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3D MT : Magnetotelluric data for natural resources exploration on land or sea, in 3 dimensions

Long forgotten, even for existing geological sites, it is now possible to enhance the quality and analysis of MT data with a **new class of technology services**:
"Coarse-to-fine 3D MT Inversion"

Sophie HAUTOT, IMAGIR CEO

Introduction

For the last 30 years we have known that only MT analysis allows to quickly and affordably identify opportunities in particular contexts

For 30 years, natural resources exploration procedures with MT data were scarce. The quality of data sources was considered insufficient for known inversion algorithms, only based on mathematical principles. Inversion procedures were lengthy and had to be repeated many times to improve the outcome. And ultimately, the resulting 2D images were difficult to analyze, even by specialists.

An "MT" service requires knowledge of MT representation in a geological environment

It thus became necessary to provide a genuine "**MT service"** based on combined knowledge of MT data in a given geological environment, on a flexible technological instrument that can treat this knowledge effectively, and to model it for 3D representation.

Research framework

Electromagnetic (EM) techniques are particularly useful in complex zones or where specific structures are present such as basalt covers and salt domes.

Overall, electromagnetic techniques complete seismic techniques for oil, gas, mining, geothermal or hydro-geological exploration. This complementary technique is particularly useful in areas with complex structures such as basalt covers and salt domes. Furthermore, although seismic methods provide the best possible reservoir descriptions, they remain poorly informative on fluids properties, EM methods provide reservoirs electrical resistivity information, thus enabling to better describe and understand fluids in the pore space. Conclusively, combining CSEM and MT together with seismic and gravimetric, these methods can provide part of the answer during drilling campaigns to evaluate the potential outcome of an oil well, thereby achieving substantial savings.

Addressing the problem of poor MT data quality

Qualify the data in relation to knowledge of the geophysical data

Sometimes, data quality can be insufficient quality because of survey, field or ambient noise conditions. In this case, traditional signal processing toolboxes provide poor results.
It becomes useful, even necessary, to qualify data in relation to response models tied to "geophysical data" knowledge. Only relevant data is provided to the transformation tools.

Addressing the inversion procedure complexity problem

Model by block with a limited number of initial parameters Increase the number of iterations by increasing the number of parameters, as areas are consecutively "qualified"

The large number of parameters to be processed makes the inversion procedure complex. Even the most powerful algorithms can diverge, making it necessary to restart a long and risky process!
The first idea is to reason by block to reduce the complexity of the original system. There remains a need to break blocks down in a pertinent manner, relative to expected models.
The second idea is to control the inversion procedure by increasing the number of parameters treated as iterations on increasingly sensitive areas. This procedure tends to increase the number of voluntary iterations but with shorter and more effective iterations.

A quantitative sensitivity analysis provides the acceptable resistivity and depth bounding values for each parameter

As 3D MT inversion is a non-linear problem, the misfit obtained for the best-fitting model is not an absolute minimum but is some compromise between all sites, periods, and data quality. Therefore, the parameters of the model may not be equally constrained by the data.

IMAGIR "coarse-to-fine" approach

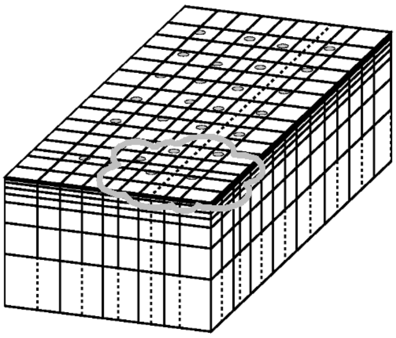
The 3-D inversion technique is based on an iterative procedure to minimise a misfit function between the observed data and the model response.

IMAGIR developed a robust full tensor 3D MT data inversion scheme with a **coarse-to-fine lattice parametrisation approach**. The technique was developed to provide a detailed geological image of sedimentary basins in complicated geological contexts such as thick basaltic screen covers. The 3-D inversion technique is based on an iterative procedure to minimise a misfit function between the observed data and the model response using a non-linear steepest gradient method with a regularization term. The data is the MT tensor (the four complex components and tipper when available) at all available frequencies and at all sites

The 3-D model is parameterised by blocks.

The 3-D model is parametrised by blocks. The size and the initial meshing of the 3D volume are determined according to the MT sites distribution and the depth of investigation of the data.

Two grids instead on one! Method well adapted for MT and for joint methods



The black dots are MT sites
In continuous line, the data grid based on distribution
In dotted lines, the grid for calculations, dependant on the geophysical method

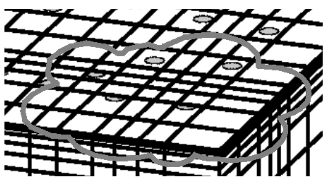
Control the inversion, for an intelligent and well managed production of the model.

IMAGIR’s industrial analysis technique allows it to control the inversion procedure through a **monitoring window**. It can impact on the inversion procedure by interrupting it and guiding it towards qualified areas with an increased number of parameters to reach a satisfactory level.

What does the "coarse-to-fine" method allow?

Change data resolution only in required areas (fault, complex zone) thanks to the operator’s interpretation capacities

The coarse-to-fine approach provides a final grid that reflects the **resolution of geological targets** in the model. Compared to other available techniques, the number of parameters is much smaller, adapted to the actual number of data and fully flexible in terms of site/frequency distribution, hence providing accurate 3D structures resolution information.

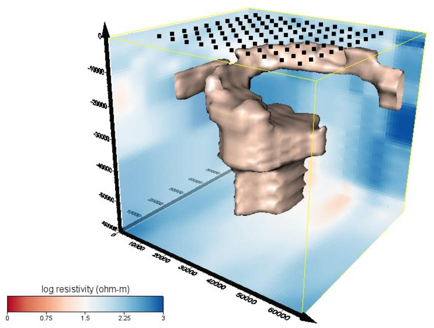


Treatment of non-homogeneous networks of sensors
More than 500 stations

The interest of this 3D MT imaging tool lays in its **high flexibility** that allows dealing with **unevenly distributed sites**, topography or bathymetry (for marine MT) **effects** and a**ny number of periods.**

Integration of complementary geophysical data

This iterative and incremental parameter approach enables an easy integration of parameters from other sources (drilling) into the procedure to add geophysical information.



Objectively measured performance on a network of 100 stations 10 X 10

The main objective of modelling is to provide a response that fits well the data. The coarse-to-fine approach enables to adjust the structure of the model to match accurately the data set. The example presented here demonstrates the superiority of the IMAGIR approach compared to standard inversion. The difficulty is to obtain a homogeneous fit for all the four components of each site of data set. The goal is achieved with our inversion approach

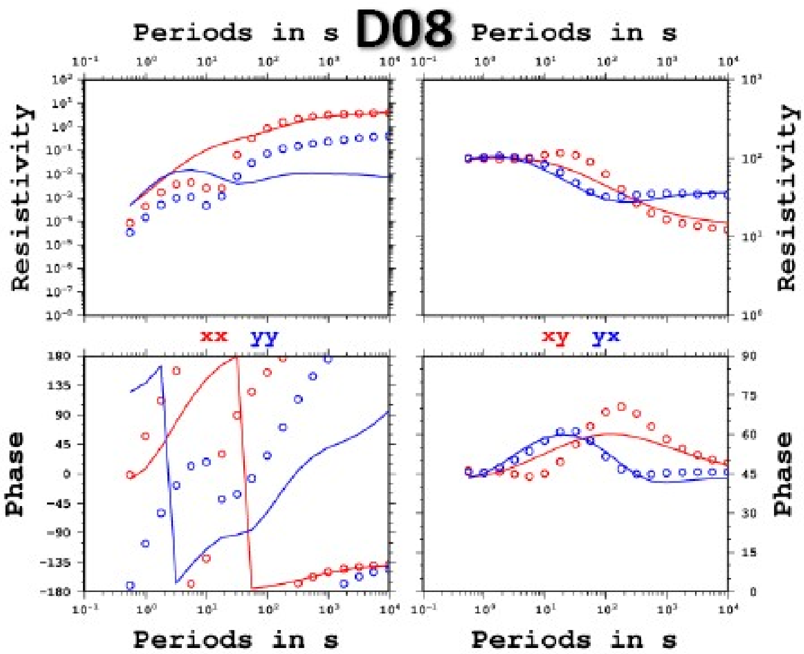
Legend:

Circle = real data

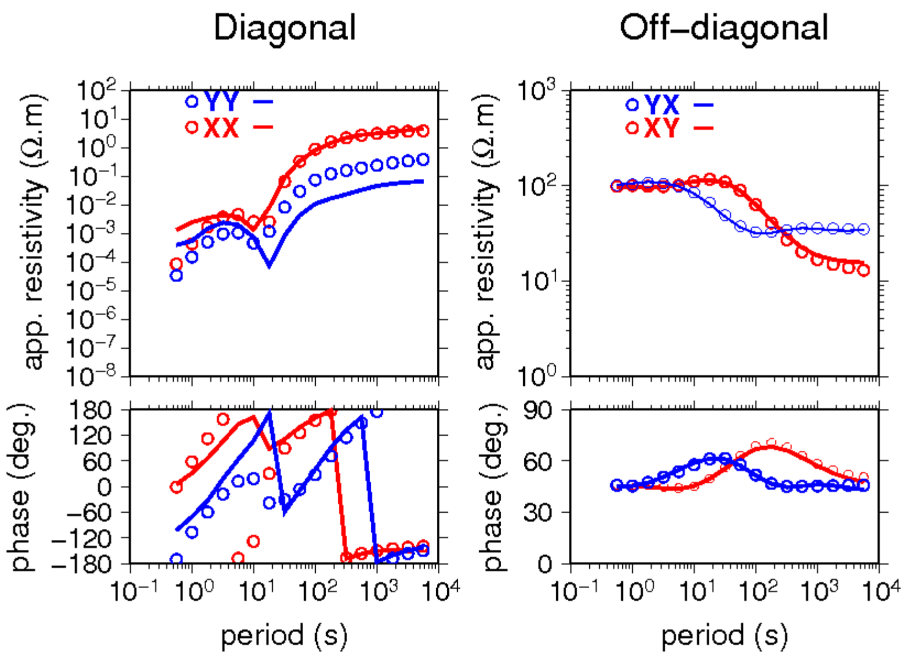
Curve = computed data

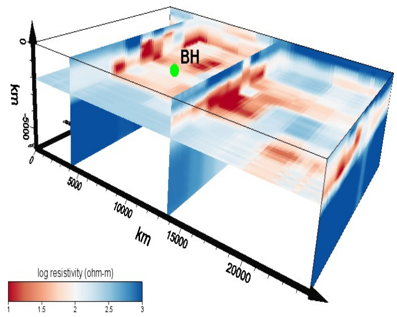
The approach, performed with known inversion codes (public and widely used), shows inaccuracies and discrepancies

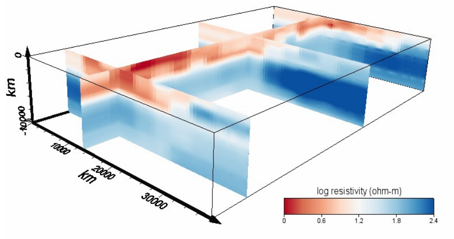
The risk is therefore to miss essential details for the geologist or to generate fakes (artefacts)



In majority, there is an excellent overlap between the actual and computed data. The visible differences are on low value data, trends are maintained







An easily interpretable 3D model

The first public 3D inversion tools date back from 2005, and remain, for the most part, almost at the laboratory stage. This explains why they are not widely used, and why there has been little user experience in the Geophysical / Geology community. IMAGIR founders wrote their first publication based on real data back in 2000. This explains how they have reached a mature system (which includes a "sensitive analysis" phase) that produces easily interpretable 3D models with the following performances:

Identifying details in the structures
Edge structure precision
Elimination of artefacts (by sensitivity analysis)

Improvement by Sensitivity Analysis

IMAGIR provides a reliable complementary quantitative analysis of the **confident interval** of the model parameters. This analysis allows a better discrimination of the model elements and really improves the following interpretation.

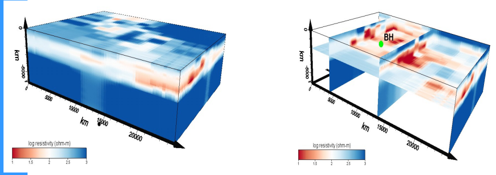
In the Hebrides geological basin, positive geological elements as well as pre drilling indicate the presence of a reservoir. Traditional seismic methods are ineffective because the basin contains many sub-basalt areas.

The exploration area is complicated. There are inaccessible zones and residential areas with their accompanying infrastructure (roads, houses, high-voltage power lines). Specific seismic exploration would be very costly.

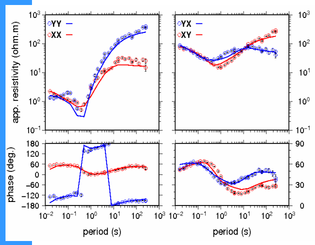
CASE STUDY 1: ISLE OF SKYE

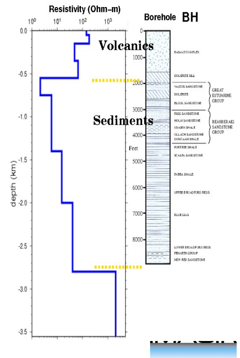
Industrial case study 1 : Hebrides

Twenty magnetotelluric (MT) soundings were carried out on the Isle of Skye, Scotland. The aim of the project is the joint interpretation of gravity, seismic, geological and MT data in order to provide a high-resolution 3-D model of the area. The geological context of the Isle of Skye corresponds to the well-known problem of sub-basalt imaging. The 3-D interpretation (left) of the MT data shows clearly that MT is ideally suited to the imaging of the sedimentary structures beneath extrusive basalt units (Hautot et al. 2007, funding SIMBA EC project)



Resistivity model of the Northern part of the Isle of Skye. The model (left) shows the succession of resistive basalt cover (top), conductive Mesozoic sediments and resistive Precambrian Torridonian sandstone (bottom). The model slices (right) show the well resolved structures in the sedimentary sequence.





Left: Amplitude and phase of the MT impedance tensor. The amplitude is scaled into apparent resistivity. The solid line is the impedance predicted by the best fitting 3-D model. The symbols are for the observed data. XX and YY stands for the diagonal tensor coefficients and XY and YX stands for the off-diagonal coefficients.
Right: The borehole log (BH) and the resistivity profile obtained from the 3D model at that location compare very well

Achievements:

Accurate perception of sedimentary basins in size and depth.

Detection in the sediments of structures essential for geological interpretation, through the iterative procedure of improving parametrization (coarse-to-fine)

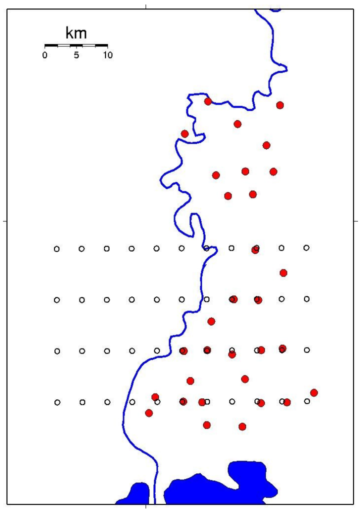
IMAGIR data confirms the geological assumptions (base).

IMAGIR data was used to interpret gravity profiles which could not be interpreted alone.

The IMAGIR model is valid; it precisely confirms data from the initial drilling.

IMAGIR allows large cuts in the budget needed to perform a full sub-basalt seismic operation (factor 100 !)

An oil company wants to drill in the basin of the River Omo in Southwest Ethiopia, to refine the geometry of the sedimentary basin and search magmatic activity occurrences.
The area is difficult to access, and deploying heavy infrastructure would be very costly



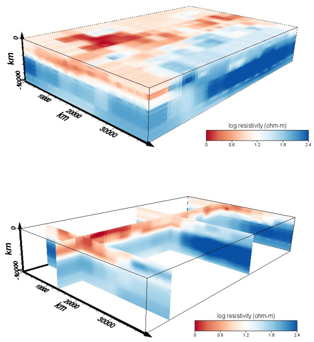
The exploration zone is geologically complicated, at the intersection of 2 geological accidents.
A latent state of conflict prevents placing sensors on the other side of the river as originally planned and therefore having a uniform grid

CASE STUDY 2: OMO

Industrial case study 2 : OMO Basin

31 magnetotelluric (MT) sites were occupied over the Omo basin in South west Ethiopia.
The inversion was run on the 31 full MT tensors at 16-33 frequencies depending on the sites, with a total of 6840 data values to recover 1000 resistivity parameters.

The final model is shown to the right. In Omo Basin, the structures are fairly smooth and the diagonal terms of the tensor are small and easy to fit at all frequencies. The model indicates a N-S geo-electrical strike, in agreement with the geological strike, with up to 4km of sediments in the southern part of the basin, but no more than 2km in the northern part, underlain by more resistive material, assumed to be the basement (funding White Nile, RPS, Ministry of Mines)



3-D Omo resistivity model. The survey provided an accurate estimation of the sedimentary basin geometry

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Achievements:
In less than 2 months of field trials and interpretation:
Accurate perception of the 3D sedimentary basin in size, depth and limits. Of the quality level that could be expected of a seismic exploration.

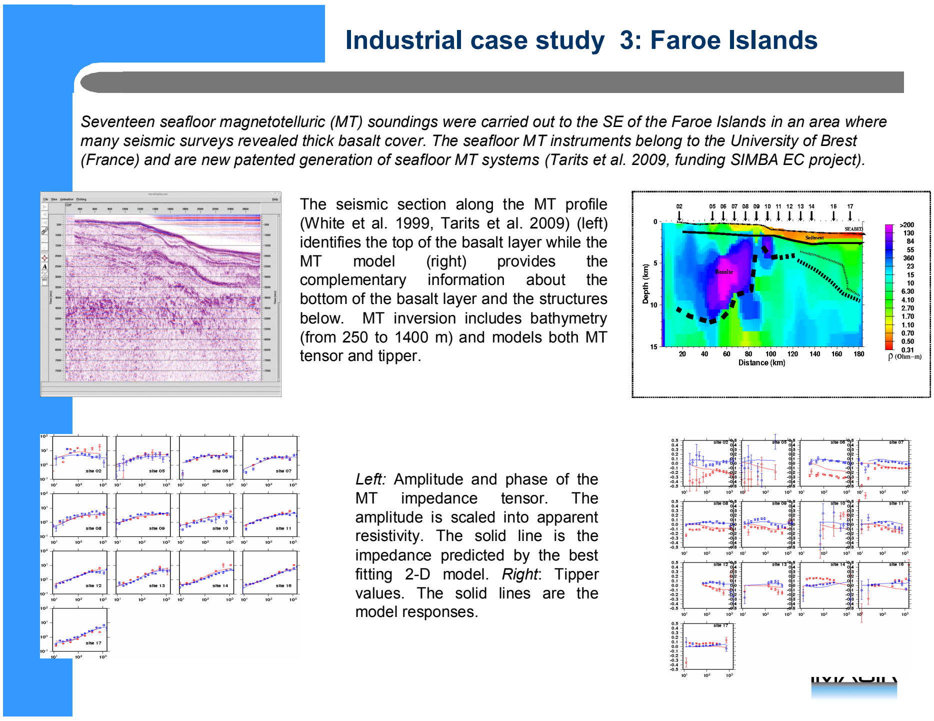
Detection of changes within the basin

Characterization of magmatic activity, even at low level.

Sub-basalt imaging is critical to quantify potential resources in sedimentary basins in volcanic provinces. A test study was carried out to the south-east of the Faroe Islands to demonstrate the potential of seafloor MT to provide an image of the thick basalt cover.

Despite numerous and often expensive studies, little is known of the sedimentary structure near the Faroe Islands because of the thick volcanic layer

CASE STUDY 3: FAROE ISLANDS



Achievements:

The technique handles topography as well as bathymetry, hence allowing to model MT data from land to seafloor
The analysis may include information from geology, seismic, gravity

IMAGIR model provides precise location of screened sedimentary basins

IMAGIR model assesses the presence or not of sedimentary structures and validates the extension of exploration in sub-basalt context

IMAGIR model provides clues to interpret seismic and gravity profiles carried out in the area

What does IMAGIR offer to exploration Geologists and Geophysicist?

With MT data competence based on scientific and business experience of over 10 years and tried-and-tested tools employed in industrial situations
IMAGIR offers specialists a **true value added complete MT service**.

The service includes the following:

Expertise in the preparation of field data collection and the layout of sensor networks with very precise adjustment

A 3D MT model based on the ”Coarse-to-fine" method. It is a dedicated geological model with unbiased geophysical results for:
Identifying details
Edge precision
Removal of artefacts

Support for results analysis
With its excellent knowledge of MT data and extensive experience in basin analysis, IMAGIR is able to effectively assist Geologists and Geophysicists in charge of analyzing 3D models.

What are the customer benefits for a complete IMAGIR MT service?
By avoiding expensive and complicated methods, IMAGIR customers take full advantage of their exploration at a reduced cost. In a minimum amount of time, they will operate the right models to make the right decisions in the right conditions.

Many scientific publications and international papers have been published within the scope of the Institut Universitaire Européen de la mer (European Institute of Marine studies) in Brest, France

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