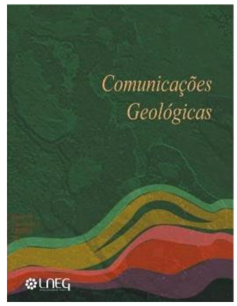
Comunicações Geológicas

Comunicações Geológicas (2022) 109, 1, 33-41
ISSN: 0873-948X; **e-ISSN:** 1647-581X

Insights about the Sines massif: a reinterpretation of geophysical data to the assessment of the potential for CO_2 storage through mineral carbonation



Notas sobre do maciço de Sines: uma reinterpretação de dados geofísicos para avaliação do potencial armazenamento de CO_2 por carbonatação mineral

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DOI: 10.34637/2fmc-mz67
Recebido em 14/03/2022 / Aceite em 27/07/2022
Publicado online em novembro de 2022

Artigo original
Original article

Abstract: The InCarbon project aims to evaluate the potential for storage of captured CO_2 using *in-situ* mineral carbonation in mafic and ultramafic plutonic rocks in Alentejo, Portugal. The Sines massif appears to be the most promising massif for mineral carbonation and its geochemistry, petrography, mineralogy, volume and extension are characterized. Its offshore volume and extension are evaluated through reinterpretation of previous geophysical data which confirms the occurrence of two well defined magnetic anomalies. The Sines magnetic anomaly is directly related with the outcropping area of the Sines massif to the continental shelf; three-dimensional modelling (3D) of apparent magnetic susceptibility correlates with a volume of 217 km^3.The offshore magnetic anomaly presents an estimated volume of 226 km^3 and is located about 10 km from the Sines anomaly to the Southwest. If both anomalies result from a single igneous body, the area of the Sines massif could as be large as 300 km^2. However, the possibility of these that those two anomalies correspond distinct mafic igneous structures in the continental shelf cannot be discarded and should be further investigated.

Keywords: InCarbon project, Sines massif, magnetic anomaly.

Resumo: O projeto InCarbon pretende avaliar o potencial para a carbonatação mineral *in-situ* das rochas plutónicas máficas e ultramáficas no Alentejo para o armazenamento de CO_2. O maciço de Sines parece ser o maciço mais promissor para carbonatação mineral no Alentejo e é caracterizado do ponto de vista geoquímico, petrográfico, mineralógico, bem assim como do ponto de vista do seu volume e extensão. A avaliação do volume e da extensão na área *offshore* foi efetuada reinterpretando dados geofísicos existentes os quais confirmam a ocorrência de duas anomalias magnéticas bem definidas. A anomalia magnética de Sines (sobre o continente) está diretamente relacionada com prolongamento do maciço de Sines para a plataforma continental. Com base em modelação tridimensional (3D) da suscetibilidade magnética aparente foi obtido um volume de 217 km^3. A anomalia magnética offshore, localizada na plataforma continental, apresenta um volume estimado de 226 km^3 e está localizada a cerca de 10 km a sudoeste da anomalia de Sines. Se ambas as anomalias estiverem relacionadas com um mesmo corpo ígneo, então a extensão do maciço de Sines poderá atingir uma área de 300 km^2. No entanto, a possibilidade dessas duas anomalias corresponderem a estruturas máficas distintas não pode ser descartada e deve ser investigada.

Palavras-chave: Projeto InCarbon, maciço de Sines, anomalia magnética.

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1. Introduction

Greenhouse gas emissions in Portugal are mainly located around the industrial areas of Sines and Setubal, which, until recently, were responsible for up to 44% of the national emissions (EU ETS, 2019), largely due to the existence of a coal power plant, petrochemical industries, and cement factories. Although the Sines Coal Power Plant was decommissioned in 2021, the remaining sources in southern Portugal still account for more than 30% of all CO_2 emissions from industrial sources in the country (Fig. 1). The climate mitigation ambition of the European Union, the Green Deal, and the target set by the Portuguese government of reaching carbon neutrality by 2050 will require the implementation of CO_2 capture and storage (CCS) as a technology to reduce CO_2 emissions from power and industrial sources (Olajire, 2013), while preserving the activity of those industrial activities.

Van den Broek *et al*. (2013) and Carneiro *et al*. (2015) have studied the possibility of capturing CO_2 at Sines and Setúbal sources and storing it in offshore deep saline aquifers; the low storage capacity and high storage costs were found not to be barriers to the deployment of CCS in conventional storage reservoirs (deep saline aquifers). Thus, given the geological conditions in the region, unconventional storage opportunities are being considered, namely mineral carbonation. *In-situ* mineral carbonation in mafic and ultramafic rocks has been proved to be a valid alternative for permanent storage of CO_2 in basalt rocks in Iceland (Druckenmiller *et al*., 2005) and Wallula (USA) (McGrail, 2014) pilot injection plants.

The multiple mafic and ultramafic rock massifs in Alentejo region, in southern Portugal, could, in principle, provide an alternative for CO_2 storage by mineral carbonation. However, the mafic and ultramafic rock massifs in the target region are plutonic and present low permeabilities and low porosities which are not found in porous basalts. Still, the rock massifs do show a mineralogical and geochemical composition similar to the basalts and, in that respect, are worth studying in the context of mineral carbonation potential for CO_2 capture. That is the aim of the nationally funded project InCarbon.

After a detailed site screening and ranking of ten mafic and ultramafic massifs (Pedro *et al*., 2020) the subvolcanic Sines massif, composed mostly of gabbros, diorites and sienites, was assigned as the most promising massif for mineral carbonation in Alentejo. This is due not only to its geochemical and petrographic features, but also to its proximity to the CO_2 emission sources in the region (Fig. 1). To understand CO_2 injection and carbonation potential, analysis of published information, processing and reinterpretation of existing geophysical information and detailed fieldwork involving structural and geophysical surveys were

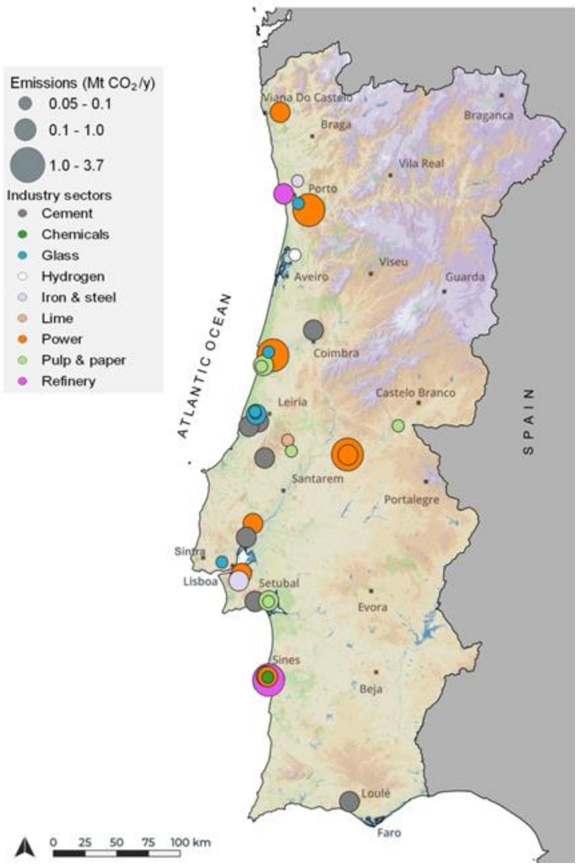

Figure 1. Distribution of main CO_2 emissions sources in Portugal (adapted from Mesquita, 2020).

Figura 1. Distribuição das principais fontes emissoras de CO_2 em Portugal (adaptado de Mesquita, 2020).

carried out to improve the knowledge about the fracture patterns of the Sines massif.

Here we present the work done to further increase the knowledge of the Sines massif structure, with a focus on the reinterpretation of existing aeromagnetic and gravimetric offshore data. We also address the possible continuity of the Sines massif as well as its possible lack of continuity, which has implications in mineral carbonation.

2. Background on the Sines massif

The Sines massif is a subvolcanic ring structure located on the West Portuguese coast (Zbyszewski, 1941; Teixeira, 1962; Ribeiro *et al*., 1979) related with the Late Cretaceous alkaline magmatic cycle (94-72 Ma; Miranda *et al*., 2009). It displays an elliptical shape elongated into the continental shelf, near the city of Sines. Onshore, due to the Plio-Quaternary cover, the Sines massif outcrops along the seacoast and in the Montes de Chãos quarry. The geological map of the continental shelf of Portugal at 1/1 000 000 (Boillot *et al*., 1978) extends the Sines massif a few kilometres offshore, while Carvalho *et al*. (1998) using magnetic, gravimetric, and seismic reflection data proposed that the massif trends NE–SW for tens of kilometres, covering an area of approximately 300 km^2.

The Sines massif (Fig. 2) is regarded as a multiphase intrusive mafic complex, mainly composed of gabbros, diorites, and syenites with a profusion of dykes of variable composition (basalts, microgabbros, microdiorites, trachybasalts, lamprophyres, trachytes, and microsyenites) originated in a common magmatic chamber by fractional crystallization (Canilho, 1972, 1989; Inverno *et al*., 1993). A multiphase emplacement is accepted for the genesis of the Sines massif (Zbyszewski 1941; Canilho 1972; Inverno *et al*. 1993) starting with the intrusion of gabbro-diorite rocks, followed by syenitic rocks and eruptive breccias, and finally the emplacement of a net of dykes that cut the intrusive massif rocks and the surrounding country rocks.

Despite the Plio-Quaternary cover, the geological map of Portugal at 1/50 000 scale (sheet 42-C, Santiago de Cacém; Inverno *et al*., 1993) shows that the Sines massif intruded and metamorphosed the Carboniferous flysch to the southern area (Mira Formation) and the Lower Jurassic carbonate rocks to the northern region, generating thermal aureoles of pelitic and calcic hornfels.

3. Methods and techniques

In the scope of the InCarbon project several geological and geophysical field campaigns were conducted in the Sines massif area, not only to confirm its geological characteristics, but also to acquire new data and to evaluate its potential for *in-situ* mineral carbonation. Abdoulghafour *et al*. (2021), Moita *et al*. (2020a, b) and Pedro *et al*. (2020) have studied two coarse-grained mafic to ultramafic samples: a melanocratic cumulate gabbro sampled at cliff near Praia do Norte and a gabbro-diorite sampled at Montes de Chãos quarry.

To clarify the main fracture network features Pedro *et al*. (2020) used the exposure at the walls of Montes de Chãos quarry to scanline studies of fracture frequency and length.

The lithological variability of the Sines massif and its extension into the continental shelf was targeted by geophysical data to distinguish and individualize the area of occurrence of mafic and ultramafic rocks and to assess its extent in the offshore area.

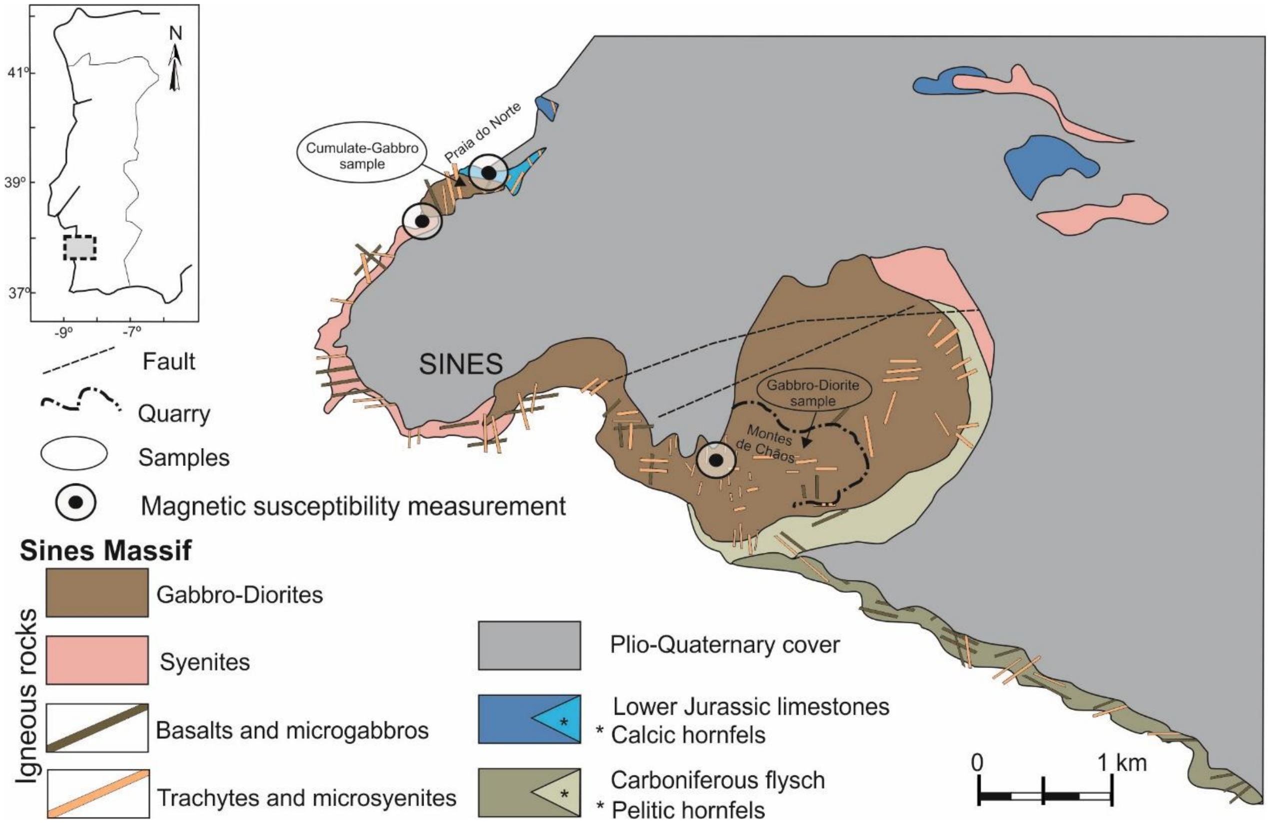

Figure 2. Geological map of Sines massif (adapted from Inverno *et al*., 1993).

Figura 2. Mapa geológico do maciço de Sines (adaptado de Inverno *et al*., 1993).

To achieve these goals, *in-situ* measurements of magnetic susceptibility of the rock-forming the onshore Sines massif and their surrounding rocks were performed, while the aeromagnetic data acquired by the company Farey Surveys Limited in 1969 was reinterpreted. The contemporaneous gravimetric data obtained offshore by GSI Inc for oil companies was also revisited. Magnetic susceptibility (k) was measured in three areas in the Sines massif and surrounding rocks (Fig. 2) taking into account surface geology, accessibility of the region; to determine the magnetic susceptibility contrast (Δk) an attempt to cover the lithological diversity of the region was tried. The measurements were performed *in-situ*, with a portable KT^{-10} Terraplus meter, which has a sensitivity of 10^{-6} SI.

Farey Surveys Limited acquired in 1969 for the hydrocarbon industry a total-field aeromagnetic survey covering the Algarve and Western Portuguese offshore platforms, including onshore strips. The continental shelf of Alentejo region was also the target of other geophysical prospecting campaigns (seismic reflection, gravity). These datasets were used to conclude that the Sines massif spreads offshore to the continental shelf over an area of approximately 300 km^2, at relatively shallow depths with a global NE-SW orientation (Carvalho *et al*., 1998; Carvalho, 1995), in contrast with the E-W orientation of the onshore area (Ribeiro, 1979).

The Farey´s total-field aeromagnetic survey was flown at an altitude of 600 m and approximately E-W oriented flight lines with an approximate 2 km line spacing and some tie lines with random orientation. In the absence of the original digital data, it was necessary to digitize from total-field anomaly paper maps the crossings of the isolines (with an equidistance of 5 nT), with the flight lines. After data validation, the International Reference Geomagnetic Field (IGRF) of 1965, subtracted at the time of the original processing, was added, and replaced, with the IGRF improved version of 1995 Carvalho (1995). In this study we interpolated these data, using the minimum curvature method to obtain a regular grid of 500 m x 500 m.

The total-field magnetic intensity map (MFI) was afterwards reduced to the pole. The reduction to the pole filter was applied using the central point of the map, with the goal of transforming the inclined magnetic field into a single vertical field. This filter helps in the interpretation as it places the magnetic anomalies over their true horizontal position (as if the anomaly were sited at the magnetic pole) and facilitates the identification of their respective geological sources.

To better understand and distinguish the geological sources of any identified magnetic anomalies the available gravimetric data acquired by the GSI over the seismic reflection profiles, was used to produce a free air gravimetric anomaly map.

The gravimetric data were interpolated using the least-curvature interpolation method, allowing to obtain a regular grid with a cell size of 285 m x 285 m from the gravimetric profiles with the free air anomaly values.

Regarding the size of the magnetic anomalies and considering the magnetic properties scenario of the Sines massif (with mafic and ultramafic rocks in contact with metapelite, siliciclastic and carbonate surrounding rocks) an apparent magnetic susceptibility 3D model was constructed, based on the inversion of magnetic data. This 3D model was obtained with commercial software

(Oasis Montaj™), using the Voxi Earth™ module (Seequent, 2020). The magnetic potential field inversion uses an algorithm that predicts three-dimensional magnetic susceptibilities from observed magnetic field measurements and allows to calculate the three-dimensional distribution of apparent magnetic susceptibility, discretized into a series of cells, each one containing a predicted volume of magnetic susceptibility (Robert *et al*., 2012).

4. Results

4.1. Mineralogical, geochemical and structural features

The geological evaluation of the Sines massif for its *in-situ* mineral carbonation potential was conducted during the InCarbon project (Abdoulghafour *et al*., 2021; Moita *et al*., 2020a, b; Pedro *et al*., 2020). The mineralogical and geochemical features were achieved by the study of a cumulate gabbro and a gabbro-diorite samples.

The cumulate gabbro displayed medium to coarse phaneritic texture that preserved the ferromagnesian mineral phases. It is composed of diopside–augite (45-55%), magnesium olivine (15–20%), tschermakite horneblende (10-15%), bytownite–labradorite (5-10%), and primary ilmenite (5%), occasionally showing accessory alteration products (*e.g*., chlorite, actinolite, and serpentine), around the olivine and some pyroxene crystals. The rock geochemistry presents a compositional spectrum with SiO_2 (42.3 wt%), MgO (12.90 wt%), CaO (12.7 wt%), Fe_2O_3 (15.15 wt%), TiO_2 (3.34 wt%), Cr (478 ppm) and Ni (117 ppm) contents compatible with an ultrabasic composition with alkaline affinities.

The gabbro-diorite exhibits a medium to coarse hypidiomorphic phaneritic texture, characterized by plagioclase-enriched layers alternated with ferromagnesian-enriched layers. It is mainly composed of calcium plagioclase (50-60%) and diopside–augite (20-25%), associated to ferrous olivine (5-10%), biotite (10-15%), Fe-rich ilmenite (5-10%) and incipient secondary chlorite and sericite. The rock geochemistry revealed a basic composition (SiO_2 = 49.00 wt%) and displayed lower MgO (4.48 wt%), CaO (8.33 wt%), Fe_2O_3 (11.20 wt%) and TiO_2 (3.26 wt%), enhanced by low Cr (20 ppm) and Ni (7 ppm) and high Sr (748 ppm) values, which were directly related to the modal abundance of plagioclase, clinopyroxene, and olivine.

The above geochemical and petrographic features are in accordance with the related features described by Canilho (1972, 1989) and Ribeiro *et al*. (2013), and it was also possible confirm the very low primary porosity exhibited by the studied samples, as expected for plutonic rocks. Since porosity is a fundamental variable for the viability of *in-situ* mineral carbonation, the characterization and quantification of fracture patterns is essential for the indirect assessment of the permeability of the Sines massif and, consequently, for the viability of using its mafic and ultramafic rocks in *in-situ* mineral carbonation process.

Pedro *et al*. (2020) used the exposure at the walls of Montes de Chãos quarry to analyse the fracture patterns of the Sines massif, and obtained a variety of orientations, suggesting a heterogeneous fracture pattern (Fig. 3). Nonetheless, the measured spacing between fractures (10.7-24.5 cm) displays a width medium-density fracture which increases the potential surface area available for mineral carbonation reactions. These fracture data analysis agree with the geotechnical data obtained by drilling cores (APS, 2019), which revealed a good to excellent geotechnical quality for the gabbro-diorite core of the Sines massif and an absence of high secondary porosity.

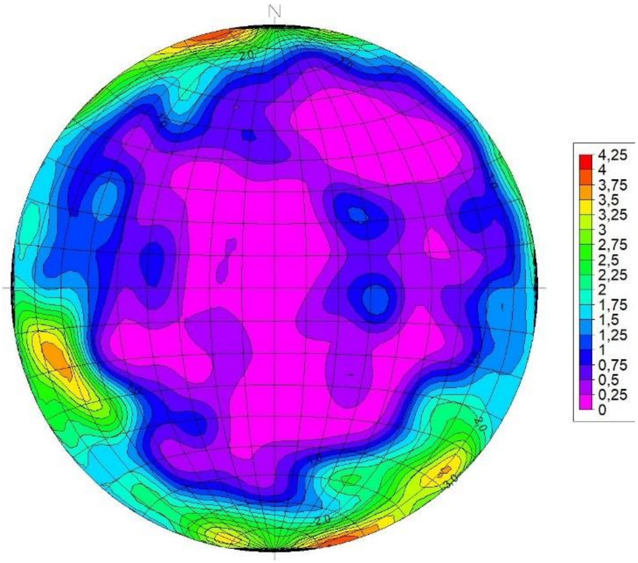

Figure 3. Fracture density diagram poles for the Monte Chãos quarry (Pedro *et al*., 2020). The projection uses the Schmidt equal area net, and the number of discontinuities represented is 425. The values in the scale represent the percentage of occurrence.

Figura 3. Diagrama de densidade de polos da fracturação na pedreira de Monte Chãos (Pedro *et al*., 2020). Projeção de 425 descontinuidades em rede de Schmidt de igual área. A escala representa a percentagem de ocorrência.

4.2. Geophysical interpretation

Table 1 presents the magnetic susceptibility survey results and reflects the expected high magnetic susceptibility of gabbros and diorites with respect to the other lithologies of the Sines massif and surrounding rocks.

Figure 4 shows the total-field magnetic intensity map (MFI) map, reduced to pole, with an equidistance between isolines of 50 nT.

To verify how the magnetic signature correlates with regional geology, the isolines of the MFI map were plotted over the geological map of the Sines massif and are presented in figure 5. From the analysis of figures 4 and 5, the following main aspects can be highlighted:

(i) A northeastern anomaly over the city of Sines – the Sines anomaly – with an average width of 4km and a length of 9 km, with values above 6000 nT. The isolines are approximately E-W, but to the offshore the isolines develop a sharp and tight curvature facing southwest.

(ii) A southwestern anomaly in the continental shelf – the offshore anomaly – with an average width of 9 km and a length of 15 km, with values above 5900 nT and a NE-SW orientation of the isolines.

(iii) The location of the lowest values northeast from the city of Sines and matching the Plio-Quaternary cover.

The five free air anomaly profiles (G1 to G5) superimposed to the MFI reduced to pole map are presented in figure 6. The gradient of the free air anomaly conveys the following remarks:

(i) The higher values of the free air gravimetric anomaly are located around the intersection of profiles G5 and G2, defining a major gravimetric anomaly with values higher than 58 mGal; a marginal gravimetric anomaly exists

Table 1. Magnetic susceptibilities of the Sines massif and surrounding rocks (N – number of measurements).

Tabela 1. Suscetibilidades magnéticas do maciço de Sines e das rochas encaixantes (N – número de medições).

Lithology	Magnetic susceptibilities (SI)				N	Coordinates (WGS84)	
	Minimum	Average	Maximum	Standard deviation		Latitude	Longitude
Gabbros and diorites	0.01	0.05	0.1	0.02	44	37.94963	8.85074
Syenites	0.0001	0.002	0.01	0.003	25	37.96546	8.87999
Trachyte and microsyenites	0.0002	0.0003	0.0004	0.00005	11	37.94898	8.85218
Margous limestones	0.0002	0.0002	0.0003	0.00003	8	37.96952	8.87104
Conglomerates	0.00005	0.0001	0.0003	0.0001	5	37.96952	8.87104
Limestones	0.00003	0.0001	0.0001	0.00003	11	37.96952	8.87104
Sandstones	0.00002	0.00003	0.0001	0.00001	6	37.96952	8.87104

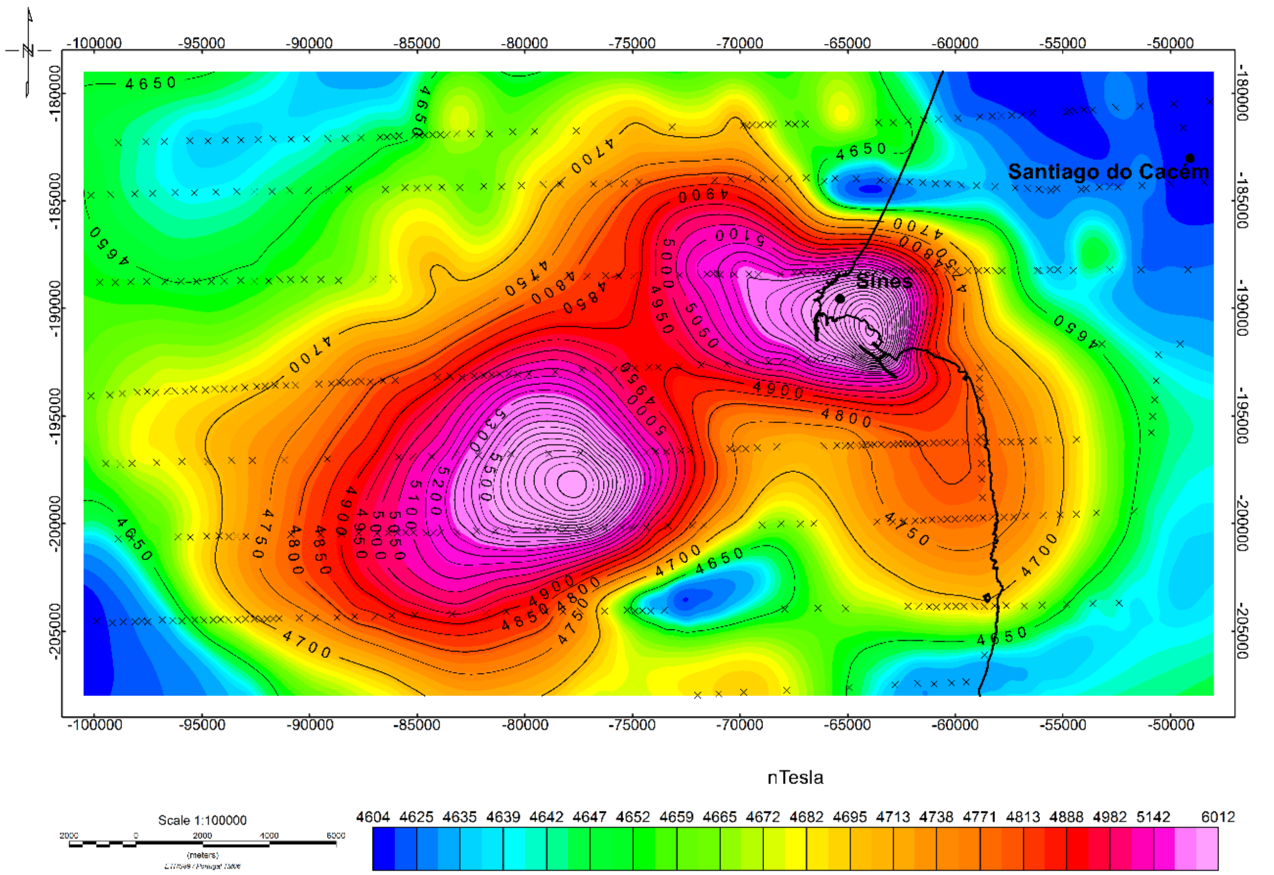

Figure 4. Map of the total-field magnetic intensity (MFI), reduced to pole, of the Sines region with two magnetic anomalies: the Sines anomaly and the offshore anomaly.

Figura 4. Mapa de intensidade do campo magnético total (ICM), reduzido ao polo, da região de Sines com duas anomalias magnéticas: anomalia de Sines e anomalia *offshore.*

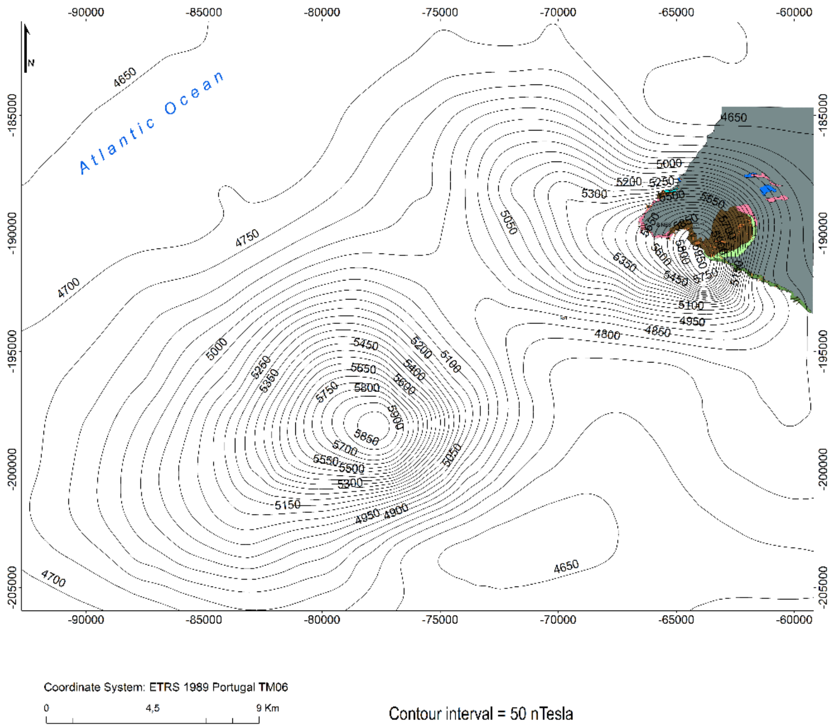

Figure 5. Map of the total-field magnetic field contour lines, reduced to pole, plotted over the geological map of Sines massif (see figure 2 for the geological legend).
Figura 5. Projeção das linhas de contorno de intensidade do campo magnético total, reduzido ao polo, sobre o mapa geológico do maciço de Sines (consultar legenda do mapa geológico na figura 2).

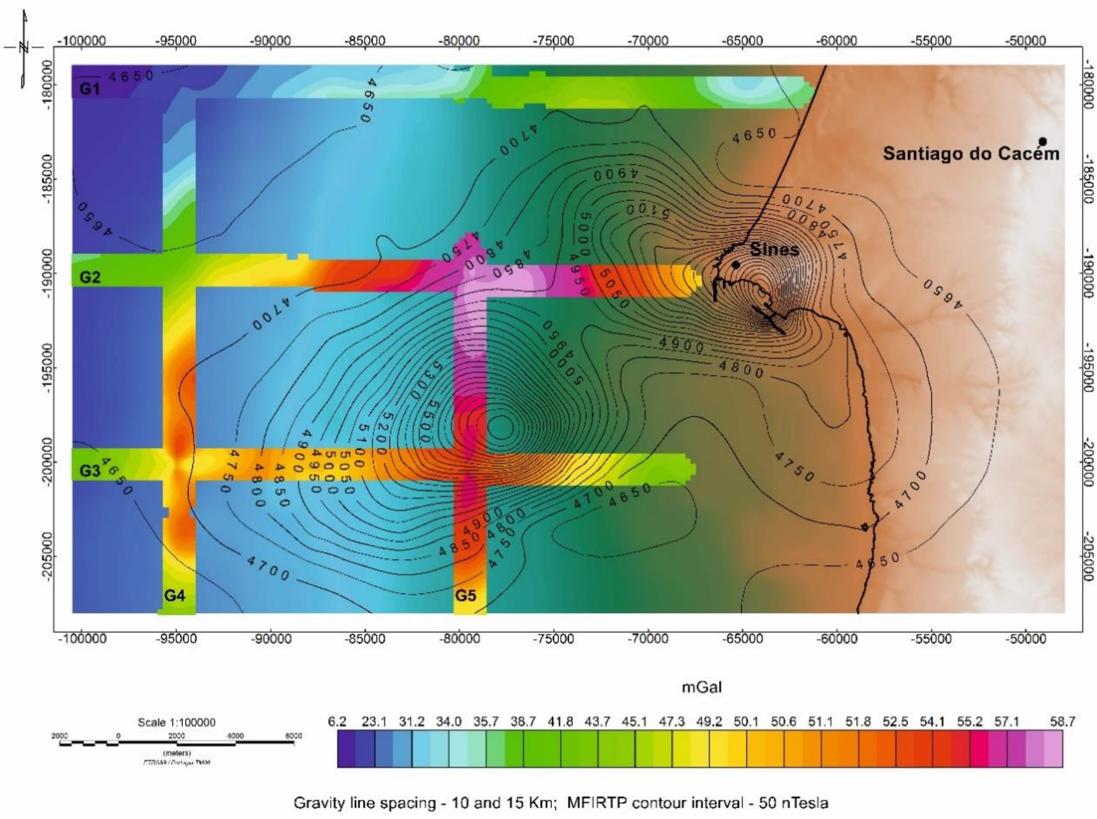

Figure 6. Free air anomaly gravimetric profiles G1 to G5 plotted over the magnetic total-field intensity map (MFI), reduced to pole.
Figura 6. Perfis gravimétricos de anomalia de ar livre G1 a G5 projetados no mapa de intensidade do campo magnético total (ICM), reduzido ao polo.

around the intersection of profiles G5 and G3, with values ranging from 54 to 57 mGal.

(ii) There is a slight increase of the free air gravimetric anomaly in profiles G2 and G3 towards the profile G5, and in profile G4 towards profile G3.

(iii) The lowest values of the free air gravimetric anomaly occur along profile G1.

(iv) There is a deviation of the major gravimetric anomaly respectively to the West and to the North of the above-mentioned Sines and offshore magnetic anomalies; the marginal gravimetric anomaly shows a slight deviation to the Southwest of the offshore magnetic anomaly. These discrepancies could be explained by using two different potential field methods in a same heterogenous rock massif which is not exactly denser in the same places that is more magnetic.

The result of the three-dimensional apparent magnetic susceptibility model obtained from the inversion magnetic data is presented in figure 7. The two volumes shown have susceptibilities of the order of 10^{-2} SI, allowing to estimate volumes of mafic and ultramafic rocks of 217 km^3 for the Sines magnetic anomaly and 226 km^3 for the offshore magnetic anomaly.

5. Discussion

The analysed samples of cumulate gabbro and gabbro-diorite from the Sines massif display geochemical, and mineralogical features required for mineral carbonation. Nonetheless, for the *in-situ* CO_2 storage injectivity is essential and depends on rock porosity and permeability, which in plutonic rocks depend on the fracture network. For the Sines massif the facture network does not display high-density fracture, and consequently the increase of the surface area available for mineral carbonation reactions through secondary porosity, is limited.

Other requirements for the capacity for CO_2 storage through mineral carbonation are the outcropping area and volume of the Sines massif. The presence of magnetic and dense structures along the offshore Sines massif is indisputable and geophysics data allows to estimate the massif volume. Despite the discrepancies between the gravimetric and magnetic anomalies, the existence of coupled magnetic and gravimetric anomalies is directly related with the occurrence of mafic and ultramafic rocks and shed light on the extension of the Sines massif.

Carvalho *et al*. (1998) refer that the gravimetric and magnetic anomalies are spatially coincident, suggesting that even if the gravimetric anomalies were the result from the Paleozoic basemen uplift, the magnetic anomalies must be caused by mafic or ultramafic rocks at relatively shallow depth, due the intensity of the anomalies.

The Sines magnetic anomaly is directly related to the extent towards the continental shelf of the outcropping onshore area of the Sines massif. The interpretation of the causative source of the offshore magnetic anomaly remains open. A first hypothesis, in line with Carvalho *et al*. (1998) is that both magnetic anomalies are correlate with the same igneous structure, and the Sines massif extends to the Southwest covering an area of 300km^2 as proposed by Carvalho *et al*. (1998).

However, the centers of the magnetic anomalies defined by the contour lines in the MFI map (Fig. 4) are about 10 km distant in a straight line and suggests an alternative interpretation. The possibility of these two anomalies corresponding to two distinct mafic igneous structures should be considered and investigated. Indeed, in a similar geotectonic context, related with the Late

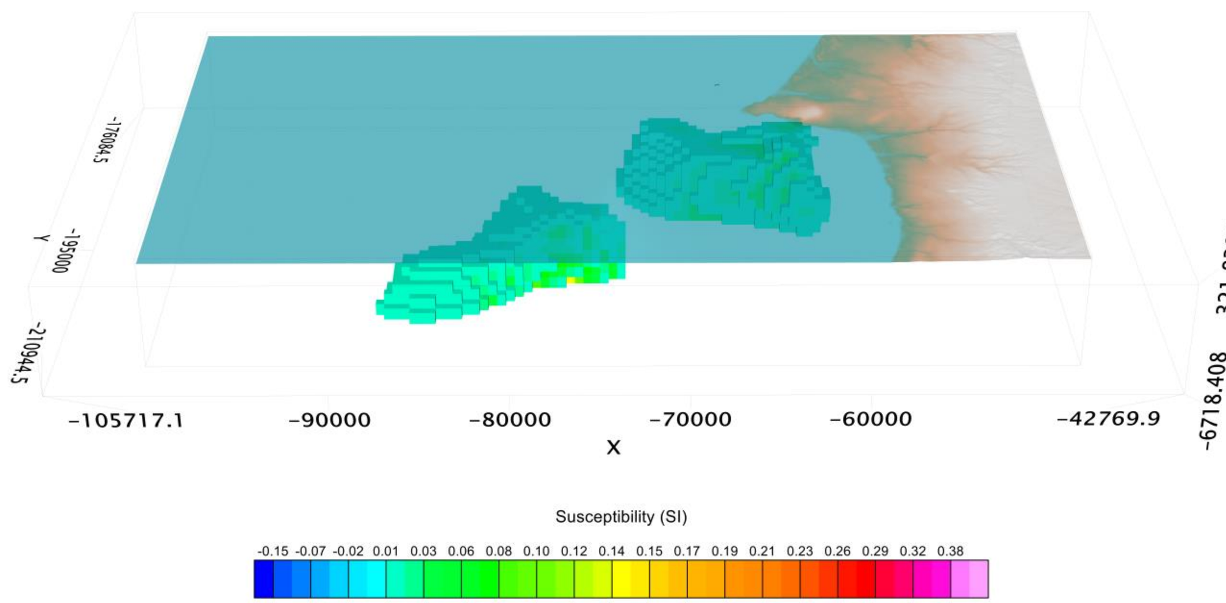

Figure 7. Apparent magnetic susceptibility 3D model for the study area.

Figura 7. Modelo 3D de suscetibilidade magnética aparente da área em estudo.

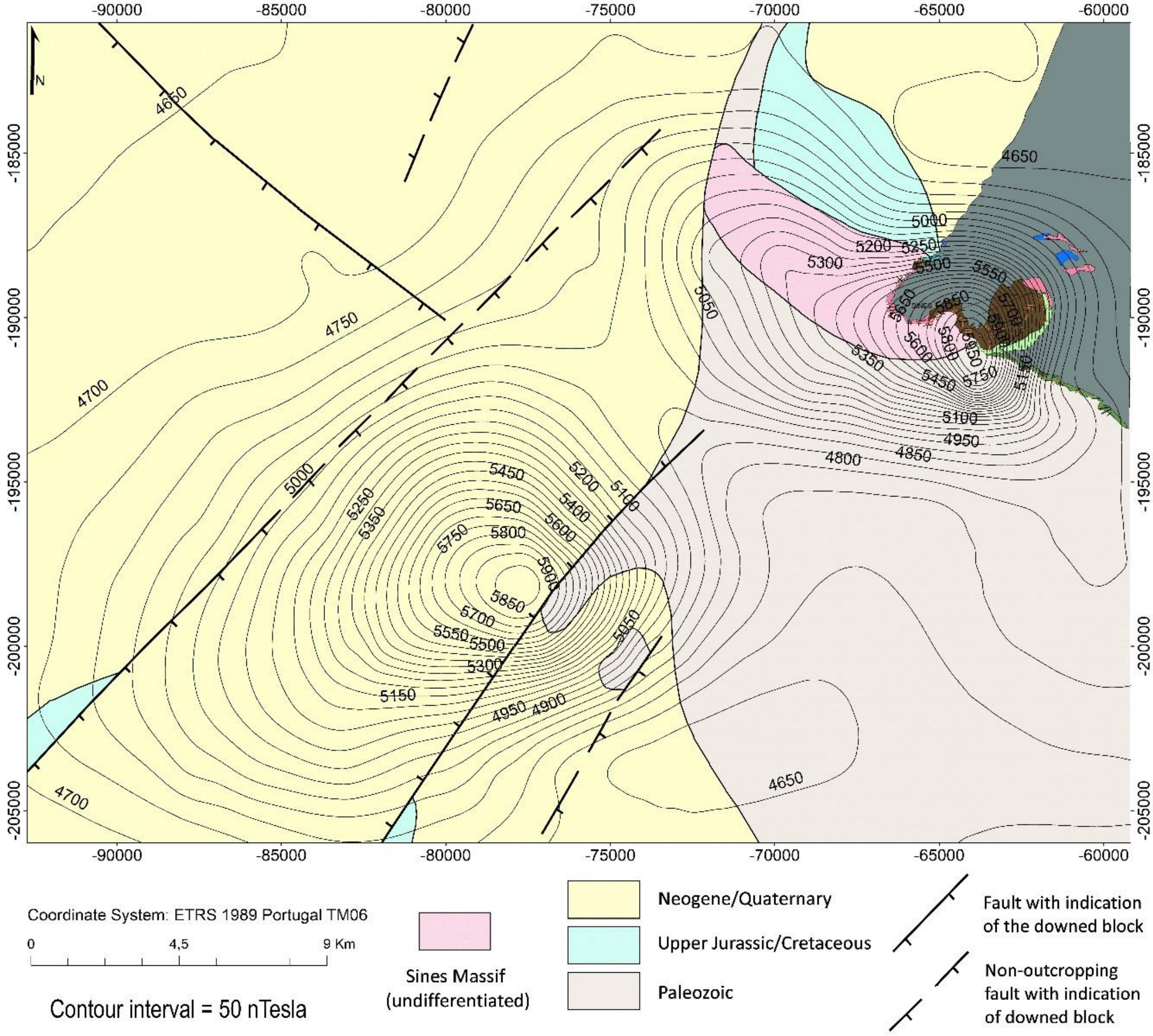

Figure 8. Overlay of the of the magnetic field contour lines, reduced to pole, on the simplified continental shelf geology (adapted from the Geological Map of Portugal at 1/200 000; see figure 2 for the legend of the onshore region).

Figura 8. Projeção das linhas de contorno de intensidade do campo magnético total, reduzido ao polo, sobre o mapa geológico simplificado da plataforma continental (adaptado do Mapa Geológico de Portugal à escala 1/200 000; consultar legenda da figura 2).

Cretaceous alkaline magmatic cycle, Pereira *et al*. (2020) refer the occurrence of a volcano structure, multiple sill complexes and a long laccolith in the West Iberian Margin, along the Sintra massif offshore.

Figure 8, resulting from superimposing the MFI map (Fig. 4) and the geological map of the continental shelf (Oliveira *et al*., 1983), shows that the /Sines magnetic anomaly onshore overlaps the outcrop area of the Sines Massif in the continental shelf and extends to the offshore. In what concerns the offshore anomaly, it is possible to verify that it lays beneath the Neogene cover and is roughly limited by NE-SW faults. This reinforces the need to investigate the West Iberian Margin along the Sines offshore massif. On the other hand, if the magnetic anomalies do not correspond to shallow igneous bodies, they could be deeper than expected and thus the estimated volume of mafic rocks, calculated by the apparent magnetic susceptibility 3D model (217 km^3 + 226 km^3) should be increased, and, consequently, increasing the volume available for mineral carbonation.

6. Conclusions

Under the framework of the InCarbon project the potential for CO_2 storage through mineral carbonation of the Sines massif was examined, as well as the evaluation of the available offshore volume for mineral carbonation.

The mafic and ultramafic rocks of the Sines massif present the geochemical and mineralogical requirements for CO_2 storage, but the low rock porosity and permeability observed in the gabbro-diorite core of the Sines massif constitute as an obstacle to the *in-situ* CO_2 storage injectivity. Therefore, the *ex-situ* mineral carbonation methodology could be a viable alternative for the use of the mafic and ultramafic rocks of the Sines massif for permanent CO_2 storage.

Available aeromagnetic and gravimetric surveys were revisited and new measurements of magnetic susceptibility in the study area were used to generate an apparent magnetic susceptibility 3D model of the massif and estimate its total volume. Two magnetic anomalies were identified: one closer to onshore and other clearly offshore. Two possible interpretations can be advanced to explain the two magnetic anomalies: one, proposed by Carvalho *et al*. (1998), defends that those two magnetic anomalies result from a single igneous body, whose implication is that the Sines massif extends for more than 300 km^2; the other is that the two magnetic anomalies result from two distinct igneous massifs, the second of which lying totally offshore and never reported in the literature. Further research is needed to know which scenario is more consistent and closer to reality. Regardless of the interpretation, the volume of the igneous massif, or massifs, is large and if it is proved they mainly have the same mineralogical and geochemical characteristics of the gabbros outcropping in Sines, they would constitute a valuable reservoir for mineral carbonation. The main challenges are, though, related to the low permeability and, therefore, low injectivity in the massif, which are essential for mineral carbonation.

A 3D magnetic susceptibility model indicates a mafic rock volume of 217 km^3 for the onshore magnetic anomaly and a mafic rock volume of 226 km^3 for the offshore magnetic anomaly; therefore, an estimated volume of about 440 km^3 is available for mineral carbonation.

Acknowledgments

Authors gratefully acknowledge the FCT support through the Projet InCarbon – Carbonatação *in-situ* para redução de emissões de CO_2 de fontes energéticas e industriais no Alentejo (PTDC/CTA – GEO/31853/2017). Direção-Geral de Energia e Geologia is also acknowledged for providing the gravimetric and aeromagnetic data. We also would like to thank the two reviewers for their constructive comments.

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