Ph.D. Thesis

Universitat de Barcelona
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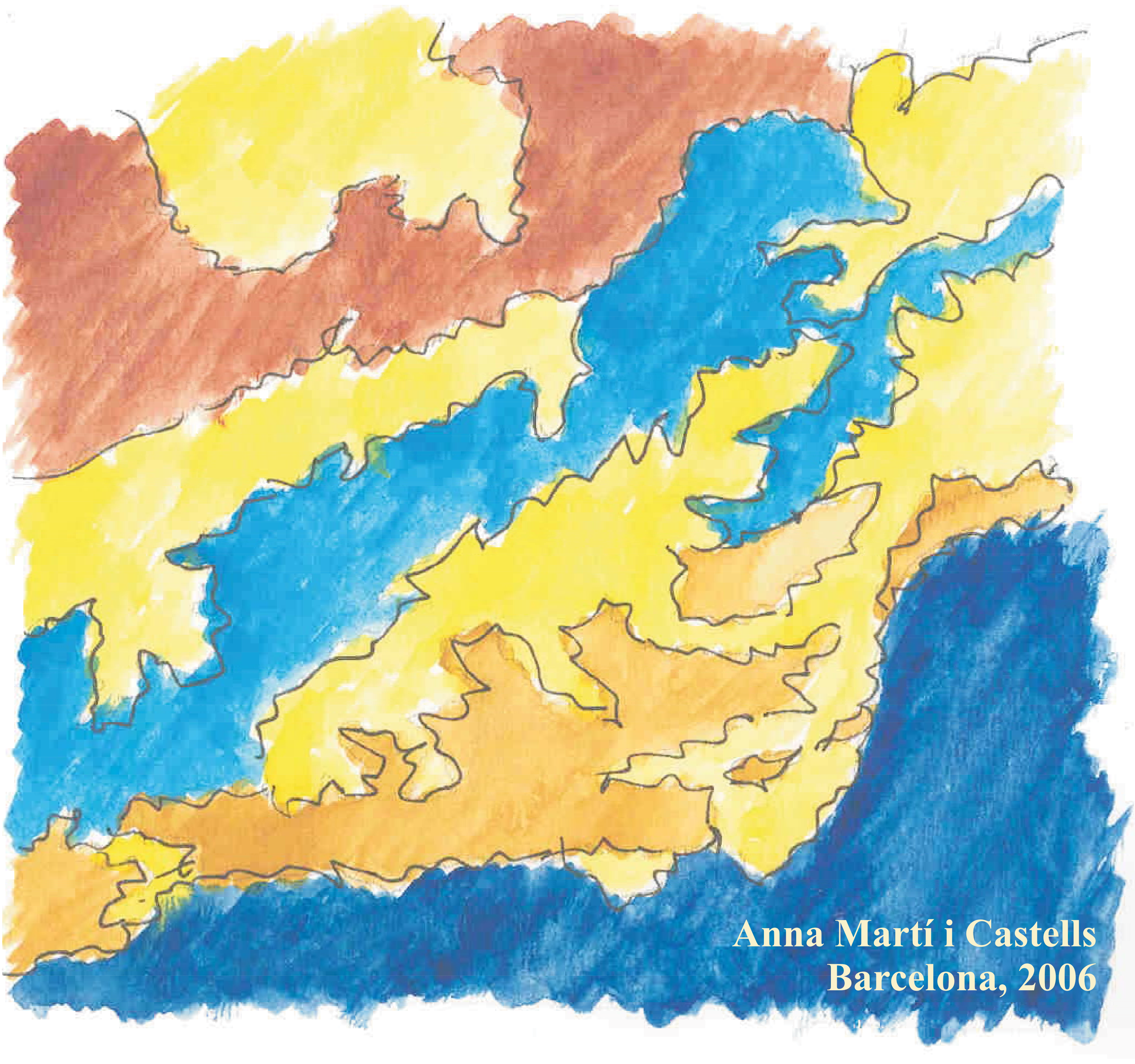
A Magnetotelluric Investigation of Geoelectrical Dimensionality and Study of the Central Betic Crustal Structure



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Conclusions

Within the framework of the magnetotelluric method, this thesis has been divided into two distinct parts. The first one consisted of an investigation and improvement of the methods used in the dimensionality analysis of MT data. The second part comprised the MT crustal study of the Central part of the Betic Chain. Accordingly, the main contributions and conclusions inferred from each part are presented separately.

Methodological contributions on geoelectric dimensionality

The purpose of this part has been to investigate the main methods used in the analysis of the geoelectric dimensionality from MT, focusing on their applications in real data. These methods have been the WAL (Weaver *et al.*, 2000) rotational invariants criteria, the Bahr invariant parameters (Bahr, 1988) and the phase tensor (Caldwell *et al.*, 2004). These methods have been compared and contrasted, highlighting the strong and weak points of each, and by making some modifications to ensure equivalency. All this work has been done using synthetic examples and real data from the public COPROD2 and BC87 datasets and from the Betics dataset with simple to complex dimensionality and from low to high noise levels.

From the revision of the WAL dimensionality criteria applied to real data and considering situations in which the data do not exactly fit the ideal 1D, 2D and 3D cases:

- The estimation of WAL rotational parameters and their errors has been tested using three approaches: classical error propagation, random Gaussian noise generation and the resampling Bootstrap method. All these lead to similar results, although classical error propagation has been chosen as the most stable way to estimate the errors of the invariants. The related strike and distortion angles and errors should be estimated using random noise generation, where a minimum value of n=100 is recommended.

- With regard to the threshold value, dimensionality results with the corresponding strike directions and/or distortion angles and errors obtained using different thresholds have been analysed and a range for which these parameters are more stable has been defined. This threshold range has been set to 0.1 to 0.15, valid for medium to high quality data.
- As a product of this study, a program has been created to perform MT dimensionality analysis using WAL criteria while considering data errors. This program (WALDIM) has been successfully applied to several datasets.

From the comparison between the WAL and the Bahr methods, and considering the revision of the latter to make both equivalent:

- The analytical relationships between the WAL and Bahr parameters have been obtained.
- The threshold values defined by Bahr, have been redefined as a function of the WAL parameters, through their analytical relationships.
- A new method has been proposed, termed Bahr-Q, which uses the Bahr parameters and the WAL invariant Q. Using the new threshold values this method is equivalent to the WAL method. Bahr and Q parameters are less affected by noise, and hence, the Bahr-Q method can be considered as more robust than the WAL.

From the study of the phase tensor:

- The phase tensor has been applied to different dimensionality cases, including errors and distortion. It has been shown that, in extreme distortion situations (shear angle close to 45^{o}), the phase tensor is not distortion – invariant.
- When data are not affected by distortion, φ_{Max} - φ_{min} (computed from the phase tensor) and WAL parameter Q have similar values. This allows for the detection of galvanic distortion, even over 3D regional structures.
- The inversion of the phase tensor data to fit a 2D description fails in general because of the use of only half of the information from the impedance tensor.

General conclusions from the first part of the thesis are:

- In the dimensionality analysis, it is always important to consider the errors, since they affect the determination of the dimensionality by any method.

- The best dimensionality analysis is performed using all the available information from the impedance (or magnetotelluric) tensor. Assumptions on a certain type of dimensionality should only be used for hypothesis testing (sometimes these assumptions are made as dimensionality analysis, leading to erroneous interpretations).
- Care must be taken when using methods such as the phase tensor, because they provide a compact description of the dimensionality, but in view of a further modelisation, information on the presence of distortion is not available, and it cannot be corrected.

Magnetotelluric study of the central Betic crustal structure

This part of the thesis has presented a synthesis of the geological and geophysical information of the Central Betics, the reprocessing of previous MT data and the acquisition and processing of new data, from which a more complete dataset to work with has been obtained. From the dimensionality analysis of the data, the 2D and 3D modelling approaches and the model interpretations, the following results and conclusions are highlighted:

- The dimensionality analysis has revealed the high complexity of the MT data, which points to 3D modelling as the best strategy. Furthermore, the pattern of the 2D cases present over the study zone can be related to the different processes which have occurred in the Betics and Iberian Massif: The existence of a more complex pattern over the Betics is related to the superposition of these processes (Alpine orogeny over Variscan materials), whereas in the Iberian Zone, only affected by the Variscan orogeny, a simpler dimensionality is observed.
- The dimensionality and the sensitivity study of the previous NW-SE 2D conductivity model show that lateral extension of the deep conductor is not ensured.
- The three 2D models created from the Internal Betics data show the presence of a conductive body below the Sierra de los Filabres, shallower than the previous 2D model.
- From the comparison of the 2D inversion codes RLM2DI, REBOCC and DetREBOCC, the latter, which inverts the determinant data, has been shown to be very useful when data are not 2D. The use of this response for the 3D modelling should be a good tool as well.
- Finally, a 3D conductivity model of the central part of the Betics crust has been created. Departing from an initial model obtained from the 1D inversion of determinant data and constrained with the geometry of known geologic structures,

this model has been obtained through a trial and error process, through the Mackie *et al.* (1993) code and using the rms to compare different model and data responses.

- The robustness of the main features of the 3D model has been proved through several sensitivity tests. Also, this model shows a pattern that reproduces the main dimensionality features of the data.
- The final model allowed characterization of the following features:
  - In the Iberian Massif, a resistive zone associated with metamorphic and granitic rocks. And within it, a conductive zone (2 km – 17 km depth), interpreted as being interconnected graphite, as observed NNW of the study area in other zones of the same geologic unit. The elongation of the resistive zone below the External Zone confirms the continuation of the Iberian basement below the Betics.
  - A shallow conductor, related to fluid circulation through the sediments of the Guadalquivir Basin. The shape of this conductor shows that the basin infill continue below the External Zone.
  - Moderately low resistivity values in the External Zone, associated with fluid circulation in the carbonate rocks, both in the Prebetic and the Subbetic zones. In the Inner Subbetic, even lower resistivity values are associated with a major content in shales and basaltic rocks, and in the eastern part of this zone, with the presence of flysch rocks.
  - In the Internal Zone, a highly resistive zone (up to 13.5 km) interpreted as being caused by metamorphic rocks from the Nevado-Filábride and Alpujárride complexes, as well as some shallow conductors interpreted as fluid circulation along the contacts between both zones or within the Nevado-Filábride.
  - A large conductive zone, located below the Sierra de los Filabres, from 4 km to 17.5 km. According to the sensitivity tests performed, this body could have an orientation from WNW – ESE to EW, and may reach a maximum depth of 30 km.
- Based on geological and geophysical constrains, the deep conductive body is interpreted as a differentiated lithologic unit formed by ophiolites or lower crustal rocks containing a conducting mineral phase, below the Nevado-Filábride complex. This body is located in the core of the main Sierra Nevada - Sierra de los Filabres antiform, and extends in depth up to the Betics detachment level.

Future perspectives

This thesis, which has solved some of the aspects of the determination of geoelectric dimensionality in MT and has obtained a description of the geoelectric structures of the Central Betics crust, still leaves some open doors to further investigation in these same directions. Next, the future perspectives proposed as a continuation of this thesis are presented:

Regarding the geoelectric dimensionality of the MT data:

- Continue investigating the dimensionality methods based on rotational invariants. Improve the WALDIM program by applying fuzzy logic, instead of a fixed threshold, to discern between dimensionality cases; and allowing for regional averages (along with the present period band averages). Allow for certain hypothesis assumptions, whose validity will be quantified by a misfit value. Finally, include the tipper information to skip the 90^o ambiguity of the strike direction.
- Investigate the use of the rotational invariants of the MT tensor in the presence of anisotropy. Decipher if there is a way to identify and characterise this property in the geoelectric structures.
- Optimise the use of the rotational invariants to compare data and model responses.
- Continue investigation of the relationships between the phase tensor angles φ_{Max} - φ_{min} and WAL parameter Q. Establishment of thresholds for the phase tensor parameters to quantify the type of dimensionality.

In relation to the geoelectric structure of the Betics, the main result has been the obtainment of a 3D model of the Central Betics crustal structure and within it, the identification of a conductive body below the Internal Zone located at upper-middle crustal depths. Future MT research in the Betics should focus on improving the knowledge of this body and on the broadening of the study area:

- Perform a 3D inversion of the Betics MT data using the code of Siripurnvaraporn *et al.* (2005). To this end, the data set up and different tests using the code are presently being performed. Try to improve the fits between the data and model responses, and compare with the present model.
- Record new data, registering longer periods, to obtain better resolution at depth; and to cover a broader area. Get complementary data to correct the static shift and constrain the conductivity of the first layers.

Due to the increasing interest of this zone, within the PICASSO Research Initiative (Program to Investigate the Cause of the Alboran-AtlaS System convective Overturn) and the research project to be developed under this initiative, the contributions of this thesis (MT dataset, dimensionality characterization and 3D geoelectric model of the Central Betics) provide an update and a departing point to the new MT studies to be made in this complex and wide zone. The main objective of PICASSO is to determine the three-dimensional inner structure of the crust and the lithosphere, with special emphasis on the geometry of the upper mantle in order to image the lithospheric processes that are taking place. Different geophysical data will be collected for an integrated interpretation. As an example, a recent MT survey (February 2006), made as a collaboration between Granada and Barcelona universities, in the north of Morocco, proceeds in this direction. Also, new MT sites at longer periods covering a wider area of the Betics will be collected soon by DIAS and also with the collaboration of UG and UB.