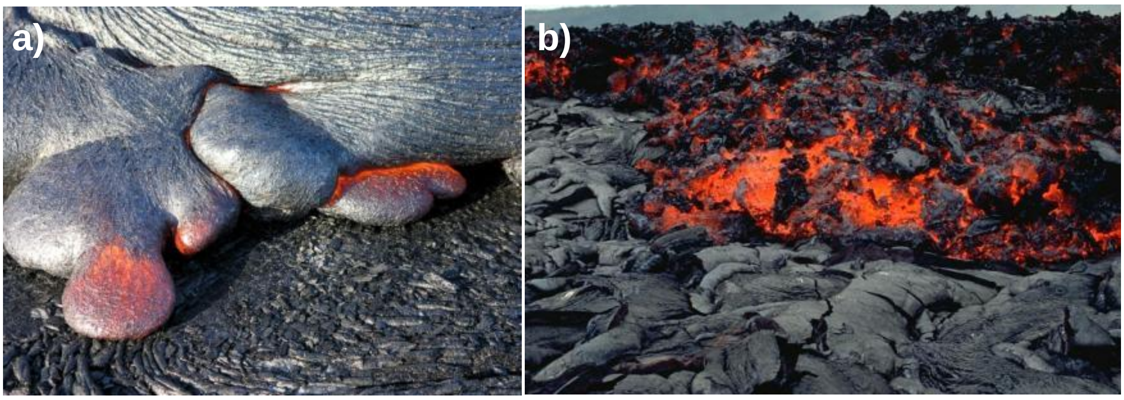


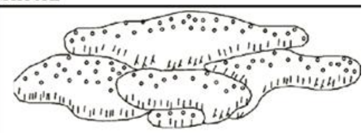
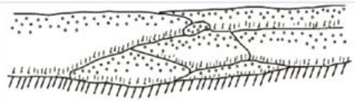
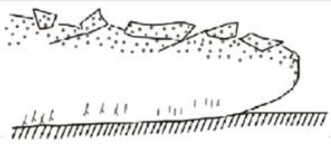
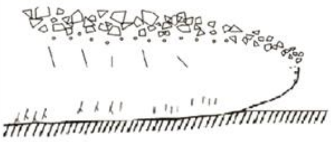
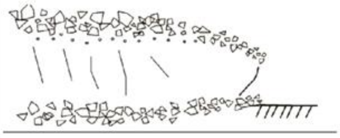
Figura 6 - Derrames básicos do vulcão Kilauea, Havaí: a) avanço de lobos *pahoehoe* (Foto: Tom Pfeiffer); b) derrames do tipo *`Ã`a* , com o avanço da lava as superfícies tendem a romper, gerando fragmentos (Foto: Paul Kimberly 1994).

Estes dois tipos morfológicos definidos em derrames básicos do Havaí (Dutton, 1884), foram referidos por Mcdonald (1953) como fluxos parcialmente ou completamente solidificados. Derrames do tipo *pahoehoe* podem transicionar para *`Ã`a* ou gerar tipos com feições de superfície características (Peterson & Tilling, 1980). Estes tipos transicionais apresentam uma variação nas feições de superfície, sendo ela descritas como *rough, spiny, slabby , ripply e grooved* (Peterson & Tilling, 1980; Rowland & Walker, 1990; Kilburn, 1990; Hon *et al.*, 2003; Loock *et al.*, 2010).

Estas características são usadas por diversos autores para definir diferentes morfologias de derrames (Quadro 1).

A origem destes diferentes tipos morfológicos de basaltos está vinculada as variações na composição, temperatura, cristalinidade, conteúdo de voláteis, taxa de efusão, duração e velocidade do fluxo e na topografia. Este conjunto de fatores afeta diretamente a viscosidade e taxa de deformação de fluxo (Mcdonald, 1953; Peterson & Tilling, 1980). Esta transição da morfologia *pahoehoe* para *\`Ã\`a* geralmente ocorre na parte distal do fluxo devido ao aumento gradativo da viscosidade associado ao resfriamento da superfície, além do aumento da taxa de efusão. De acordo com Hon *et al*. (2003) a dinâmica de uma erupção, como variações na taxa de efusividade, na perda de gás, na taxa de resfriamento, pode promover a transição de uma lava o tipo*\`Ã\`a* para *pahoehoe.*

Quadro 1 - Quadro resumido que engloba os diferentes tipos morfológicos de lavas básicas (modificado de Duraiswami *et al.*, 2013).

Tipo de derrame	Características	Descrição	Referências	Sketch
Pahoehoe	Superfícies lisas, onduladas ou em corda e por uma estruturação interna dividida em crosta superior, núcleo e crosta inferior .	A dinâmica dos derrames *pahoehoe* envolve baixa taxa de efusão. Inicialmente observa-se um avanço na forma de lobos com pequena espessura, onde a crosta superior é rapidamente formada, podendo ser posteriormente inflado se a superfície de base possuir baixa inclinação.	Macdonald (1953), Walker (1993), Self et al. (1998), Jay et al. (2009) and Vye-Brown et al. (2013a,b)	
Hummocky pahoehoe	Variedade de derrame *pahoehoe* que compreende *oflava toes*, pequenos lobos e *tumuli*. A superfície deste tipo é ondulada, *bun-like* e *hummocky*.	Este tipo de derrame composto se forma com baixas taxas de efusão e em uma topografia ondulada.	Swanson (1973), Bondre et al. (2004), Duraiswami (2009)	
Sheet pahoehoe	Variedade de derrame *pahoehoe* , que consiste em lobos tabulares e lençóis espessos. O empilhamento destes tipos formam uma geometria tabular.	Lobos inflados e coalescentes com o topo composto por lençóis e a estrutura interna semelhante a pahoehoe	Aubele et al. (1988), Self et al. (1998) & Duraiswami (2009)	
Slabby pahoehoe	Série de placas com espessura centimétrica levemente espaçadas ao longo da superfícies pela quebra no movimento da lava ou por um fluxo interno.	É considerado o tipo gradacional entre *pahoehoe* - *\`a\`a* e apresenta caracteristicas predominantemente de *pahoehoe* , mas com uma crosta rompida.	Peterson & Tilling (1980) & Guilbaud et al. (2005)	
Rubbly pahoehoe	Lavas com base preservada e topo brechado. e são geralmente mais espessos e extensos que lobos individuais de *pahoehoe* .	Tipo de lava transicional entre *pahoehoe* - *\`a\`a* . Possui uma taxa de efusão maior que tipo *pahoehoe* .	Managave (2000), Keszthelyi & Thordarson (2000), Guilbaud et al. (2005) and Duraiswami et al. (2008)	
\`A\`a	São caracterizados por topo e base escoriáceos, vesiculas esparsas e estiradas e por reentrâncias das zonas escoriáceas na porção central maciça em função do avanço do fluxo.	Geralmente lavas do tipo \`a\`a são as mais viscosas e avançam mais lentamente que lavas do tipo pahoehoe.Tendem a se formar em topografias canalizadas	Macdonald (1953) & Walker (1993)	

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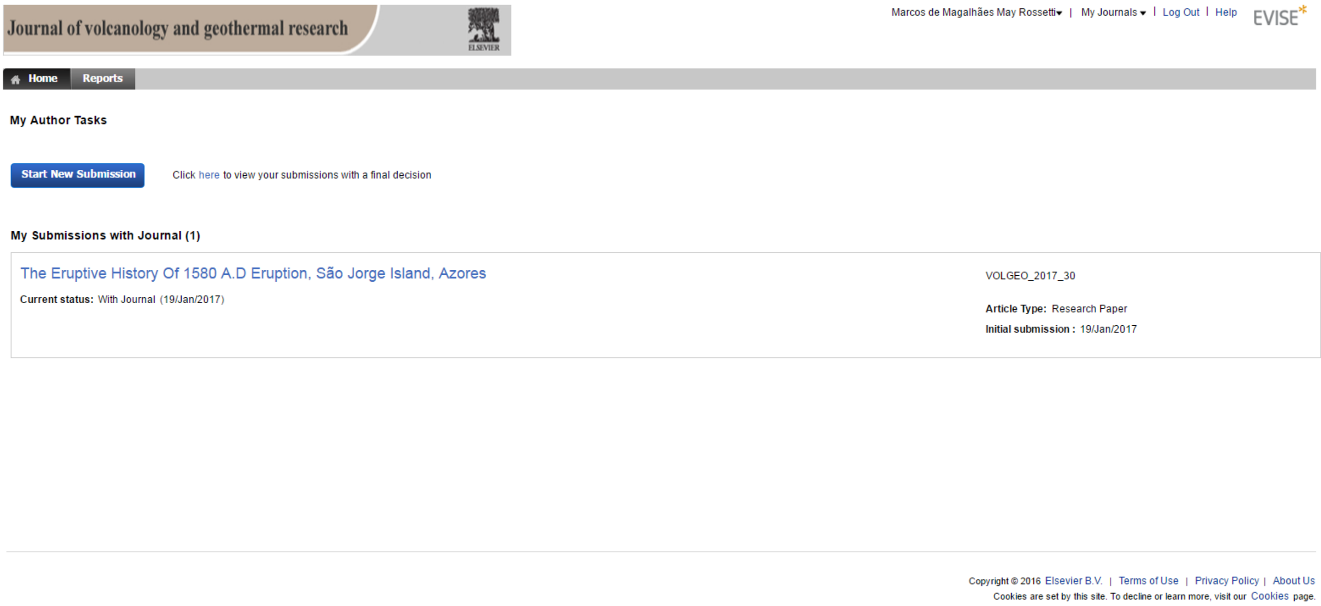

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The historic eruption of 1580 A.D. occurred in the southwestern of São Jorge Island, in the central Azores covering a total area of 4 km^2. This work provides a characterization of the distribution and morphology of the 1580 A.D. lava flows, integrated to petrography and geochemistry. The eruption formed four distinct flows fields: Ribeira do Almeida, Queimada, Ribeira do Nabo I and Ribeira do Nabo II. Detailed geological analysis allowed the identification of spiny, sheet and sllaby pahoehoe and ‘a´ā lava morphotypes. Near the vent, the flow fields are characterized by channelized ‘a´ā flows. With continuous eruption, these lavas flowed downwards forming fan-shaped lava deltas when entering the sea. Sheet pahoehoe flows overlay the ‘a´ā lavas and with continuous inflation the surface of the flows breaks generating slabby pahoehoe surface. The gradual increase in surface fragmentation form rubbly surfaces. In the late stages of the eruption channelized ‘a´ā flows were emplaced, depositing laterally and over the sheet pahoehoe flows. The variations in the lava surface are controlled by the effusion rates and the topography. Petrographically, all lava flows are olivine basalts. The chemistry of the basalts indicate an alkaline nature for the 1580 volcanism. The lessevolved compositions are found in Ribeira do Almeida and this fact can be related to continuous recharge of the magma chamber with more primitive melts. Normalized REE profiles show that the basalts were generated by low volumes of melt of an enriched OIB source. The study of the physical aspects of 1580 lava flows with petrography and geochemistry allowed understand the geologic history of this event.

Keywords Azores archipelago; basalt lavas; Ocean Island Basalts; lava emplacement

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The Eruptive History of 1580 A.D Eruption, São Jorge Island, Azores.

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Abstract

The historic eruption of 1580 A.D. occurred in the southwestern of São Jorge Island, in the central Azores covering a total area of 4 km². This work provides a characterization of the distribution and morphology of the 1580 A.D. lava flows, integrated to petrography and geochemistry. The eruption formed four distinct flows fields: Ribeira do Almeida, Queimada, Ribeira do Nabo I and Ribeira do Nabo II. Detailed geological analysis allowed the identification of spiny, sheet and sllaby pahoehoe and ‘a´ā lava morphotypes. Near the vent, the flow fields are characterized by channelized ‘a´ā flows. With continuous eruption, these lavas flowed downwards forming fan-shaped lava deltas when entering the sea. Sheet pahoehoe flows overlay the ‘a´ā lavas and with continuous inflation the surface of the flows breaks generating slabby pahoehoe surface. The gradual increase in surface fragmentation form rubbly surfaces. In the late stages of the eruption channelized ‘a´ā flows were emplaced, depositing laterally and over the sheet pahoehoe flows. The variations in the lava surface are controlled by the effusion rates and the topography. Petrographically, all lava flows are olivine basalts. The chemistry of the basalts indicate an alkaline nature for the 1580 volcanism. The less-evolved compositions are found in Ribeira do Almeida and this fact can be related to continuous recharge of the magma chamber with more primitive melts. Normalized REE profiles show that the basalts were generated by low volumes of melt of an enriched OIB source. The study of the physical aspects of 1580 lava flows with petrography and geochemistry allowed understand the geologic history of this event.

Keywords - Azores archipelago; basalt lavas; Ocean Island Basalts; lava emplacement

1.Introduction

Historical eruptions generally present well-preserved outcropping primary structures, providing a unique possibility to access the physical characteristics of lava flows in detail. At least 13 subaerial historic eruptions were documented in the Azores Islands, of which two in São Jorge.

The historical eruptions of Sao Jorge occurred in 1580 and 1808 AD. (Zbyszewski, 1963; Weston, 1963/64; Madeira, 1998). The 1580 A.D. eruption, located in the southwestern portion of São Jorge Island, covered approximately 4Km² of the island surface in at least four different outcropping areas with well-preserved key lava morphologies. The lava flow surface morphology provides important information on the dynamic of emplacement of an eruption. Volcanological data on the recent eruptions of São Jorge is scarce and most of the studies are focused in isotopic dating and in understanding how the magmatism interacted with tectonics (Madeira and Silveira, 2003; Hildenbrand, et al. 2008; Millet, et al., 2009; Mendes, et al. 2013).

This study presents the first comprehensive descriptions of the historical eruption of 1580 A.D, from Sao Jorge Island. We characterized the flow morphologies along four different flow fields produced during the volcanic event and integrated the data with geochemical and petrographic features. This paper is firstly structured in a brief review of basaltic lava flows surface structures and general geological setting of the Azores Archipelago and São Jorge Island. Following, we present the distribution of lava types in the different flow fields, with the petrography and the geochemical aspects. Finally we proposed a model of emplacement for the 1580 A.D. eruption.

2.Basaltic Lava flows

Subaerial basaltic lava flows can be classified as either pahoehoe or ‘a´ā according to their surface morphology (Macdonald, 1953). Pahoehoe has a continuous smooth, billowy, or ropy surface, flows are initially emplaced as thin sheet or lobes, with a sustained supplied in a relatively flat slope, can subsequently, be inflate forming larger flow fields, in some cases reaching very long distances (Swanson 1973; Hon et al., 1994). ‘A´ā lavas have brecciated rough, spiny, or clinker surface and ‘a´ā flow fields are formed where lava is transported by open channels, during high effusion rates or associated with high shear strain (Macdonald 1953; Pinkerton and Sparks 1976; Peterson and Tilling, 1980; Kilburn, 1990; Rowland and Walker 1990; Hon, et al. 2003; Loock et al., 2010). Petrographic textures, vesicle patterns and jointing style define the internal structures of the lava flow and can divide into an upper crust, lava core, and a basal lower crust (Self et al., 1996; Self 1997). The terms ‘a´ā and pahoehoe are used to partly or completely solidified crusts (Macdonald 1953) but these terms cannot be applied to molten lava in channels, because in the pahoehoe - ‘a´ā transition facies change along the flow (Hon, et al. 2003). The transition from pahoehoe to ‘a´ā is directly controlled by the apparent viscosity, which is affected by a series of factors such as composition, temperature, crystallinity, melt polymerization, volatile content and vesicularity (Macdonald, 1953; Shaw *et al.*, 1968; Swanson 1973; Kilburn 1990; Sato, 1995; Cashman *et al.*, 1999). The transition can also be affected by effusion rate, channel configuration, flow velocity and duration, and ground slope, directly related to the applied shear stress, and affect the rate of shear strain promoting lava tearing (Peterson and Tilling, 1980; Rowland and Walker 1990; Hon *et al.* 2003).

The transition from pahoehoe to ‘a´ā can be also reversed and it is strongly controlled by slope and local lava supply, rather than effusion rate (Hon *et al.*, 2003). This transition can occur at the ‘a´ā flow front with the decreasing strain rate, for example, due to a decrease in slope or increase in channel width, generating pahoehoe morphology.

For describing the 1580 AD lava flows, we adopted a similar terminology propose by Self et al. (1997) which divided the products of an eruption into three terms levels: lava flow field, lava flows, and lava lobes. We use the term “lava flow field” to designate the lava produced in a single vent of 1580 AD eruption and “lava flow” for a body formed by an individual outpouring of lava from the vent, corresponding ideally, to a single episode of magma effusion during the eruption (Guilbaud, et al. 2005). The term “flow lobe” is used to describe segments of a lava flow (Self, et al. 1997).

3. Geological Settings

The Azores archipelago is located in the North Atlantic Ocean (37°- 40°N and 25°-31°W) close the triple junction between North American, Eurasia and Nubia plates (Fig. 1). The Azores comprises nine volcanic islands: Flores, Corvo (Western Group), São Jorge, Pico, Faial, Graciosa, Terceira (Central Group), São Miguel and Santa Maria (Eastern Group). These islands are spread over an oceanic plateau with a surface area of approximately 400 000 km² of elevated oceanic crust, roughly underlined by 2000 m isobath (Lourenço, et al. 1998). The plateau is cutted by the Middle Atlantic Ridge (MAR) in the west and limited by the East Azores Fracture Zone (EAFZ), linked to the Gloria Fault, in the south. The Terceira rift zone forms the northeastern limit of the plateau, which consists in a morphological pattern of *en echelon* faults (Lourenço, et al.1998).

The volcanism results the interaction of the Mid-Atlantic Ridge and the Azores hot spot from 20 to 7 Ma ago (White et al., 1976; Searle, 1980; Luís et al., 1994; Lourenço et al., 1998; Cannat et al., 1999; Gente et al., 2003; Vogt and Jung, 2004; Luis and Miranda, 2008). The anomalously high melt production is attributed, in many cases to the effect of a hot mantle plume (White et al., 1979; Davies et al., 1989; Widom and Shirey, 1996; Turner et al., 1997; Moreira et al., 1999; Madureira et al. 2011) or alternatively, it is explained by volatile-enriched upper mantle domains (Schilling et al., 1980; Bonatti, 1990, Asimow et al., 2004; Beier et al. 2012).

The archipelago formation and development has been focused along the NW – SE trending Terceira Rift (Searle, 1980; Madeira and Ribeiro, 1990) for at least 5.5 Ma (Féraud, et al. 1980). Different models were proposed to explain the formation of Azores Islands: Terceira Ridge model (Udias et al., 1986; Buforn et al., 1988), Azores microplate model (Forjaz, 1988) and the Leaky Transform model (McKenzie, 1972; Laughton and Whitmarsh, 1974; Searle, 1980). According Madeira and Ribeiro (1990) the Leaky Transform model is the only one that fits the paleomagnetic, seismotectonic and neotectonic evidence. In this model the eastern branch of the junction is a WNW - ESE oblique strike-slip fault linking the MAR to the Gloria Fault (Madeira and Ribeiro, 1990). A strong tensile component is evident by the volcanic activity and normal faults in the island of the central and eastern groups. Lourenço, et al., (1998) suggest that Azores are a diffuse plate boundary acting simultaneously as an oblique ultra slow spreading centre and as a transfer zone that accommodates the differential shear movement between the Eurasian and African plates.

The São Jorge Island (SJI) has an elongated morphology with 55 km length and a maximum width of 7 km covering a total surface area of 244 km², sub-parallel to the Terceira rift system (WNW-ESE) and sub-perpendicular to the Middle Atlantic Ridge (Fig. 1). São Jorge is the only Azores Island with fissural character and was formed by basaltic volcanism associated with two major tectonic trends (WNW-ESE and E-W). The volcanism was predominantly effusive being the pyroclastic deposits restricted to scoria cones in the vent areas (Forjaz and Fernandes, 1975; Madeira, 1998).

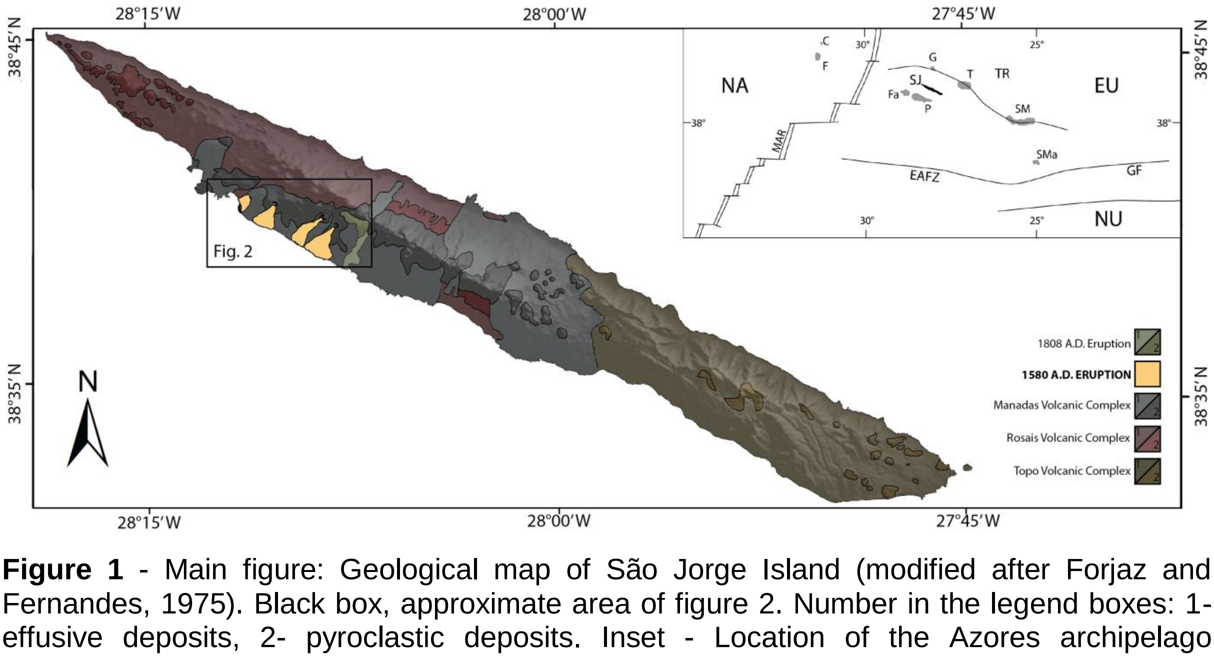

Figure 1 - Main figure: Geological map of São Jorge Island (modified after Forjaz and Fernandes, 1975). Black box, approximate area of figure 2. Number in the legend boxes: 1- effusive deposits, 2- pyroclastic deposits. Inset - Location of the Azores archipelago (Modified from Madeira and Brum Silveira, 2003) close to the triple junction between North America (NA), Eurasia (EU)and Nubia (NU). The plateau comprises nine islands: Corvo (C), Flores (F), Graciosa (G), Terceira (T), S. Jorge (SJ), Faial (Fa), Pico (P), S. Miguel (Sm) and Santa Maria (SMa). Limits of the plateau: Mid Atlantic Ridge (MAR) in the west, East Azores Fault Zone (EAFZ) and Gloria Fault in the south and the Terceira Rifte (TR) in the northeastern.

According to Madeira and Ribeiro (1990), SJI has geometry at the surface of strike-slip faults: dextral en échelon Riedel shears, anastomosing segments, sag ponds and even a very small pull-apart basin. The eastern side is cross-cutted by a WNW-ESE fault called Urze-São João Fault (Mendes, et al V2013). The western side of the island is dominated by two fault zones (FZ), Picos FZ (WNW-ESE) and Pico do Carvão FZ (E-W) developing two alignments of Hawaiian/Strombolian and Surtseyan cones (Madeira and Ribeiro, 1990; Madeira and Silveira, 2003 Mendes et al., 2013). The two sides are marked by a facing slope interpreted as a normal fault (NNW-SSE) called Ribeira Seca (Madeira and Silveira, 2003).

Forjaz and Fernandes (1975), based on the morphology and volcano-stratigraphy, divided the island in three main volcanic complexes (Fig. 1). The Topo Volcanic Complex (TVC) constitutes the eastern and oldest part of the island and is composed of basalt, hawaiite and mugearite lava flows, pyroclastic deposits and scoria cones. Within the TVC, K/Ar ages range from 1.32 to 1.20 Ma in the southeast of the island (Fajã de S.João), and 0.73 to 0.69 Ma in Fajã de Cuberes and Fajã dos Bodes, northern and southern halves of the island, respectively, showing an important quiescence period in the volcanic activity, of about 0.45 Ma (Hildenbrand, *et al.* 2008). The western and central part of the island were built during a second main evolutive phase (Hildenbrand, *et al.* 2008).The Rosais Volcanic Complex (RVC) comprises basalt to hawaiite lava flows and scoria cones and represents the basement of the western part. K/Ar dates indicate Upper to Middle Pleistocene ages 0.37 to 0.27 Ma (Hildenbrand, *et al.* 2008). The Manadas Volcanic Complex (MVC), the younger unit, flowed over the RVC creating lava deltas, locally called *fajãs* and it is characterized by Hawaiian, strombolian and Surtseyan eruptions of basalt to hawaiite compositions.

The recent eruptive history of São Jorge Island has been documented from radiocarbon dating (^{14}C) on 21 samples from the MVC (Madeira, *et al.*, 1998b). Fragments of peat, wood, charcoal and paleosols collected in pyroclastic deposits indicate Holocene ages (5580±70 to 700±70 years BP).This set of ages comprises 13 volcanic events, including the historic eruptions of 1580, 1808 and 1964 (Weston, 1963/1964), with an estimated recurrence interval of 200 to 300 years between eruptions (Madeira et al., 1998b). The historical documented eruptions in 1580, 1808, and a probable submarine event in 1964 occurred along E-W trending structures of the Pico do Carvao FZ in the central part of the Island (Madeira, *et al.* 1998; Madeira and Silveira, 2003). In this study, we described the evolution of the 1580 AD volcanism based on the lava morphotypes, petrographic patterns, and geochemistry of these three events.

4. General Aspects of 1580 AD eruption

The 1580 A.D. eruption started on 28th of April in the southwestern of São Jorge Island (38°38' - 38°41'N and 28°8' - 28°12'W) and last for four months affecting the villages of Ribeira do Almeida, Queimada and Ribeira do Nabo (Fig. 2, Fouquet, 1873; Weston, 1964; Krafft, 1993). The eruption is characterized by a Hawaiian/Strombolian event along an E-W fissure.

The eruption covered a total surface area of approximately 4 km² and can be divided into four flow fields: Ribeira do Almeida, Queimada, Ribeira do Nabo I and Ribeira do Nabo II (Fig. 2). The physical characteristics of the lavas vary along the flow field being mainly influenced by the paleotopography. A geomorphological analysis of the 1580 A.D. eruption was performed from a Digital Elevation Model (DEM) with 30 m spatial resolution in order to identify the limits of the lava fields and the variation in the slope degree.

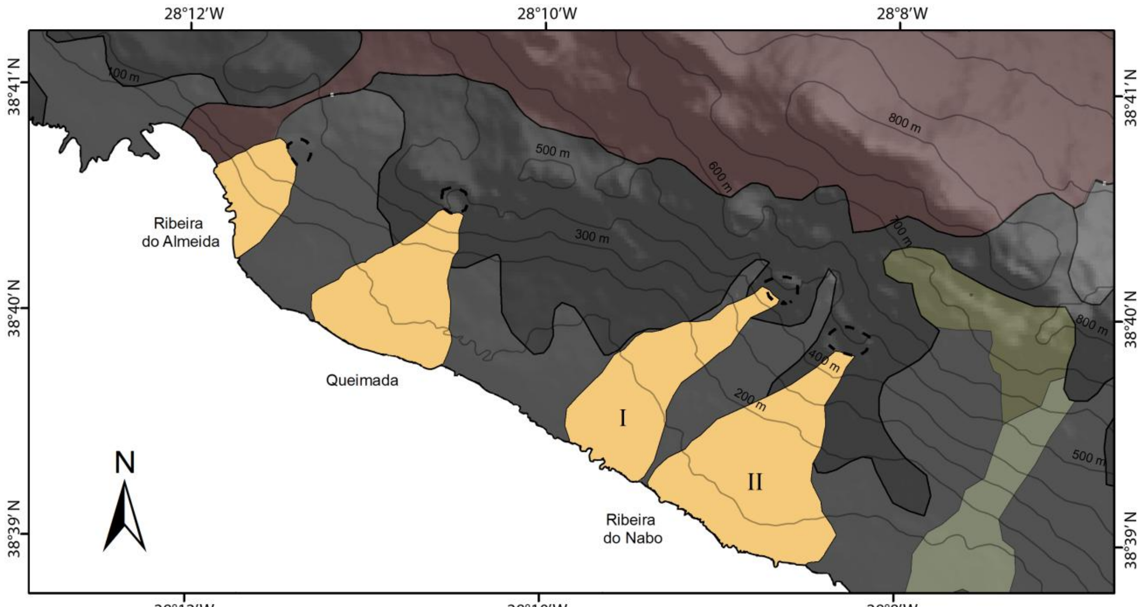

Figure 2 - Map showing extent of flows from 1580 A.D. eruption. Divided in four flow fields: Ribeira do Almeida, Queimada, Ribeira do Nabo I and Ribeira do Nabo II. The dashed circles indicate the source cones of the flow fields. Contour interval, 100 m. The white circles indicates the outcrops described.

Along the main fissure, spatter cones related to the lava flow fields were formed by a strombolian event and were identified using satellite images, including DEM, fieldwork, and based on the description available in historic documents (Fouquet, 1873; Weston, 1964). The cones are 60 - 130m height with 380 to 460 m of diameter, characterized by large red to black spatter deposits formed of lapilli and bombs, with a maximum diameter of 40 cm intercalated with thin (20 cm) lava layers. The cones show an increase in layers of lava towards the top and a decrease in the fragmentation of pyroclasts. The sequence of the volcanism was marked by a Hawaiian event with a sequence of lava eruptions.

The majority of the lava deposits are cover by vegetation near the vent zones, therewith the detailed description is focused in the distal zone outcrops. We use the term lava apron to determine the zone along a gentle gradient (<4°), similarly used by Thordarson and Sigmarsson (2009) for describing the 1963-1967 Surtsey eruption (Fig. 3). The lavas described here are classified according to their surface morphology and their internal structure.

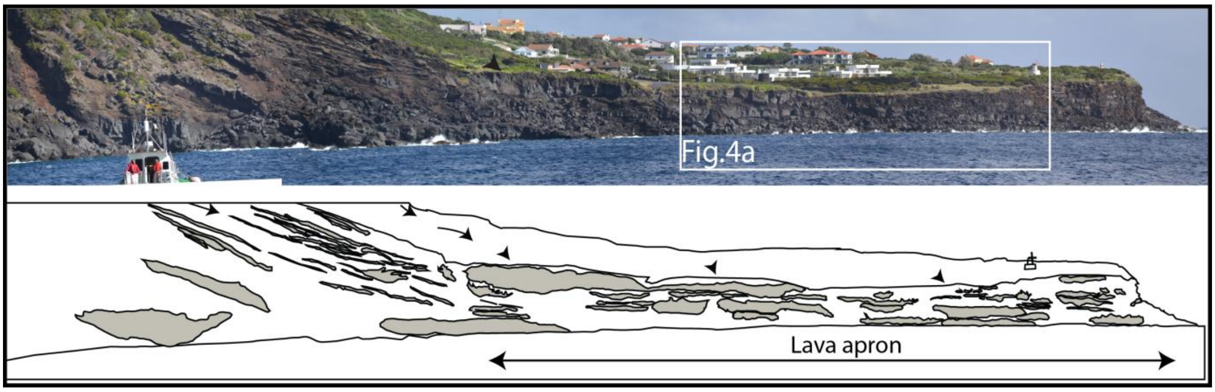

Figure 3 - Cliffs at the shore showing the internal structure of the Ribeira do Almeida lava flow field and the contact to a pre-eruption terrain with a steep slope (15° to 25º). Lava apron - zone along a gentle gradient (<4°). White box, approximate area of figure 4.

4.1. Ribeira do Almeida Flow Field (RA)

The Ribeira do Almeida flow field covered an area of 0.4 km² flowing by 0.9 km from the vent to the coast in an SW direction. The cliffs at the shore provide excellent outcrops, showing the internal structure of the lava flow field and the contact to a pre-eruption terrain with a steep slope (15° to 25º) (Fig. 3). Unfortunately, the proximal succession of lava flow emplaced in the steeper paleotopography are exposed in an inaccessible area, therefore, the description provided for these lavas are based on general observations.

The proximal succession is characterized by thin clinker rich lava layers with small proportion of core. Some of these lavas flowed for a WNW direction forming “fingers” of lava on the shore.

Differently, the lava apron is well-preserved and the outcrops are accessible, allowing the detailed description in this area. The succession is dominated by 2 to 5 m thick sheet flows intercalated to ‘a´ā flows (Fig. 4a). The sheet flows generally exhibit a finely crystalline core and a clinker base and top. The base is constituted by a thin rubble layer (15 cm) with an irregular geometry (Fig. 4b and c). The core is massive and characterized by a high vesicle concentration at the upper portions. The flow top is marked by 0.2 to 0.5 m thick slabs, and rubble fragments. The sheet flows can develop gas blister (1-1.5 m) formed by the exsolving gasses or small lava tubes (Fig. 4b), with the interior of these slabs showing stalactite structures. Thordarson and Sigmarsson (2009) described similar sheet flows preserved in the 1963/64 A.D. eruption of the Surtsey Island in Iceland. According to the authors, the rubble surface dominated by fragments of slabs was formed during the break-up of solidified lava crust above gas blisters, and the rubble layer at the flow top was formed during viscous tearing. Small toes lobes of pahoehoe with ropy surface are present between the sheet flows.

A sequence of ‘a´ā flows (4 - 5 m) are concentrated in the top of the section, intercalated to thicker sheet flows. The individual flows present 1 to .1.5 m of thickness with base and the top brecciated with fragments of irregular shapes with a modal diameter of 4 cm (Fig. 4d).

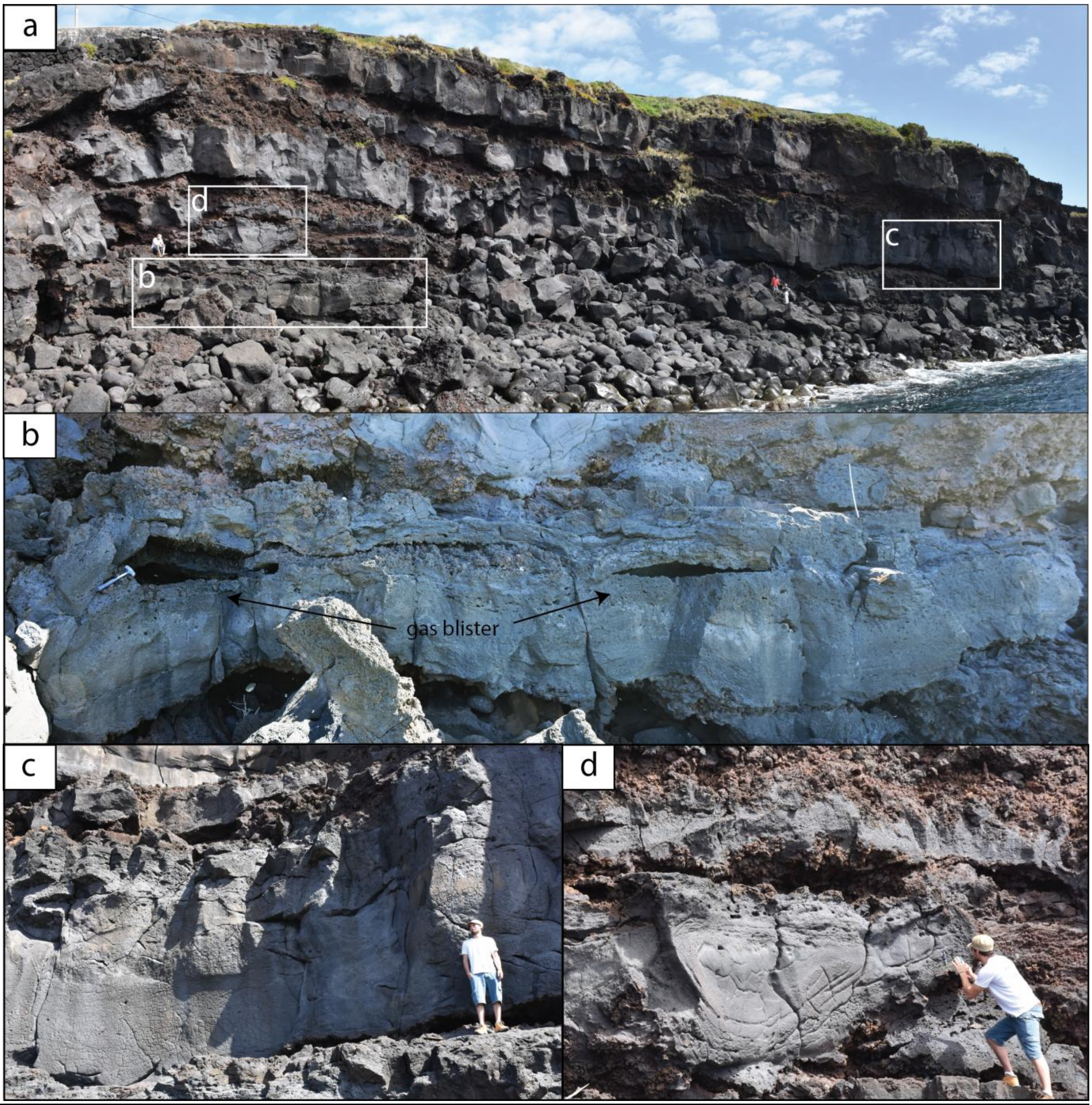

Figure 4 - Representative photographs of the different surface morphologies of the Ribeira do Almeida lava flow field. a) Lava apron present a succession of thick sheet flows (2-5 m) with intercalated `a`a flows. White boxes, area of figure b and d. b) and c) Sheet flows exhibiting core characterized by a high vesicle concentration at the top and a clinker base and top. Gas blister (1-1.5 m) formed by the exsolving gases or small lava tubes indicate by the black arrows. d) `A`a flows with1 to 2 m of thickness present base and the top are brecciated with fragments of irregular shapes with a modal diameter of 4 cm.

4.2 Queimada Flow field (QM)

The descriptions of Queimada flow field are restricted to a marginal area of the lava apron therewith presents a minor variation of morphotypes than in any other area. The lava flowed for at least 1.3 km from the vent to the coast covering an in land surface of approximately 0.97 km². This flow field was probably emplaced in a slope gradually varying from 15 to 30º and is formed of a sequence of ‘a´ā flows. The lava apron base is characterized by ‘a´ā flows with a massive and aphanitic core with 3.5 m of thickness with irregular undulate columnar joints (Fig. 5a). The flow top is marked by 1 to 2 m of broken lava clinker consisting of clasts of 2 to 15 cm in diameter, with a spiny surface. The fragments of the base and the flow front were eroded by the marine action but fragments impressions and marks are engraved in the core. This lava can be interpreted as an ‘a´ā that flowed from the land into the water forming a fan-shaped lava delta on the shore. The front of the flow when the lava penetrated the water imbricates, probably because of fast quenching (Fig. 5a).

A sequence of channelized thinner ‘a´ā` lava flows (7 m) overlay the base lavas. They have 1 to 1.5 m of thickness, a holocrystalline and vesicular core with elongated megavesicles (15 cm) at the top (Fig. 5b). The base and the top are brecciated with fragments of irregular shapes with a modal diameter of 5 cm. Injections of largely degassed lava crust rising into the rubble layer occur in the top and lateral portions of the flows (Fig. 5c).

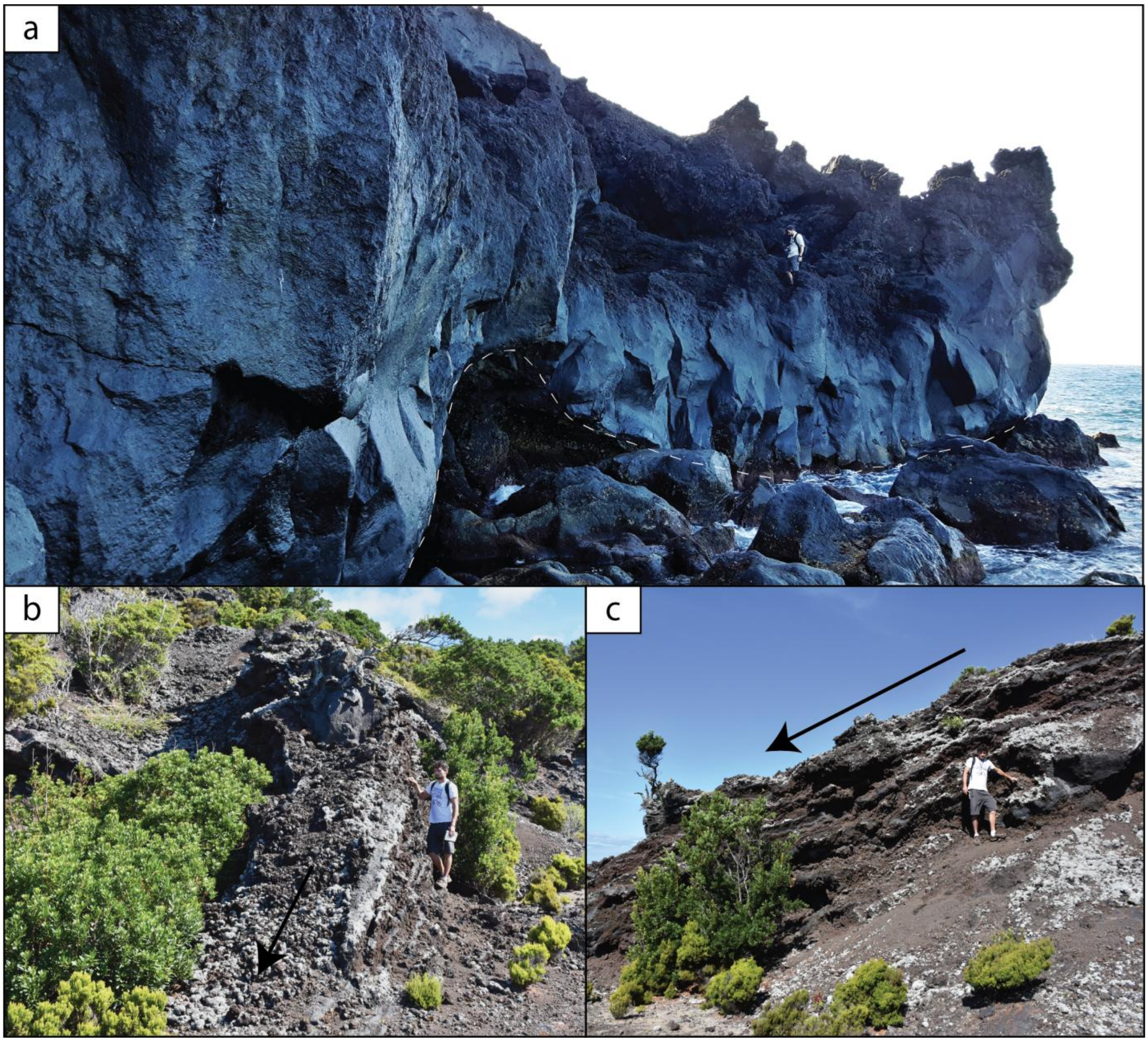

Figure 5 - Representative photographs of the different surface morphologies of the Queimada lava flow field. a) ‘A´ā flows with a massive and aphanitic core with irregular undulate columnar joints, the flow top is marked by 1 to 2 m of broken lava clinker, the fragments of the base and the flow front were eroded by the marine action but fragments impressions and marks are engraved in the core. b) and c) Channelized \`a\`a\` lava flows (1 to 1.5 m). The figure b shows the front of the \`a\`a flow, core with elongated megavesicles (MV) at the top. The figure c indicates the injections of largely degassed lava crust rising into the rubble layer of the top and lateral portions of the flows.

4.3 Ribeira do Nabo I Flow Field (RN)

The Ribeira do Nabo I flow field was emplaced in a channelized pre-eruption terrain flowing at least 2.5 km from the vent in a gradually changing slope with 20º. This eruption overlaid an area of ~ 0.94 km². The lava sequence observed in the lava apron is characterized by ‘a´ā flows at the base, overlaid by sheet pahoehoe flows and channelized \` a \`a flows in the lateral portions of the outcrop.

The first flows observed in the base of the succession present similar characteristics of the ‘a´ā flows described in the base of Queimada Flow field with a massive core grading to a core with undulate columnar joints in the flow front (Fig. 6a). The flow upper crust is formed of angular fragments with 3 to 20 cm of diameter. Injections of degassed lava crust rising until 2 m intrude the fragmented flow top indicating a fast quenching caused by the contact to the water (Fig. 6b). The base flow is below the sea level and is not described.

A sequence of thin sheet pahoehoe (0.6 to 1 m) covers the base lavas. These lava flows present a spiny surface and is marked by vesicle layers occurring every 10 cm (Fig. 6c). Some surface present polygonal inflation clefts. Lava tubes are formed by the inflation of the sheet flows and, in the most cases, are partially filled by pahoehoe with ropy surface (Fig. 6d). Tumuli with 5 – 7 m in diameter are present in this lava flows (Fig. 6e). It consists of tilted crustal slabs that are split by inflation clefts. Normally the tumulis are filled by sheet pahoehoe. Laterally to the sheet flows, in the marginal areas, channelized ‘a´ā flows are described. These lavas present a thickness of 1 to 2 m and a base and top clinker formed of fragments 5 to 10 cm of diameter.

4.4 Ribeira do Nabo Flow field II (RN II)

Lavas formed in Ribeira do Nabo II covered a total area of 1.5 km² flowing for 1.2km from initially high slopes (20º) towards the shoreline where the lavas were deposited in a relatively flat terrain (~7°) forming 20 m high cliffs. On-site examinations of surface morphologies are restricted to the “flat” terrain being the front of the apron zone inaccessible. The outcrop in this zone is characterized by a chaotic distribution of pahoehoe, slabby pahoehoe and ‘a´ā morphologies (Fig. 7a). Thin toes of pahoehoe lava (10-20 cm) with a spiny and/or ropy surface were identified (Fig. 7b). Thicker pahoehoe flows (1 - 1.5 m) presents megavesicles (10 cm) in the core and thin vesicle layers at the flow top (Fig. 7c). The slabs are tilted randomly with a tabular to curved geometry and with 10 to 20 cm of thickness, displaying a ropy and spiny surface (Fig. 7d). When mixed to the rubble zones the slabs are more fragmented, represent the interaction between the solidified crust with the lava flow interior and consequently the break of the flow surface.

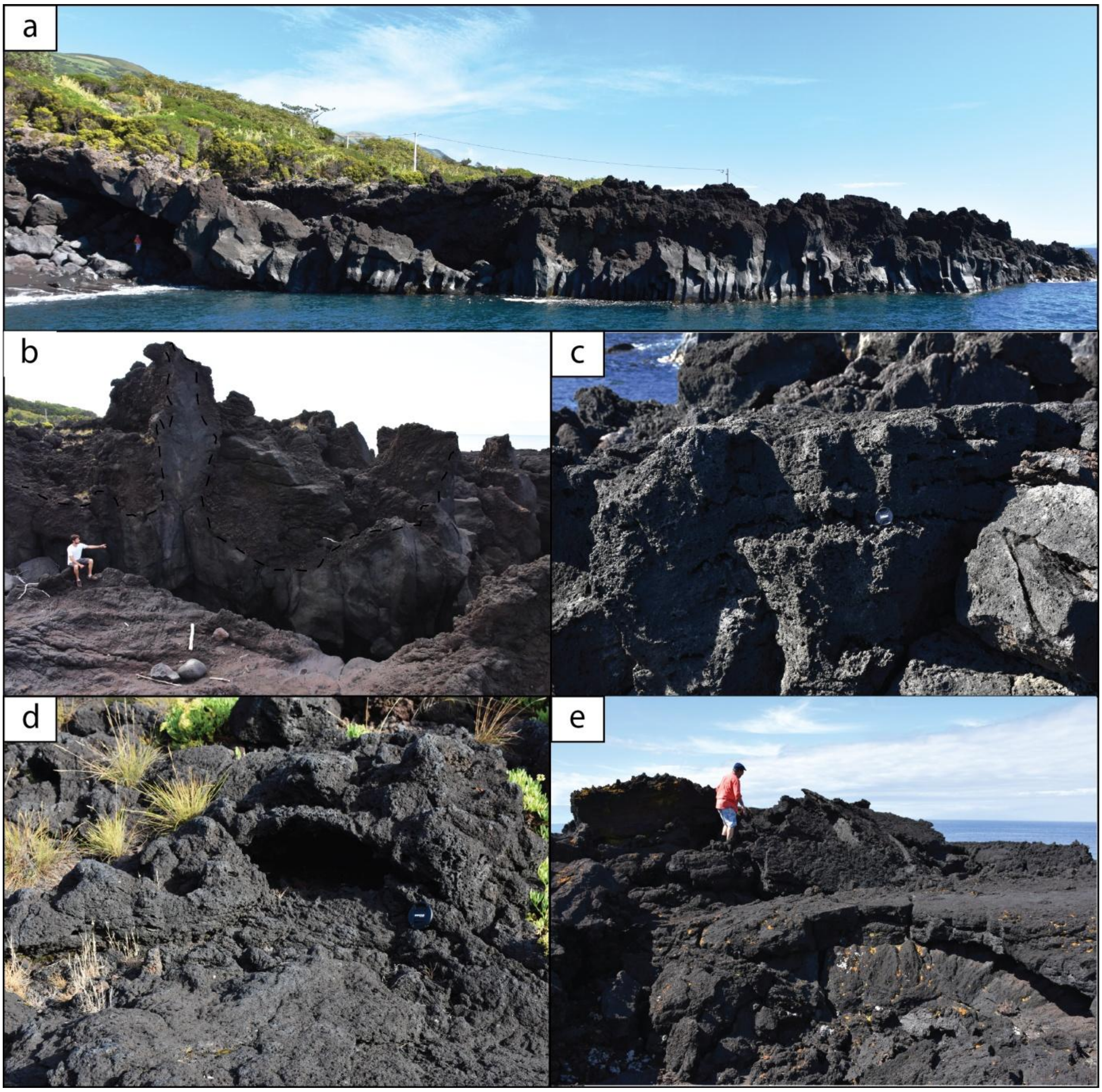

Figure 6 - Representative photographs of the different surface morphologies of the Ribeira do Nabo I lava flow field. a) Lava flows from the base of the succession. The lava flow present a massive core transited to a core with undulate columnar joints in the flow front b) Injections of degassed lava crust rising until 2 m intrude the fragmented flow top c) Sheet pahoehoe with spiny surface and marked by vesicle layers occurring every 10 cm. d) Lava tubes partially filled by pahoehoe with ropy surface. e) Tummulis structure in the sheet flows. It consists of tilted crustal slabs that are split by inflation clefts

The ‘a´ā flow vary from 0.5 to 2 m of thick and are characterized by a holocrystalline and massive core (Fig. 7e). The top and base are brecciated with oxidized vesicular fragments varying 3 to 15 cm in diameter. Injections of the core in the clinker zone are also present in the flow top of ‘a´ā. Is inferred that these ‘a´ā flows were channelized from the vent and the slabby and spiny pahoehoe were formed in a flatter portion of the topography.

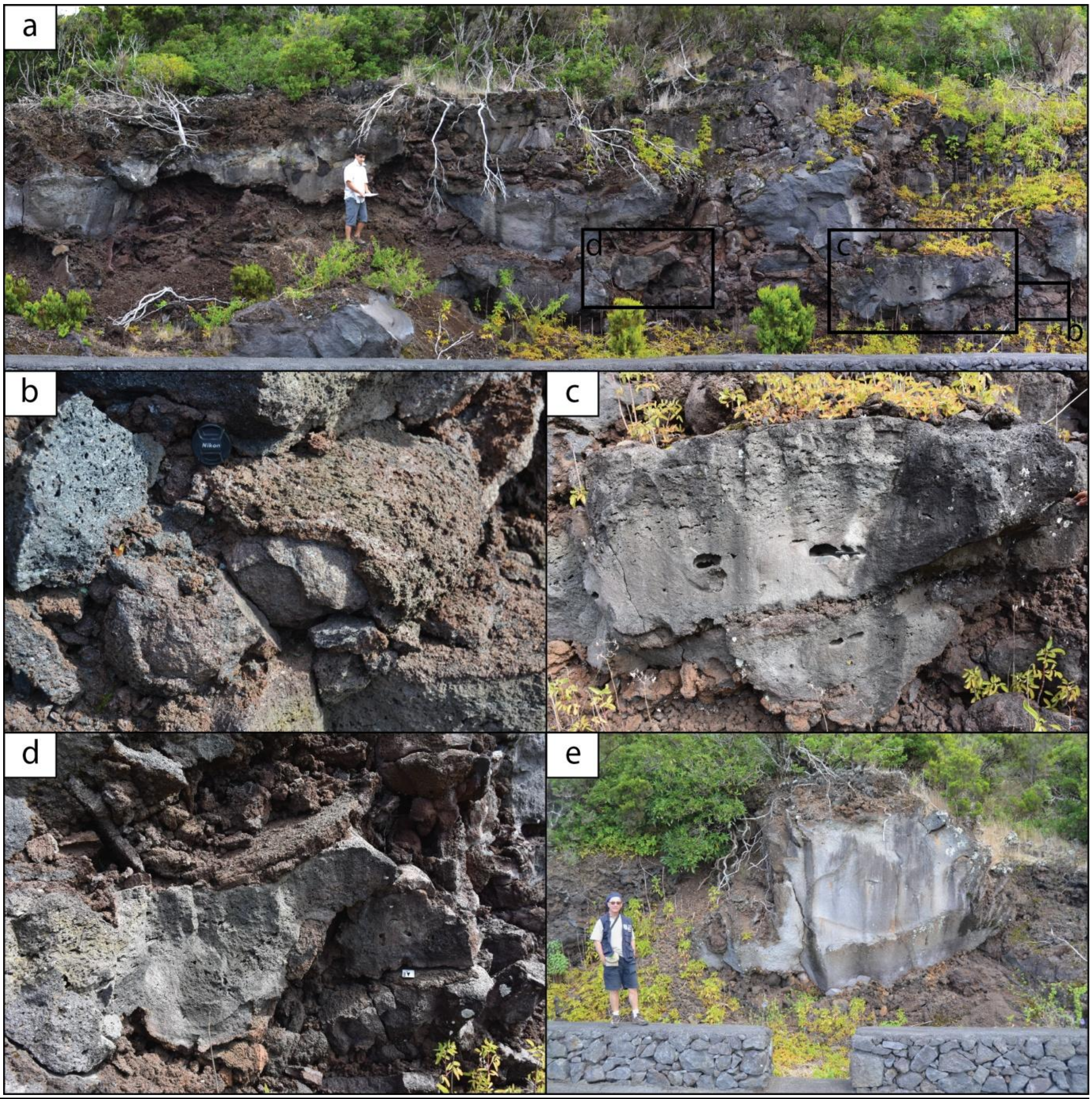

Figure 7 - Representative photographs of the different surface morphologies of the Ribeira do Nabo II lava flow field. a) Chaotic distribution of pahoehoe, slabby pahoehoe and \`a\`a morphologies in the outcrop. b) Thin toes lobes of pahoehoe (10-20 cm) with spiny surface. c) Thicker pahoehoe flows (1 - 1.5 m) with megavesicles (10 cm) in the core and thin vesicle layers at the flow top. d) Slabby pahoehoe with tabular break slabs surface. Note other fragments of slabs mixed in the rubble layer. e) Thick channelized \`a\`a flow (2 m) with top and base brecciated, with oxidized fragments.

5. Petrology and Geochemistry

5.1. Analytical Procedures

Seventeen samples were collected from two of the different 1580 AD eruptions, fourteen from Ribeira do Nabo and three from Ribeira do Almeida. The whole-rock chemical analyses were performed in ACME analytical laboratories Ltd., Vancouver, Canada. The contents of main oxides and several trace elements were measured by means of ICP-AES (Inductively Coupled Plasma Atomic Emission Spectroscopy) and the concentration of rare-earth and refractory elements by means of ICP-MS (Inductively Coupled Plasma Mass Spectrometer) (Table I). In both procedures, 0.2 g of powdered sample was used. The analytical errors are less than 0.01% for oxides (0.04% for FeO), and rare-earth elements less than 1 ppm. All samples also show low LOI contents <1 wt. %, confirming the absence of significant alteration.

For the mineral chemical compositions, a representative number of crystals of each mineral phase present in the lava flows were analyzed using a Cameca SXFive electron microprobe at the Federal University of Rio Grande do Sul, Brazil. Plagioclase, Clinopyroxene and oxides were analyzed using a 15 kV, 15 nA, 5 µm, and olivines 15 kV, 25 nA, 1 µm. The analyses are expressed as a function of the cation percentage Fo* [100XMg/(Mg+Fe)] for olivine, Wo* [Ca/(Ca+Mg+FeT)], En* [Mg/(Ca+Mg+FeT)] and Fs* [FeT/(Ca+Mg+FeT)] for clinopyroxene and An* [100XCa/(Ca+Na+K)] for plagioclase.

5.2. Petrography

Petrographically the samples were analyzed using a point counter to determine modal compositions, proportions of phenocrysts and groundmass and vesicularity. All lava types sampled from 1580 AD volcanism can be classified as olivine basalts. These lavas are typically porphyritic and glomeroporphyritic, although intergranular textures are also identified. Phenocrysts are subhedral and euhedral plagioclase (1.8 – 3.2 mm), clinopyroxene (1.2 – 3.2 mm), olivine (1.2 -1.4 mm) and Fe-Ti oxides. Some phenocrysts of olivine and plagioclase show reabsorption and sieve textures and late overgrowth (Fig.8d). The groundmass is holocrystalline with microlites of plagioclase, clinopyroxene, Fe-Ti oxides and rare olivine. The proportion of phenocrysts and microphenocrysts range from 28 to 34% of the whole rock volume. For the lavas from Ribeira do Almeida Eruption some crystals and glomerocrysts of olivine show an undulated extinction characteristic of deformed crystals typical of mantle xenocrysts and xenoliths (Fig 8a). The proportion of olivine phenocrysts in R.Almeida lavas ranges between 7 to 11%, higher than the maximum of 4 % (of the rock volume) observed for Ribeira Nabo lavas. However, the proportion of plagioclase phenocrysts is significantly smaller (8-11%) for the maximum of 22-27% described in Ribeira do Nabo.

R. do Nabo lava cores are highly vesicular (21 – 23 %) when compared to R. Almeida lavas, with vesicles typically representing less than 10% of the rock volume. Petrographically, the different morphotypes, present similar phenocryst and mineralogical compositions, with major differences present in the groundmass size, ranging from 0.1 to 0.3 mm for the pahoehoe lava flows (Fig.8b) and a much finer groundmass in the aa flows, ranging from 0.03 up to 0.2 mm (Fig.8c).

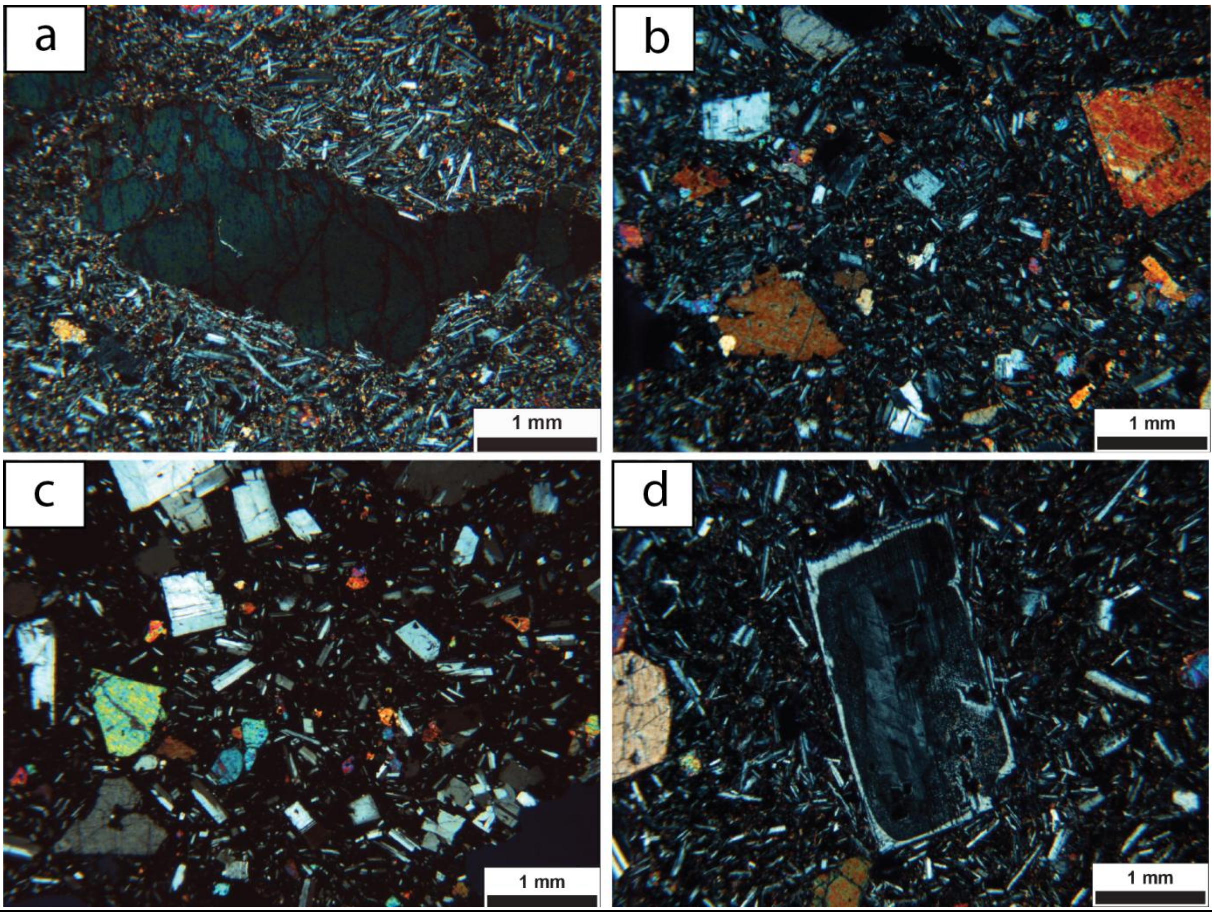

Figure 8 – a) Microphotography with crossed polarizers a) Crystals of olivine with an undulated extinction. Sample from Ribeira do Almeida Flow field. b) Petrographic pattern of pahoehoe flow: porphirytic texture in a fine crystalline groundmass. c) Petropraphic pattern of `a`a lava flow: porphirytic texture in a aphanitic groundmass d) Zoned phenocrysts of plagioclase with reabsorbed cores in Ribeira do Almeida lavas

5.3. Chemical composition of the main mineral phase

5.3.1.Olivine

Olivine phenocrysts from R. do Almeida eruption show an inverse composition zoning with crystal cores ranging from 75 to 77% Fo* and increasing of forsterite molecules towards the crystal rims (Fo^*_{77-81}). The groundmass crystal compositions are scattered between 59-68% Fo*. Conversely, lavas from Ribeira do Nabo have olivine phenocrysts with normal zoning, composition range from 75 to 78 % Fo* in crystal core to iron rich crystal rims, but a similar composition of Fo* (58-65%) in the matrix. In both groups, the CaO concentration (0.17-0.45%) have an inverse correlation with %Fo in olivine cores. The content of CaO > 0.19% suggests a low pressure of crystallization to olivine since the solubility of Ca in olivine is known to decrease with increasing pressure (Simkin and Smith, 1970; Hirschmann and Guiorso, 1994).

6.3.2 Clinopyroxene

Clinopyroxenes of both eruptions are compositionally equivalent to diopside following the Morimoto *et al.* (1988) classification. Phenocrysts scattered from Wo_{45}-En_{38}-Fs_{10} to Wo_{48}-En_{42}-Fs_{15} and matrix crystals from Wo_{46}-En_{30}-Fs_{13} to Wo_{47}, En_{-40}, $Fs_{20.}$ Abundances of CaO varies from 20 to 22 wt. %, Al_2O_3 varies from 3 to 9 wt.% and MgO from 12 to 14wt. %. The Al/Ti ratio in Ribeira do Almeida is 4.94 to phenocrysts and 2.45 to matrix crystals, similar to pyroxenes of Ribeira do Nabo eruption with 4.64 and 2.13, respectively. This ratio is also described in Terceira and Graciosa (Madureira et al, 2011; Larrea et al, 2014) and it is indicative of with less evolved magma compositions.

6.3.3. Plagioclase

Plagioclase is present as phenocrysts, microphenocrysts, and microlites in the matrix. Phenocrysts of Ribeira do Almeida have reverse zoning with ranging from labradorite cores (An^*_{53-67}) and bytownite rims (An^*_{62-74}). Microphenocrysts in the groundmass have a composition similar to the border of phenocrysts (An^*_{72}) and plagioclases of the matrix are labradorite (An^*_{59-66}). Zoned phenocrysts with reabsorbed cores are a common feature of Ribeira do Almeida lavas (Fig 8d) This fact associated to an inverse zoning, also observed in the olivines, can be related a recharge of magma more primitive. Plagioclase is a major phase in the lavas from Ribeira do Nabo. The phenocrysts of plagioclase are normally zoned or compositionally homogeneous and An* range from 78 to 67%. The microphenocrysts

(An^*_{57-62}) and the groundmass (An^*_{43-51}) have more evolved compositions when compared to the phenocrysts.

6.3.4 .Iron Oxides

Iron oxides are common in the matrix of the lavas and rare phenocrysts. Compositionally the oxides in the groundmass are ilmenite Abundances of TiO_2 in the ilmenite is 57.7 wt. %. FeO content is 35.1wt. %, whereas the MgO is less than 5 wt. %. Oxides are also present recovering other silicate phases and along intra-granular fractures.

6.2. Geochemical characterization

Samples from 1580 AD volcanism are scattered from 44.78 to 45.88 wt.% SiO_2 and 4.13 to 5.03 wt.% total alkalis (NA2O + K2O) plotting on basalt to trachybasalt (hawaiite) for the rocks from Ribeira do Nabo Eruption and basalt to basanite (Ol_n>10%) for samples from Ribeira do Almeida Eruption in the TAS diagram (Fig 9a, after Le Bas, 1986). Ribeira do Nabo lavas have MgO contents of 5.08 to 6.12 wt. % and major elements including Al_2O_3 (17.06-17.40 wt.%) and SiO_2 increase with decreasing MgO, whereas P_2O_5 (0.69-0.71 wt.%), TiO_2 (3.56-3.64 wt.%) Na_2O+K_2O e Fe_2O_3 (12.16-12.55 wt. %), decrease with decreasing MgO. The lavas from Ribeira do Almeida are more primitive when compared with Ribeira do Nabo magmas with higher MgO contents (8.72-8.91 wt. %) and lower values of Al_2O_3 (15.28-15.65 wt. %) and P_2O_5 (0.48-0.49 wt. %). The Fe_2O_3 and TiO_2 contents are similar and vary from 12.19 to 12.28 wt. % and 3.35 to 3.41 wt. %, respectively. The highest MgO contents are caused by the accumulation of pyroxene and olivine phenocrysts, as observed in the petrographic studies. All the analyzed lavas have similar compositions to other basaltic lavas from Manadas and Rosais Complex (Hildenbrand et al, 2008; Millet et al, 2009).

Table 1 - Lithogeochemistry data from lavas of Unit I (major elements in wt. %; trace elements in ppm).

Sample	SJ-61A	SJ-6/1B	SJ-6/1D	SJ-6/2B	SJ-6/3A	SJ-6/3C	SJ-6/4A	SJ-6/4B	SJ-6/4C	SJ-6/5A	SJ-6/5B	SJ-6/6A	SJ-6/6B	SJ-6/6C	SJ-7/1	SJ-7/2	SJ-7/3
Area	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Nabo**	**R.Almeida**	**R.Almeida**	**R.Almeida**
TAS classification	basalt	basalt	basalt	trachybasalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basanite	basanite
SiO_2	45.88	45.34	45.46	45.50	45.67	45.19	45.19	45.73	45.67	45.41	45.03	45.65	45.40	45.49	45.14	44.21	44.78
TiO_2	3.64	3.56	3.60	3.59	3.57	3.61	3.60	3.59	3.58	3.64	3.58	3.56	3.59	3.61	3.43	3.41	3.35
Al_2O_3	17.15	17.06	17.23	17.30	17.40	17.27	17.52	17.24	17.20	17.12	17.22	17.34	17.30	17.19	15.65	15.28	15.52
Fe_2O_3	12.36	12.35	12.33	12.33	12.12	12.28	12.33	12.29	12.40	12.52	12.55	12.16	12.16	12.48	12.19	12.34	12.28
MnO	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.16	0.16
MgO	5.82	5.96	5.91	5.80	5.82	5.94	5.95	5.96	5.90	5.97	6.12	5.99	5.97	6.03	8.72	8.81	8.91
CaO	9.50	9.41	9.41	9.34	9.59	9.66	9.67	9.56	9.56	9.42	9.31	9.49	9.51	9.39	10.23	10.03	10.06
Na_2O	3.54	3.59	3.45	3.68	3.51	3.53	3.50	3.59	3.54	3.60	3.55	3.60	3.57	3.67	3.28	3.21	3.01
K_2O	1.31	1.30	1.30	1.35	1.30	1.31	1.33	1.31	1.32	1.30	1.31	1.29	1.29	1.32	1.10	1.12	1.12
P_2O_5	0.70	0.71	0.70	0.69	0.69	0.71	0.70	0.70	0.70	0.71	0.71	0.71	0.69	0.70	0.49	0.49	0.48
LOI	-0.40	0.20	0.10	0.00	-0.20	0.00	-0.30	-0.50	-0.40	-0.20	0.10	-0.30	0.00	-0.40	-0.70	0.60	0.00
Total	100.00	99.46	99.57	99.75	99.85	99.67	99.97	100.15	100.05	99.87	99.56	99.97	99.66	100.06	100.42	99.09	99.70
Cr	75.26	68.42	68.42	75.26	68.42	61.58	68.42	68.42	68.42	68.42	68.42	68.42	68.42	68.42	239.47	246.31	253.15
Ni	43.00	43.00	47.00	48.00	51.00	40.00	48.00	46.00	46.00	46.00	42.00	45.00	47.00	45.00	126.00	130.00	123.00
Co	38.40	38.50	37.70	38.60	37.40	38.40	38.60	38.50	39.50	38.20	40.40	39.10	40.00	39.30	50.10	48.50	49.30
Rb	27.10	28.00	26.80	27.30	25.80	27.00	26.50	27.40	26.50	27.00	25.30	26.80	26.40	26.30	22.30	23.40	21.70
Ba	316.00	350.00	325.00	342.00	335.00	346.00	331.00	333.00	333.00	337.00	327.00	339.00	330.00	345.00	293.00	278.00	276.00
Sr	872.40	892.10	891.70	885.00	903.40	895.40	888.00	876.00	901.70	909.80	880.80	898.70	923.50	880.80	669.90	657.60	642.90
Zr	304.90	327.50	307.90	308.70	304.70	308.10	305.60	310.60	314.00	304.90	316.60	309.50	307.70	302.70	252.00	243.30	236.70
Th	4.00	3.90	4.10	3.80	4.00	3.90	4.00	3.70	4.10	4.00	3.80	3.80	3.70	4.10	2.70	2.90	2.60
U	1.50	1.50	1.20	1.40	1.50	1.40	1.60	1.60	1.40	1.50	1.40	1.50	1.40	1.30	0.90	1.10	0.90
Nb	55.40	59.10	56.10	56.50	55.70	57.80	55.70	55.60	55.80	57.40	56.30	56.90	56.50	57.30	43.00	42.50	41.30
La	40.60	45.30	43.50	42.10	41.40	43.00	43.10	41.60	42.20	42.80	42.20	43.10	42.20	41.80	31.30	30.70	28.90
Ce	85.40	95.60	90.30	88.20	87.80	91.10	91.20	90.00	92.80	94.30	93.80	92.40	89.70	92.40	69.40	64.50	64.70
Pr	10.93	11.57	11.21	11.16	11.18	11.20	11.06	11.45	11.09	11.38	11.15	11.46	11.12	11.18	8.37	8.10	8.10
Nd	44.60	48.00	47.60	46.90	47.70	48.70	46.10	47.60	48.10	49.40	47.30	47.60	47.50	46.10	36.10	35.40	34.20
Sm	9.03	10.13	9.33	9.78	9.42	9.41	9.49	9.63	9.44	9.36	9.51	9.70	9.56	9.61	7.39	7.29	7.36
Eu	2.90	3.22	2.97	3.04	2.92	3.07	3.02	3.16	3.08	3.08	3.09	3.11	3.08	2.97	2.35	2.33	2.35
Gd	8.18	9.01	8.38	8.55	8.09	8.62	8.65	8.69	8.57	8.93	8.49	8.67	8.54	8.55	7.01	6.56	6.97
Tb	1.23	1.28	1.25	1.23	1.20	1.23	1.25	1.24	1.22	1.25	1.21	1.27	1.21	1.24	1.01	0.96	1.00
Dy	6.32	6.85	6.41	6.26	6.34	6.32	6.26	6.34	6.27	6.55	6.38	6.26	5.89	6.38	5.47	5.19	5.35
Y	28.90	31.00	30.30	29.80	28.70	29.70	29.40	29.50	30.20	29.90	29.10	30.50	30.70	30.10	23.70	25.60	23.70
Ho	1.15	1.23	1.15	1.19	1.16	1.19	1.22	1.21	1.21	1.16	1.16	1.17	1.17	1.22	0.97	0.95	0.92
Er	3.00	2.94	3.05	3.01	3.00	2.98	2.92	3.00	3.07	3.09	2.95	2.92	2.98	2.85	2.56	2.33	2.45
Yb	2.40	2.54	2.52	2.49	2.40	2.52	2.49	2.46	2.39	2.38	2.44	2.49	2.45	2.43	2.06	2.10	1.98
Tm	0.40	0.42	0.42	0.40	0.40	0.40	0.42	0.39	0.41	0.39	0.43	0.43	0.41	0.40	0.36	0.34	0.34
Lu	0.36	0.35	0.35	0.36	0.35	0.34	0.35	0.34	0.34	0.34	0.37	0.33	0.34	0.35	0.31	0.29	0.29
Th/Yb	1.67	1.54	1.63	1.53	1.67	1.55	1.61	1.50	1.72	1.68	1.56	1.53	1.51	1.69	1.31	1.38	1.31
Nb/Yb	23.08	23.27	22.26	22.69	23.21	22.94	22.37	22.60	23.35	24.12	23.07	22.85	23.06	23.58	20.87	20.24	20.86
Ol*n*	9.98	10.34	10.48	10.18	10.00	10.08	10.32	10.17	10.17	10.39	11.04	10.37	10.24	10.48	13.33	13.68	14.26
Ne*n*	2.54	3.39	2.38	3.37	2.82	3.72	3.77	3.31	3.07	3.42	3.59	3.27	3.42	3.90	4.87	5.23	3.55

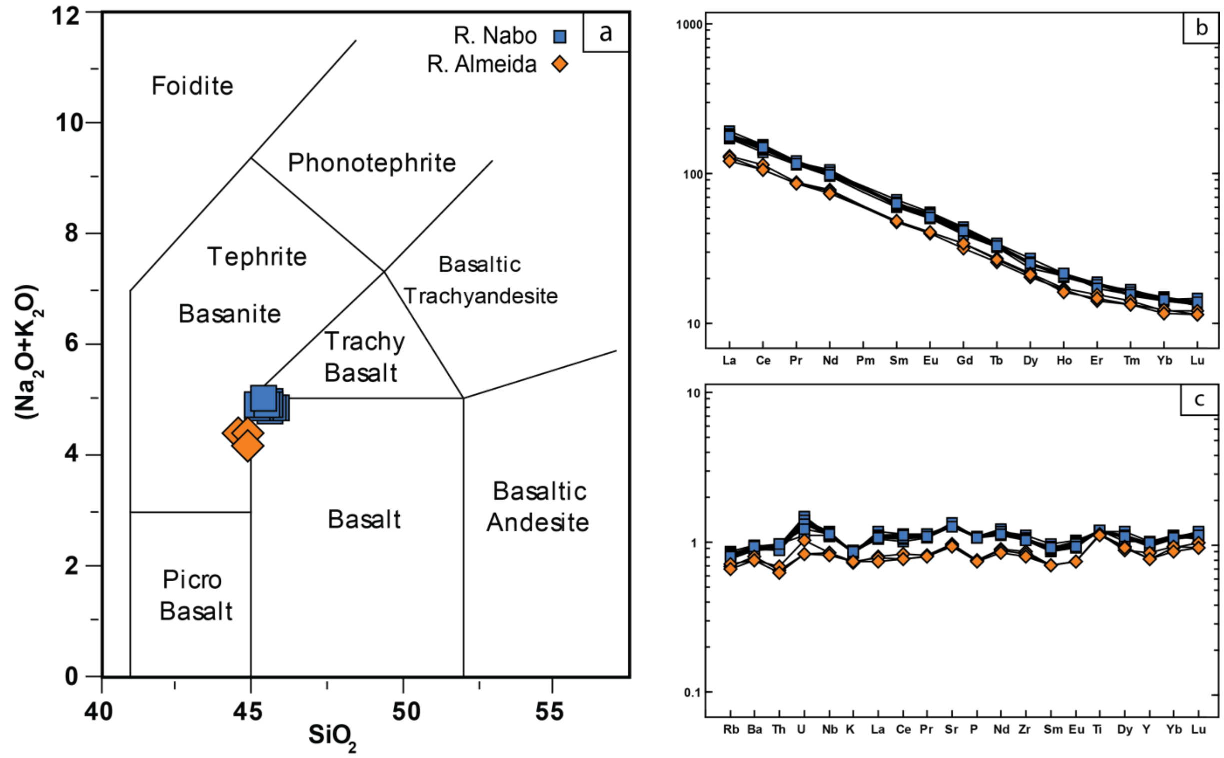

Figure 9 - Representative lithogechemistry data of 1580 A.D. samples. Blue square – Ribeira do Nabo , orange diamond - Ribeira do Almeida. a) Total alkali vs silica diagram (after Le Bas et al., 1986). Multi- elementary plot normalized by b) Condrite Sun and McDonough (1989). and c) OIB Sun and McDonough (1989).

The primitive character of Ribeira do Almeida lavas is also marked by trace element and REE abundances, with these lavas having typically higher concentrations of Ni, Cr and Co and lower LILE (Ba, Sr, Rb) and HFSE elements (Nb, Zr, Y) when compared to Ribeira do Nabo samples. In condrite normalized diagrams the lavas show a marked enrichment in light REE relative to heavy REE (Fig. 9b, Sun and MacDonough 1989). All the analyzed lavas have similar patterns of REE when normalized to OIB compositions (Fig. 9c, Sun and MacDonough, 1989). Plotting the samples in a Th/Yb – Nb/Yb diagram (Pearce, 2008), which exhibits the array of oceanic basalts from MORBs to OIB, the lavas from 1580 AD volcanism lie on the OIB field (Fig 10a). In a multi-element diagram with the oceanic basalt patterns, generally normalized to an average MORB composition (Pearce, 2008), the samples shows a typical alkaline OIB trend (Fig 10b). In these oceanic basalt patterns normalized also to TiO_2=1, which highlights the difference between the right side of the pattern, garnet-dependent, and the left side, partial melting and source-composition-dependent (Pearce, 2008), the 1580 eruption samples have negative trends over the Ti –Yb, and positive trends over Nb-Ti, indicating that the magmas were formed by relatively low melt of an enriched OIB source, with garnet as a residue (Fig 10c).

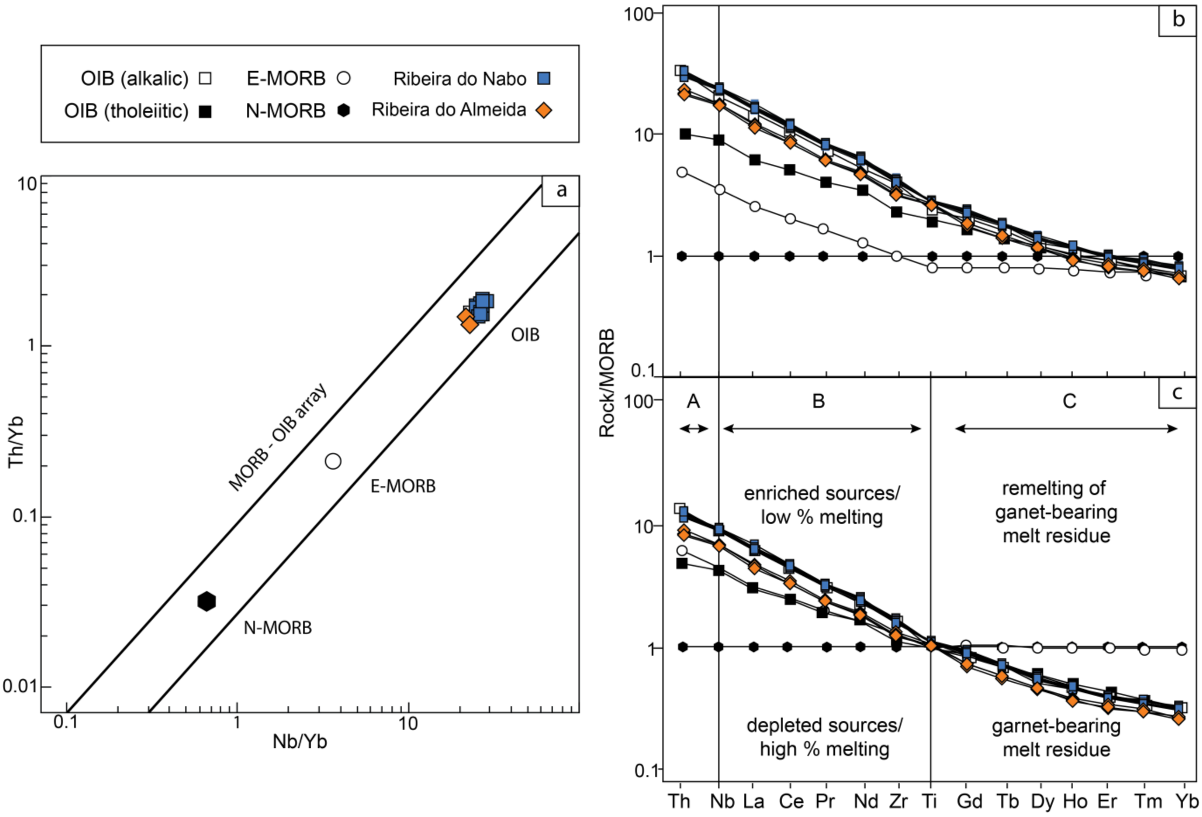

Figure 10 - . a) Th/Yb – Nb/Yb diagram (Pearce, 2008), which exhibits the array of oceanic basalts from MORBs to OIB. b) MORB-normalized geochemical patterns for some type oceanic basalts. The N-MORB and E-MORB data are from the compilation by Sun and McDonough (1989); intra-plate islands (islands on ridge-distal oceanic lithosphere) are represented by alkalic OIB (the OIB average of Sun and McDonough, 1989). c) shows the oceanic basalt patterns normalized also to TiO2=1, which highlights the difference between the RHS of the pattern (garnet dependent) and the LHS (partial melting and source composition-dependent).

7.Discussion

The observations in the different flow fields show a structural pattern in the lava flow succession. The factors which control the lava morphology involve composition, temperature, crystallinity, melt polymerization, volatile content and vesicularity, affecting the apparent viscosity (Macdonald, 1953; Shaw *et al.*, 1968; Swanson 1973; Kilburn 1990; Sato, 1995; Cashman *et al.*, 1999) and effusion rate, channel configuration, flow velocity and duration, and ground slope, directly related to the applied shear stress, and affect the rate of shear strain (Peterson and Tilling, 1980; Rowland and Walker 1990; Hon *et al.* 2003). Based on the analysis of the flow fields, we described the emplacement of 1580 A.D. eruption.

7.1. Model of Emplacement of 1580 A.D.

In a general way, the 1580 A.D. eruption started with strombolian activity along the E-W Pico do Carvão Fault zone. The pyroclastic material accumulated in the areas near the fissure forming six spatter cones. An increasing in the frequency of lava bodies within the upper part of the spatter cones points to a gradual transition from strombolian to Hawaiian eruptive style. This fact can be explained by the continuous degassing of the magmatic system. In Kilauea, Hawaii, fissure eruptions which produce primarily linear spatter ramparts and lava flows are controlled by cooling mechanism and driving pressure and are classified as longer-lived fissure eruptions (Parfitt, *et al.*, 2002).

The lava flows were initially emplaced in a steep slope (~20º) forming channelized ‘a´ā flows in the proximal areas, with relatively constant effusion rates. The ‘a´ā lavas flowed downwards reaching the shore and entering the sea in many cases, spreading as fan-shaped deltas on the coastal plain. In the relatively flat coastal plain flows are thicker, as a reflex of flow deaccelerating. The temperature contrast of the lava core and the sea water promote the formation of columnar cooling joints in this thicker flow cores, and the formation of degassed injections in the flow breccia. Similar deposits have been described in modern volcanism in Iceland, Nesjahraun eruption (Stevenson et al, 2012) and for historic eruptions in Japan (Kuno, 1954; Sakaguchi *et al.* 1987; Obata and Umino 1999) where ‘a´ā flow lobes entered the water, forming hackly fractured lava bodies, sometimes with columnar jointing and/or a glassy appearance in the lowest 1.5 m. For the Nesjahraun eruption, the interactions of ‘a´ā flows with water are associated with the generation of tephras deposits, which is not formed in the 1580 A.D. eruption. In Japan historic eruptions, the majority of the lava delta was emplaced on dry land, the flow front entered into the sea and stagnated under water.

The basal portion of the eruption is covered by a sequence of 1 to 5 m of sheet flows. The sheet flows were initially emplaced as thin pahoehoe toes developing an external crust that was posterior inflated by the continuous lava supply. With continuous inflation and the increase in effusion rates the flow surface was broken into slabs, and in some cases rubble. The surface of sheet pahoehoe eventually presents polygonal inflation clefts and consequently surface breakout in crustal imbricated slabs form elliptical tumuli. A tumulus is formed in response to magmatic overpressure within the flow as the surface thickens (Walker, 1991). Hon, et al, (1994) show in the Kilauea and Mauna Loa the sheet flows are initially emplaced as thin sheets, given sustained lava supply, follow a progression from thin sheet to thick inflated flows. As advanced rates slow, newly formed crust retains incoming lava and begins to inflate. Finally, advance is effectively halted, and the sheet-flow inflates until the internal pressure ruptures the crust to form a new outbreak. The final form of the sheet flow will depend on topography, effusion rate, and eruption duration. Guilbald et al, (2005) describe thin pahoehoe flows near the vent and an inflation of these flows in the portions more distal of the vent. For the 1580 A.D. eruption, the stepper topography near the vent restricted the formation of the sheet flows in the distal zones, where a flat terrain was created by the ‘a´ā basal flows. Channelized ‘a´ā flows overlay the pahoehoe sheet flows and were formed during high effusion rates probably emplaced in the high slope and flowed down to the shoreline laterally and over the sheet flows.

7.2. Petrographic and Geochemically

We identified similar petrographic patterns for the lava flows, with major differences only in the groundmass size, ranging from 0.1 to 0.3 mm for the pahoehoe lava flows and 0.03 to 0.2 mm in the ‘a´ā lavas. It can be explained by the higher undercooling conditions in the ‘a´ā flows.

Geochemically lavas from R.Almeida present a more primitive character than Ribeira do Nabo present higher MgO, Ni, Cr and Co contents and lower Al_2O_3, LILE and HFSE elements. Petrographically lavas from R.Almeida shows highest accumulation of pyroxene and olivine phenocrysts (10 to 14 %) than Ribeira do Nabo (7 %). These are also illustrated in the composition of phenocrysts of olivine and plagioclase from Ribeira do Almeida, which shows an inverse composition zoning, being the rims more primitive than the core crystals. This primitive character can be related to a recharge of more primitive magma in the magmatic chamber of. R.Almeida. Some crystals and glomerocrystals of olivine are considered, petrographically, mantle xenocrysts based in the undulated extinction, but the values of Fo (77 to 81 %) is less that 87 to 90 % of forsterite described for xenocrysts in other Azores islands (França, et al. 2006; Madureira, et al. 2011; Larrea, et al. 2014).

8. Conclusion

The1580 A.D. was 4 months long and registers a very broad variation in lava morphology from pahoehoe to aa. The detailed description and analysis of this deposits might provide important information on what concerns eruptive and storage variations in short lived magmatic systems.

The 1580 AD. eruption records different flow morphologies along a relatively continuous eruption. The vent areas record the transition of strombolian to Hawaiian eruptive styles, controlled by the continuous degassing of the magmatic system. The onset of the eruption is marked by channelized ‘a´ā flows emplaced in a steep topography in the proximal areas and reaching the shoreline to form relatively flat topography lava deltas. This flat topography made possible the emplacement of sheet pahoehoe, initially emplaced as thin pahoehoe lobes that developed an external crust and were latter inflated by the continuous lava supply. Oscillation in effusion rates with periods of increased effusion caused localized rupture of the flow surface into slabs, and in the some cases rubble. The stepper topography near the vent, restricted the formation of the sheet flows to the distal zones of the eruption. High effusion rate periods formed the latter ‘a´ā flows that cover most of the eruption. The variations in the lava surface provide important information on the dynamic of emplacement and was majorly controlled by the paleotopography and effusion rates.

Chemically, the less-evolved compositions are found in Ribeira do Almeida and are associated to continuous recharge of the magma chamber with more primitive melts. Normalized REE profiles show that the basalts were generated by low volumes of melt of an enriched OIB source.

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