Magnetic and gravimetric modeling of the Monchique intrusion in south Portugal

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Reasearch made in the frame of a MSc thesis.

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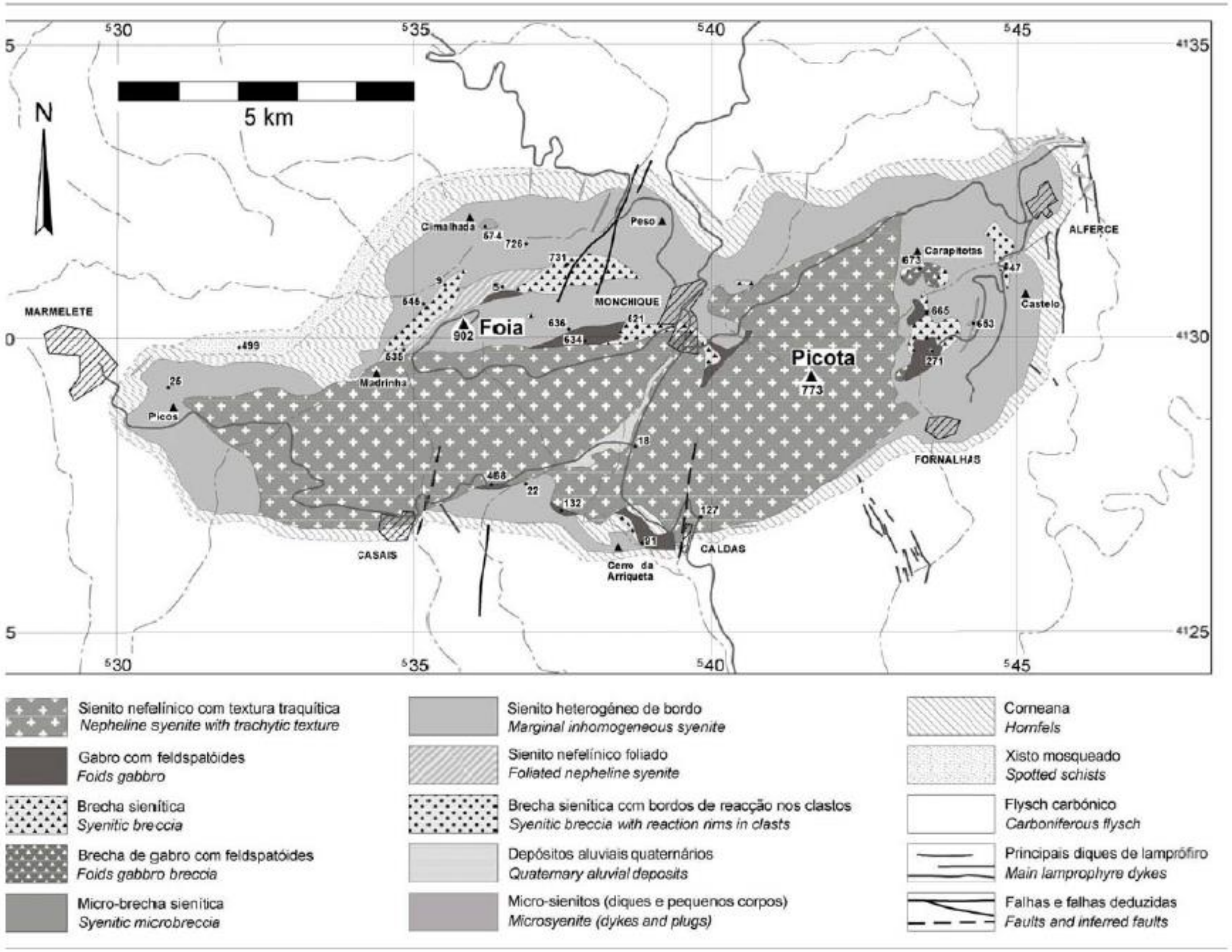
1. Monchique alkaline complex

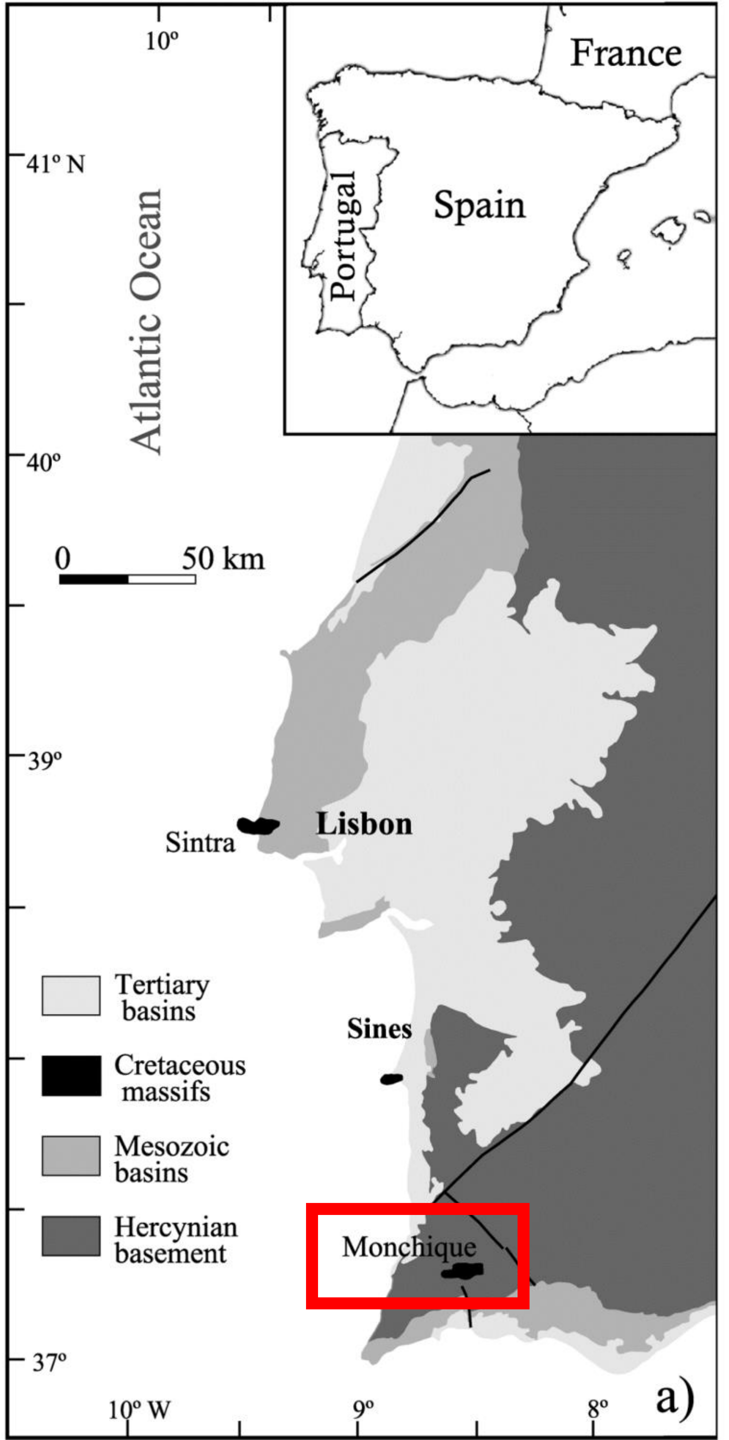
- The Monchique alkaline complex (MAC) crops out in southern Portugal with a roughly elliptical shape of about 80 km^2 elongated along ENE-WSW direction
- It comprises two main types of syenites: a central homogeneous nepheline syenite surrounded by a heterogeneous syenite unit, and some less expressive outcrops of mafic rocks (gabbros, hornfels, breccia and basalts).
- The complex has been dated to the Late Cretaceous, 72 ± 4 Ma (Miranda et al., 2009) and 68.8 ± 1 Ma (Grange et al., 2010a);

(Valadares, 2004)



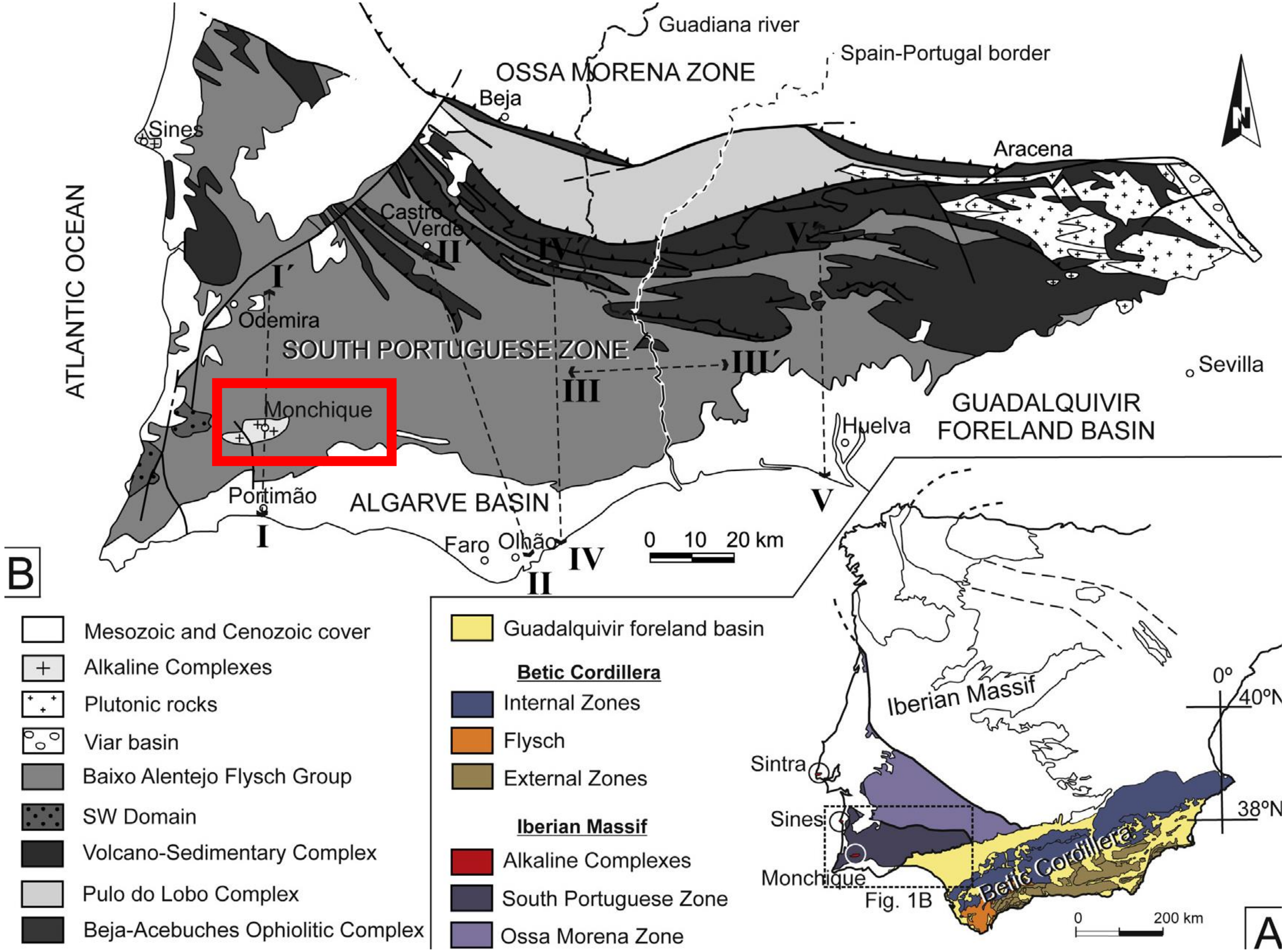
2. Geological/geophysical setting

- It intrudes the Baixo Alentejo Flysh Group in the South Portuguese zone
- The MAC belongs to the Upper Cretaceous West Iberia alkaline magmatic event, characterized by alkaline magmatism of sublithospheric origin and active from approximately 100 Ma to 69 Ma (Miranda et al., 2009).
- The alignment of the 3 major complexes (Sintra, Sines , Monchique) suggests that their intrusion was controlled by deep NNW-SSE oriented faults.
- The Monchique region hosts the most active seismic cluster of mainland Portugal, with low magnitude earthquakes (M < 4) that occur along lineations with NNE–SSW and WNW–ESE preferred orientation (figure in the next slide).

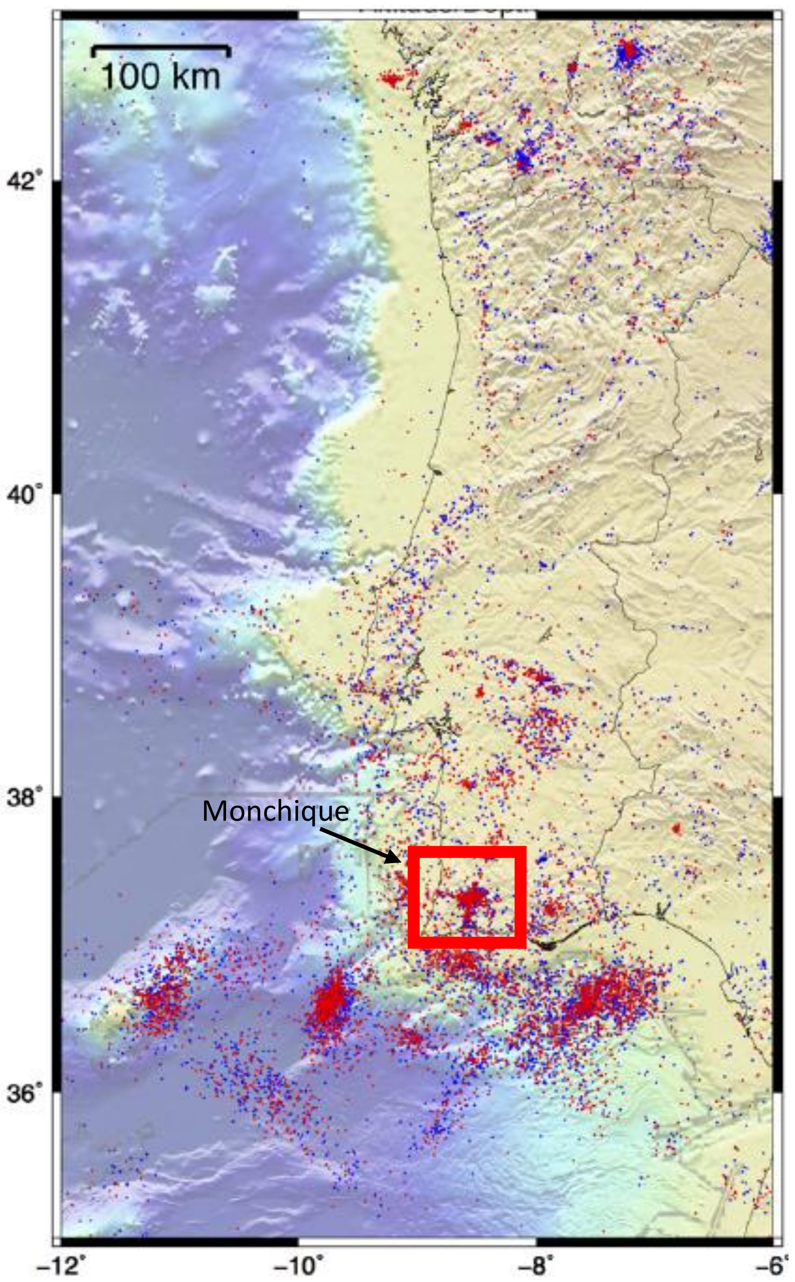


(modified from Ribeiro et al., 2013)

2. Geological/geophysical setting



(modified from González-Castillo et al., 2013)



Epicentres of earthquakes recorded in 2009–2013 (red) overlaid on top of earthquakes that occurred in 1995–2008 (blue) (modified from Custódio et al., 2015)

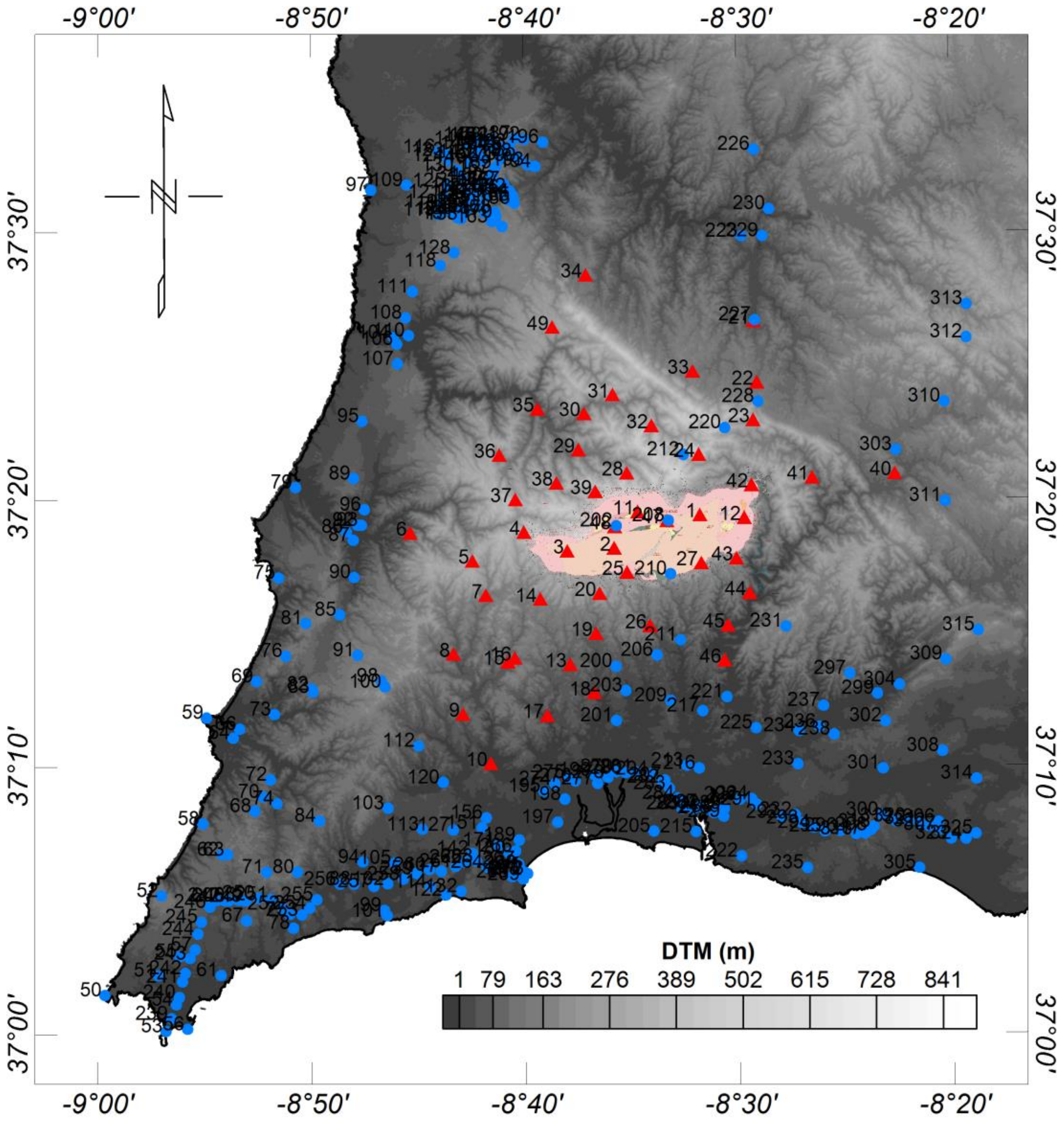
3. Data and methods

Data:

- Recently acquired data: (i) ground gravity survey in 2019 (49 points) and (ii) drone-borne aeromagnetic survey 2020-2021.
- Preexisting data: (i) gravimetric data from IGP (Instituto Geográfico Português) 1997 and (ii) Iberian anomaly map from Socias and Mezcua (2002)
- Density analysis (2021), 73 samples.

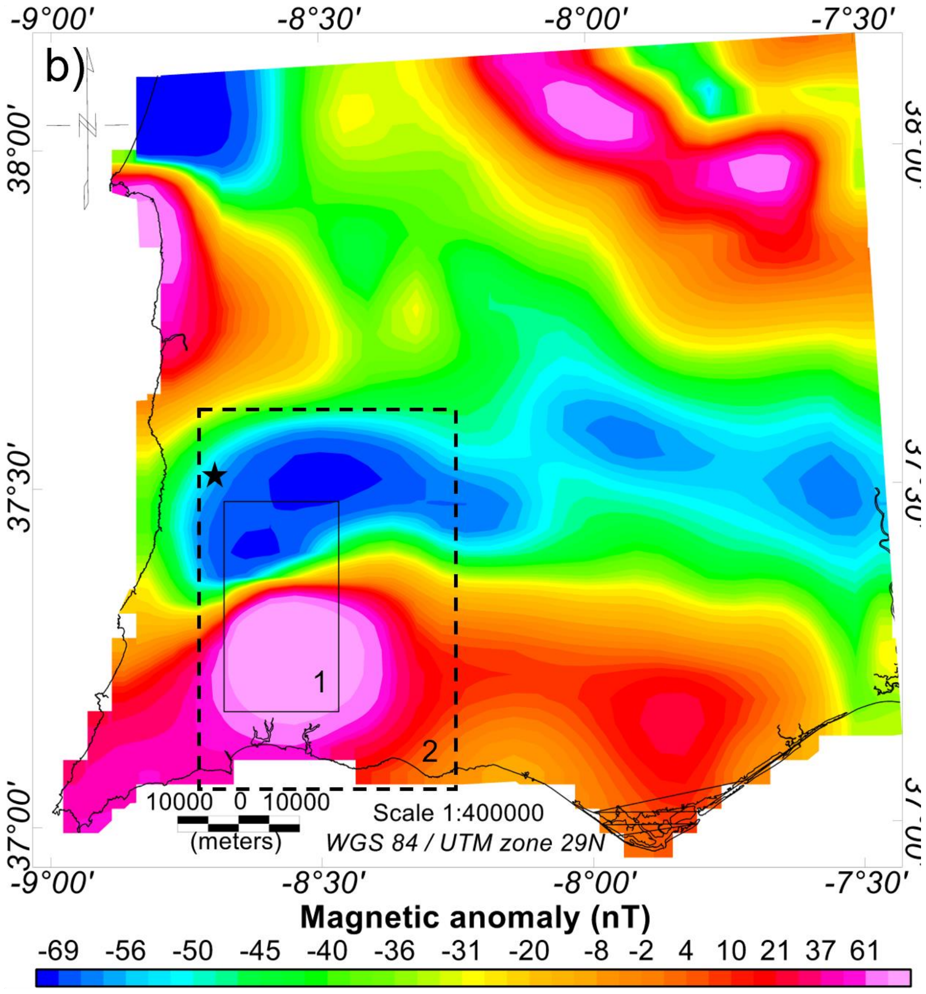
Methods:

- In-house made program by Machiel Bos for initial corrections: tidal and instrumental corrections for gravity data and magnetic diurnal variations and drone instrumental drift.
- Other gravimetric corrections, IGRF removal, 3d inversion and 2d forward modeling, were made with Oasis Montaj.
- The total inducing magnetic field considered was 43658 nT, with inclination of 50.8º and declination of -1.4º (27/05/2021)
- 2D forward modeling was further developed for a representative NNW-SSE profile.

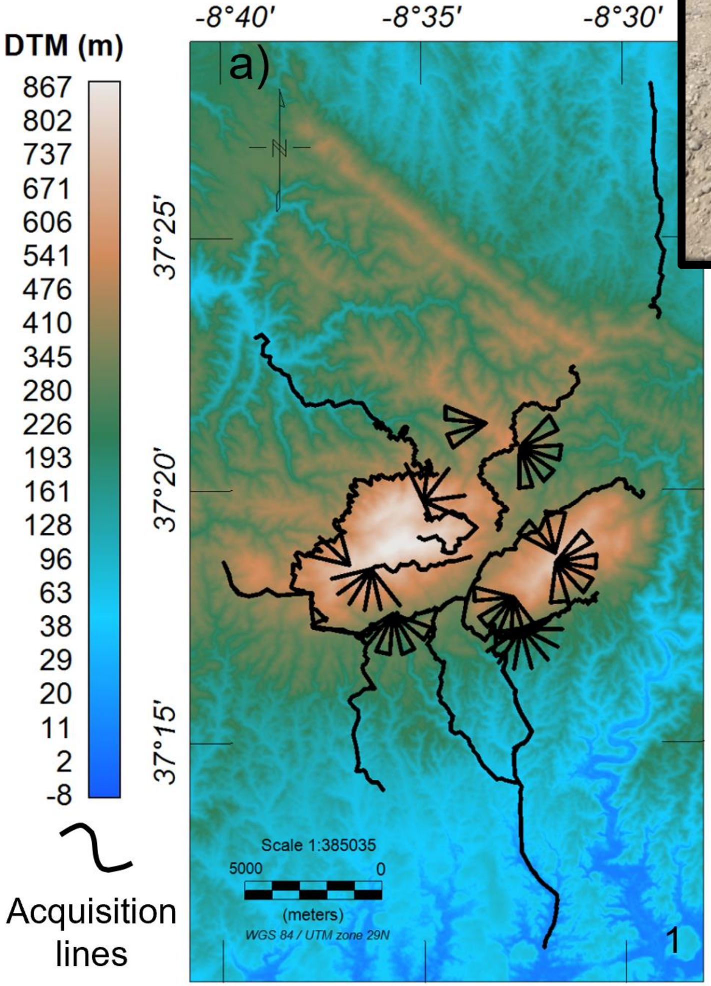


Location of gravity measurements: the red triangles are the points of the SPIDER project, and the blue circles the points from IGP data. Also shown the Monchique intrusion geological map.

3. Data and methods



Aeromagnetic anomaly map cut from (Socias and Mezcua, 2002) magnetic anomaly map of Iberian Peninsula; Portugal area corresponds to (Miranda et al., 1989). Area 1 (full black rectangle): location of map shown in a); The black star indicates the location of the São Teotónio magnetic base station.



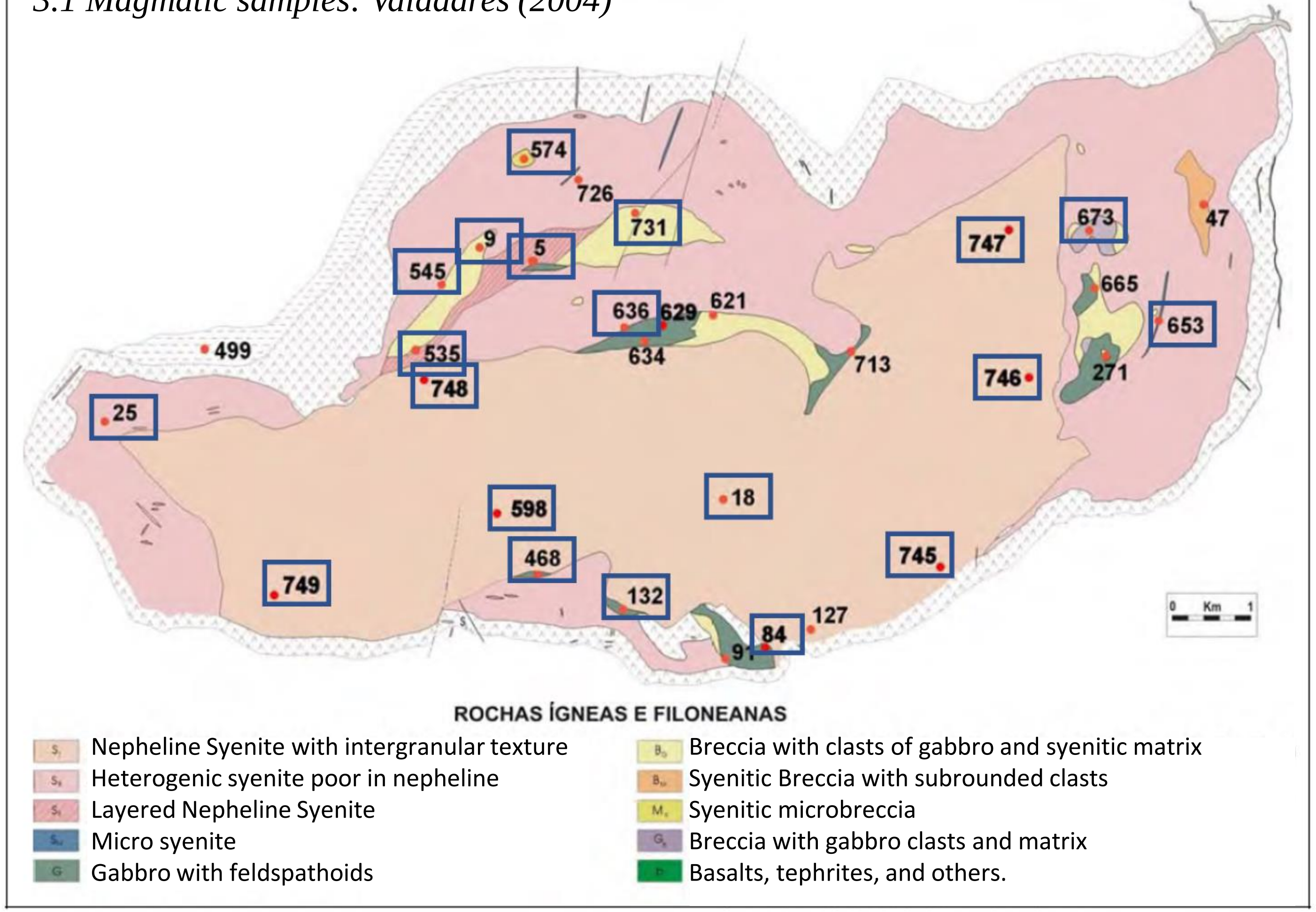
Raw magnetic data of Monchique: acquisition lines with drone in ATLAS project campaigns. And drone photo.

Drone with triaxial magnetometer
SENSYS MagDrone R3

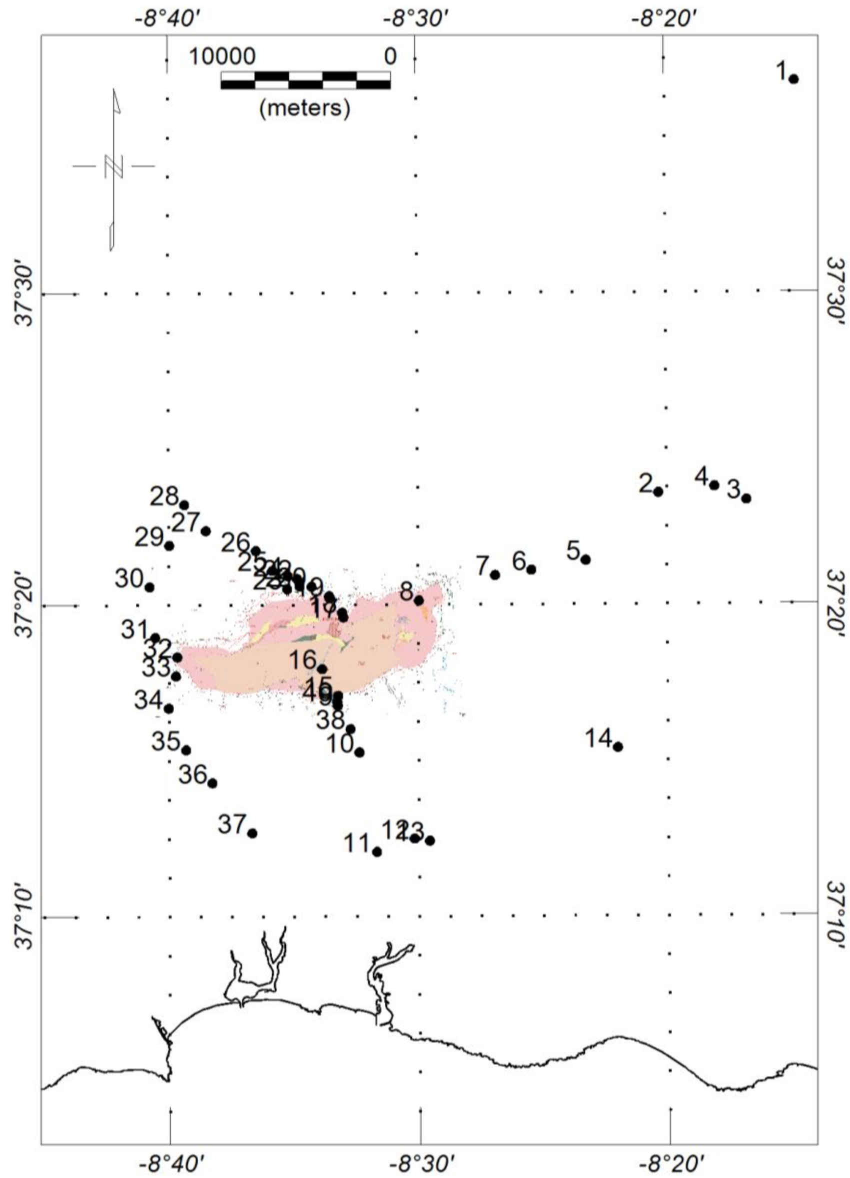
3. Data and methods

- Density samples

3.1 Magmatic samples: Valadares (2004)



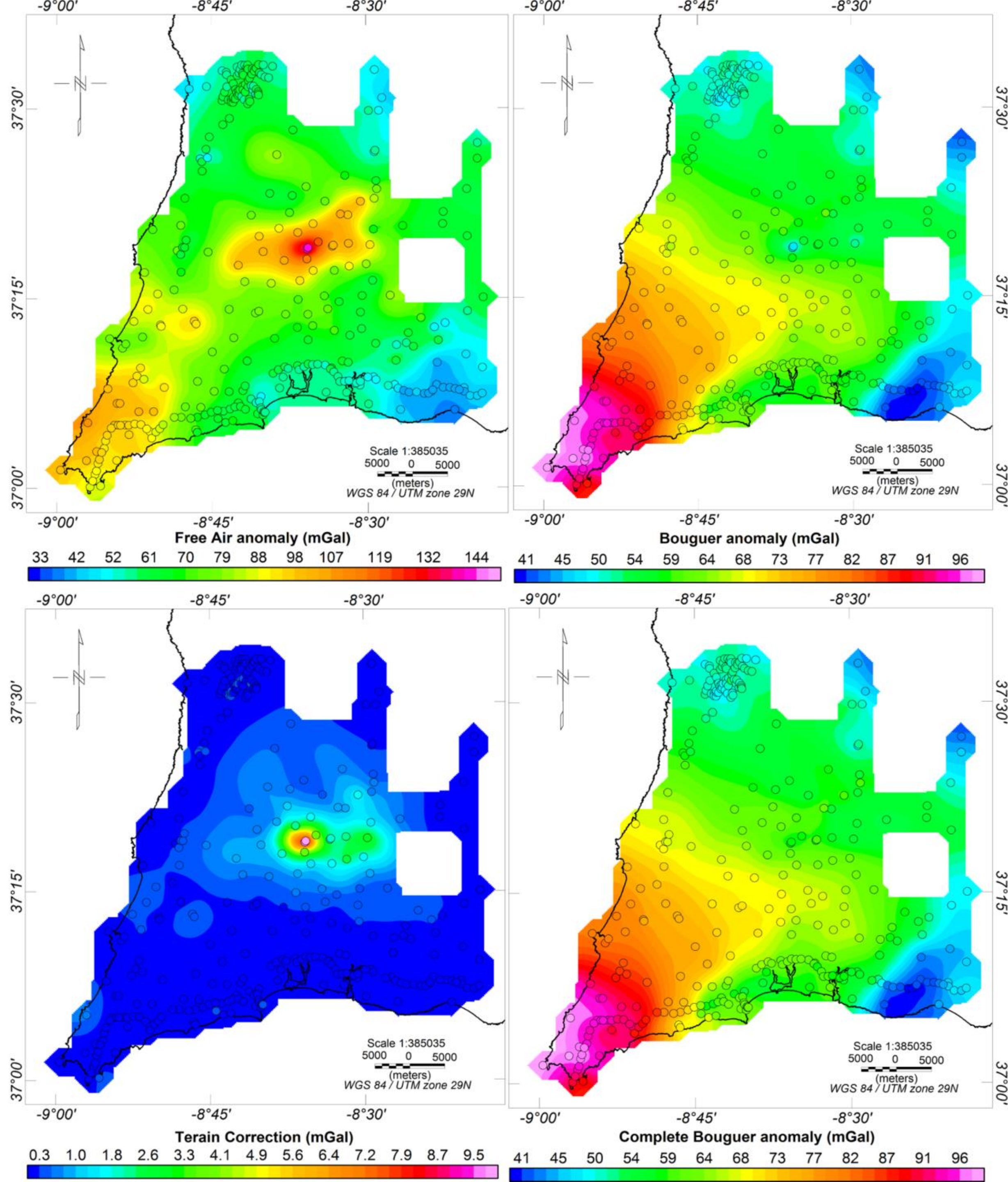
Geological map of Monchique with Valadares (2004) samples, the rectangles indicates the samples analized for density (Modified from Valadares, 2004)



Location of ATLAS samples, 2021 (this study), with the geological map of the Monchique Hill

4. Gravity field Results

- The calculated Bouguer gravity anomaly shows a positive gradient towards the southwest with a negative peak in the center of the Monchique Mountain. However, when applied the terrain correction (complete Bouguer anomaly), this peak vanishes. This is justified by the similar mean density values for the syenite and host rocks, respectively 2560 kg/m^3 and 2530 kg/m^3.
- The gravity field shows a significant positive anomaly (both free-air and Bouguer) in the SW part of the study region, close to Ponta de Sagres. This anomaly and its associated gradient, complemented by results from our 3D density inversion model, imply the presence of high-density rocks in this region suggesting a decrease in the crustal thickness.



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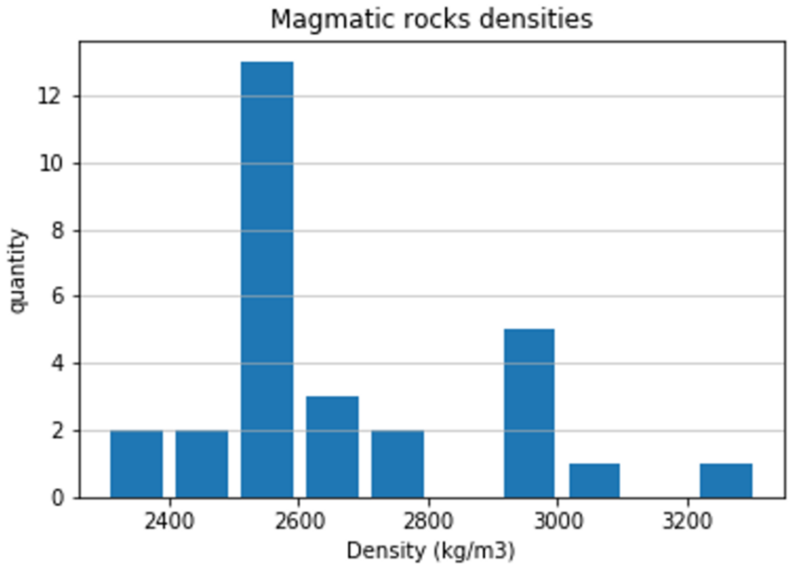
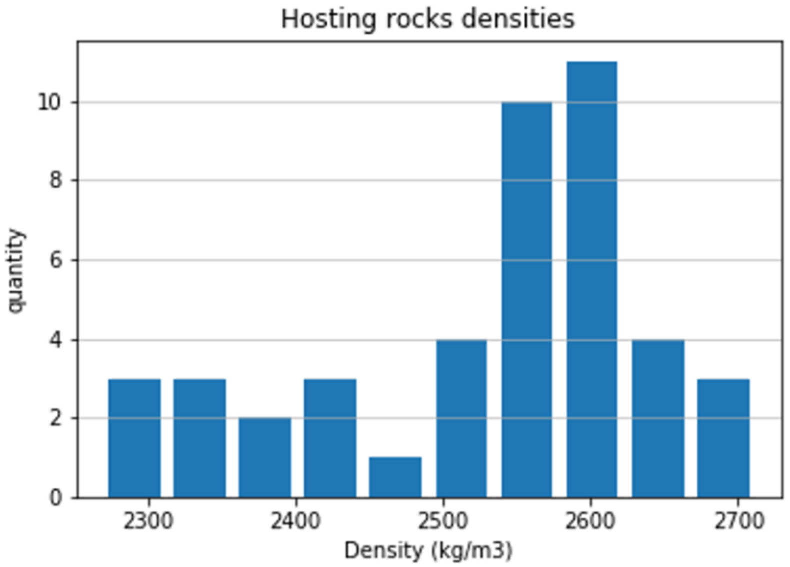
4. Gravity field Results

- Density results

Similar density mean values was found for the hosting rocks and the Syenites (major part of the massif).

Total				
Rock type	Mean	Maximum	Minimum	Samples
Hosting rocks	2530	2694	2269	43
Intrusion rocks	2665	3310	2299	28
Syenites	2560	2975	2299	17





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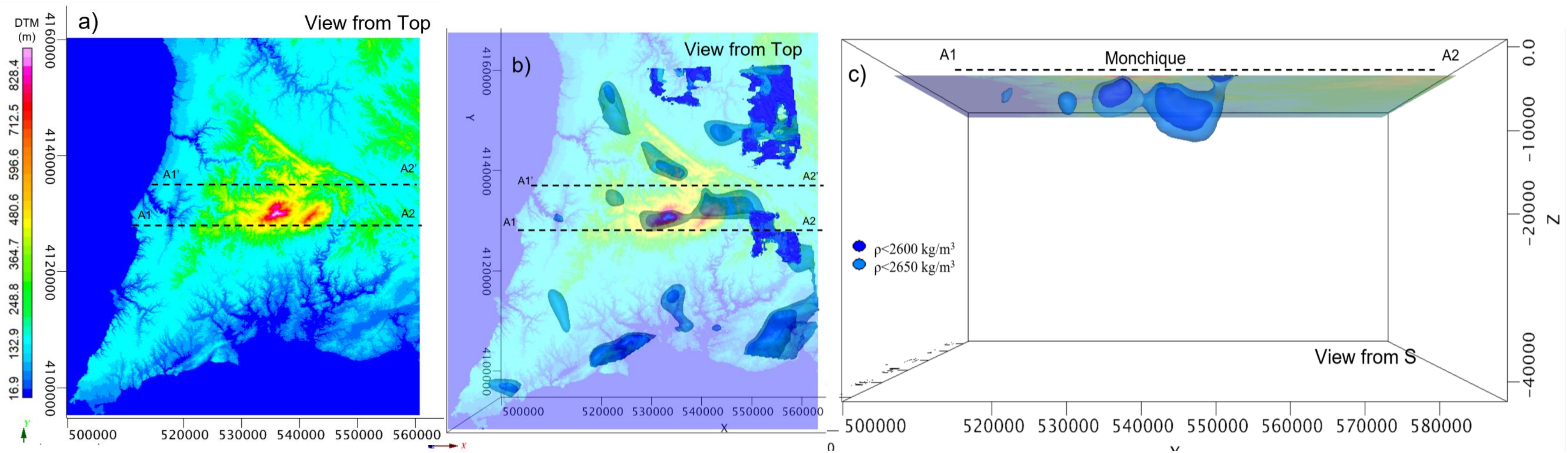
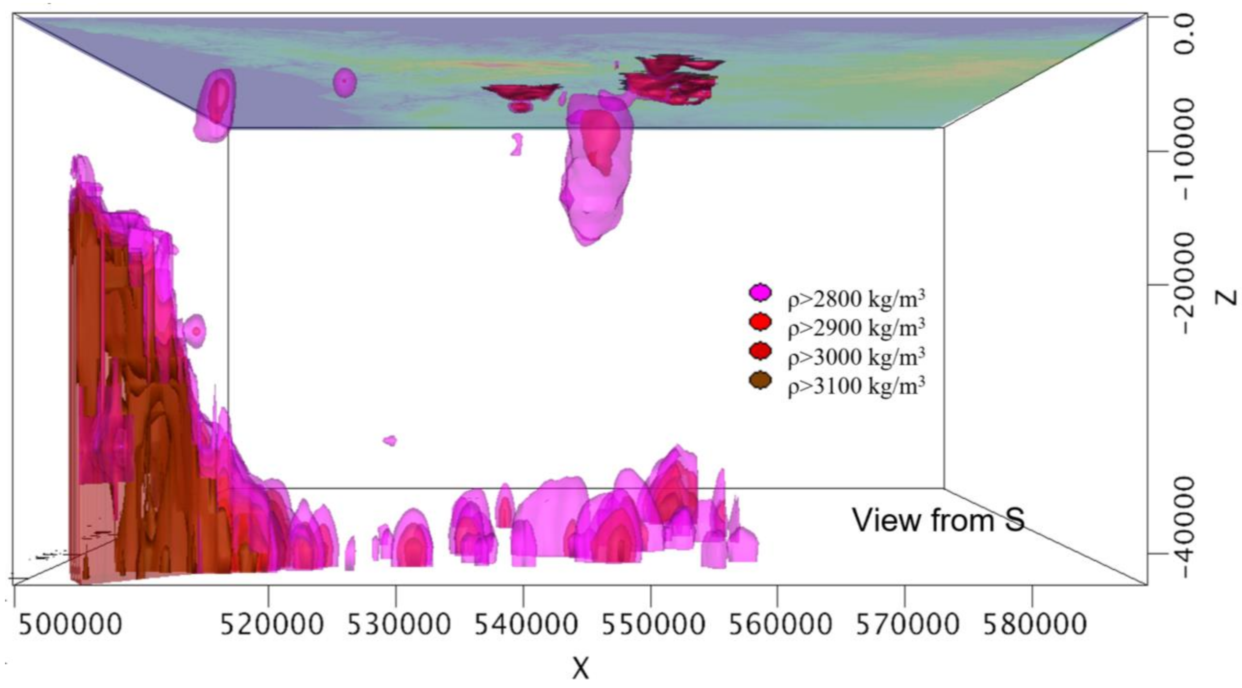
4. 3D density inversion model

- The density model is probably not too informative for the Monchique area considering that the gravity field of the region shows no significant anomalies and even the negative Bouguer peak in Monchique vanishes when the terrain correction is applied. Anyway, the model suggests a volume underneath Monchique that extends to east, with slightly decrease in density, around 70 kg/m^3 less than surroundings (not relevant for the regional trend).

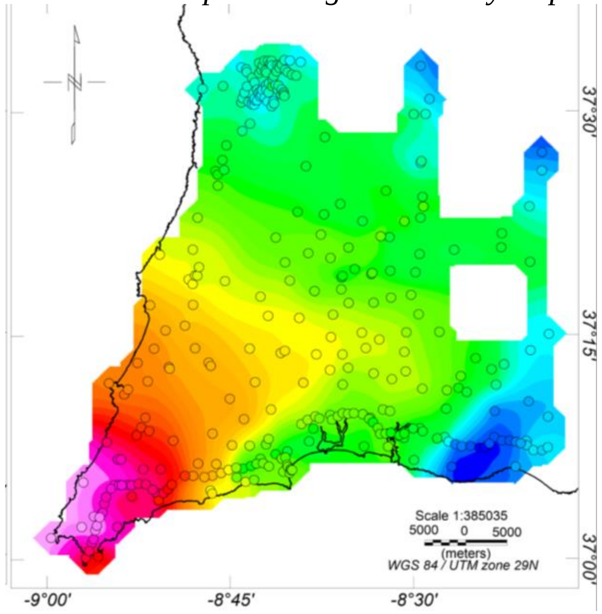


4. 3D density inversion model

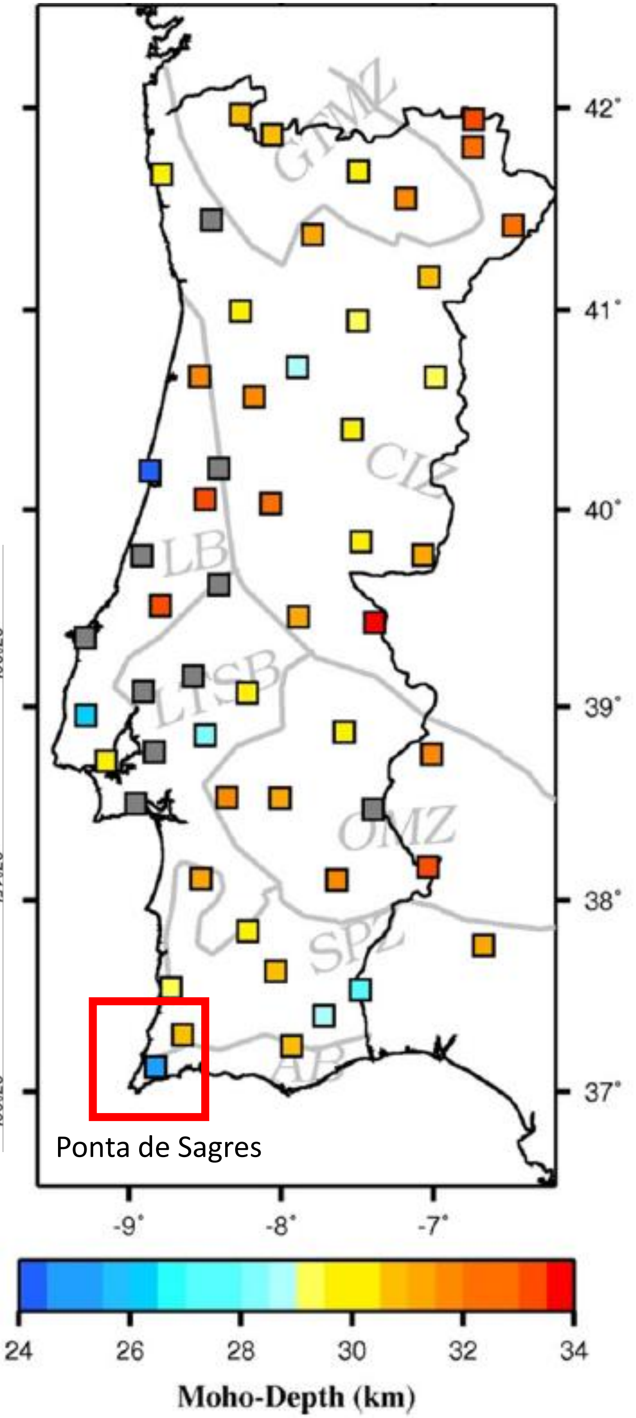
- The positive density anomaly isosurfaces suggests the existence of a high-density body shallowing towards Ponta de Sagres. This density anomaly shows a steep vertical gradient, from 2800 kg/m^3 to 3000 kg/m^3 in less than 4 km in depth. The tomography (Dündar et al. 2016) supports a rising of the Moho to 24 km of depth in the area.



Complete Bouguer anomaly map



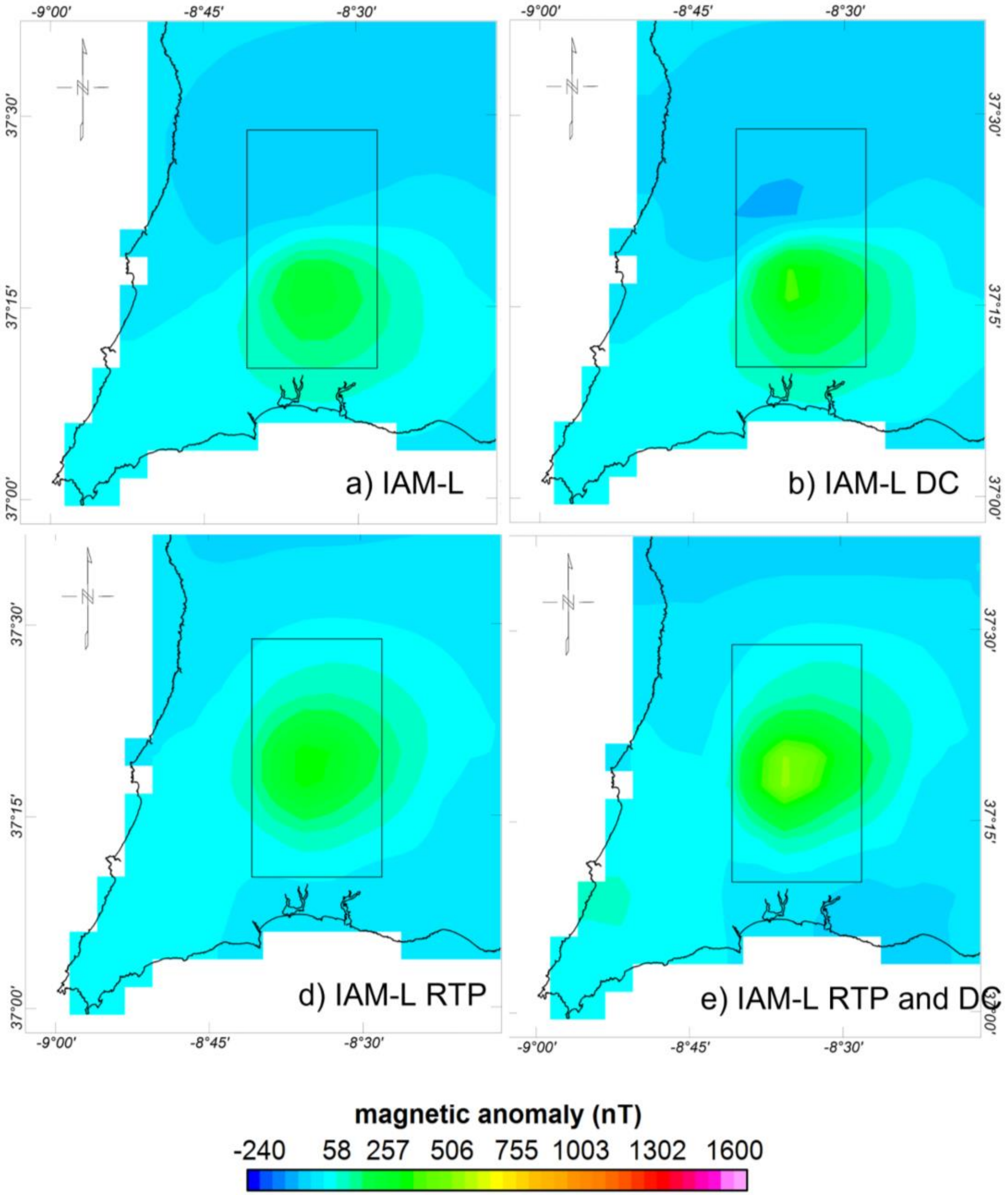
(Modified from Dündar et al. 201



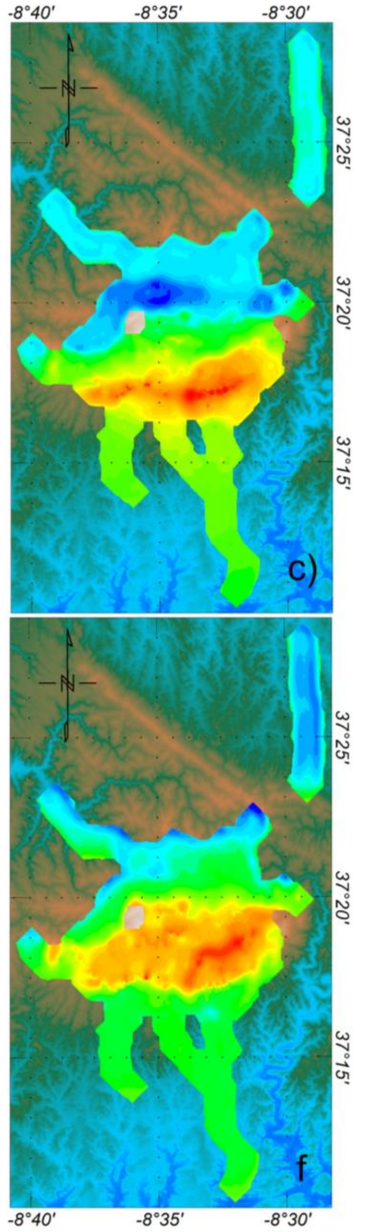
5. Magnetic anomaly Results

- The new aeromagnetic drone data allows for mapping the Monchique magnetic anomaly with unprecedented detail and reveal a 10 km elongated anomaly with ~3 km wavelength with maximum 1707 nT amplitude.
- The negative branch of the dipole at north and the positive at south (as expected for normal polarity magnetized bodies in the northern hemisphere).
- The anomaly is better defined in the drone data as the acquisition had more resolution, and it reaches values of 1700 nT as positive peak and -700 nT as negative peak, i.e., 2400 nT of peak-to-peak amplitude.
- Meanwhile, in the previous Iberian Anomaly Map data, the positive dipole has the higher values around 500 nT, and the lowest around -70 nT, i.e., 570 nT peak-to-peak amplitude. And the anomaly is more diffuse.

Iberian anomaly map Monchique and surroungdings (a) non-modifeid data, (b) Downward continued data for 2km; (d) reduced to pole data; and (e) downward continued for 2km with reduction to pole.



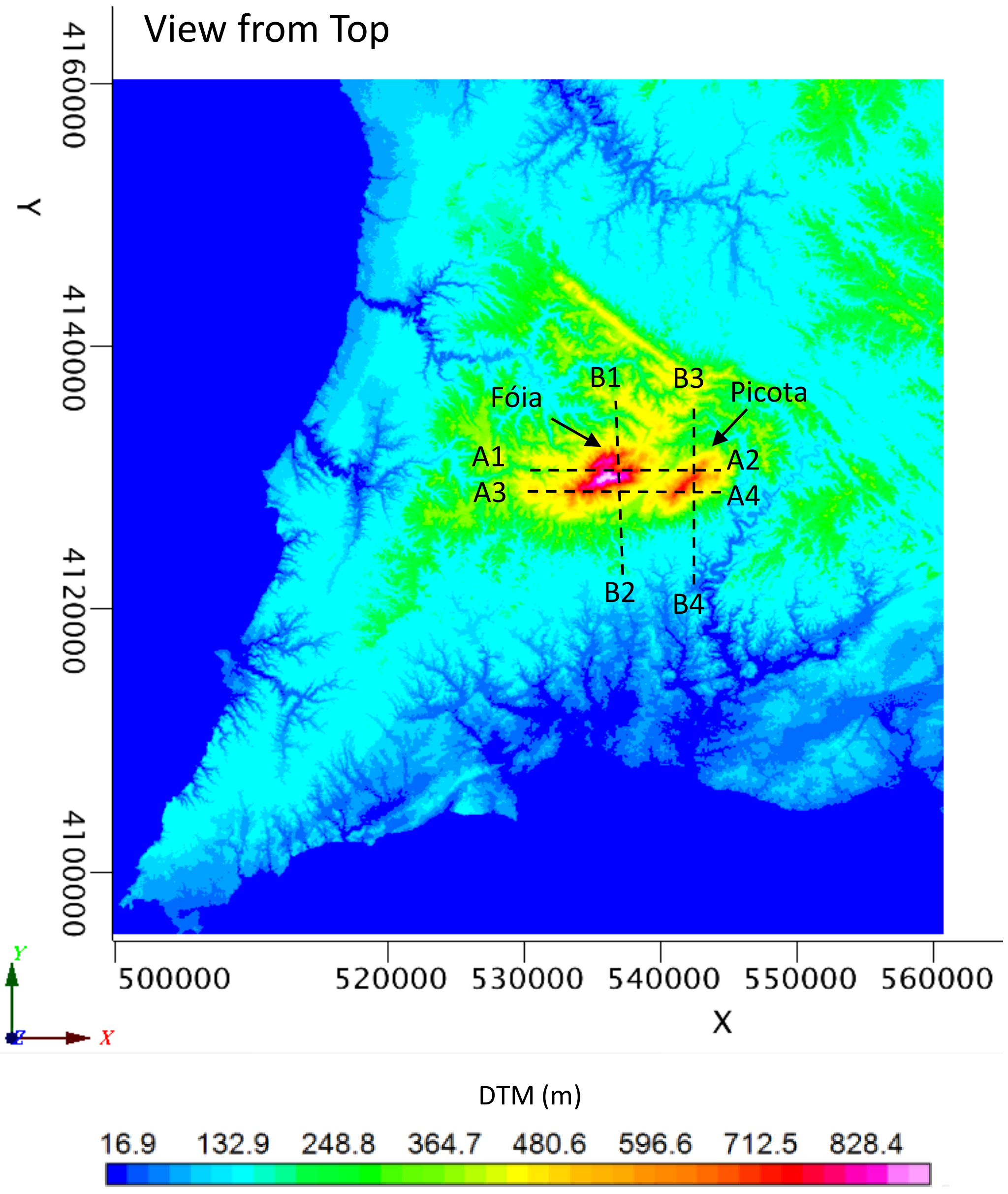
Drone data (c) non- reduced to pole and (f) reduced to pole.



5. 3D susceptibility models

- The 3D susceptibility inversion models for the Monchique intrusion show a 15 km long body extending to depths between 5-10 km, and susceptibility >0.02 SI, in agreement with previous susceptibility analysis in the region (Barbosa, 1999).
- A second high susceptibility body is modeled underneath the main intrusion, from 15 to 27 km of depth, but is still needed data with better resolution and spatially wider to validate its existence.
- Model 1: non reduction to pole (RTP) input data
- Model 2: RTP input data.
- We note that for model 2 the shallower body is more concentrated close to the surface mostly above 5 km of depth.
- The highest magnetic anomaly is found at Picota hill (east), but the deepest parts of the intrusion seem to be bellow Foia hill (west).

Profiles are shown in the next slide.



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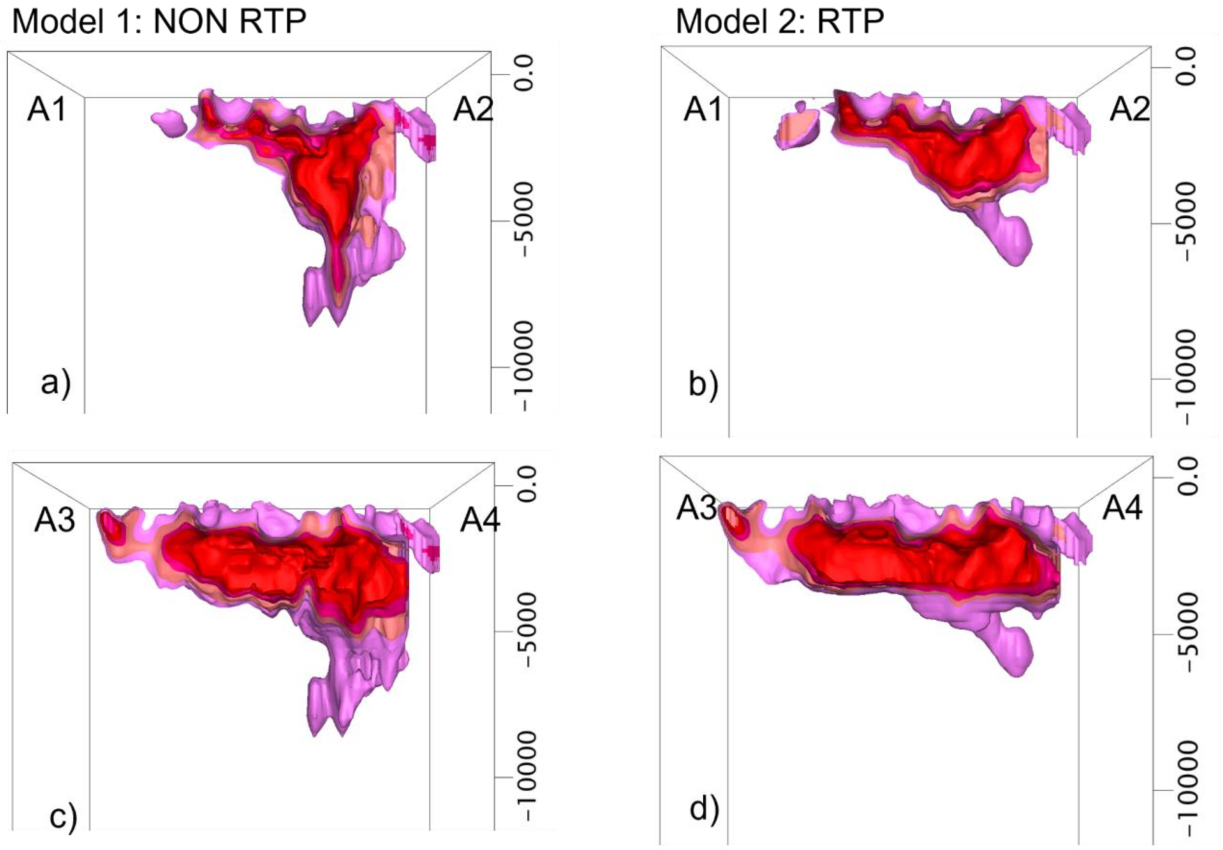
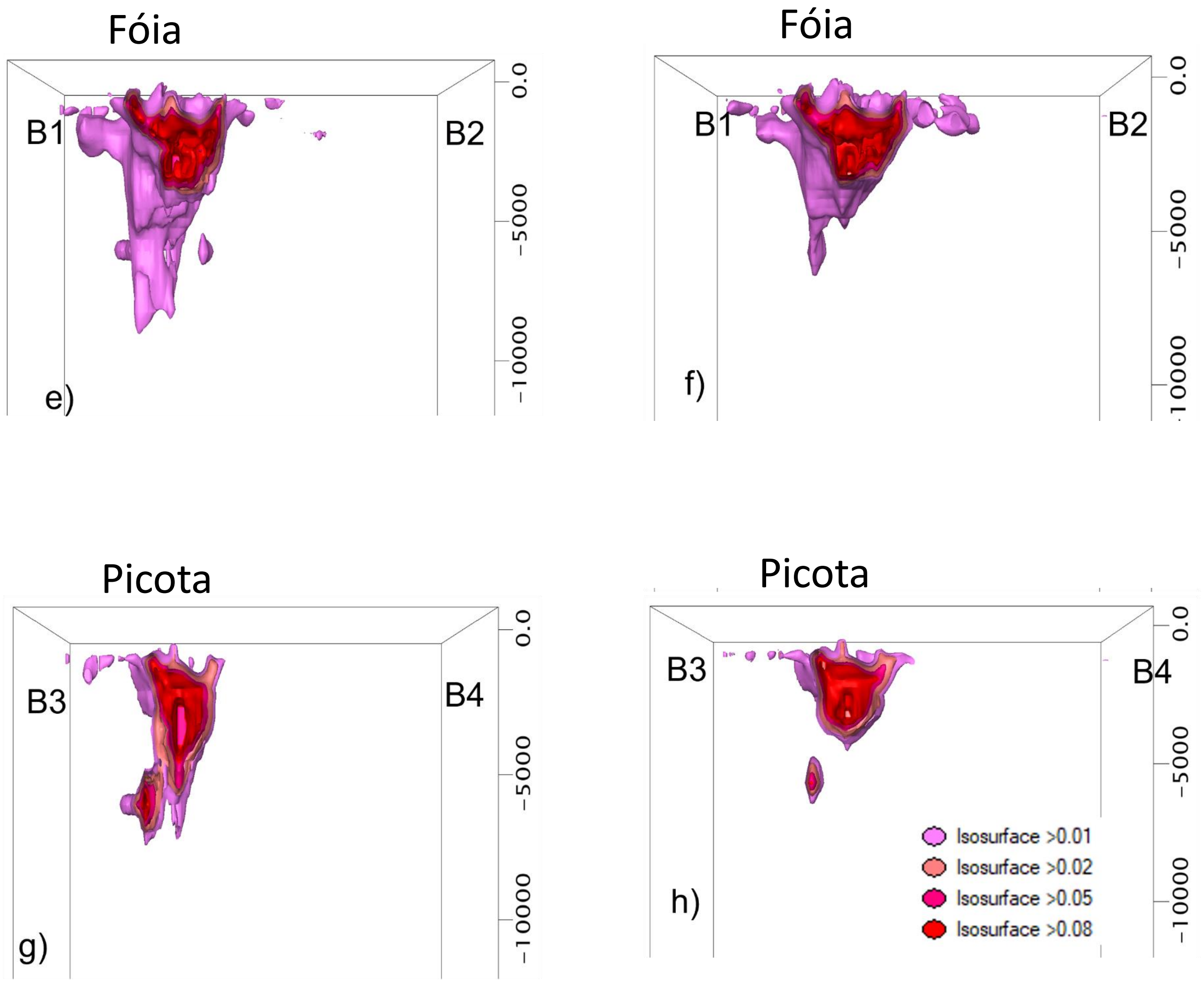
5. 3D susceptibility models





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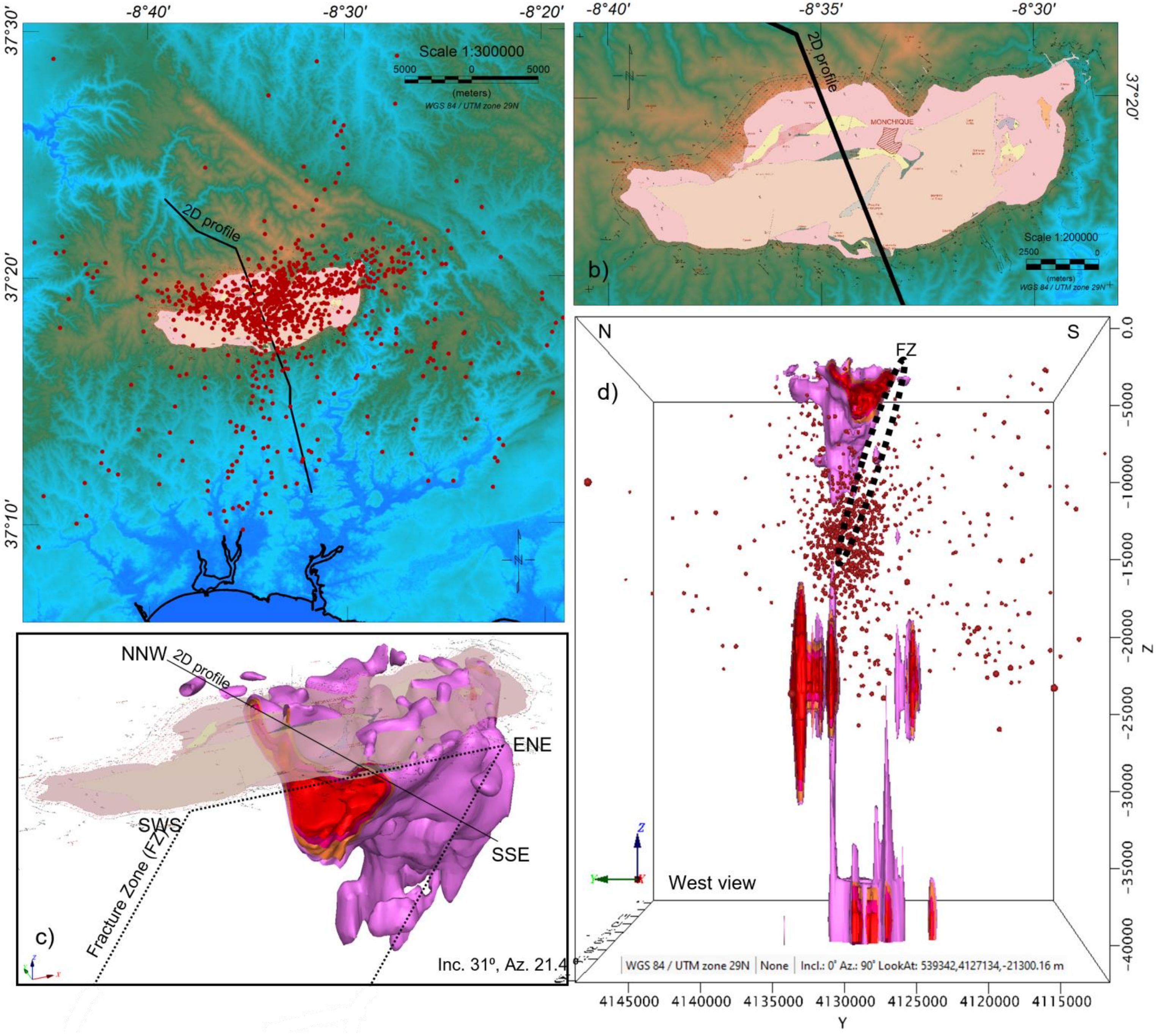
5. Relation with seismicity

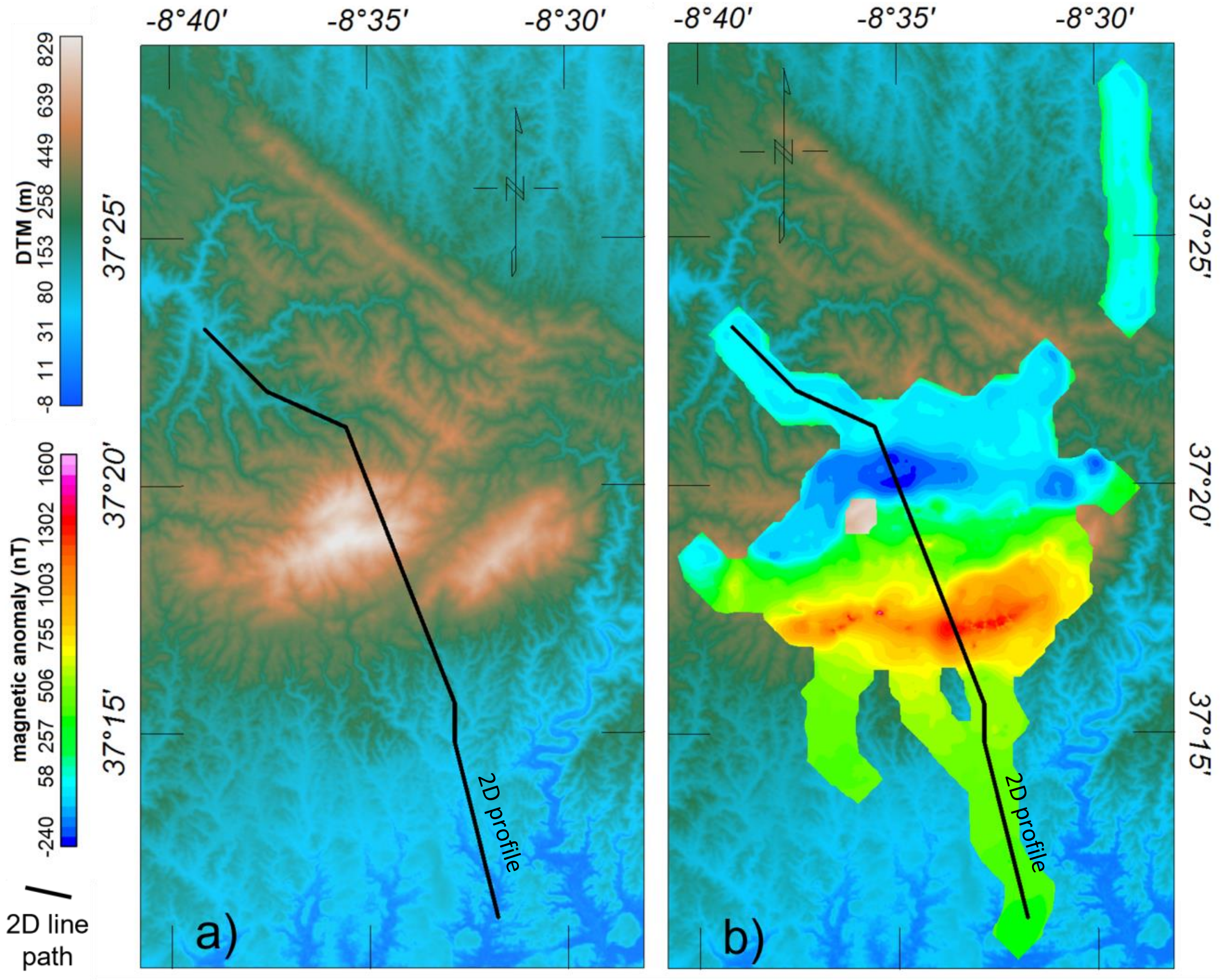
- Earthquake hypocenters of the Monchique seismic cluster (Soares, 2018) concentrate at depths of 5-20 km, thus mostly below the modeled magmatic intrusion. This indicates a fracture zone oriented preferentially ENE-WSW possibly related with hydrothermal activity.
- This orientation may indicate the presence of pre-Mesozoic structures as suggested by Clavijo and Valadares (2003) that could have controlled the intrusion of the massif. The fracture zone may pass South of the massif and justify the existence of hot springs (temperatures between 27º e 31.5º C).
- The tomography of the area (Veludo et al. 2017) also supports the fracture zone in depth although there is a need for a better resolution tomography.

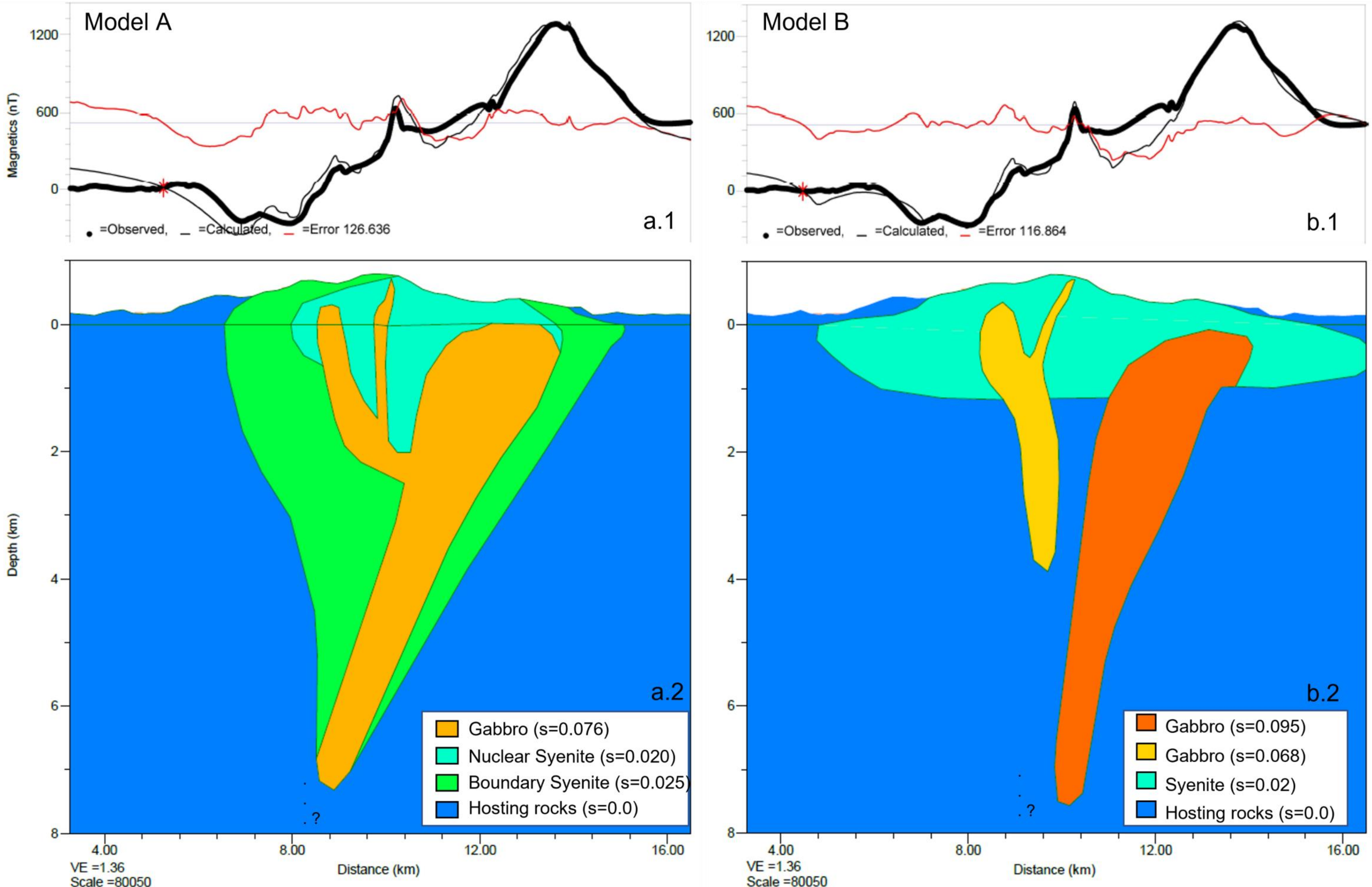


● Hypocenters from Soares (2018).

6. 2D Susceptibility forward models

- We have achieved two different models as the most likely to reflect the morphology of the Monchique intrusion.
- A main observation from our modeling efforts is that the high susceptibility volume must have a NW-dipping border at its southern side in order to fit the anomaly gradient.
- Model A has a "fork-like" morphology with a single gabbro that divides in several branches while ascending. One of the thin branch reaches the surface in the exact location where a gabbro body crops out. Following the geological map, we identified the two syenite units.
- Model B has two separated gabbro plugs (S=0.095 SI and S=0.068 SI) and the syenite (S=0.02) body was modeled with a laccolith morphology.
- In both models the base of the intrusion reaches depths around 8 km.





Model A
1200
600
0
Magnetics (nT)
=Observed, =Calculated, =Error 126.636
a.1
Model B
=Observed, =Calculated, =Error 116.864
b.1
Depth (km)
0
2
4
6
8
?
a.2
Gabbro (s=0.076)
Nuclear Syenite (s=0.020)
Boundary Syenite (s=0.025)
Hosting rocks (s=0.0)
b.2
Gabbro (s=0.095)
Gabbro (s=0.068)
Syenite (s=0.02)
Hosting rocks (s=0.0)
4.00
8.00
12.00
16.00
Distance (km)
VE =1.36
Scale =80050

Conclusions

- There is no Bouguer gravimetric anomaly caused by the magmatic intrusion of Monchique. Despite the high amplitude of the observed positive free air anomaly, it is canceled after the Bouguer and terrain corrections are applied. This implies that density variations between the intrusion and surrounding materials (host rock) are too small to be noticed in the regional pattern of the area.
- At the southwest, towards Ponta de Sagres, our gravity results support a rapid shallowing of high-density rocks compatible with mantle material, suggesting a significant crustal thinning. Available seismic modeling corroborates a decrease of crustal depth to around 25 km in this region (Dündar et al., 2016). Further studies are needed to confirm these results and estimate the precise depth of the crust, including offshore data.
- The intrusion is composed by a syenite body with plug-like gabbroic bodies, the latter causing the major part of the magnetic anomaly. Because in the geological map the gabbros represent a smaller part of the outcropping massif, the fit of the magnetic anomaly implies that these bodies are larger in depth reaching around 8 km. The continuity of the intrusive body, or the existence of other deeper bodies bellow 8 km is still open for discussion and may be better understood with a spatially wider data acquisition, with better resolution and closer to the source. The deeper part of the intrusion locates bellow Picota hill on the east, and the magmatic body elongates for about 10 km in W-E direction.
- Underneath the main intrusive body, a fracture zone between approximately 10-20 km in depth is supported, likely along the same direction as the major concentration of hypocenters, that extends with ENE-WSW directions outcropping on the south part of the massif carrying water from the hydrothermal activity.

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