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Magmatic flow and structural control in dikes of the West Iberia Late Cretaceous Alkaline Province between Cabo Raso and Oeiras based on field work and marine magnetic data

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Acknowledgments

This final report is lovingly dedicated to my late paternal grandmother, Rosária, who always wished to see me graduate.

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Resumo

Este trabalho tem como objetivo investigar o fluxo magmático e o controlo estrutural dos diques pertencentes à Província Alcalina do Cretácico Superior da Margem Oeste Ibérica, numa área delimitada entre o Cabo Raso e Oeiras. A abordagem metodológica consistiu na integração de várias linhas de evidência: trabalho de campo detalhado, análise estrutural, utilização de cartografia geológica disponibilizada pelo LNEG, bem como a interpretação de dados de anomalias magnéticas offshore adquiridos no âmbito do levantamento TAGUSMAG e analisados com o software Oasis montaj. A conjugação de dados onshore e offshore permitiu não apenas caracterizar os diques aflorantes, mas também estabelecer conexões com estruturas magmáticas submarinas, contribuindo para uma compreensão mais abrangente da dinâmica magmática e tectónica desta região da margem portuguesa.

O trabalho de campo constituiu uma etapa essencial da investigação, permitindo a observação direta dos diques e das rochas que os rodeiam, a descrição sistemática dos afloramentos e a recolha de dados estruturais. Foram efetuadas medições de orientações de diques com recurso a bússola geológica, bem como o registo fotográfico e cartográfico detalhado das principais estruturas. Estes dados foram posteriormente integrados em ambiente digital, nomeadamente num software SIG designado por QGIS, permitindo uma análise espacial mais rigorosa da distribuição e orientação dos diques, tornando possível elaborar um mapa com todos os dados recolhidos. Esta abordagem foi complementada com a análise crítica da cartografia geológica previamente existente, disponibilizada online pelo LNEG, o que possibilitou validar e integrar a informação disponível para a região em estudo.

Paralelamente, a utilização dos dados offshore do levantamento magnético TAGUSMAG e de parte do levantamento ROCHEL permitiu alargar o alcance da investigação para além da área emersa. As anomalias magnéticas registadas no setor marinho adjacente constituem um complemento fundamental, pois oferecem evidências indiretas da continuidade e geometria das intrusões em subsuperfície. A integração destes dados com as observações de campo possibilitou a construção de um modelo mais completo, no qual a rede de diques em terra se encontra diretamente relacionada com estruturas que se prolongam para o domínio submarino. Este tipo de abordagem é ainda pouco explorado em trabalhos realizados na margem portuguesa, pelo que representa um avanço significativo para a compreensão da evolução geodinâmica regional e, nesta área de estudo em específico, é um trabalho que utiliza dados nunca antes trabalhados.

As observações realizadas em afloramento e a análise estrutural efetuada permitiram demonstrar que os diques desta região se distribuem em duas famílias composicionais distintas, refletindo possíveis diferenças na idade e/ou na fonte magmática que lhes deu origem. Para além disso, verificou-se que os diques se organizam também em dois grupos principais relativamente à sua orientação. O primeiro grupo, com orientação preferencial NNW-SSE, foi interpretado como estando associado a um corredor de cisalhamento pré-existente e já relatado em trabalhos anteriores, com idade atribuída ao Jurássico Médio, relacionado com a fase de rifting do Oceano Atlântico. Este facto indica que estruturas tectónicas herdadas tiveram um papel determinante no controlo da instalação dos diques, canalizando e condicionando o percurso do magma em ascensão. O segundo grupo, com orientação NNE-SSW, foi relacionado com o padrão radial que converge diretamente para a anomalia magnética do Cabo Raso, o que sugere que esta estrutura poderá ter desempenhado um papel como fonte magmática na região.

A análise detalhada de estruturas de mesoscala nos diques permitiu ainda identificar que alguns deles se propagam de sul para norte. Este dado é particularmente relevante, uma vez que estabelece uma ligação direta entre o enxame de diques e a anomalia magnética do Cabo Raso, suportando a hipótese de uma origem associada ao mesmo. Assim, a interpretação mais plausível é que o corpo associado à anomalia do Cabo Raso tenha funcionado como uma importante fonte, cuja atividade magmática condicionou fortemente a intrusão dos diques na região em estudo.

Outro aspeto inovador deste trabalho prende-se com a identificação, através do mapeamento de alinhamentos magnéticos, de condutas anteriormente desconhecidas associadas à anomalia magnética do Cabo Raso. Algumas destas lineações estendem-se pelo offshore, estabelecendo uma ligação entre a anomalia magnética do Cabo Raso e a rede regional de diques. Esta evidência reforça a ideia de que esta anomalia offshore não deve ser interpretada apenas como uma anomalia magnética isolada, mas provavelmente como um centro de alimentação magmática ativo durante o Cretácico Superior, com implicações significativas para a compreensão da evolução magmática da Província Alcalina da Margem Oeste Ibérica.

Tomados em conjunto, estes resultados apontam para um cenário em que a anomalia do Cabo Raso funcionou como uma zona-chave de alimentação de magma, com a possibilidade do enxame de diques desempenhar um papel na atividade vulcânica do Complexo Vulcânico de Lisboa. Embora este último tenha sido predominantemente de caráter efusivo, existem evidências de episódios piroclásticos mais explosivos, dos quais o ignimbrito identificado na região de Paço de Arcos em Oeiras poderá ser um vestígio. A presença deste tipo de depósitos reforça a ideia de que a evolução vulcânica do setor em análise foi marcada por uma complexidade considerável, em que episódios explosivos pontuais se intercalaram com fases de extrusão mais efusiva.

Em termos metodológicos, importa sublinhar que o tempo disponível para a realização deste trabalho não permitiu aplicar de forma sistemática técnicas de Anisotropia da Suscetibilidade Magnética (ASM/AMS), que poderiam ter fornecido informações adicionais e mais detalhadas acerca do sentido preferencial de fluxo magmático no interior dos diques. Ainda assim, a abordagem integrada desenvolvida — combinando observação direta em afloramento, análise estrutural e interpretação de dados magnéticos — revelou-se eficaz para alcançar os objetivos principais do estudo. Para investigações futuras, a integração da análise AMS de amostras dos diques, com dados geofísicos offshore será fundamental para refinar a caracterização da dinâmica de transporte de magma e da interação entre estruturas herdadas e intrusões magmáticas neste setor da Margem Oeste Ibérica.

De forma geral, este estudo contribui para a compreensão da importância dos fatores estruturais no controlo da intrusão de diques e para o reconhecimento do papel da anomalia do Cabo Raso como centro de alimentação magmática regional. Os resultados obtidos não só acrescentam novos dados ao conhecimento geológico da região em estudo, como também oferecem uma perspetiva mais integrada da evolução magmática da Província Alcalina do Cretácico Superior da Ibéria Oeste. Para além disso, o trabalho evidencia o potencial de abordagens multidisciplinares, que articulam dados de campo com dados geofísicos, para a reconstrução da história geológica e magmática de províncias magmáticas complexas.

Em síntese, a investigação realizada permitiu: (i) identificar duas famílias composicionais de diques; (ii) reconhecer dois grupos de orientações principais, com destaque para o papel de estruturas herdadas do Jurássico Médio; (iii) estabelecer a ligação entre os diques e a anomalia magnética do Cabo Raso, em detrimento de uma origem exclusiva no Complexo Vulcânico de Lisboa ou no Complexo Ígneo de Sintra; (iv) identificar condutas previamente desconhecidas que prolongam o papel alimentador da anomalia magnética offshore para o onshore; e (v) salientar a relevância de estudos futuros que incluam análises de anisotropia magnética para melhor compreender os sentidos de fluxo do magma. Estes contributos reforçam a visão de que a evolução magmática deste setor da margem portuguesa foi controlada por uma interação complexa entre estruturas tectónicas herdadas e centros alimentadores ativos, resultando numa arquitetura vulcânica marcada por diversidade composicional, variação estrutural e episódios eruptivos de distinta natureza.

Finalmente, importa destacar que este estudo não se limita a fornecer novos dados sobre a geologia local, mas promove também uma melhor compreensão do WILCAP (West Iberia Late Cretaceous Alkaline Province), não só nas implicaçoes que esta província pode ter para a evolução tectónica da Margem Oeste Ibérica, mas também acerca da sua extensão geográfica.

Palavras-chave: diques magmáticos; fluxo magmático; WILCAP; cartografia estrutural; anomalia magnética do Cabo Raso.

Abstract

This study investigates the magmatic flow and structural control of dikes belonging to the West Iberia Late Cretaceous Alkaline Province, within the area between Cabo Raso and Oeiras. Field work is integrated, supported by cartographic data from LNEG and the interpretation of offshore magnetic anomalies acquired through the TAGUSMAG survey. The combined onshore and offshore approach provides new insights into the geometry, orientation, and emplacement mechanisms of the dike swarm in this sector of the Portuguese margin.

Field observations and structural analysis suggest that the dikes are organised in two main orientation groups. One orientation group, NNW-SSE is interpreted as being associated with a pre-existing shear corridor of Mid-Jurassic age, indicating that inherited tectonic structures exerted a strong control on the emplacement of the dikes, while the other one, NNE-SSW, is associated with the radial pattern that comes directly from the Cabo Raso magnetic anomaly. Some dikes propagate from south to north, directly linking the dike swarm to the Cabo Raso anomaly rather than to the Lisbon Volcanic Complex or Sintra Igneous Complex. In addition, the identification of previously undocumented conduits associated with Cabo Raso, some of which extend offshore, establishes a clear connection between this anomaly and the regional dike network.

Taken together, these results suggest that Cabo Raso anomaly functioned as a key magma feeder zone, with the dike swarm likely contributing to the activity of the Lisbon Volcanic Complex. While time constraints limited the application of Anisotropy of Magnetic Susceptibility (AMS) methods, which could have refined the determination of magma flow directions, the present study highlights the structural and magmatic complexity of the region. Future work integrating AMS analyses with offshore geophysical data will be crucial for further constraining the dynamics of magma transport in this sector of the West Iberia Margin.

Keywords: magmatic dikes; magma flow; WILCAP; structural cartography; Cabo Raso magnetic anomaly.

Nomenclature

Abbreviations

AMS - Anisotropy of Magnetic Susceptibility
CAMP – Central Atlantic Magmatic Province
CR – Cabo Raso
DivGM – Divisão de Geologia e Georecursos Marinhos
EMEPC – Estrutura de Missão para a Extensão da Plataforma Continental
EMODNET – European Marine Observation and Data Network
FF – Foz da Fonte
IPMA – Instituto Português do Mar e da Atmosfera
LB – Lusitanian Basin
LVC – Lisbon Volcanic Complex
LNEG – Laboratório Nacional de Energia e Geologia
MRDC – Mafra Radial Dike Complex
PMO – Passeio Marítimo de Oeiras
SIC – Sintra Igneous Complex
WILCAP – West Iberia Late Cretaceous Alkaline Province
WIM – West Iberian Margin

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1 Introduction

Dikes are usually vertical to subvertical tabular bodies that form by magma feeding sourced from a deeper-seated intrusion. It flows from the magmatic chamber up and/or radially, releasing tension and transporting magma and heat to the surface (**Figure 1.1**). They can fill pre-existent fractured zones in the host rock or intrude new fractures created by a coeval remote or local stress field.

Their geochemical signature depends on the nature of the magma inside the chamber, but also to the nature of the host rock. This occurs because, after exiting the chamber, the magma interacts with the host rock and undergoes contamination, resulting in a geochemical composition distinct from its original one. The most common dikes are basaltic, with low silica content, but there can be dikes that originate from acidic magma sources, thus forming felsic rocks. Their length and width are very variable, ranging from just a few kilometres long up to more than 150km, as reported in NW Mauritania (Tait et al., 2013). As for their width, it also may vary from a few centimetres to several metres.

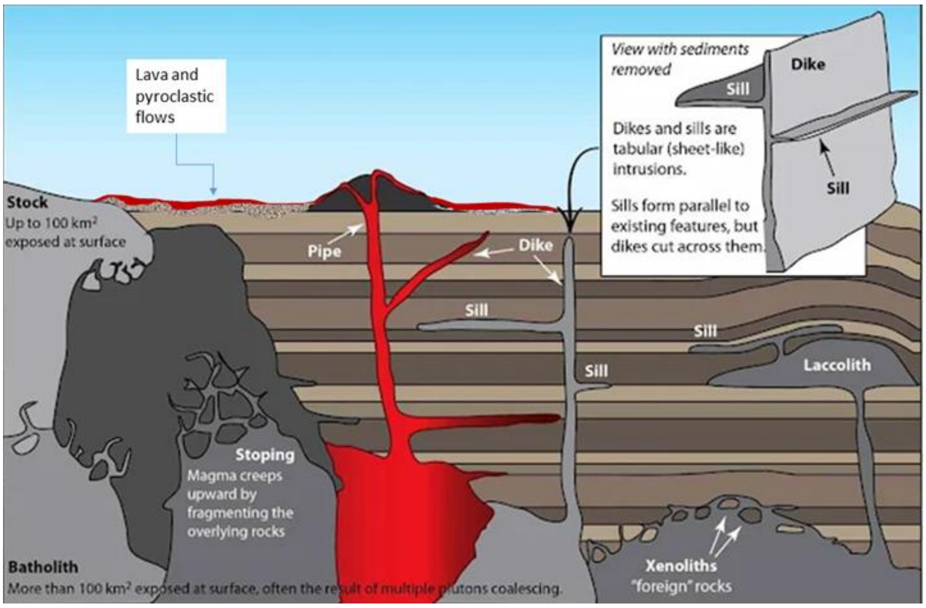


Figure 1.1 - Schematic diagram of various types of plutonic, sub-volcanic and volcanic magmatic bodies. Adapted from (*GeologyIn*, 2018), available in https://www.geologyin.com/2018/03/types-of-intrusive-igneous-rock.html

The study area of this report comprehends the coastline between Cabo Raso and Paço de Arcos, in Oeiras, where several dikes crop out. Many of these dikes are mapped in published cartography at the 1/50 000 scale of Cascais (Ramalho et al., 2001) It is suspected that these dikes are part of one of two complexes: the SIC or the LVC (Terrinha et al., 2017). Good exposures of these bodies outcrop in the sandy beaches or in the Lower Cretaceous sandstone or limestone that form the cliffs of the region (**Figure 1.2**).

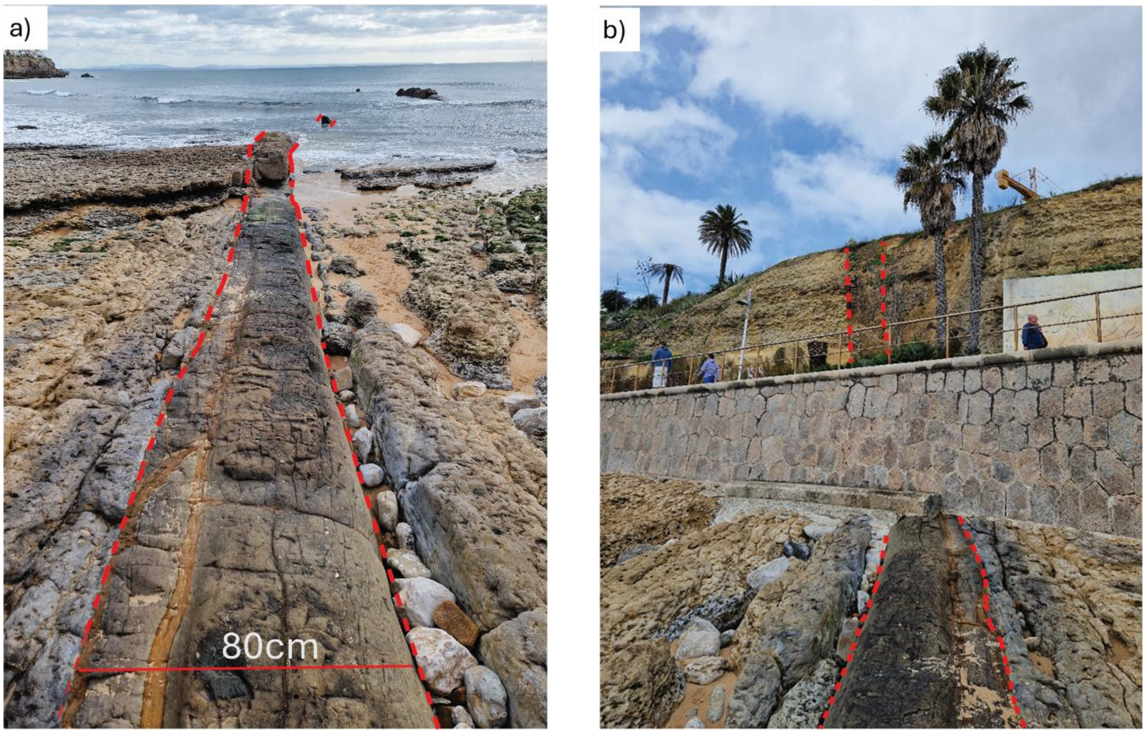


Figure 1.2 – Photos taken E of the Tamariz Beach, standing right on top of a N43ºE/~90º dike that is limited between the red dashes. **a)** Facing SSW, cutting throw the Lower Cretaceous limestones and extending into the ocean, where it shows a slight direction change to south. **b)** Facing NNW, the dike is breaching not only though the beach Cretaceous limestones, but also its propagation through the cliffs.

These bodies usually contain internal mesoscopic structures, such as mineral filled gas vesicles and mineral layering which allow inference on direction and sense of flow as well as fluid behaviour (Geoffroy et al., 2002; Neres et al., 2014). Collecting information about the magma flow and comparing it with location of known magma sources is expected to give information on the origin of dikes, stress field and chronology of intrusions.

In addition to information on the magma flow, these dikes can also give information about the structural control of the area, allowing to infer possible stress fields that controlled the magma emplacement and types of magmatic bodies. The depth at which the dikes were emplaced has not been discussed in the previous inspected bibliography. These are the main topics that I intend to elaborate on and provide new contributions to in this report.

The dikes to be studied are located within the WIM, in the LB, and are part of the WILCAP (Neres et al., 2023). This magmatic event, the third out of three of Mesozoic age, spans from 94 to 69Ma. The occurrences of the WILCAP are widespread in the WIM, both onshore and offshore, resulting in several complexes of intrusive and extrusive bodies and seamounts that have already been identified and some of them studied, e.g. for geochronology, paleo and rock magnetism. However, it is likely that the full extension and volume of this event is still underestimated.

The previous two magmatic events from the Mesozoic occurred: (i) during the Central Atlantic opening (~200Ma), a tholeiitic basalt cycle from Late Triassic- Early Jurassic (Martins et al., 2008) and (ii) around 148-140 Ma, a transitional to mildly alkaline cycle (Mata et al., 2015).

Onshore, the WILCAP is represented by three very well-known intrusive bodies: the Sintra (Terrinha et al., 2017), Sines (Ribeiro et al., 2013) and Monchique (Neres et al., 2024) Igneous Complexes (from north to south, respectively). A NNW-SSE alignment that extends through 300km and can be further connected to the Guadalquivir Bank where a buried magmatic intrusion was also inferred

(Neres et al., 2018). Other studied onshore bodies of the WILCAP are the LVC, the MRDC, the Paço d'Ilhas Diorite, the FF micro-gabbro sill (Miranda et al., 2009; Neres et al., 2012, 2014).

In the offshore, the main occurrences of the WILCAP are a number of volcanic peaks along the 1100 km long Madeira-Tore-Rise (Geldmacher et al., 2006), the sills and plugs of the Ormonde peak of the Gorringe Bank (Geldmacher et al., 2006), the plutonic core of the Guadalquivir Bank and the dikes, sills and volcanoes of the Estremadura Spur, such as the Fontanelas Volcano (Escada et al., 2022). Besides the ones referred, there are many other intrusive and extrusive bodies with smaller dimensions.

Altogether the WILCAP extends over an area of approximately 500 000km^2, straddling across the Azores – Africa Fracture Zone, i.e. the Africa – Eurasia plate boundary in the Atlantic Ocean as proposed by (Neres et al., 2023).

North of the study zone and breaching through the Jurassic and Cretaceous sediments, the SIC is emplaced, one of the largest intrusive bodies of the WILCAP. It has two known magmatic phases: the more recent one with a granitic and syenitic affinity, and an older one with a gabbroic nature (Terrinha et al., 2017).

South of the Cabo Raso and very close to the study area, a series of magnetic anomalies has recently been mapped. One of them, the larger one, is called the CR magnetic anomaly that most probably corresponds to a plutonic complex. This magnetic anomaly is well known since the XV century, because of the magnetic deviation that it caused to the ship compasses when entering in the Tagus River, probably causing several shipwrecks (Neres et al., 2023). Although more detailed studies are needed to better describe this anomaly and its geological causes, it is already known that this is a Cretaceous intrusion and seismic data from marine surveys that were already carried out show that one of these bodies lies only 7 meters below the surface of the sea, covered with Quaternary unconsolidated sediments (Neres et al., 2023). One of the aims of this report is to analyse more data recently acquired close to this anomaly, especially in its north surroundings, to discuss possible relationships between the CR magnetic anomaly and the dikes observed along the coastline.

2 Objectives

The main aims of this report are to (i) discuss the possible magmatic sources of the dikes in study and discuss the probable magma flow pattern; ii) map the overall geometry of the complex of dikes, iii) infer what controlled their emplacement; iv) improve the structural mapping of the region.

The nearest intrusive bodies are the SIC and the CR anomaly (or Cabo Raso Plutonic Complex). Therefore, one of them is the most probable magma source. The examination of the dikes at a mesoscopic scale will be used as an indicator of the sense of flow of the magma, using structures such as gas vesicles that are presently filled in with calcite and may be imbricated with respect to the dikes' margins. According to the data shown in (Sheet 34-C) (*LNEG Dados Abertos*, n.d.), the dikes follow a rough N-S strike and are located between the two large, mentioned plutons, so discriminating the magma sense of flow within the dikes will help establishing an origin for the complex of dikes.

There are other goals that I plan to reach upon this report, namely (i) to determine the stress field that was acting at the time of intrusion of the dike complex based on inspection of deformation structures, and (ii) the correlation of that stress field with the tectonics of the west Iberian margin at that time.

To determine the possible paleo-stress field, an extended field work will be required to study the dikes, as well as interpretation of Google Earth or other satellite images to observe and analyse them at different scales. Analysis and interpretation of geological charts will also be made to map the main regional structures and integrate the study area.

A bibliographic study of the tectonics of the region at the west Iberian margin scale will be carried out to discuss possible correlations between the inferred stress fields and the tectonics of the WIM back then.

With this report I expect to give a good contribution to the scientific knowledge of the geology of this region, but especially to the WILCAP concept.

3 Methods

Multiple methods will be used to accomplish the goals of this work, including both direct and indirect methods for observation or inference of the intrusions and their magnetic anomaly field.

The main method that will be used is the field work. In the field, the mapped (and eventually unknown) dikes will be identified, followed by analysis and interpretation at several scales: large scale mapping and interpretation with support of Google Earth; outcrop scale; and mesoscale. At mesoscale, mesoscopic structural analysis will be conducted to examine mesostructures generated through the magma flow along the dikes, such as gas vesicles often filled in by secondary minerals. Structural measurements also include the strike of the dikes and their dip. This analysis will allow to propose a structural interpretation of them and discuss many important aspects about their emplacement, such as: if these intrusions were forced or not; the stress field associated with them; the kinematics of the intrusions; when possible, the direction of magma flow; eventual recognition of different families of dikes.

The data acquired in the field will be compiled and organised in databases and graphically represented using appropriate methods and software. Structural parameters of the dikes, vesicles, and other field structures will be measured and plotted in a net grid using Stereonet software, enabling the representation of their orientations and the interpretation of geometrical relationships.

Although the field work is important, a cartological analysis is also necessary, in a larger scale, to observe the intrusions as a whole and how they are inserted in the regional geology. All the area from north of Sintra up to Arrábida at south will be analysed and, if needed, geological cross sections will be made to give a 2D view of certain areas, along with identification of deformation structures such as bends or faults. To help this process, I will use Adobe Illustrator, to gather the geological maps required, interpret and draw the structures that might be interesting and give useful information. This will allow to have a larger picture of the regional geology to integrate the field work results. I will also use this software to develop geological cross-sections on how all those structures were formed.

Throughout this report I will be using QGIS, a valuable tool to gather all the georeferenced information acquired in the field, as well as satellite images from Google Earth, which allow to identify and follow the intrusions observed in the field through the coastline in a different point of view. This way it will be possible to analyse their emplacement onshore and make indirect calculations about their length, width differences and possible direction changes. Plus, it is possible to add the georeferenced geological maps of the region and its surroundings to improve the geological significance of the interpretation. With all this gathered information and using a bathymetry layer provided by (*European Marine Observation and Data Network (EMODNET)*, n.d.), a map (**Figure 3.1**) of the whole region will be developed.

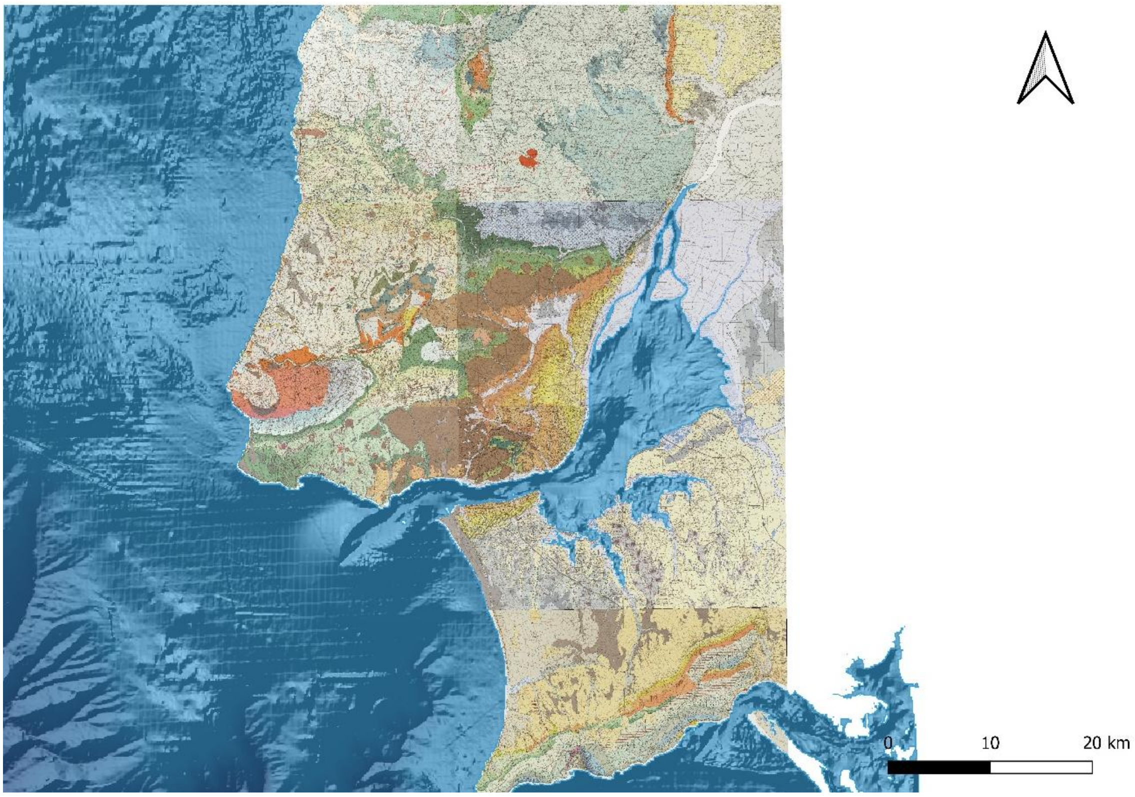


Figure 3.1 - Map developed using QGIS, gathering the georeferenced geological maps of the region along with a bathymetry file provided from (*European Marine Observation and Data Network (EMODNET)*, n.d.).

To study the offshore Cabo Raso intrusion in more detailed resolution and investigate the extension of magnetic anomalies (interpreted as magmatic bodies) towards the coast, a new data set of high-resolution marine magnetic data will be analysed, the TAGUSMAG magnetic data (**Figure 3.2**). This data set was already acquired by the IPMA DivGM team onboard of R/V *Selvagem Grande* of EMEPC during the TAGUSMAG survey in 2020 and 2021 (https://www.emepc.pt/embarcacao-selvagem-grande). The software Oasis Montaj will be used to process both the newly acquired data and previously published magnetic datasets from the ROCHEL and MINEPLAT surveys (**Figure 3.3**), with the aim of providing a more detailed characterisation of the magnetic anomalies, including variations in amplitude, wavelength, and geometry. This software also enables the study of magnetic anomalies using processing techniques and the generation of contours that enhance specific characteristics of the anomalies. This analysis will allow the interpretation of the data in terms of the presence of magmatic bodies and their properties.

A subsequent stage of this work will involve relating the field observations and data to the marine magnetic data, allowing discussion of the offshore continuation of the dikes and their probable source. Finally, an overall interpretative model will be developed by integrating the coastal and offshore results with the onshore structural and cartographic maps.

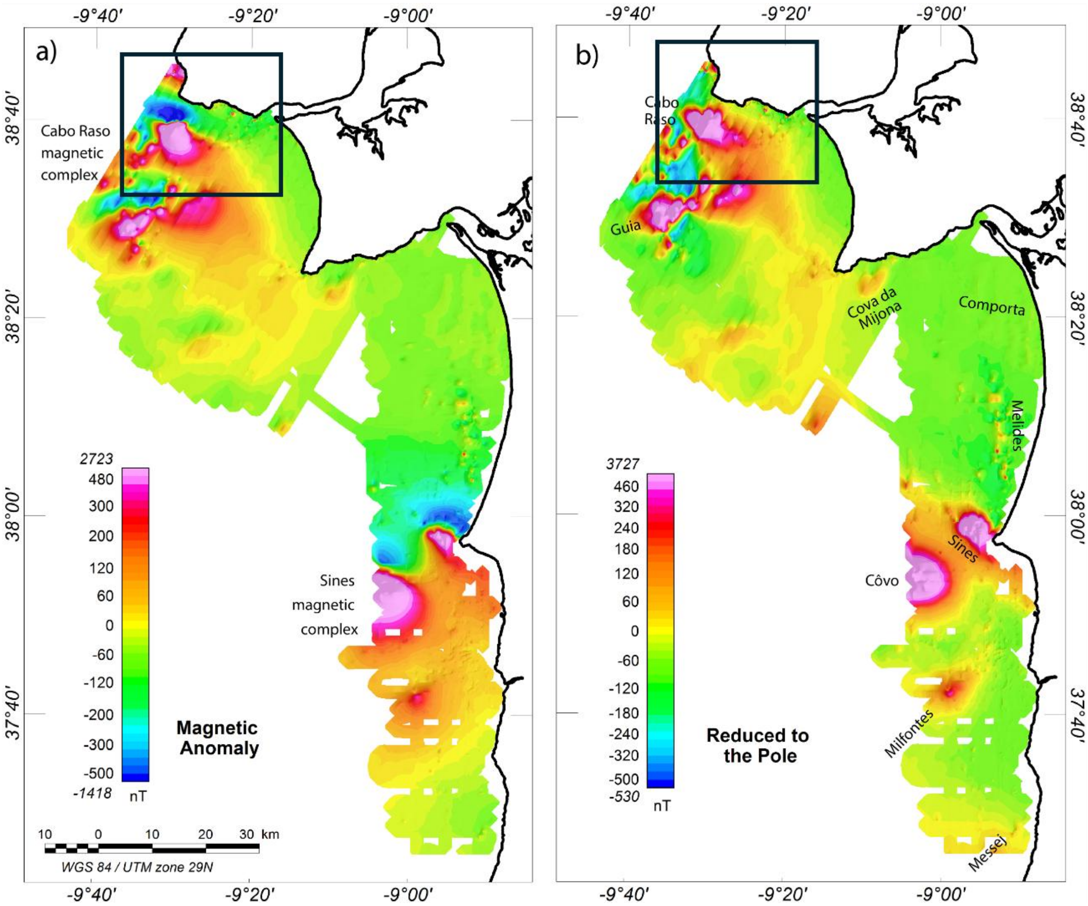


Figure 3.2 - Published magnetic data (ROCHEL and MINEPLAT Surveys) through the centre and south coastline of the West Iberian Margin: **a)** Magnetic Anomaly; **b)** Reduced to Pole, in (Neres et al., 2023). The rectangle corresponds to the limits of the study area in this work (represented in **Figure 3.3**).

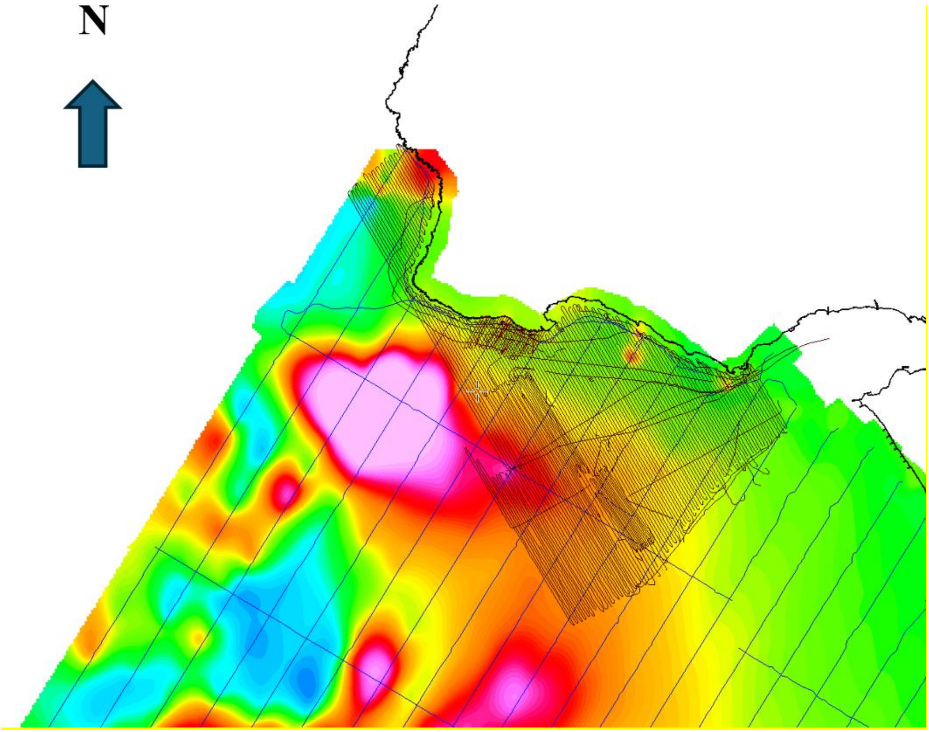


Figure 3.3 - Detail of the previous marine magnetic data (ROCHEL survey, with 1 nautic mile of line separation, i.e. 1852m) overlapped with the acquisition lines of the TAGUSMAG survey, with 125m of line separation. Note the very significant increase in the density of acquisition lines, that will lead to map the anomaly field of the study area in much higher resolution. Provided by Marta Neres.

4 Geological Setting

4.1 Lusitanian Basin

The area of study of this report is in the central sector of the Lusitanian Basin along the WIM (**Figure 4.1**).

This rift-basin is located both offshore and onshore of the north and centre of the WIM (Terrinha, Ramos, et al., 2019) and is associated to the rifting process of the North Atlantic during the Mesozoic. The older sediments of this basin were deposited during the Late Triassic (200Ma), but the formation of the basin started earlier, with collisions from Palaeozoic continents, and continued with the opening and then closing of the Tethys Ocean, ending with the spreading of the North Atlantic (Reis et al., 2011). These Mesozoic extensional episodes lasted until the Early Cretaceous (133-128 Ma, Hauteverian) and after that, the inversion of this basin (along with the Algarve Basin) began, with a compressive character. This inversion, associated with the Alpine Orogeny, started during the Late Cretaceous and continued until the Quaternary (Ramos et al., 2016) and was a consequence of the collision between the Eurasian and African plates. It reached its climax during Miocene, although the Algarve Basin was affected by this compression for a shorter period, just until Oligocene - Early Miocene (Miranda et al., 2009). During this compressive episode, the Bay of Biscay opened in the north of Spain, result from the 35º counterclockwise rotation of Iberia during Aptian (Märton et al., 2004; Vissers & Meijer, 2012).

Geometrically, the LB has a relatively simple shape and an NNE-SSW alignment with 250 kms length, 100 kms width and only 4 kms of maximum sediment thickness (Wilson et al., 1989). It is one of the multiple marginal basins along the coast of the Atlantic North, with the Peniche Basin located W of the LB, in the deep offshore, the Algarve Basin located at South and the Alentejo Basin at SW (Reis et al., 2011).

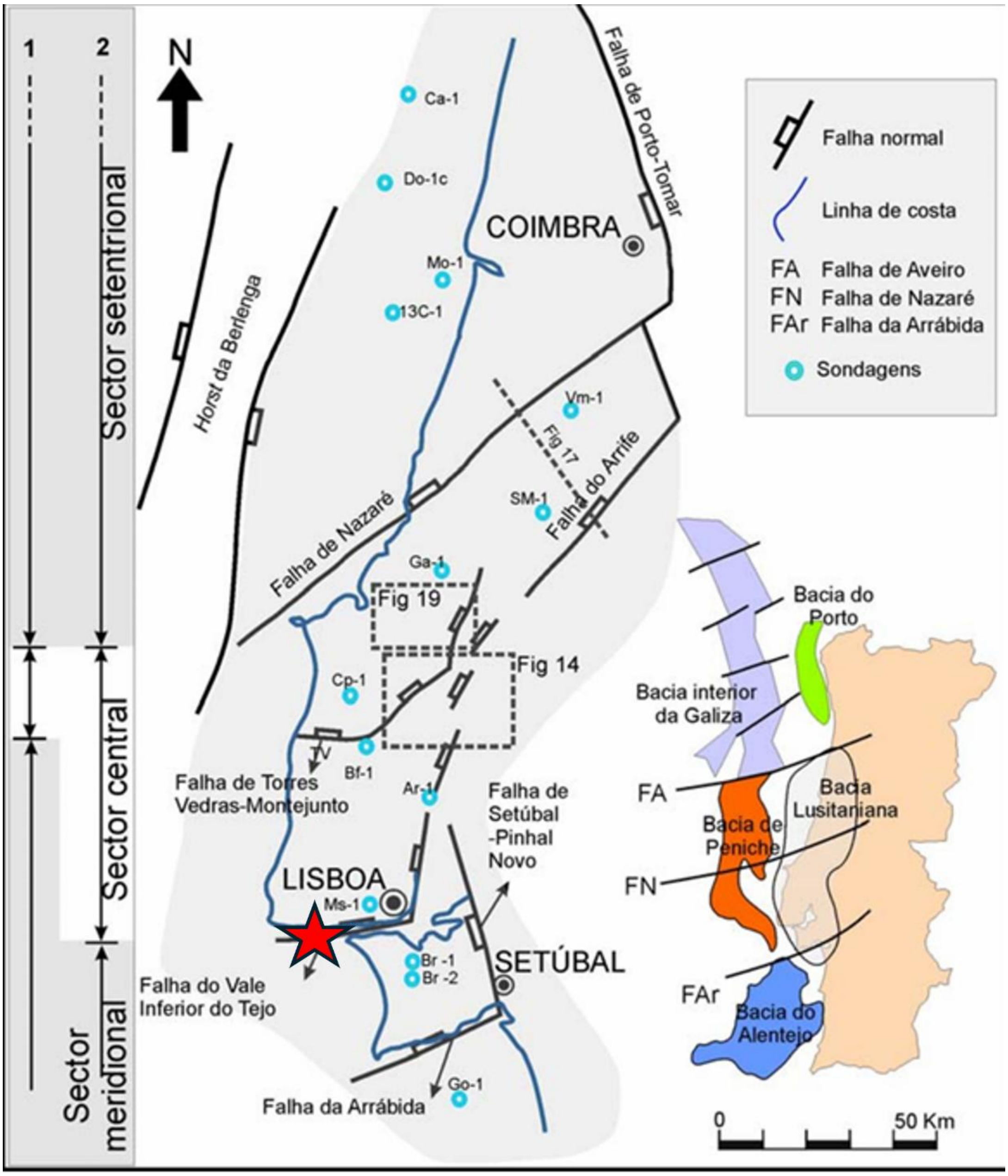


Figure 4.1- Tectonic and Geological Setting of the Lusitanian Basin. The red star indicates the study area. Adapted from (Kullberg, J., et al., 2006).

4.2 West Iberia Late Alkaline Province

The WIM is a prime example of a magma-poor hyperextended continental margin (R. Pereira et al., 2023). It was structured upon the rifting of the Atlantic during Mesozoic times, from Early Triassic to Lower Cretaceous (Soares et al., 2012), after the break-up of Pangea (Terrinha et al., 2017). The evolution of the WIM was controlled not only by the opening of the Ocean, but also by the tectonic structures that were inherited during the Variscan Orogeny, which had great impact upon the formation of sedimentary basins in the area, both onshore and offshore (Alves et al., 2009; Pinheiro et al., 1996). According to (Pinheiro et al., 1996), the opening of the Atlantic took place from south to north, more precisely: i) 136Ma in the Tagus Abyssal Plain; ii) 126Ma in the Iberian Abyssal Plain and; iii) 112 Ma in the Galiza Bank.

Numerous studies (Grange et al., 2008, 2010; Mata et al., 2015; Miranda et al., 2009; Neres et al., 2014) have been conducted to determine the age of the magmatic cycles based on the determined age of the onshore bodies that belong to the WIM. This way, it is possible to determine 3 distinct magmatic cycles. The older one is a basaltic tholeiitic from Early Jurassic (202-198 Ma), the CAMP, associated with the breakup of the Pangeia. The second one is a transitional to mildly alkaline cycle, coeval with the thinning of the oceanic lithosphere, with Jurassic-Cretaceous transition age (148-140Ma), from melting of the metasomatized lithosphere (Mata et al., 2015). This is the least understood cycle since it is only existent in the LB in two sub-meridional alignments between Rio Maior and Soure (Mata et al., 2015). The third one is the most important for this study and also the most significant one in the WIM with the most outcropping bodies, the WILCAP, with ages between 94-69Ma, a post-rifting event (**Figure 4.2**).

The WILCAP event, according to geochronological studies on onshore rocks, can be divided in two pulses: i) the first one, that age from 94-88 Ma, which is synchronous with the opening of the Bay of Biscay and the rotation of Iberia, and can be observed mostly through sills (94Ma FF and Paço de Ilhas sills, for example) (Miranda et al., 2009); and the second one, younger, with ages between 78-69Ma, can be observed onshore from south of Portugal (Monchique) to north of Lisbon, where it is represented by the SIC and the LVC, along with other small intrusions such as dikes and sills (Miranda et al., 2009; Neres et al., 2014; Terrinha et al., 2017). It is synchronous with the tectonic inversion of Mesozoic sedimentary basins due to the fast convergence of the African and European plates (Miranda et al., 2009).

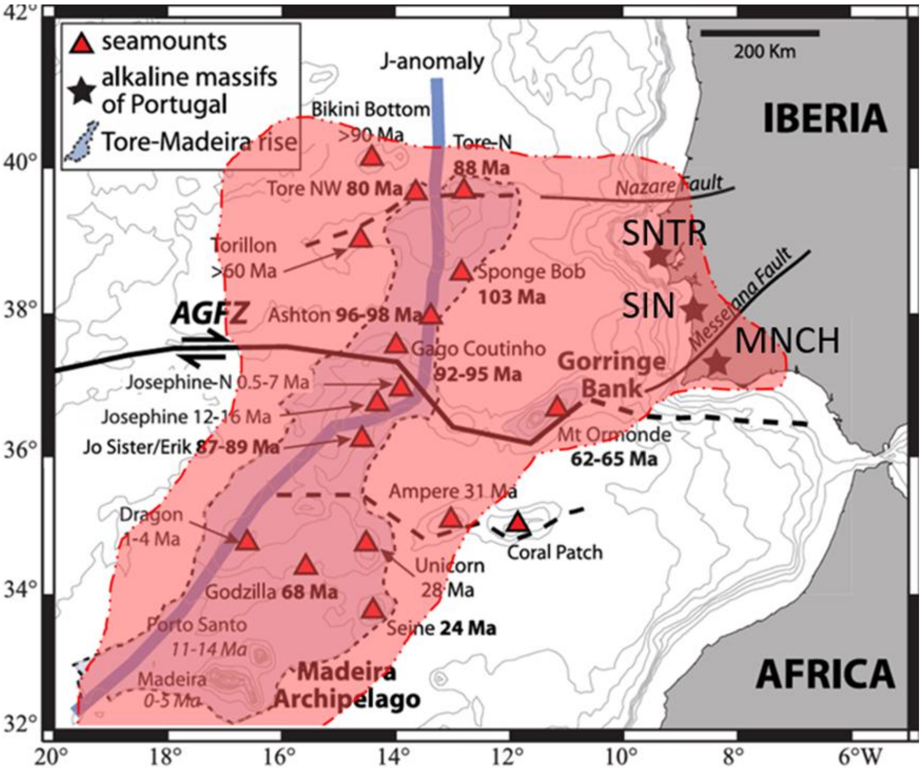


Figure 4.2 - WILCAP straddling in red, along with the 3 principal onshore intrusive bodies forming the NNW-SSE alignment (Sintra-Sines-Monchique, from north to south respectively) and all the seamounts currently known. Adapted from (Grange et al., 2010).

As referred above, the WILCAP event generated many intrusive (and some extrusive) bodies, the best-known ones present in the onshore. The 3 larger plutonic massifs (Sintra, Sines and Monchique), show an NNW-SSE alignment, with at least 300kms length and ends south near the Guadalquivir Bank (Neres et al., 2018; Ramalho et al., 2001), being present in the LB, the Algarve Basin and the Alentejo Basin. The Sintra and Sines Complexes extend into the sea, while Monchique only crops out on land (Neres et al., 2023).

According to (Terrinha, 1998), this alignment is deeply rooted into the asthenosphere mantle, being a dextral fault that generates releasing bends where the magma can ascend, reaching the lithosphere and then being controlled by much shallower structures. All the massifs have an elliptical roughly W-E shape, and therefore they were probably controlled by faults with that direction.

Petrographic analysis show that the 3 massifs are very similar, which together with the dated ages allows to assume that they are all part of the same magmatic event. The SIC has a syenite core (80.1 ± 1.0 Ma), surrounded by a 81.7 ± 0.4 Ma granite ring and other gabbro-diorite discontinuous ring (83.4 ± 0.7 Ma) (Grange et al., 2010; *Tectónica Das Regiões de Sintra e Arrábida*, 2000). As for the Sines complex, outcropping in the Alentejo Basin, it is dated 77-76 Ma and includes a gabbro-diorite-syenite suite and an associated dike swarm (Oliveira, 1990). Recently, offshore magnetic surveys (Neres et al., 2023) showed that the intrusion extends offshore, and that other, even larger, plutonic bodies are intruded off Sines (the Côvo intrusion). The Monchique alkaline complex is the most recent one out of the three, aging around 72Ma (Miranda et al., 2009). It is formed by a small gabbro that outcrops within two larger concentric nepheline syenite bodies (Rock, 1978). It is the most voluminous of the southern alkaline intrusion and the only one intruding exclusively in rocks of Palaeozoic age (Miranda et al., 2009; Neres et al., 2014).

Back to the LB, the LVC emerged mostly at East of the Sintra massif, with little portions at its northern side too. Covering an area of 200 km² with basalts and basanites that are shown through vents, plugs, lava flows, sills, and dikes that range from basanitic to rhyolitic composition (Palácios, 1985), this complex was dated at around 72 ± 3.1Ma, although this age has been contested by paleomagnetic data (Neres et al., 2012) and unpublished geochronology data (Miranda, personal communication). According to (Ramalho et al., 2001) the dikes in study in this report are the probable magma feeders for the LVC.

Other smaller onshore intrusions are also part of this event, despite not being emplaced along the NNW-SSE alignment. Some examples are the Paço de Ilhas and Anços sills, and the MRDC, to the north of Sintra (Miranda et al., 2009; Neres et al., 2012; Nogueira, 2008). The FF Sill, located at 30km SW of Lisbon in the Setúbal Peninsula, between Sintra and Sines and dated 93.8 ± 3,9Ma (Miranda et al., 2009), is the southernmost intrusion in the LB, showing a 8m thick sill intruding Early Cretaceous sediments (M. C. Kullberg et al., 1996; Neres et al., 2014).

The offshore of this province is very vast and rich in occurrences, with evidence of intrusive and extrusive complexes along the Madeira-Tore Rise, the Estremadura Spur and nearshore, such as the CR and Sines offshore magnetic complexes.

The Madeira-Tore Rise is a 1000km long bathymetric anomaly, that raises from depths larger than 4000 m bsl and achieves 150 m bsl. It is cut by the Azores-Gibraltar Fault Zone. The Madeira-Tore-Rise is punctuated by several seamounts which, according to (Geldmacher et al., 2006), reach ages of 95Ma, although there are smaller younger sub-seamounts. The isotopic composition and trace elements of magmatic rocks collected at seamounts that crop out along the Madeira-Tore Rise show similarities with the mantellic plume derivation of the Canarias. (Geldmacher et al., 2006) propose an interaction between Canarias' hotspot and the mid-Atlantic spreading centre as the origin for this complex.

The Estremadura Spur is a bathymetric anomaly that extends offshore, from the region of Sintra up to the Tore seamount. It hosts a large number of magmatic intrusions and extrusions, identified through magnetic anomalies (Neres et al., 2014) and by seismic interpretation and magnetic modelling (Escada et al., 2022; R. Pereira et al., 2023).

The Fontanelas Volcano (**Figure 4.3**), emplaced in Estremadura Spur, is a typical triangular profile shaped volcano (R. Pereira & Gamboa, 2023) with 26x17 km.

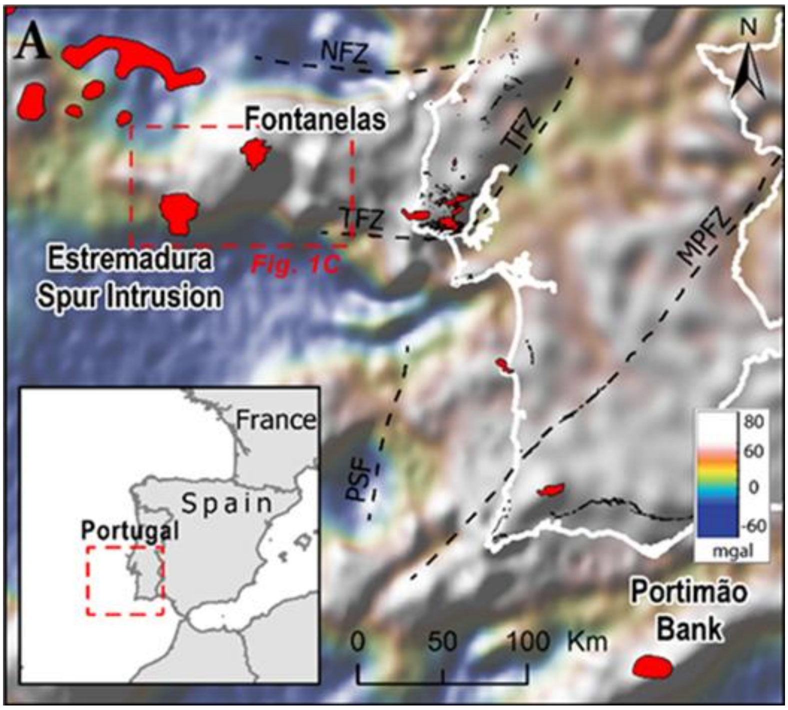


Figure 4.3 - Fontanelas and Estremadura Spur, from (Escada et al., 2022).

5 Study Area

5.1 Onshore

The dikes in the area of study, between the red arrows in **Figure 5.1** are placed onshore near the coastline between Cabo Raso and Paço de Arcos, in Oeiras The most prominent lithologies that hosts these intrusions between Tamariz Beach and Santo Amaro de Oeiras Beach are Albian to Cenomanian limestones and marls, a geological layer called “Calcários e margas do Balesiano”. West of that area, these intrusions are hosted by older layers, from Early-to-Middle Cretaceous, but still being the same lithologies.

East of the study zone, the LVC outcrops in the great Lisbon area, sometimes covered with sands and clays from Early-to-middle Tertiary, Cenozoic. To the east of that area, the LVC is no longer observed, and only Late Tertiary sediments outcrop, near the Tagus River.

North of the study area the SIC is emplaced. This unit breaches through Late Jurassic layers, with ages comprehended between the Upper Oxfordian to the Tithonian forming compact and marly limestones. Plus, some Early Cretaceous layers are also affected by this intrusion, namely between Berrasian and Early Hauteverian ages, in the form of reef limestones, marls and sandstones. **Figure 5.2** represents the caption of the geological maps.

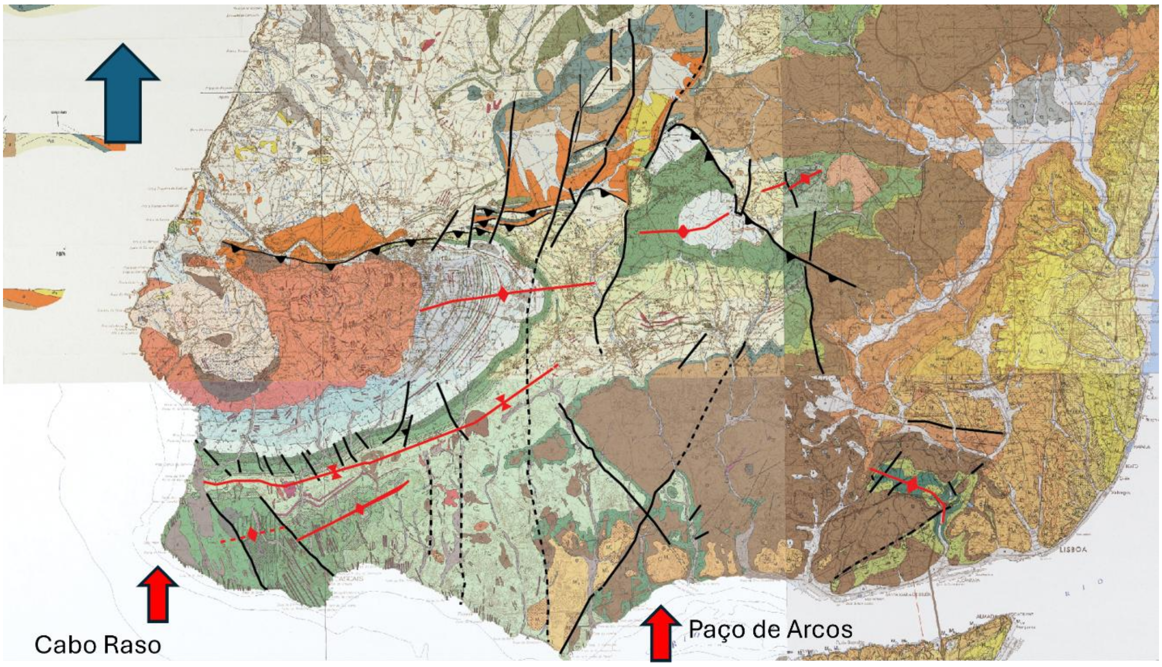


Figure 5.1 - Scheme elaborated in Illustrator with 1:50 000 scale geological maps of the Sintra, Cascais, Lisboa and Loures regions, available in (*LNEG Dados Abertos*, n.d.). The faults are represented in black segments and the bends in red.

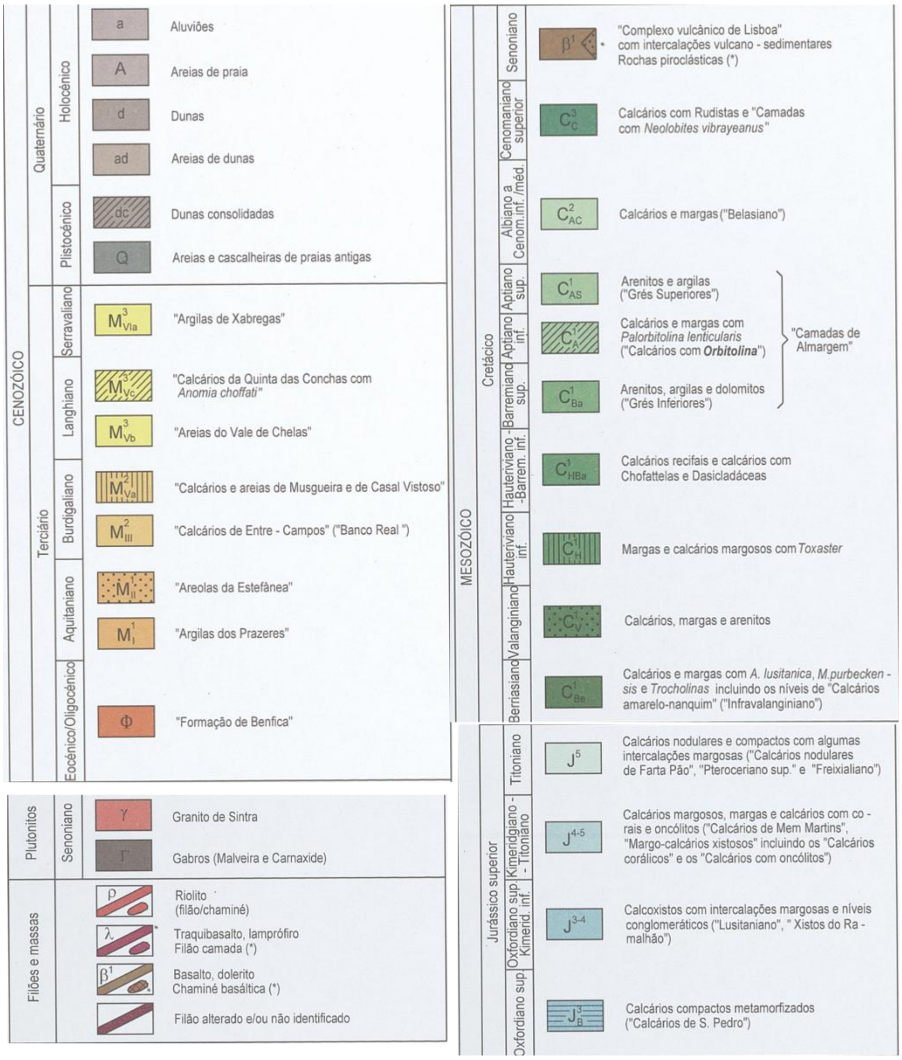


Figure 5.2 - Caption for the Geological maps, from Carta 34-C Cascais available in (*LNEG Dados Abertos*, n.d.).

5.2 Offshore

One most important offshore feature for this report is the CR magnetic complex, located south of Cabo Raso, in the offshore of the LB, observed in **Figure 3.2**, along with the full area of MINEPLAT and ROCHEL surveys. Both these magnetic surveys (Neres et al., 2023), particularly the ROCHEL survey (conducted from Cabo da Roca to Cabo Espichel), and interpretation of mapped magnetic anomalies support that this is a vertical-edged, deep-rooted plug-like volcanic body, highly magnetized. The top of the magmatic body that causes this anomaly is imaged by seismic reflection data, covered by only 7 meters of Cenozoic clastic sediments (Terrinha, Duarte, et al., 2019).

A new magnetic survey, the TAGUSMAG survey, was conducted in 2020 and 2021 to complement results from the ROCHEL survey, by acquiring data with much higher spatial resolution, aiming at mapping in high detail the magnetic anomalies close to the coast, and infer smaller scale links between the large Cabo Raso magnetic anomaly and the offshore magmatic occurrences. One of the aims of this report is to analyse with the software Oasis montaj the TAGUSMAG magnetic data. Some magnetic maps that result from processing of this data set developed previously are showed in **Figure 5.4** and **Figure 5.5**. The objective is to identify magnetic lineations and describe other types of anomaly variations, with the main goal of relating the information acquired from the magnetic data to the one obtained in the field, in order to discuss the offshore continuation and probable provenance of the dikes.

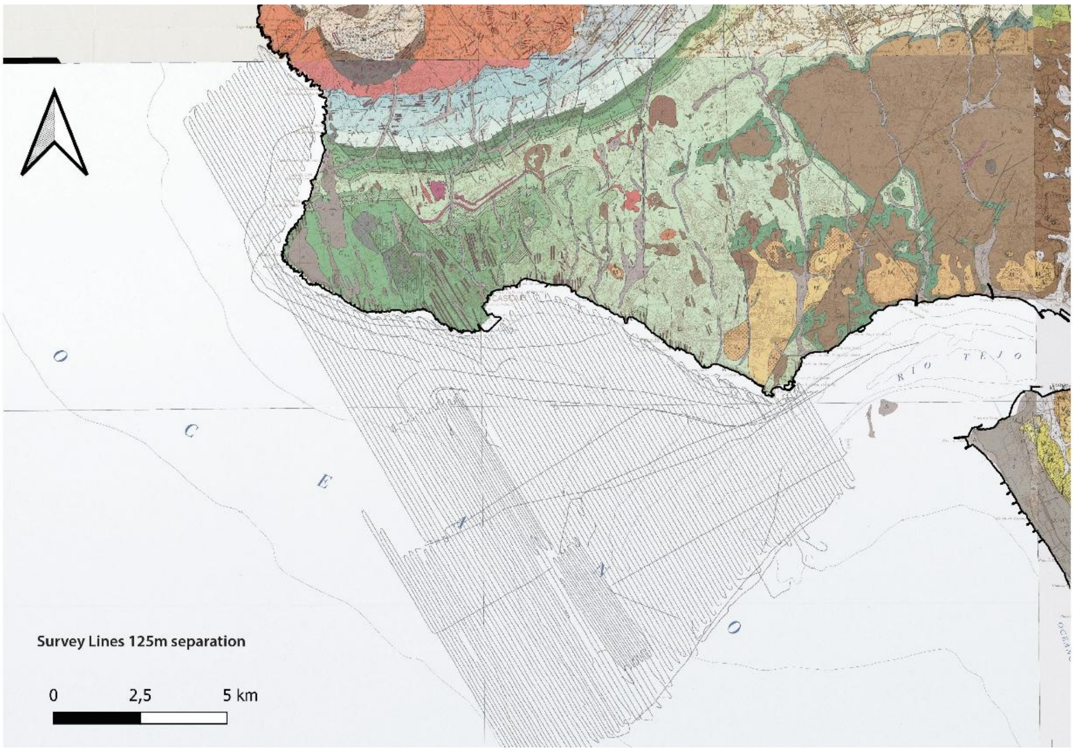


Figure 5.3 - Survey lines from TAGUSMAG survey, with 125m of separation. Unpublished data, (Neres, personal communication).

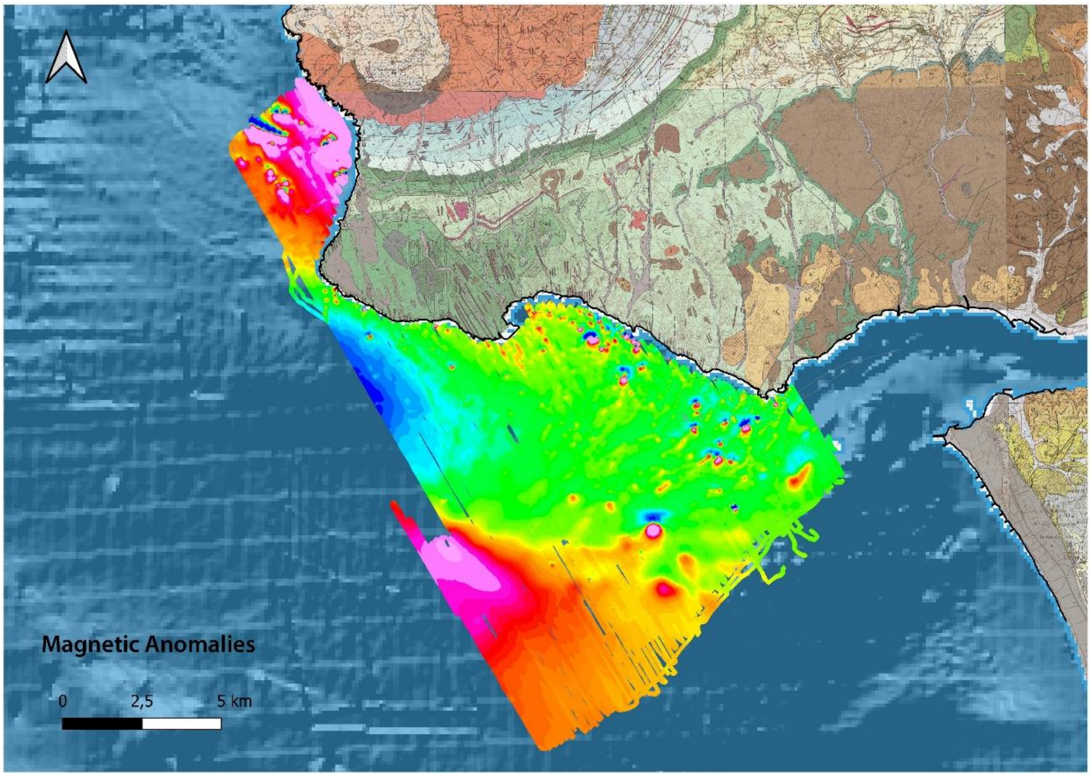


Figure 5.4 - Magnetic anomalies after processing of TAGUSMAG data. Unpublished data (Neres, personal communication).

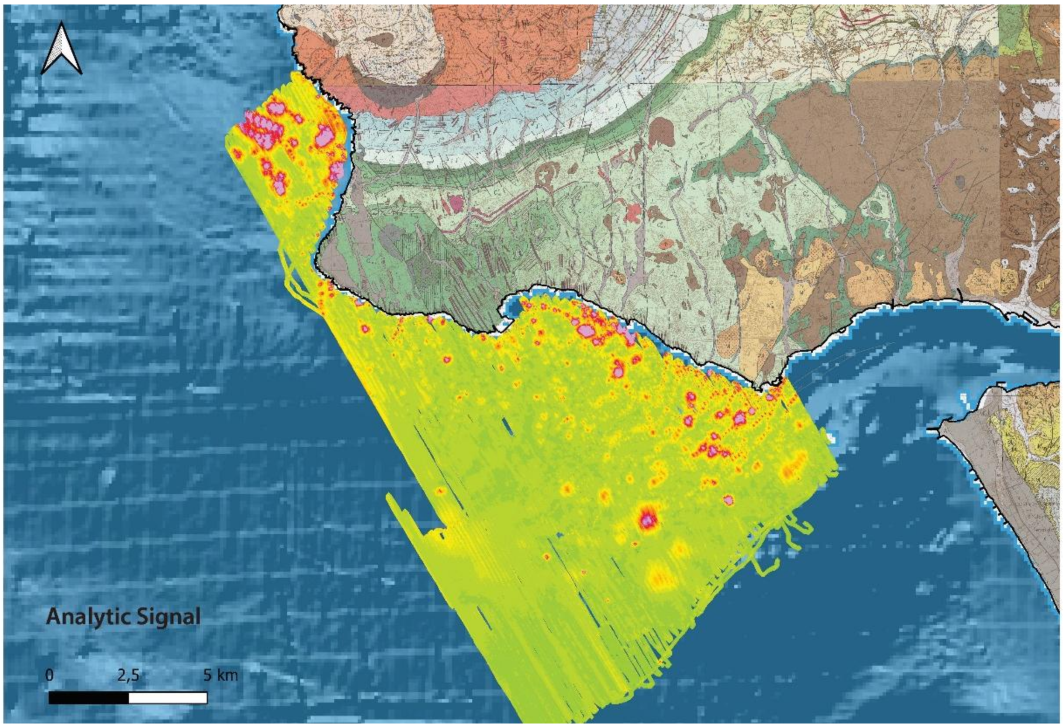


Figure 5.5 – Analytic signal map of the magnetic anomaly field. Unpublished data (Neres, personal communication).

These maps were created using the software QGIS, by gathering the different types of maps and data. In the **Figure 5.3**, the onshore map represents the 34-C geological map of Cascais, (*LNEG Dados Abertos*, n.d.), with the acquisition lines from the TAGUSMAG survey. These lines have 125m separation and were obtained with a magnetometer towed by the R/V "*Selvagem Grande*" (*Estrutura de Missão Para a Expansão Da Plataforma Continental (EMEPC)*, n.d.) in collaboration with EMEPC (*Estrutura de Missão Para a Expansão Da Plataforma Continental (EMEPC)*, n.d.). In **Figure 5.4**, in addition to the geological map referred above there is also a bathymetry map (*Estrutura de Missão Para a Expansão Da Plataforma Continental (EMEPC)*, n.d.) downloaded from https://emodnet.ec.europa.eu/en and the magnetic anomalies map after processing placed on top. **Figure 5.5** represents all the data above, with the offshore map representing the analytic signal of the magnetic field. The analytic signal is a very useful tool since it measures the magnetic anomaly gradient and locates the magnetic sources, aspects that are important for this report.

6 Regional Tectonic Interpretation

Using the software Adobe Illustrator and the geological maps of Portugal on a scale of 1:50 000 from *https://geoportal.lneg.pt/pt/dados_abertos/cartografia_geologica/cgp50k/* (*LNEG Dados Abertos*, n.d.), a tectonic interpretation has been elaborated, with special attention to the study zone and its surrounding areas as shown in **Figure 5.1**.

Along the elaboration of this tectonic interpretation, many important aspects in the geology of the region were observed. In the Sintra massif zone, there is a W-E anticlinal structure, with the fold hinge right in the centre of the massif, with layers from Late Jurassic and Early Cretaceous outcropping through the south and east flanks. The west flank is probably submersed into the Atlantic Ocean, and the north flank was cut by a thrust fault. This thrust fault, with a rough W-E direction, cuts the Mesozoic layers of the anticlinal, around the Sintra intrusion, with exhumation of this south block, outcropping in the northern area layers from a very younger age (Late Cretaceous to Miocene/Oligocene). The thrust fault is being cross by transfer faults at its eastern end, all of them in a dextral strike-slip fault.

At south of the intrusion, a series of strike-slip faults cut the Late Jurassic/Early Cretaceous layers, with a preferred orientation of NNW-SSE, with some NNE-SSW occurrences too. As observed during field work, this is a very common direction observed as the main strike of the dikes, which may suggest that the geological phenomena that gave origin to those faults, is probably the same that generated the structural control of the path that the magma went through when feeding the dikes.

7 Field Work for dike mapping

7.1 Main Goals

The main goal of this field work is to conduct a detailed study of the dikes present between Cabo Raso and Paço de Arcos, aiming to characterize them at mesosetructural levels. This part of this study seeks to identify different types of dikes, describing their mineralogical composition and morphology, as well as analysing the presence of vesicles, inclusions and other filling features, documenting their distribution and dimensions. Other goals to be achieved include mapping the orientation, extent and geometry of the dikes and to determine their structural control, including faults and fractures near them, while relating their occurrence to the regional geological structure. Finally, the collected data will be integrated to produce maps and diagrams that include information on their mineralogy and structural control, allowing for the interpretation of the genesis and evolution of those dikes in the geological context of the region and suggesting possible relationships between intrusion processes and pre-existing structures.

7.2 Studied areas/dikes

In **Figure 7.1** is shown a satellite photograph of the area of study with the red stars numbered from 1 – 11, locating all the dikes observed throughout the conducted field work.

Figure 7.1 – Map of the study area with studied dikes represented by the red stars, numbered from 1 to 11, each one representing a zone with dikes present. 1 – Boca do Inferno; 2 – West of Farol-Museu de Santa Marta; 3 – East of Tamariz Beach; 4 – São João do Estoril Beach; 5 – Bafureira Beach; 6 –Avencas Beach; 7 – West of Restaurante Bérrio; 8 – East of Parede Beach; 9 – Santo Amaro Beach; 10 – East of São João das Maias Fort; 11 – East of Fontainhas Beach.

7.3 Mesoscale characterization of dikes

Field work has already been carried on between Boca do Inferno and Paço de Arcos, where many dikes were identified and studied in detail. The field work allowed to distinguish two different families of these intrusions (**Figure 7.2**): a first family of mafic dikes, darker and usually very rich in phenocrystals (**Figure 7.3.a**) of an unknown mineral, possibly amphibole,; and a second family of felsic dikes, from magmas with a higher silica percentage, resulting in a lighter colour and some gas vesicles that only appear in this family of dikes and are often filled in with calcite.

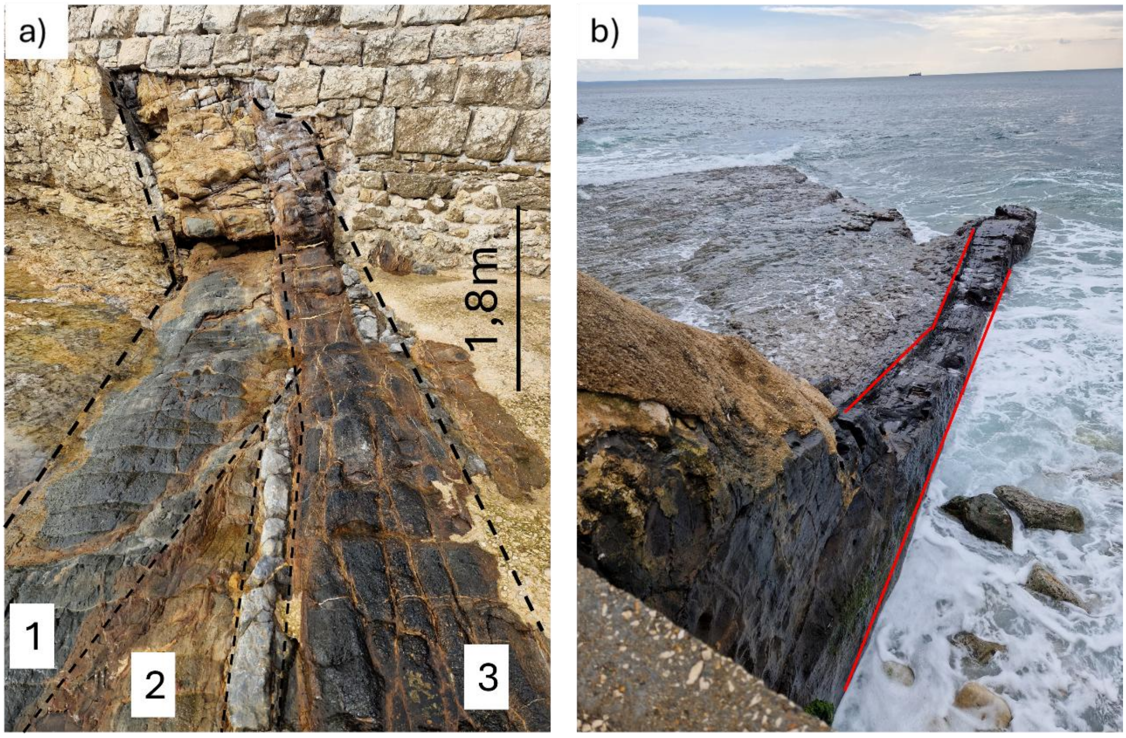


Figure 7.2 - Dikes from: **a)** east of Parede Beach, picture taken facing NNW, N20ºE/~80º dikes limited by the black dashes. Dikes 1 and 2 show a felsic composition and abundance of vesicles. In contrast, dike 3 is mafic and has no vesicles but contains some phenocrystals. **b)** picture taken facing SSE of a N8º/90º mafic dike with close to 50cm width, limited by the red lines, between Avencas beach and Parede beach, next to Restaurante Bérrio. This dike is emplaced between limestones on its left, and sandstones/beach sand on its right.

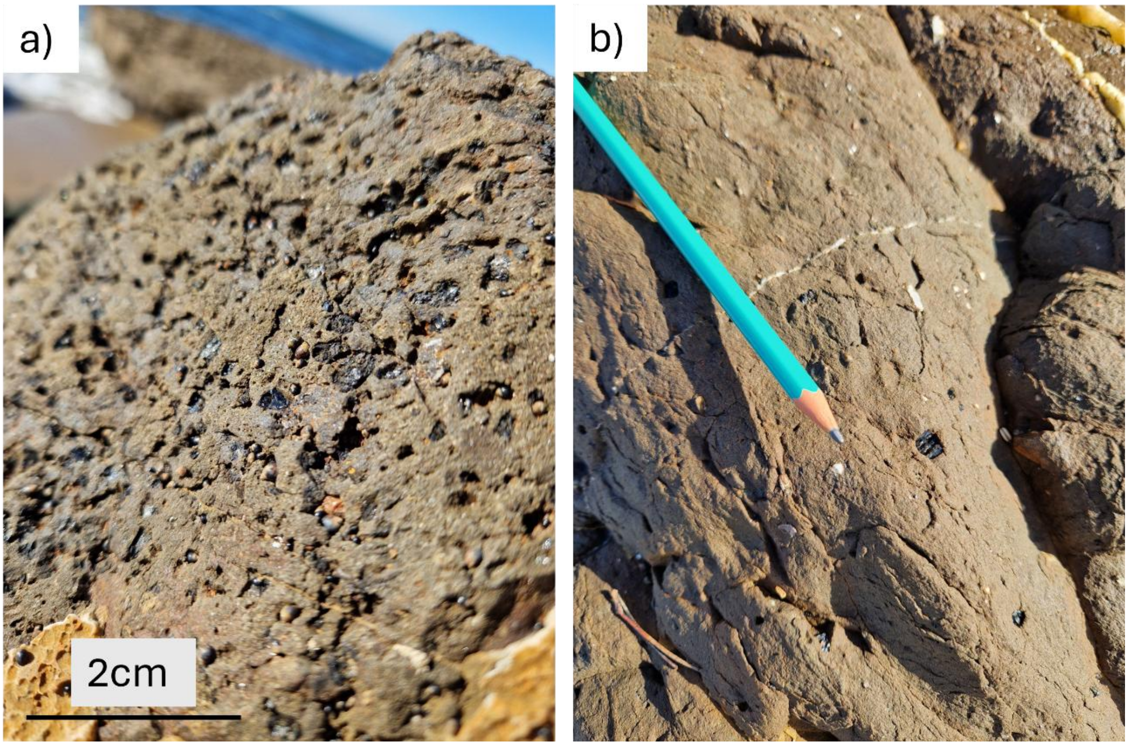


Figure 7.3 - Photographs of dikes with black phenocrystals – **a)**: mafic dike from Avencas Beach; **b)**: mafic/intermediate dike from Bafureira Beach.

The presence of vesicles in many dikes provides valuable information about their formation. Their occurrence suggests that the magma had a high silica content, which increases its viscosity and hinders the ascent of gas bubbles, trapping them within the cooling magma. As a result, most vesicles developed an elongated shape, aligned with the flow of the moving magma. Along the contacts with the host sediments, these vesicles may exhibit tilting relative to the dike margin, a feature known as imbrication. When this imbrication is consistent along the margins of a dike in a symmetrical manner, it can provide information about the direction of the magmatic flow that fed the dike. These vesicles may also become filled with secondary minerals, such as calcite, and can be exposed when the dikes undergo erosion and weathering. While most dikes display vesicles elongated along the flow direction, only a few show vesicles with clear imbrication.

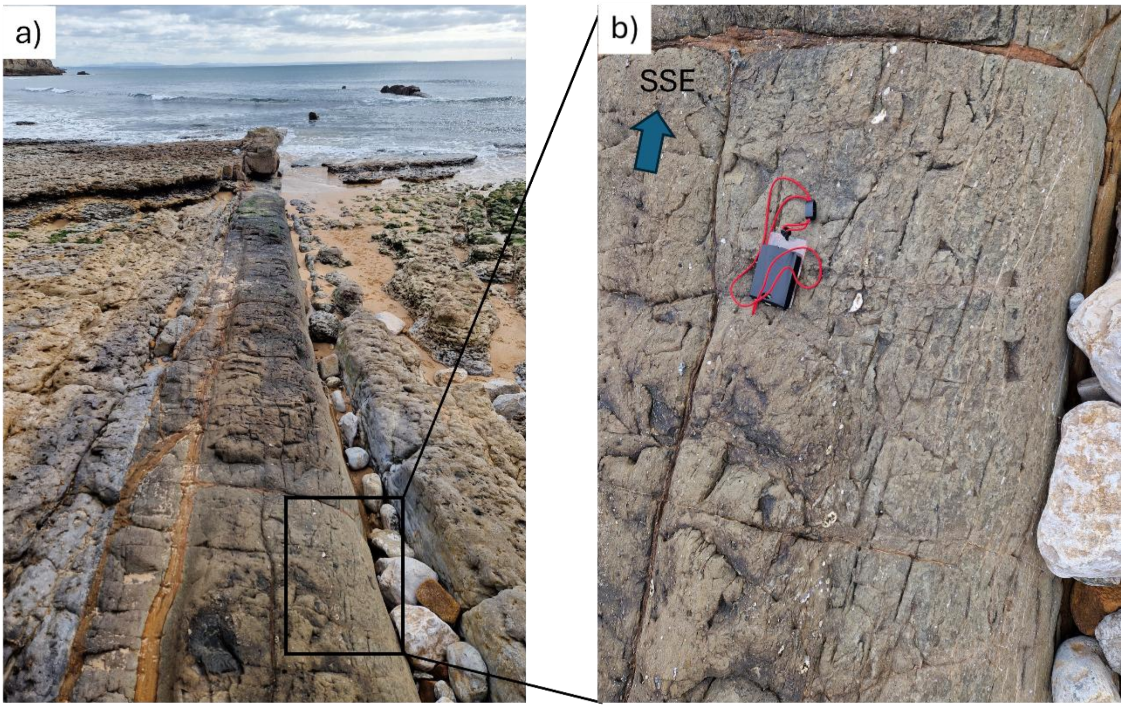


Figure 7.4 – **a)**: Picture taken facing SSE, same dike from **Figure 1.2**; **b)**: closer picture of the white vesicles near the compass, seen in the western margin of the same dike, suggesting imbrication.

In **Figure 7.4-b)**, the vesicles displaying imbrication are filled with calcite and suggests a magmatic flow direction from south to north, likely from offshore towards onshore. This interpretation is based on the orientation of the tilted vesicles. Specifically, as shown in **Figure 7.5**, these vesicles are located on the western margin of the dike, with their northern ends tilting toward the interior of the dike, which implies that the magma flowed from south to north.

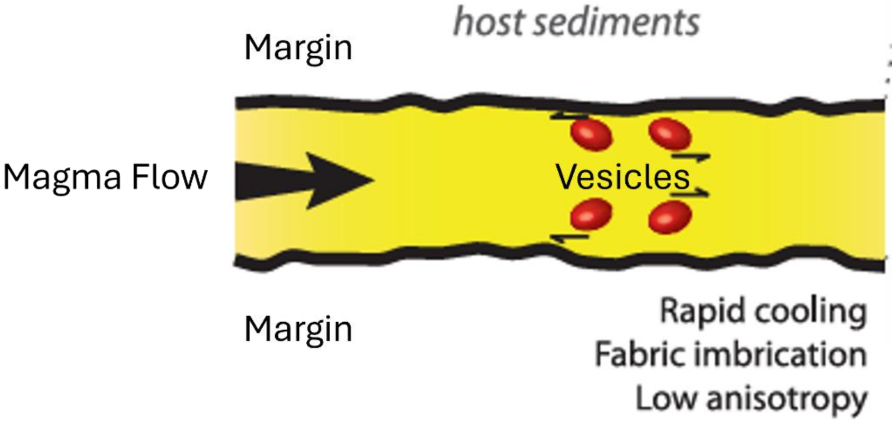


Figure 7.5 - Adapted scheme from (Neres et al., 2014), of the direction of imbrication of the vesicles through the margin of the dike and its correlation with the sense of the magmatic flow.

7.4 Geometric measurements of the dikes

The orientations and inclinations of all the dikes observed in the study area were measured, as well as any variations where these existed. In this way, two families of preferred orientations were determined: one with an approximate NNW-SSE (NW-SE) orientation and the other with an NNE-SSW (NE-SW) orientation. All orientations measured in the field were placed in stereographic networks, one for each family of preferred orientations, using Stereonet software, obtaining the results presented in the **Figure 7.6**. **Figure 7.7** is an example where both orientations can be observed in the same outcrop, with dikes displaying both left-lateral and right-lateral offsets along their extent.

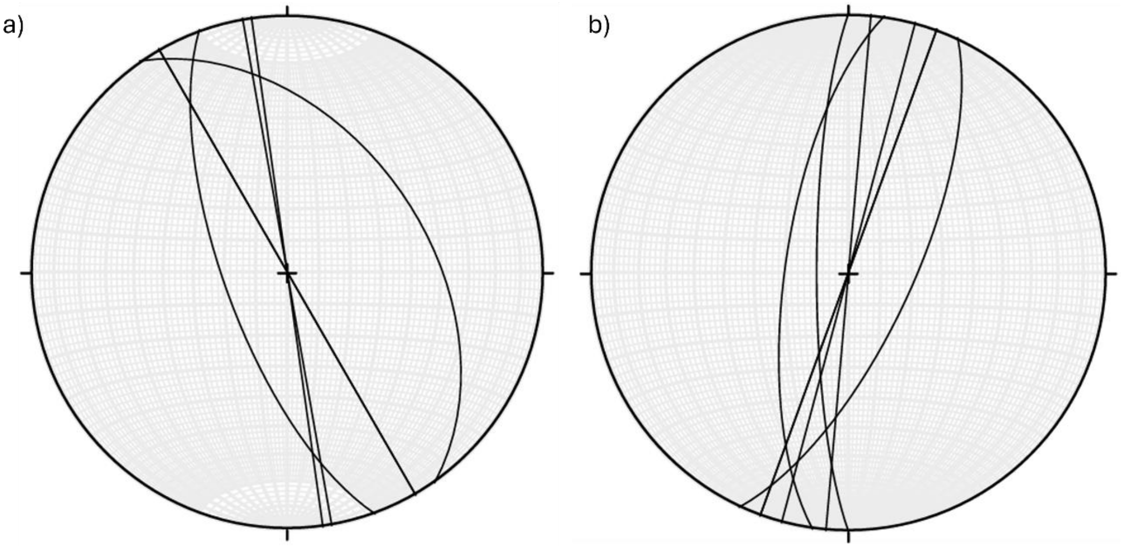


Figure 7.6. Stereographic network with all the observed dikes, representing strikes and dips. **a)** NNW-SSE strike and **b)** NNE-SSW strike.

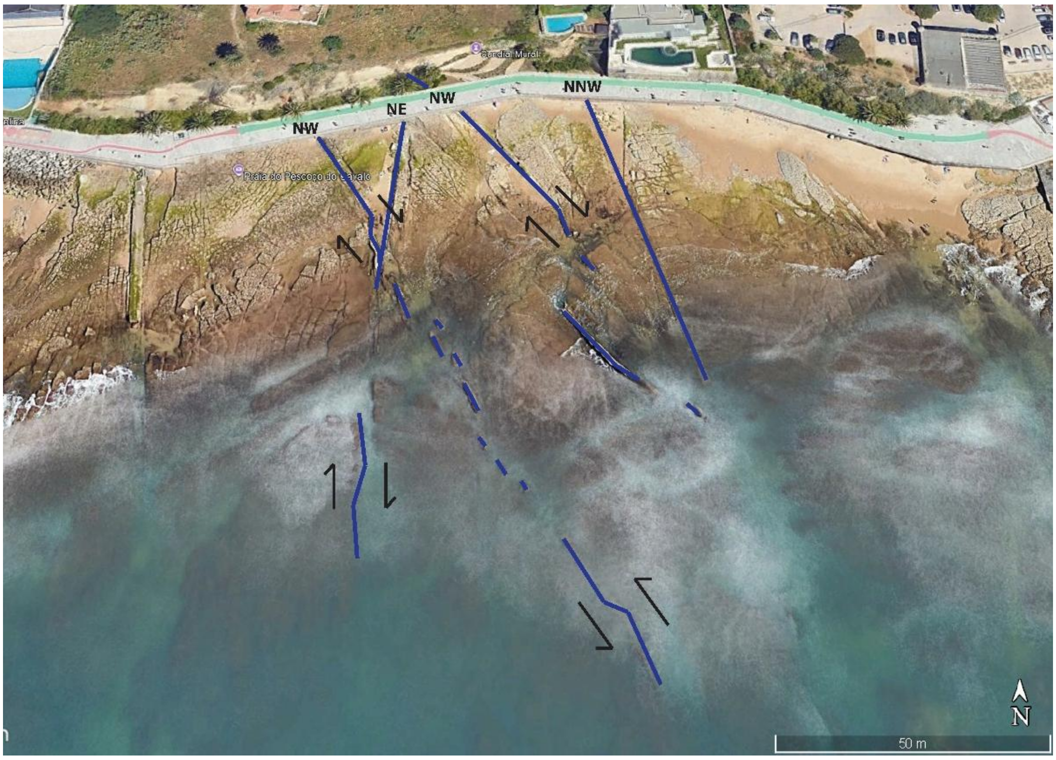


Figure 7.7 - Example of dikes identified in blue. The black arrows near the dikes represent the right-lateral and left-lateral offsets. These dikes are breaching through the limestones in the beach and in the same site the two orientation families are observed. Picture taken from Google Earth, east of Tamariz Beach.

8 Field work between Paço de Arcos Beach and Forte de São João das Maias

8.1 Introduction and study Zones

Fieldwork was carried out on March 3rd of 2025 in the area known as Fontainhas, along the coast between Paço de Arcos and Santo Amaro beaches. The construction of the PMO in 2009 exposed different outcrops along this area, allowing for improving of the existing geological mapping. This work provided various insights into the distinct geological characteristics observed. The present lithologies were mostly composed of Upper Cretaceous limestones (Ramalho et al., 2001), designated as Limestones with Rudists and "Beds with *Neolobites vibrayeanus*"), with slight variations among them in terms of fracturing, crystallinity, compaction, and fossil content. Equally important, some volcanic occurrences were also part of the study, appearing in the form of an ignimbrite and dikes (which, according to the aforementioned 34-C map, belong to the LVC and are represented as basalts and dikes).

The study area was divided into five zones, according to:

- **Zone 1**: Outcrop with compact limestones showing almost perpendicular fracturing (rhombus pattern);
- **Zone 2**: Immediately west of Zone 1, a limestone layer also showing fracturing, but with more heterogeneous strikes;
- **Zone 3**: Two felsic dikes;
- **Zone 4**: West of Fontainhas Beach, presence of an ignimbrite possibly bounded to the east by a fault. A basaltic dike is also present;
- **Zone 5**: A small area corresponding to an inclined limestone layer, leaning against the wall of the Fort.

The map in **Figure 8.1** was created, showing the different study zones and their respective lithologies, as well as the observed faults and dikes. The stereonets for Zones 1 and 2 represent the orientation of fractures, while in Zones 3 and 4 indicate the directions of the fault and dikes in their vicinity.

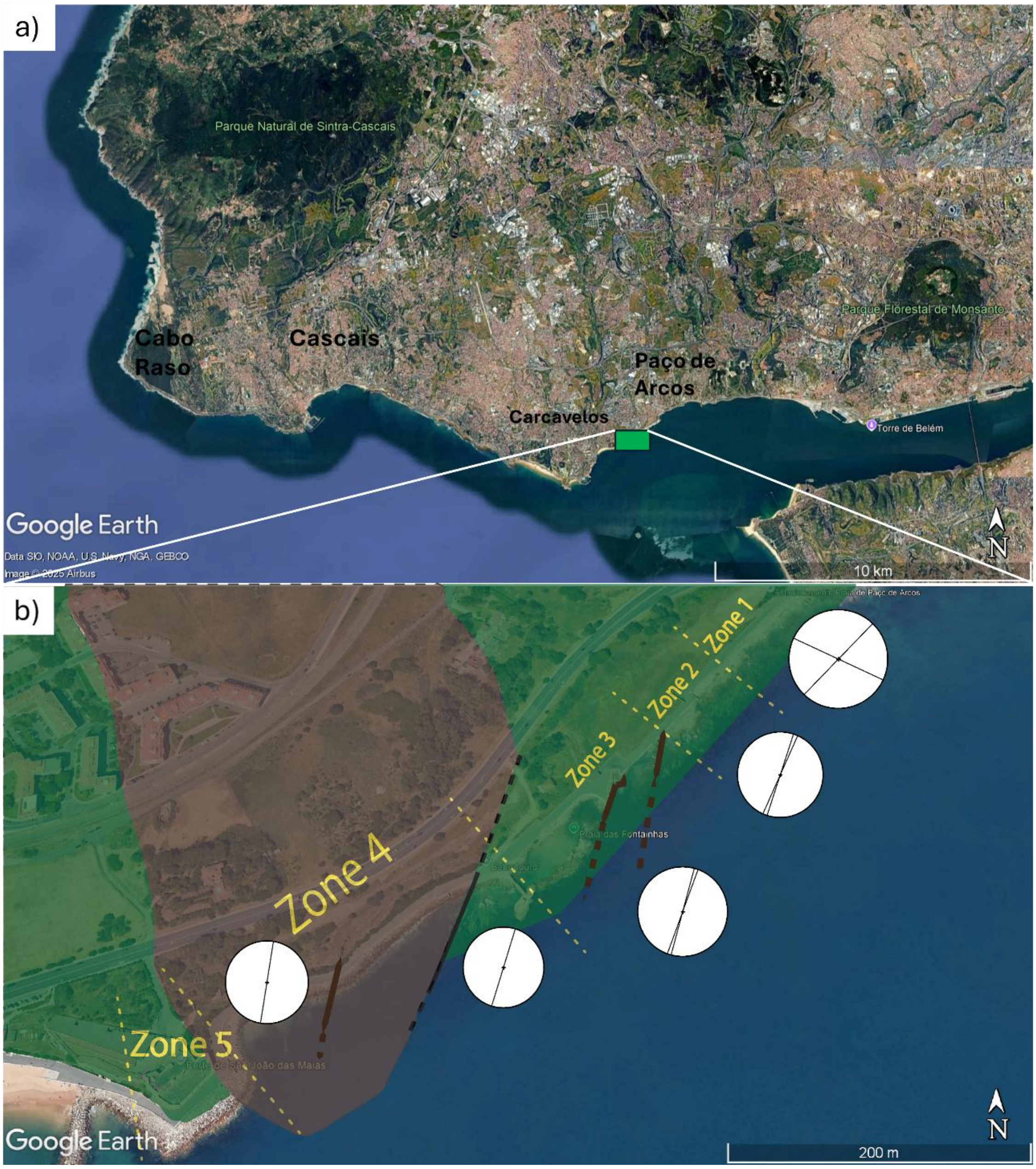


Figure 8.1 - Map of the Study Zones, with stereonets providing the orientation of each dike and fault that stands next to. Brown area: ignimbrite; Green area: limestones; Fault in Zone 4 represented by a single black line; Dikes represented in Zones 3 and 4 with brown lines.

8.1.1 Zone 1

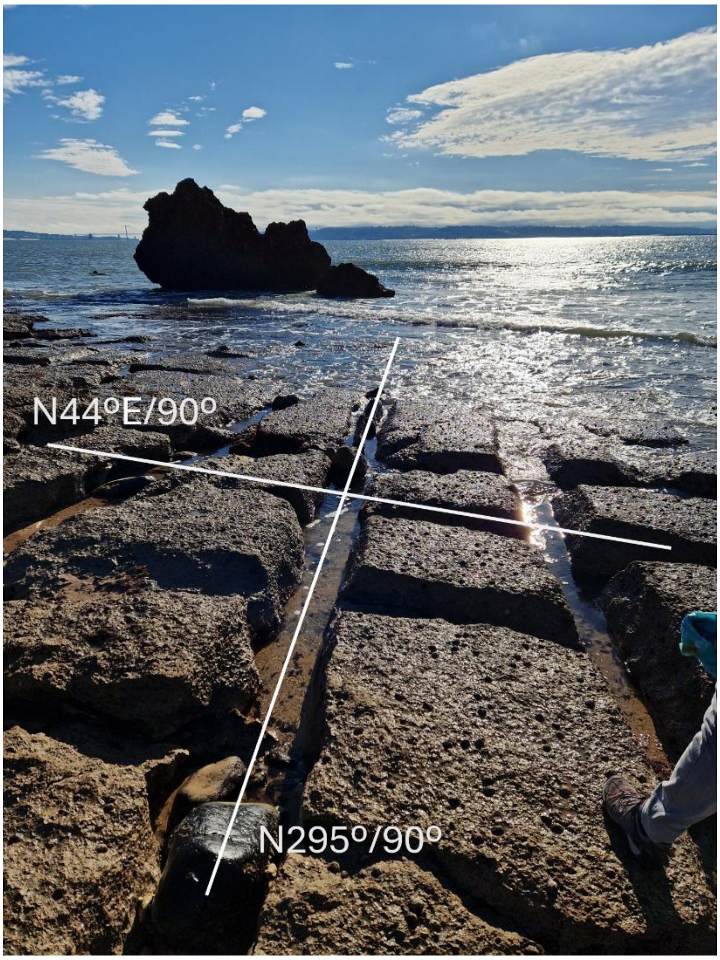


Figure 8.2 – Picture taken facing ESE, west of Paço de Arcos Beach, displaying the preferential fracture pattern in the limestones.

Near the sea, the almost perpendicular limestones (**Figure 8.2**) do not show signs of karstification, and their highly homogeneous fracturing follows a "chocolate tablet" pattern, i.e., with fractures along two well defined directions. The preferential fracture orientations are N295º/90º and N44ºE/90º, suggesting the possible existence of one or more stress fields. Collected samples show strong compaction of the limestones.

8.1.2 Zone 2

Immediately to the west, just a few meters from Zone 1, the regular fracturing pattern comes to an end, giving way to a much more random one, as it is possible to observe in **Figure 8.3**. However, the fracturing remains well defined, which may suggest a change in the accommodation of the stress field or a variation in the limestone material that fractured.

Figure 8.3 – Picture taken facing SSE, just a few meters west of where the **Figure 8.2** was taken, showing how the preferential fracture pattern is slowly disappearing.

In both zones (1 and 2), moving inland from the sea towards the PMO, karstification of the limestones increases. This karstification reveals a limestone layer positioned above the level of the fractured limestones, as shown in **Figure 8.4** between the two red lines. This specific layer has approximately 1m of thickness.

Figure 8.4 – Picture taken facing SSW, with compact crystalline limestones at the top corresponding to Level 1 (above the upper red line); karstified limestones represented at Level 2 between the two red lines; and below, more porous limestones with a marly component at Level 3.

There are also areas where the limestones show intermediate karstification; however, they are less compact and even contain marly material in their composition (**Figure 8.5**). Occasional fossil records were found in the more compact limestones located farther from the sea.

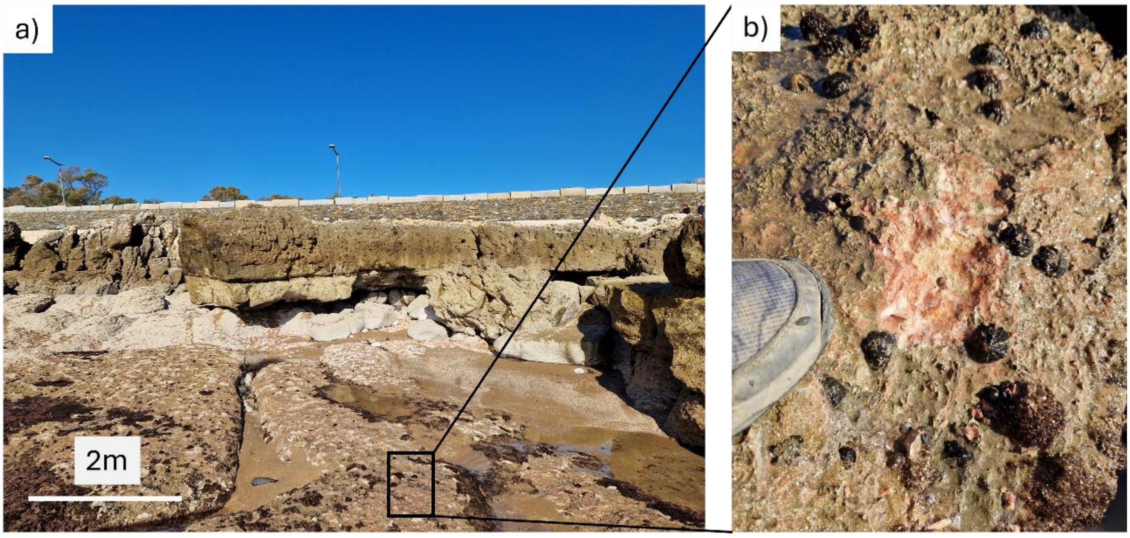
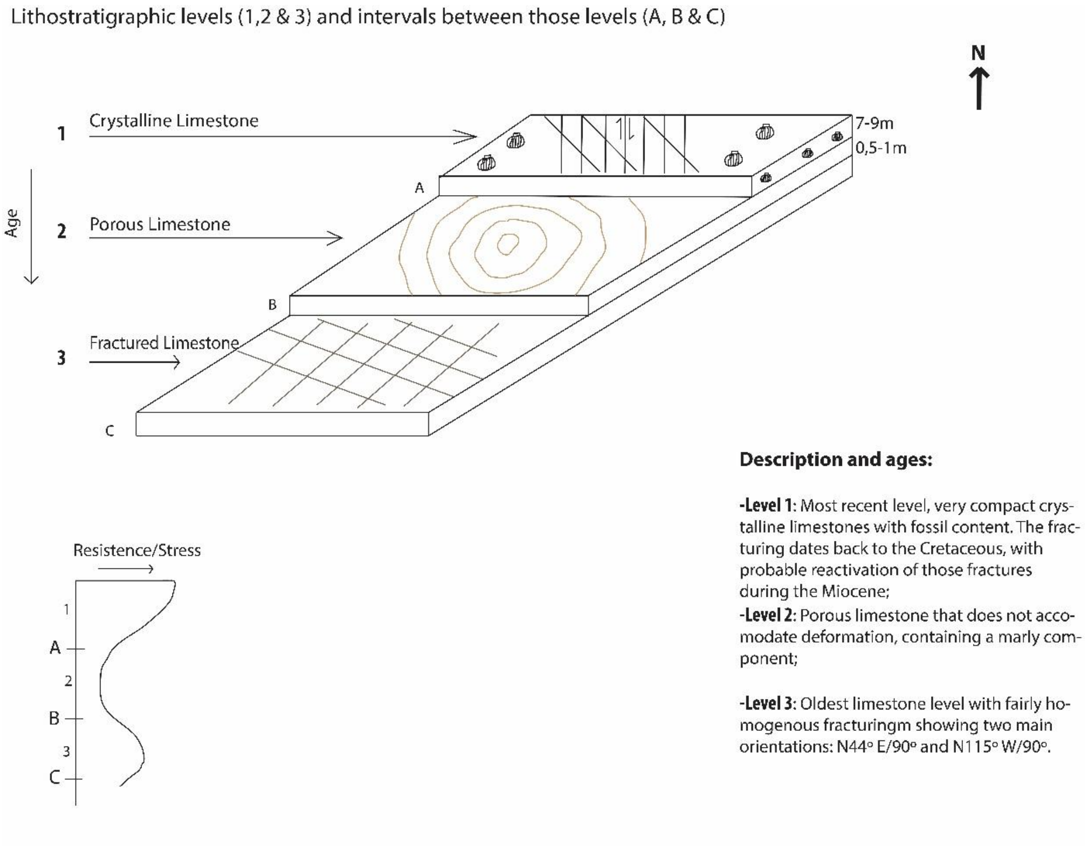


Figure 8.5 – **a)** Picture taken facing NW, where it is possible to see all the three levels specified in **Figure 8.6**.; **b)** Detailed picture of the Level 3, with a red marl within the limestones.

8.1.2.1 *Proposed schematic for the limestones observed in these two zones*

The **Figure 8.6** below shows the three types and levels of limestones observed, along with descriptions of the lithologies, hardness, and possible ages of the fracturing.



Description and ages:

-Level 1: Most recent level, very compact crystalline limestones with fossil content. The fracturing dates back to the Cretaceous, with probable reactivation of those fractures during the Miocene;

-Level 2: Porous limestone that does not accomodate deformation, containing a marly component;

-Level 3: Oldest limestone level with fairly homogenous fracturingm showing two main orientations: N44° E/90° and N115° W/90°.

Figure 8.6 – Schematic illustration representing the fracture directions, layer thicknesses and their descriptions.

8.1.3 Zone 3

Figure 8.7 – Picture taken facing NE. Dike with orientation N15ºE/90º bounded by red lines, cutting through layers of limestone and with many loose blocks of limestone and basalt on top. Marta Neres as scale.

In Zone 3, east of Zone 2, two dikes were found between karstified limestone levels. The easternmost dike (**Figure 8.7**) was 3–4 meters wide and oriented N 15ºE/90º. It exhibited a more felsic composition but was heavily rotten, possibly due to constant marine erosion. Upon detailed observation, calcite-filled vesicles were identified, showing imbrication of vesicles that suggests flow from south to north. However, in certain areas that indicated a more "turbulent" flow during emplacement, these vesicles displayed random orientation. The dike walls had chilled margins with a high concentration of ferromagnesian minerals (**Figure 8.8**), from which samples were collected.

Figure 8.8 – Detail of the chilled margin (circled) of the dike in the figure above, *in situ*. The distinct purple colour results from the oxidation of ferromagnesian minerals during the cooling of the dike.

Just beyond a limestone "wall" to the north of this dike, another dike was found. This one also appeared to have a width similar to the first, and also the same orientation. Moving northward along the dike, a well-defined curved zone was observed, forming an angle close to 90º before "unfolding" again towards the northern quadrant, as it is possible to observe in the schematic picture below (**Figure 8.9**). Like the previous one, this dike appears to have a felsic composition, is heavily rotten, and shows chilled margins.

Figure 8.9 – Scheme of the dikes present in Zone 3. The westernmost dike shows a clear fold, and its western limit is represented by a black dashed line because it is uncertain if it propagates below the near limestones wall.

8.1.4 Zone 4

Located west of Fontainhas Beach, an ignimbrite (**Figure 8.10**) is exposed in an area bounded to the west by the São João das Maias Fort, but without a clearly defined western limit. This ignimbrite, which appears to be a stratigraphic level, has fractures filled with a mineral, probably calcite, and contains numerous large basalt "bombs", as shown in **Figure 8.10.a)** by the darker clasts. In this area, a fairly wide basaltic dike (approximately 4–5 m) oriented N 15–20ºE/90º is visible on the cliff and extends to the sea (**Figure 8.11**), cutting across the ignimbrite layer. Although it is cut by the PMO, the dike observed on the cliff can be easily correlated with that on the beach due to the similar nature of the material and the very similar fracturing pattern in both zones.

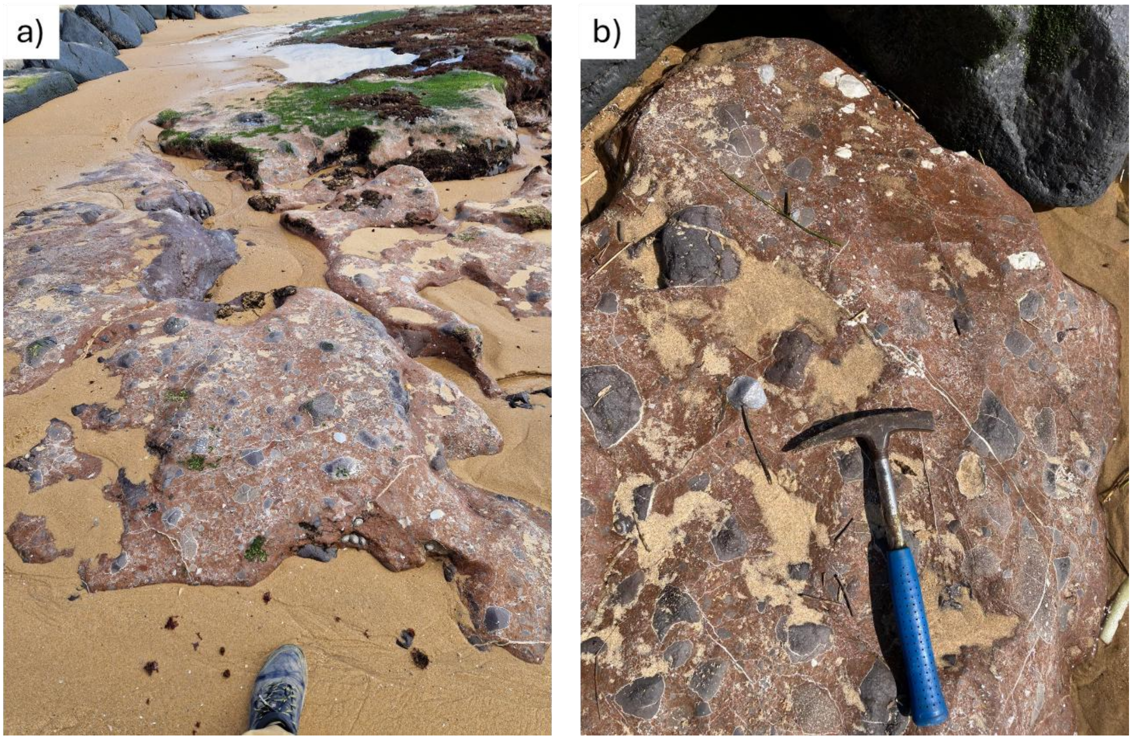


Figure 8.10 - Ignimbrite in detail, with visible basalt “bombs” represented by the darker pieces and fractures filled with calcite.

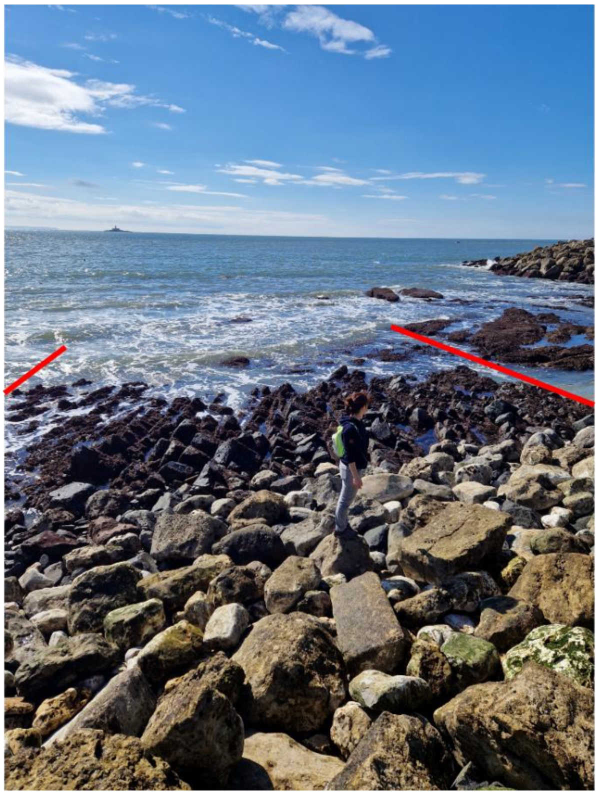


Figure 8.11 - Photo taken facing SSW, just over 100m east of the São João das Maias Fort. Basaltic dike oriented N15-20ºE/90º, whose boundaries are represented by red lines. This dike shows a very strong fracture pattern. Marta Neres as scale.

8.1.5 Zone 5

Zone 5 refers to a limestone stratification leaning against the western wall of São João das Maias Fort, observed in **Figure 8.12**. This stratification has a strike of N50ºW and dips 8–10º towards SSE. These strata exhibit the same limestone levels described above: crystalline limestone with some fossil record overlying a more porous limestone that does not accommodate deformation, and, beneath it, the oldest level, composed of fractured limestones. As these limestones dip towards SSE, it was possible to observe all 3 levels, as represented in **Figure 8.13**.

Figure 8.12 - Picture taken facing N where it is possible to observe that the Fort was built on top of the 3 limestone levels described before.

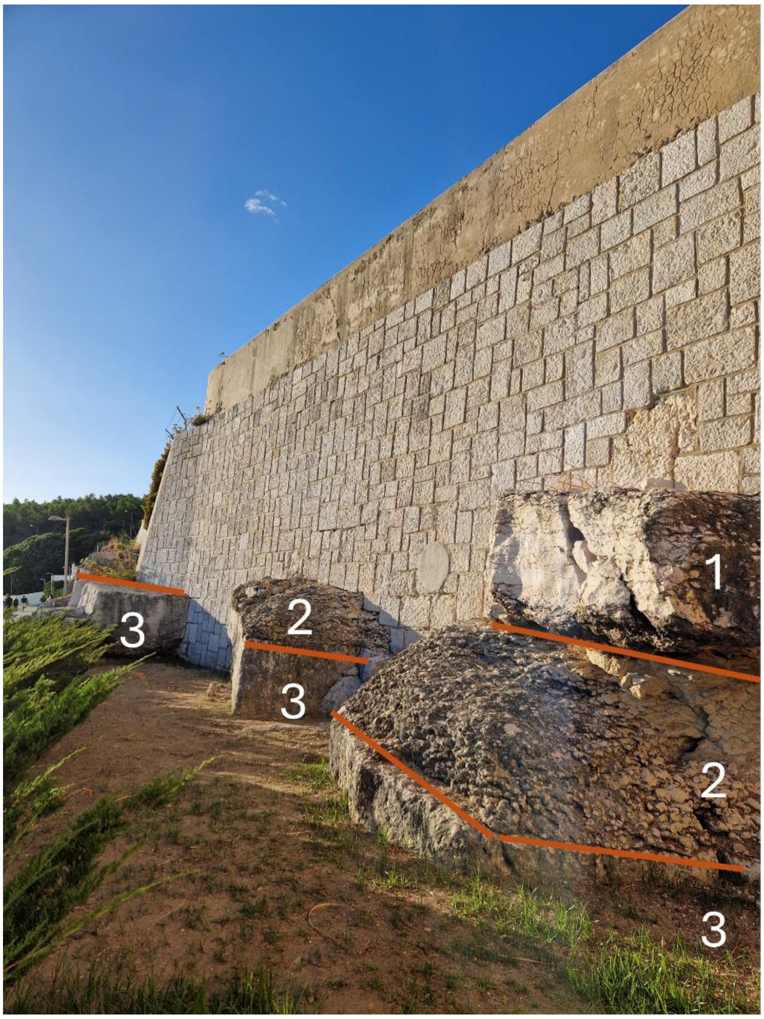


Figure 8.13 – Photograph of the western wall of the Fort, taken facing NNW, showing the three limestone levels separated by brown lines and labelled with the corresponding numbers indicated in **Figure 8.6**.

8.2 Description of Results

In Zone 1, the limestone layer observed near the sea displays a very distinct and homogeneous fracturing pattern, with fractures forming rhombus shapes whose measured orientations were N 295º/90º (or N 115ºE/90º) and N 44ºE/90º. This way, an acute bisector angle can be calculated, explained as follows:

$$115^0 - 44^0 = 71^0$$

$$\frac{71^0}{2} = \sim 35{,}5°$$

$$44^0 + 35{,}5^0 = 79{,}5\,° = \ \sigma_1$$

Thus, the value of the maximum compression direction σ₁ that explains these homogeneous fractures, based on the field measurements, would be N 79,5ºE.

This result raises a problem, as none of the currently known stress fields that have affected this region present this value for σ₁, which remains to be understood.

To the west of this zone, just about 80 meters away as shown on the map, lies Zone 2, which contains limestones with similar characteristics to those in Zone 1. However, the fracture pattern in Zone 2 is much more heterogeneous, displaying no rhomboid shapes, but rather fractures with an approximate direction of N 15ºE. This orientation closely matches that of the felsic dikes located in the western part of the same zone. One possible explanation for the organized fracturing in Zone 1 but not in Zone 2 is the influence of the dike emplacement on the limestone layer. Zone 1 is located approximately 160 meters from the dikes, meaning the intrusions likely had minimal influence there. In contrast, Zone 2 lies much closer to these intrusions (<80 meters), which suggests that during emplacement, the flow of high-temperature magma may have deformed this limestone stratification and even altered pre-existing fractures—though not with sufficient temperature or proximity to affect Zone 1. Using Google Earth data/images to approximate (**Figure 8.14**), it is evident from observations that in the transition from Zone 1 to Zone 2, the fracturing becomes noticeably weaker and increasingly chaotic, especially in the N 115º direction, further supporting this theory.

Figure 8.14 – Zones 1 and 2 separated by a black dashed line, where it is possible to observe that transitioning from Zone 1 to Zone 2, the fracture pattern becomes much more heterogeneous.

Further west, near the Forte de São João das Maias, it can be observed a layer of ignimbrite, which constitutes Zone 4. This volcanic rock contains numerous large basalt bombs, indicating a high-energy pyroclastic flow. Despite the LVC being largely effusive in nature (M. L. Pereira, 2018), pyroclastic volcanic episodes did occur, and the presence of this ignimbrite could be interpreted as the result of one of these events (Ramalho et al., 2001). This ignimbrite is marked by a relatively abrupt transition from limestone (to the east) to ignimbrite (to the west), possibly explained by a fault with an approximate direction of N 20ºE — a direction very similar to that of the dikes previously mentioned in Zone 2. Based on Google Earth imagery, and on direct field inspection, north of this zone and between the PMO and Estrada Marginal, there is an area with soil of a more reddish hue, consistent with the colour of the volcanic material observed, suggesting a northward continuation of this layer. Its western boundary, however, is not clearly defined. It is speculated that this boundary lies beneath the Forte de São João das Maias, since to the east of the fort the outcropping material is ignimbrite, while to the west — right next to the fort's wall — *in situ* limestones with slightly inclined stratification can be observed, corresponding to Zone 5. The terrain between the PMO and Estrada Marginal, north of this last section, has a whitish tone, matching the colour of the limestones.

Still within Zone 4, there is a basaltic dike with an approximate orientation of N 20ºE that extends across the cliff. This body has a considerable width (between 4–5 meters) and a clearly visible and orderly fracturing pattern. It was not possible to observe this body in detail due to the tide level and the inaccessibility of the cliff area where it outcrops. It was also not possible to precisely delimit the ignimbrite layer in the northern terrains due to the extensive urban development in the area.

8.3 Geological Interpretation

Based on all the data collected and its integration with the previous knowledge, two possible geological cross-sections are proposed for the study area, represented below and followed by a discussion of each:

- Geological Cross-Section 1 – Model with a single fault affecting monocline strata.
- Geological Cross-Section 2 – Model featuring two faults and, consequently, a graben structure.

8.3.1 Alternative cross-section models

Both cross-sections represent an extension of approximately 750 meters and are quite similar in their eastern parts, with their differences concerning only how the geological layers are arranged to the west of the fault that places the ignimbrite/basalt alongside the crystalline limestones.

In Geological Cross-Section 1 (**Figure 8.15**), the fault with an orientation of N20–25ºE is the only one present and likely dips toward the western quadrant. Based on the field data regarding the position of the limestones relative to sea level, along with the 8–10ºE dip observed in the limestones that are adjacent to the fort's wall, it is possible to estimate that this fault has an offset of approximately 50 m. The ignimbrite and basalt to the west of the fault do not appear to have any stratification; however, if considering the limestone stratification below this unit exhibits the aforementioned dip, this block can be considered as a monocline. The dip of this monocline would have resulted from a tilting toward the eastern quadrant, which could be verified if the fault itself dips toward the western quadrant. All of these data render this interpretation quite viable for explaining the geological setting of the area in question.

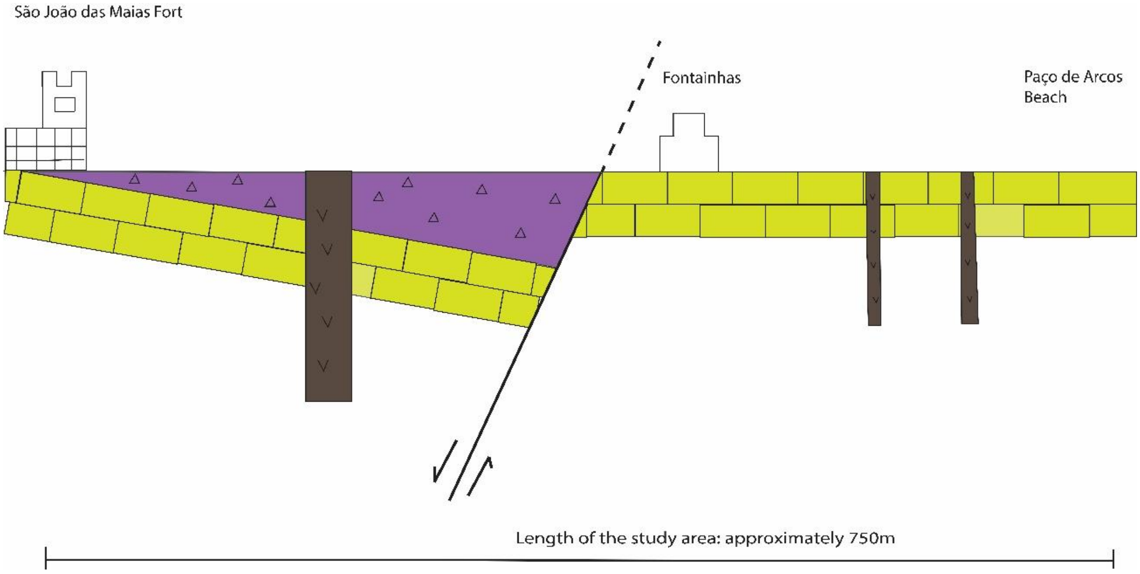


Figure 8.15 - Diagram of the geological cross-section corresponding to Model 1, featuring a single fault (black fault represented in **Figure 8.1**) being responsible for the outcrop of the ignimbrite in Zone 4, implying a monocline structure. The dikes are represented in brown, limestones in yellow and the ignimbrite in purple.

In <u>Geological Cross-Section 2</u>, an additional fault located beneath the São João das Maias Fort is proposed. Since no dip is observed in the ignimbrite stratification but is present in the limestones adjacent to the fort's wall, a fault must exist between these two lithologies to place them at the same level. This fault's exact location and orientation are impossible to determine; therefore, in the diagram below, I chose to depict it as a vertical fault, oriented N–S and positioned beneath the fort. This fault would have an upward movement of the western block relative to the eastern block, forming a graben between this fault and the one located east of it. This interpretation raises several questions regarding when the tilting of the strata adjacent to the fort occurred — whether it happened before or after the fault rupture — and if after, then the fault itself would also have had to undergo tilting. For it to currently appear vertical as shown in **Figure 8.16**, before tilting, it would have needed to be oriented NW–SE. This scheme with the additional fault resolves the "problem" of the ignimbrite layer showing no dip but raises other questions about the presumed fault, notably its precise location and current orientation, and which of the two faults appeared first. Although it is a more complex interpretation than first model, it is not impossible, but perhaps less likely.

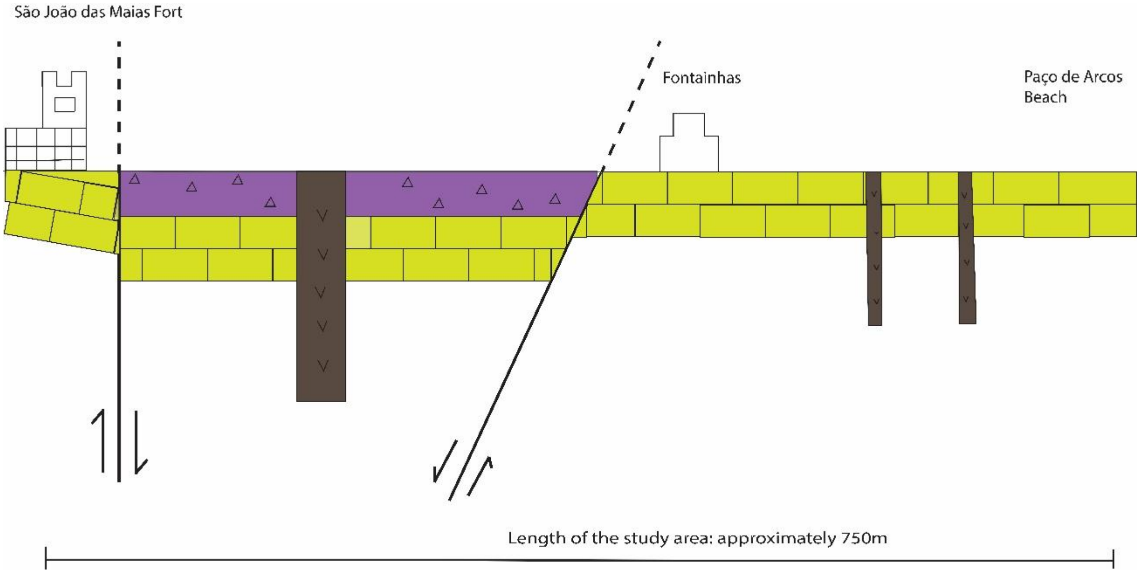


Figure 8.16 - Diagram of the geological cross-section corresponding to Model 2, with two faults forming a graben. The dikes are represented in brown, limestones in yellow and the ignimbrite in purple.

8.4 Conclusions for the field work of this study area

After evaluating the two models proposed for the study area and considering their implications, it is concluded that Model 1 best fits the field observations, particularly due to key factors such as the dip of the structures and the fault located west of Fontainhas. This model is strongly supported by actual observations and relies less on assumptions, unlike Model 2, which depends on a hypothesized fault cutting the limestones beneath the Fort. In Model 1, the tilting observed in the limestones adjacent to the Fort would have occurred after the faulting event, suggesting that the fault was originally closer to vertical. This tilting is not observed in the ignimbrite at the beach, as this pyroclastic-flow-derived rock does not exhibit morphological features indicative of tilting. The basaltic dike intruding the ignimbrite is highly fractured, supporting the presence of a stress field in the area that contributed to the tilting.

While some uncertainties remain regarding the precise timing of tilting, this interpretation provides a robust framework for understanding the structural evolution of the site and can guide future mapping and studies of local magmatic and tectonic processes.

9 Marine Magnetic Data Information

9.1 Introduction to magnetic data

In this study, marine magnetic data was used to identify magnetic anomalies in the offshore area of the study region. The analysis aims to assess the potential structural continuity between the offshore and onshore domains, specifically investigating whether there is any correlation between the offshore magnetic anomalies and the dikes observed onshore. This may provide evidence for a connection between these structures, contributing to a better understanding of the regional geological evolution.

The magnetic data were processed and analysed, where several transformations were applied to enhance the visibility of the anomalies and highlight relevant magnetic features. To further refine the interpretation and visually represent structural trends, the processed outputs were exported and edited, allowing for the addition of interpretative elements such as lineaments and curvature trends.

9.2 Offshore magnetic data analysis

Based on magnetic data acquired in the TAGUSMAG and Rochel surveys (**Figure 9.1**) between Cabo Raso and Oeiras, and analysed with the software, it is possible to get an interpretation of the magnetic anomalies that were detected, especially about their orientation and their magnetic peaks. In that same software the high amplitude anomalies were delimited to infer their orientation. This way, preferential orientations were obtained in this study area. The volcanic chimneys and single anomalies were also taken in consideration, as well as the already know CR magnetic anomaly.

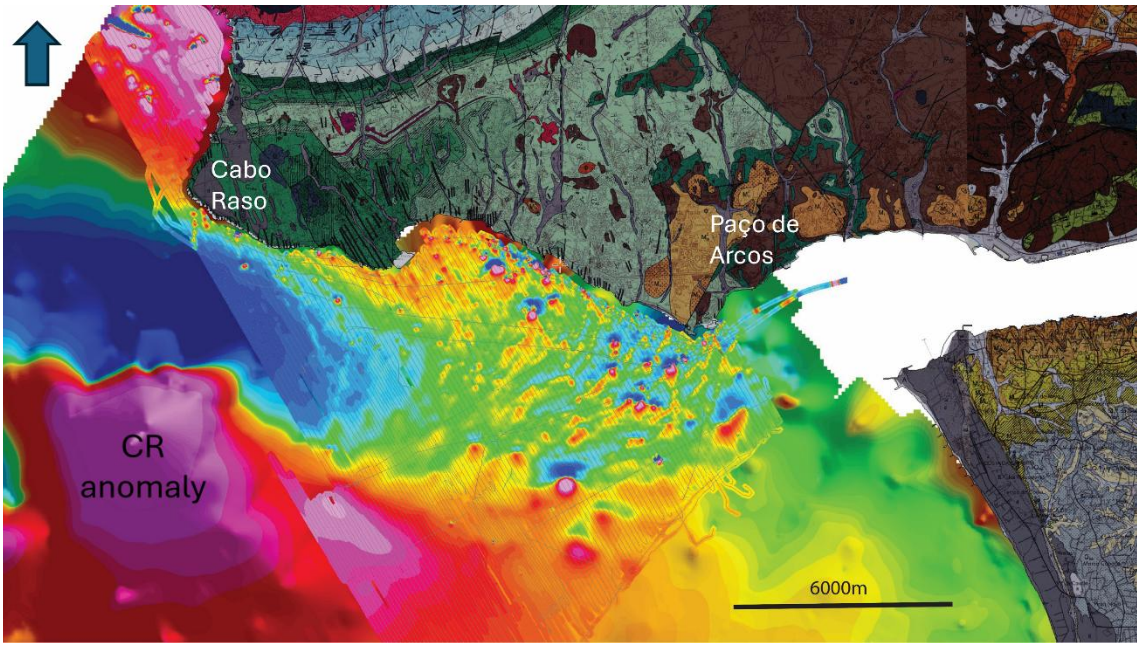


Figure 9.1 – Geological map of the region with raw marine magnetic data from the ROCHEL and TAGUSMAG surveys.

With this analysis, two preferential orientations were verified (**Figure 9.2**): one NE-SW that can be observed on the Eastern side of Estoril, and the other is NW-SE, more dominant on the Western side of Estoril. Punctual anomalies were also taken in consideration, and it is possible to observe that in the easternmost zone, there are a lot more of punctual anomalies, that may correspond to plugs. It is important to refer that some of them might not be of geological nature, but rather of human nature, like shipwrecks, or other features placed at the seafloor or buried.

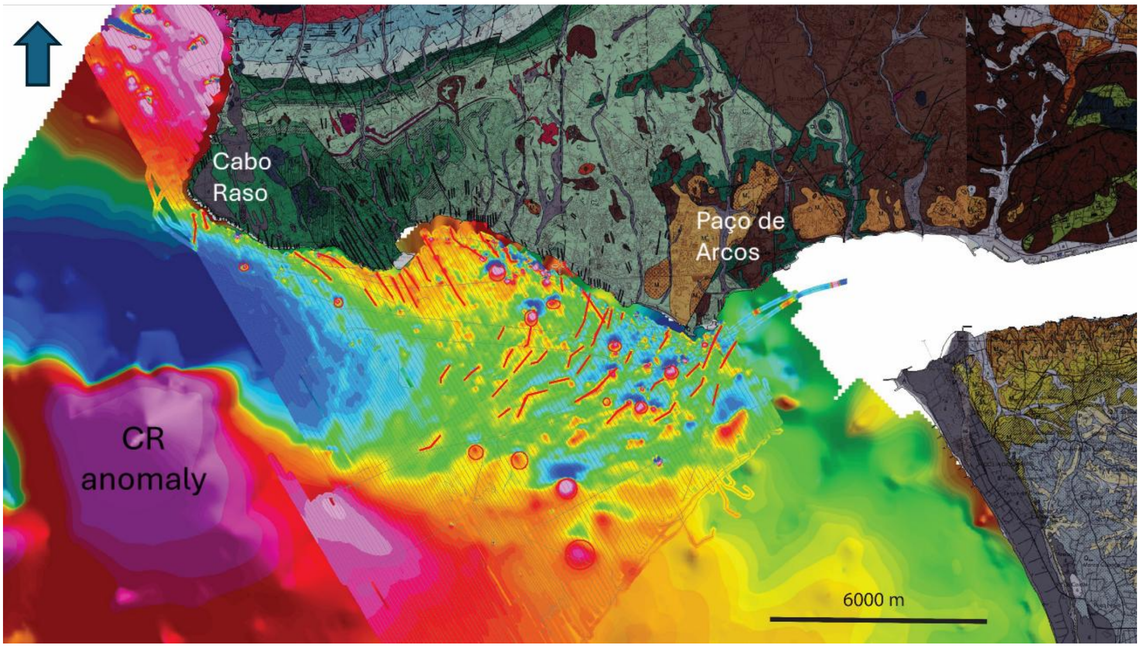


Figure 9.2 – Geological map of the region with interpreted marine magnetic data, showing red lines over lineations corresponding to the highest anomaly values.

Figure 9.3 represents a map with the two preferential orientations of the dikes and the punctual magnetic anomalies, without the magnetic information below to make it easier to observe. The circular dots represent possible volcanic chimneys. Two alternative models are presented to interpret the observed anomaly patterns.

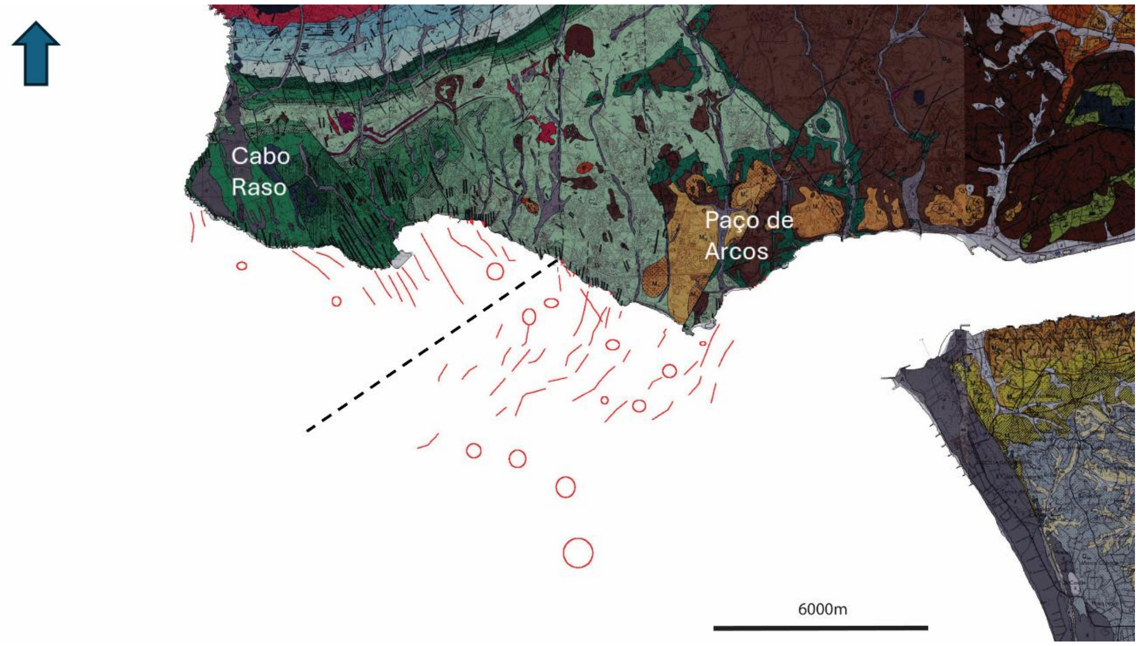


Figure 9.3 – Map without magnetic data to highlight submarine magmatic conduits and their orientations, as well as point anomalies, both outlined in red. Black dashed lines indicate the possible geological boundary separating the two orientation families.

9.3 Model 1 – Two diachronic emplacement events separated in space by a physical boundary

The first model is based upon the presumption of the existence of a physical boundary that separates the two preferential orientations. In **Figure 9.3**, a map representing this model is shown with the boundary as a black dashed line between the two sets of orientations of the offshore dikes, which are highlighted in red, without the underlying magnetic information.

However, it is not possible to determine how far this possible boundary extends, as at south it is interrupted by the CR anomaly. Nevertheless, through a study of the 1:50 000 geological maps of Cascais and Lisboa, it is observed that this directional pattern is repeated onshore to the north, as can be seen in the figure above, where the offshore dikes highlighted once again in red and the dikes on the geological maps shown with brown lines. This boundary therefore has an approximate speculative NE-SW direction, although it is not possible to determine its real offshore path.

9.4 Model 2 – Curvilinear dikes' emplacement controlled by two pre-existent fracture systems

Based on the same analysis, an alternative model can be proposed, in which curvature is attempted within the dike network rather than the existence of a boundary separating two distinct orientations. In this interpretation, the two directions of the dikes are connected, and the dikes are curving along their extension. **Figure 9.4** illustrates this conceptual model, with the inferred curvature axes represented by dashed lines. These lines have been traced along the locations of highest magnetic anomaly values, providing a structural framework for understanding the deformation and continuity of the dike system within the study area.

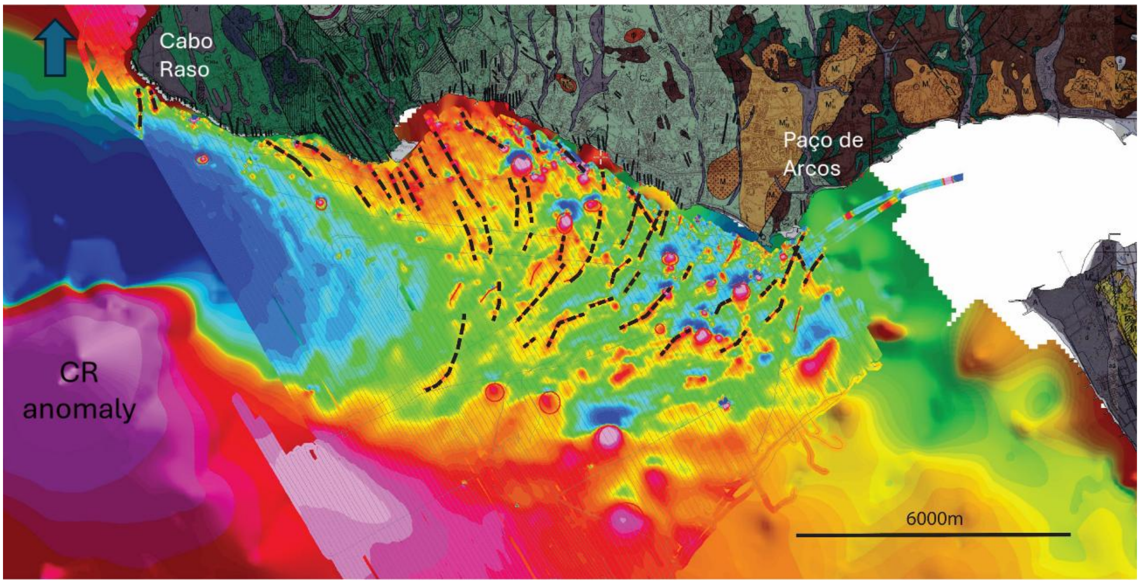


Figure 9.4 – Illustration of Model 2, showing submarine magmatic conduits outlined with black dashed lines, exhibiting a curvature between the two preferred orientations.

Using the same software for magnetic data analysis, a transformation known as the Tilt Derivative (observed in **Figure 9.5** without any interpretation) was applied to enhance the visualization of subtle magnetic features and to better delineate the curvature lines connecting the two observed preferential orientations. The resulting map, shown in **Figure 9.6**, highlights the most prominent curvatures, which have been indicated with black dashed lines.

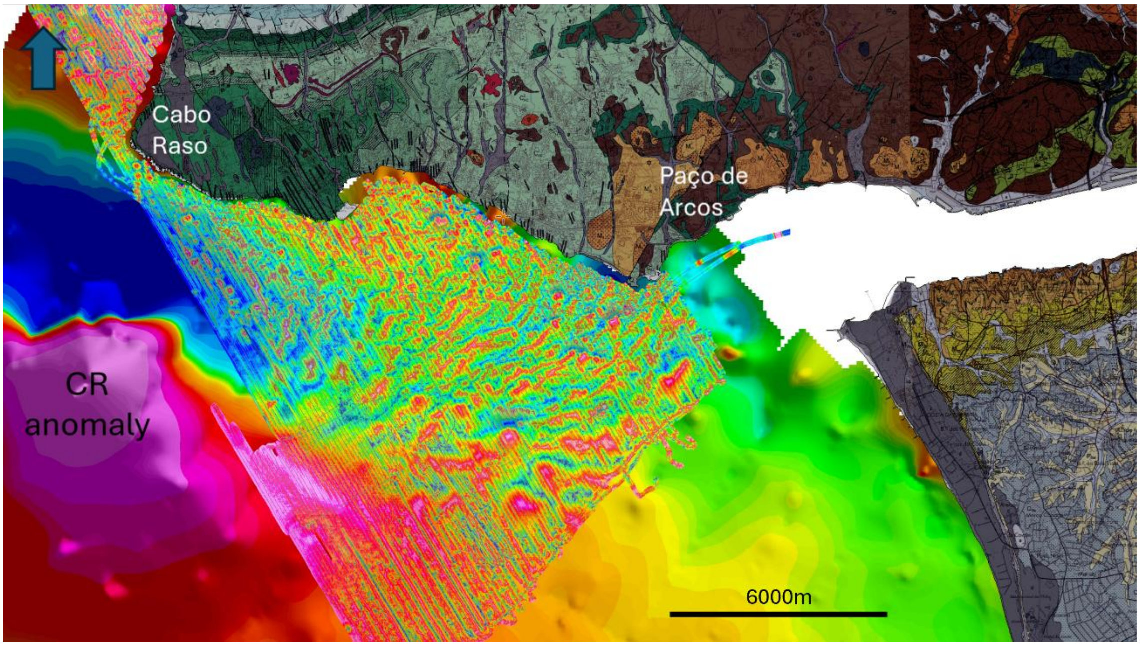


Figure 9.5 – Uninterpreted Tilt Derivate transformation map.

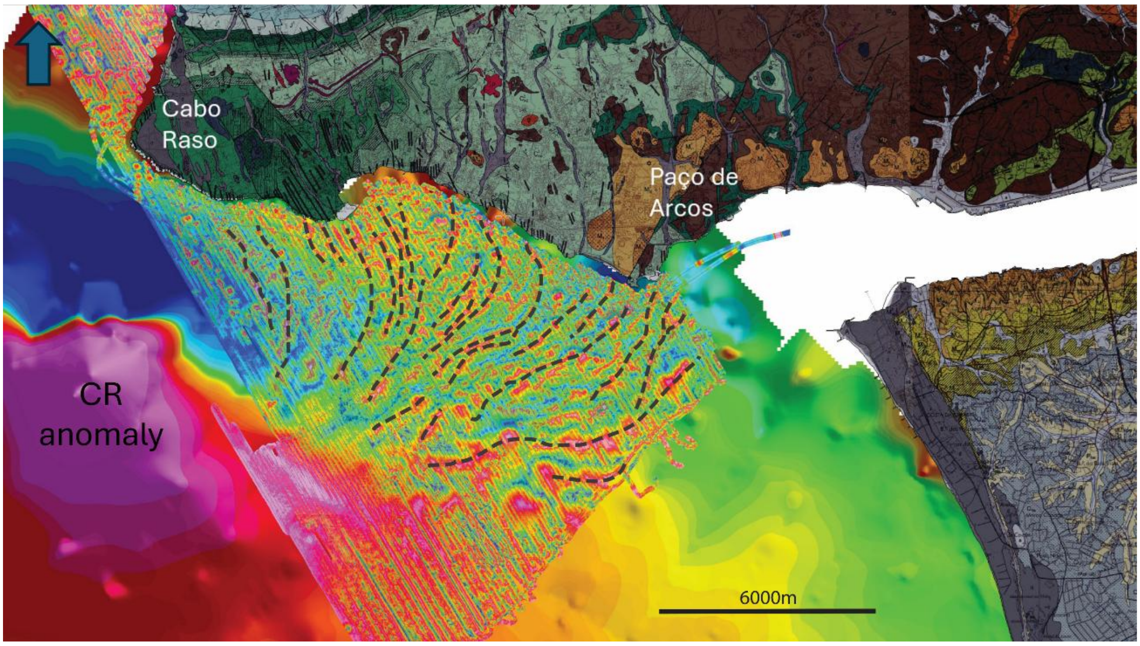


Figure 9.6 – Magma conducts pathways represented by black dashed lines after interpretation.

10 Discussion

10.1 Dike emplacement models from magnetic data

Model 1 (Figure 9.1) assumes the existence of a physical boundary separating the two preferred dike orientations. This way, the emplacement of the dikes was separated in space by that limit, which implies that that were more than one emplacement events. This physical boundary would not be confined only to the offshore area but would also extend onshore. Studies of the geological map of the region indicate that the onshore dikes display the same preferred orientation patterns observed offshore. Therefore, one would expect this boundary to be identifiable onshore or documented in existing maps or cartographic sources, yet no such evidence is found. Regarding its offshore extension, determining its precise location is highly challenging, as the boundary is hypothetical; consequently, both its exact position and the extent of its continuation remain uncertain. Its age and how this boundary would have been formed are other questions that are highly challenging to answer.

Regarding **Model 2**, it is suggested that there is a radial dike complex in which the northern part of the mapped dikes is curvilinear. We speculate that the source of these dikes lies towards the west of the study area, as shown in **Figure 9.6**, and this model implies that there is one emplacement event only.

In the northern sector, dikes initiate with a NE-SW strike and as they approach the coastline, they curve towards the NW. This NW strike is parallel to the rifting phase fault system of the LB, as old as Mid-Jurassic, being reactivated during the Paleogene and Miocene compressions (Kullberg, J. C., 2000; Terrinha et al., 2017). The observed curvature from NE to NW should not be interpreted as the result of tectonic folding. Instead, by considering the connection between the offshore magmatic conduits and the coastal dikes, it becomes evident that the latter owe their curved geometries to the influence of pre-existing structural controls that guided their emplacement when they reached that area. Indeed, field observations consistently show that whenever dikes exhibited curvature, this geometry was directly associated with preexisting structural control, with no evidence to suggest that the dikes themselves had undergone folding. This way, the NW strike has interfered with the natural path of the dikes that would emerge from the anomaly in a radial pattern.

10.2 Magma source for dikes

From the fieldwork carried out, it was observed that most of the dikes contain elongated vesicles; however, these do not always display imbrication that could provide indications of the sense of magma emplacement. Nevertheless, in two specific locations—east of Tamariz Beach (**Figure 7.4.b**) and east of Parede Beach (**Figure 10.1**)—the dikes exhibit imbricated vesicles filled with calcite, which suggest a magma flow direction from south to north. It is not possible to generalise or conclude that all dikes in the study area share the same age or source, since two distinct compositional families are recognised: one mafic and the other more felsic. The presence of two orientation families is most likely related to the structural control of the region, active before or during dike emplacement. This factor, however, cannot be used as explanation for their source, as the dikes may derive from different sources and ages, and their emplacement could have exploited the same pre-existing structural framework at different times.

Figure 10.1 – White, elongated and imbricated vesicles from a dike located east of Parede Beach. The black dashed line defines the western extent of the dike, and the alignment of vesicles (NE-SW) indicates a magma flow direction from south to north.

Through the analysis of the magnetic data and based on the results shown above, it was observed that, in addition to the CR magnetic anomaly being the closest prominent anomaly to the study area, this study also reveals the presence of magma conduits distributed across the region. These conduits are interpreted as feeder pathways, extending from the anomaly itself towards the onshore domain, where they align spatially with the dikes mapped in the study area. This spatial correspondence strongly suggests a genetic link between the offshore magmatic structures associated with the CR anomaly and the emplacement of the coastal dike swarm, providing further evidence of a shared magmatic system that operated during the tectono-magmatic evolution of the region.

It becomes possible to assume that, although maybe not all, at least a significant portion of the dike swarm located along the coastal sector between Cabo Raso and Paço de Arcos originated from the magmatic source associated with the magnetic anomaly identified south of Cabo Raso, in the offshore domain. This interpretation implies that the anomaly acted as a feeder centre, supplying magma that propagated northwards through pre-existing structural weaknesses and ultimately intruded into the Upper Cretaceous limestones exposed along the present-day coastline. While alternative sources cannot be entirely excluded, the spatial continuity between the offshore anomaly and conducts observed in the magnetic data, and the onshore dike orientations provides compelling evidence for a genetic connection, reinforcing the role of CR anomaly as a key magmatic focus in the evolution of the study area.

10.3 Tectonic Model

10.3.1 Large scale

Up north and in the offshore, according to (Neres et al., 2014), high-resolution marine magnetic data reveal several discrete positive magnetic anomalies from Madeira-Tore-Rise all the way to SIC, notably including the Fontanelas Seamount (**Figure 10.2**). These anomalies collectively form a coherent lineament of ridges or intrusive bodies that extend between the Tore Seamount and passing through the

SIC and the FF sill. The clear alignment of these features in a general NW–SE orientation suggests the presence of a large-scale tectono-magmatic corridor linking offshore volcanic and onshore plutonic structures. This orientation is significant, as it may reflect the influence of pre-existing crustal structures or a regional stress regime that controlled magma ascent and emplacement over a distance exceeding 350 km. This suggests that the dikes mapped onshore are part of a broader tectono-magmatic alignment, potentially linking structures with anomalies.

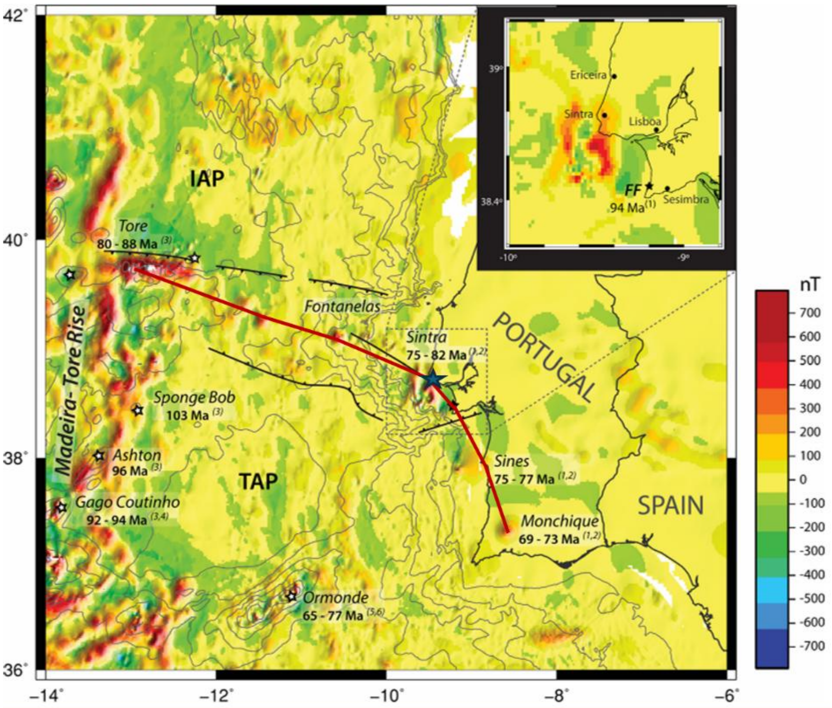


Figure 10.2 - Diagram adapted from (Neres et al., 2014), showing the lineament from the Madeira Tore Rise to Monchique indicated with a red line. The blue star represents the study area.

10.3.2 Regional Scale - cartographical analysis and magnetic data

In the study area, the dikes observed during fieldwork near the coastline can be grouped into two main families according to their orientation: NE–SW and NW–SE. These orientations are consistent with those represented in the official geological mapping of the Cascais sheet 34-C (*LNEG Dados Abertos*, n.d.), confirming the reliability of the field observations. The dikes are emplaced within limestones, which, according to regional geological data, belong to the Cretaceous, specifically the Albian (Lower Cretaceous) and Cenomanian (Upper Cretaceous) stages, meaning that their emplacement is younger than those. Furthermore, available magnetic data reinforce this interpretation by revealing a clear offshore continuation of these structural trends, with a visible propagation of the two main families of orientations. Later studies (Neres et al., 2023) also revealed that, south of CR anomaly, other two smaller anomalies exist, named Guia East and Guia West. Both display an alignment very similar with the main orientation of NE-SW observed both in the coastal dikes and the magnetic data (**Figure 10.3**). However, since the TAGUSMAG survey is restricted to the northern part of the CR anomaly, magnetic data as detailed as this one is not available to the south part of this intrusive body, which limits the possibility of confirming that these orientations persist further offshore.

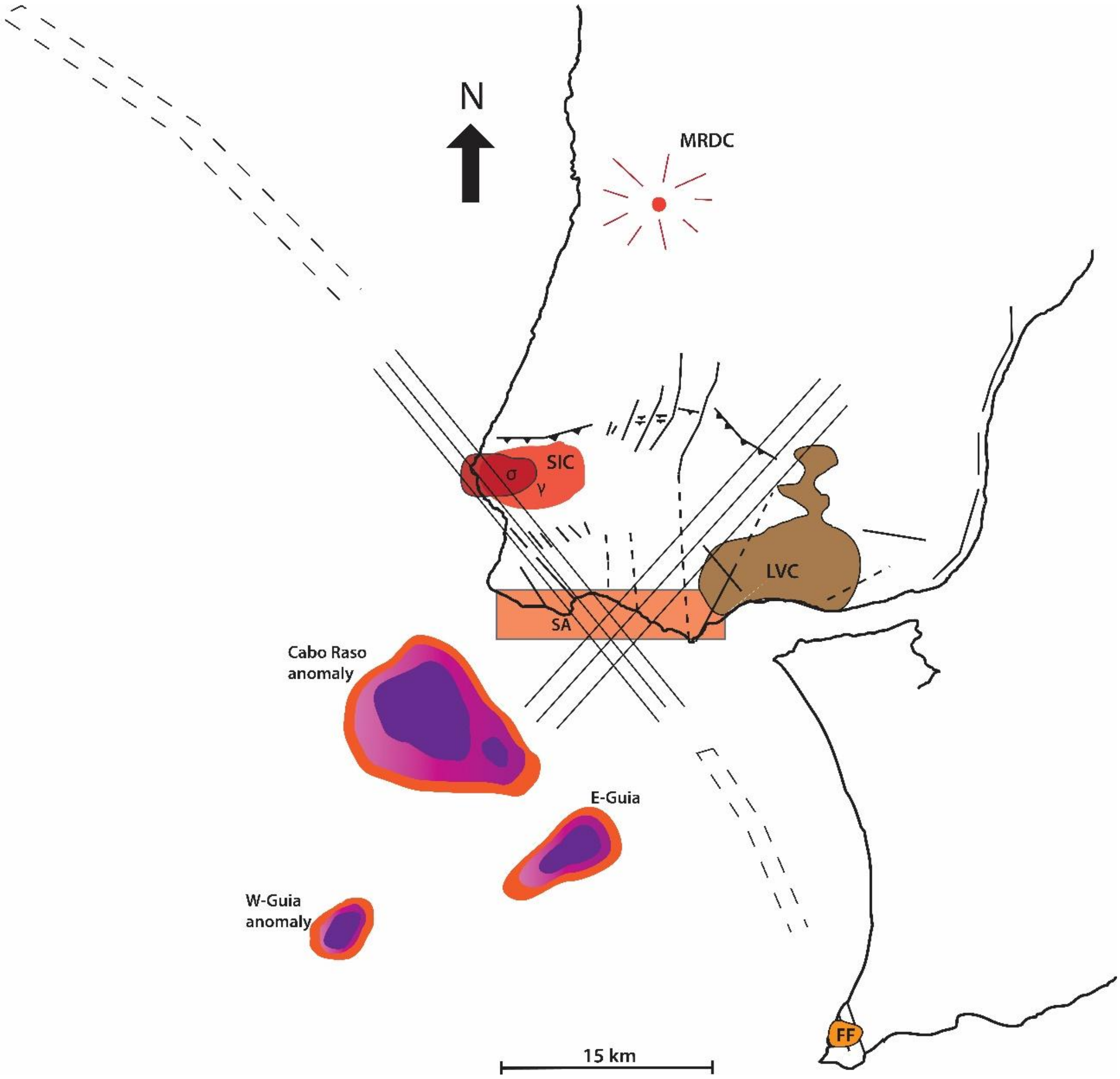


Figure 10.3 – Schematic geological map of the study area, showing the main onshore occurrences of the WILCAP in the LB, as well as the main offshore occurrence within the study area (SA). Based on (Neres et al., 2023).

10.3.3 Mesoscale - Field Work

In addition to their preferred orientations mentioned before, many of the NW-SE dikes exhibit noticeable curvatures, particularly those at Bafureira Beach, east of Tamariz, and east Parede Beach. Displacements are also observed, including both left-lateral and right-lateral offsets. For example, at Bafureira Beach, a dike initially oriented N16°E/90° abruptly changes direction to N30°W/90° and continues offshore along the coast for nearly 500 meters, displaying several left-lateral offsets along its extent (**Figure 10.4**).

The dikes east of Tamariz, illustrated in **Figure 1.2** and **Figure 7.7**, display right-lateral offsets along their length, although without abrupt changes in orientation. Similarly, the dikes east of Parede Beach, observed along the cliff where they are exposed (**Figure 10.5**), are initially oriented N20°W/20°N, but their orientation shifts to N8°E/20°N towards the offshore.

Figure 10.4 – Satellite photograph showing the dike at Bafureira Beach in red along its entire extent, with its respective left-lateral offsets and orientations. The dike on the western part of Avencas Beach is shown in black.

The observation of both dextral, and sinistral offsets in the NW-SE dikes suggests the possibility of two distinct phases of strike-slip movement. When considering the ages of previously dated onshore structures, such as the SIC (84–80 Ma) and the FF sill (94 Ma), it is evident that, despite their geographical proximity, there is an age difference of approximately 10-14 Ma. During this geological interval, Iberia was undergoing counterclockwise rotation (Miranda et al., 2009), which may account for phases of inversion that explain the observed changes in the sense of displacement. It is therefore likely that this change in kinematics can be recognised not only in dikes, but also in other fault systems present onshore. However, this explanation might only serve for the NW-SE oriented dikes, since the ones whose orientation is NE are usually very linear and straight, rarely showing offsets and only few of them change direction.

Figure 10.5 – Dikes observed in east of Parede Beach, outlined in red dashed lines, showing a clear change in direction and respective strikes. Photo taken facing SSE.

Building upon the observations of the dikes and their associated left-lateral and right-lateral offsets, attention is drawn to the ignimbrite body within the study area, more precisely in Paço de Arcos. In contrast to the predominantly effusive dikes, the ignimbrite represents a distinct style of magmatic activity. This contrast clearly illustrates the variability of magmatism in the area. Although the ignimbrite lacks a defined orientation like the dikes, its presence provides valuable insights into the complexity of magmatic processes and complements the structural and compositional analysis of the dikes, thereby enhancing the understanding of their emplacement, the influence of regional tectonics, and the magmatic system as a whole.

11 Future Work

The determination of magma flow directions for a larger number of dikes was limited due to time constraints and the lack of application of the AMS. Future studies employing this method could improve understanding of magma transport, dike emplacement mechanisms, and the overall magmatic evolution of the area.

Future work could also include the acquisition of new marine magnetic data, particularly in the deep offshore area, to determine whether the radial pattern observed around the CR anomaly extends throughout the region. Additionally, a reinterpretation of existing reflection seismic data south of the coastline, between Cabo Raso and Paço de Arcos, may be warranted, considering the offshore dike occurrence patterns identified during this study. Furthermore, the application of geochronological analyses could help establish the ages of the two compositional families or clarify the timing of structural controls, thereby providing insights into whether a single dike complex or multiple complexes were emplaced.

12 Conclusions

Based on the results of this study, the following key points can be concluded:

1. **Regional structural control**: At a broader scale, the dikes can be interpreted as part of the regional lineament identified in previous studies, indicating that their emplacement was structurally controlled and not random. This highlights the importance of considering regional tectonic features when analysing magma transport pathways.

2. **Compositional diversity of dikes**: Two distinct compositional families of dikes were identified. One of these families shows a clear south-to-north orientation, which provides insight into the dynamics of magma flow and the structural framework controlling the emplacement of these intrusions.

3. **Cabo Raso magnetic anomaly and offshore conduits**: The CR anomaly hosts multiple conduits that had not been documented before this study. Some of these extend offshore, establishing a direct connection between the anomaly and the dike network, and demonstrating that CR anomaly played a central role in the emplacement of the dikes.

4. **Dike orientation and source implications**: Part of the dike swarm predominantly propagates from south to north, directly linking it to the Cabo Raso anomaly rather than to the LVC or SIC. This observation corrects earlier assumptions regarding possible magma sources and clarifies the regional magmatic system.

5. **Evidence of explosive volcanism**: The presence of an ignimbrite indicates that explosive volcanic activity occurred in the area. Its characteristics suggest formation during one of the less frequent but more energetic eruptive episodes. This complements the otherwise predominantly effusive character of the LVC and contributes to understanding the variability of volcanic processes in the region.

6. **Potential feeding of the LVC**: The dike swarm may have contributed to feeding the LVC. This scenario provides an explanation for structural and geochemical links observed in the study and suggests that CR anomaly' conduits could have been an additional magma pathway sustaining volcanic activity in the LVC.

7. **Overall significance**: This study demonstrates the structural and compositional complexity of the dike swarm in the Lisbon region. It emphasises the dual character of the LVC, integrating both effusive and explosive products, and highlights the importance of combining structural, geochemical, and volcanological evidence to reconstruct the magmatic history. Future investigations, particularly those employing magnetic fabric analyses, have the potential to further elucidate the interplay between tectonics, magma transport, and volcanic activity in this geologically significant area.

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