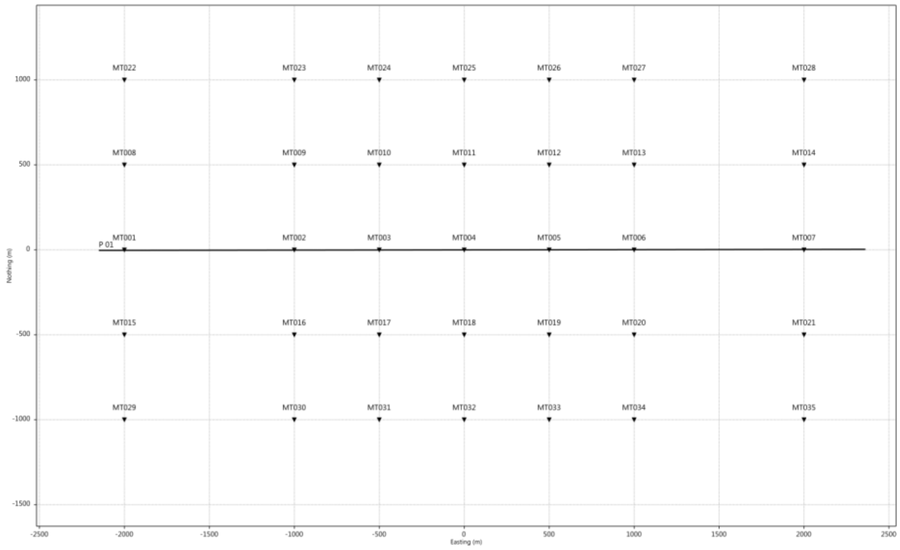
Geotools™ exercises for GeoCap WP 1.02 Magnetotelluric course

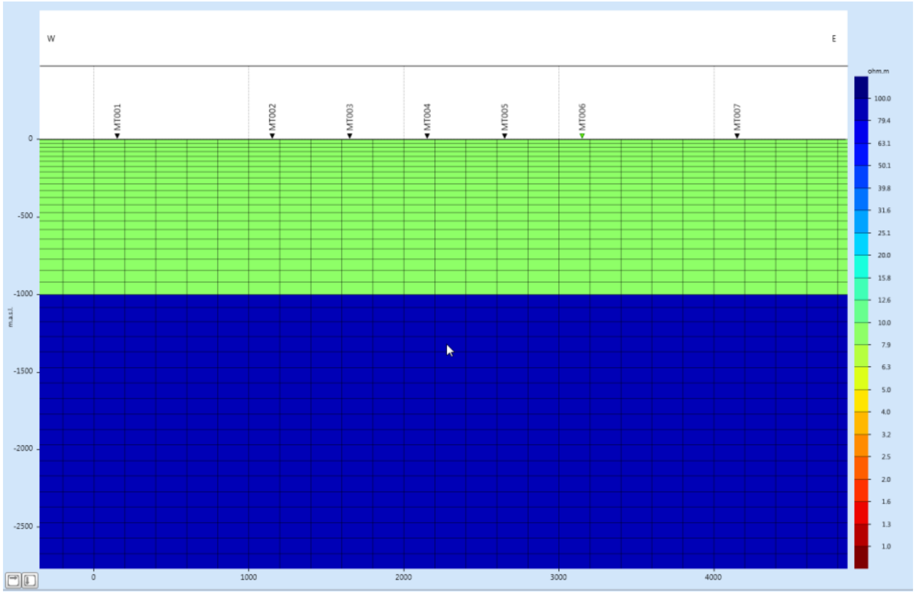
Introduction

The following exercises deal with different subsurface resistivity scenarios in an imaginary subsurface measured with a (synthetic) MT survey. A map showing the layout of the synthetic MT survey is given below. Plotted on this map is profile P 01 with associated synthetic MT stations MT001 to MT007. MT responses for a range of different resistivity cross-sections, with subsurface structures representing various geological scenarios, are investigated using Geotools™ software.



1. Layered model

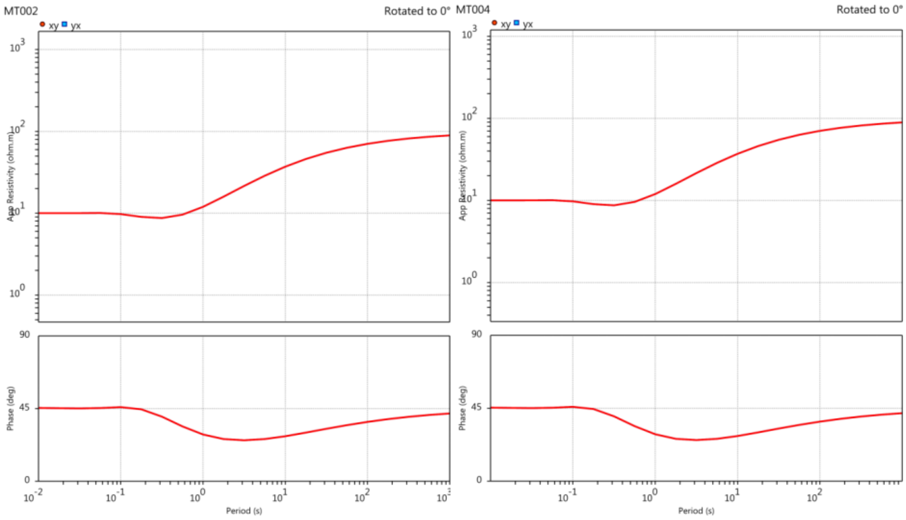
A layered resistivity model is defined for the subsurface. A portion of the corresponding resistivity cross-section for profile P 01 is shown here.



- *Q01:* By looking at the resistivity variation with depth, how might the geological setting of this resistivity cross-section be described?
- *Q02:* By using the skin-depth equation, estimate the period at which the top of the resistive basement becomes visible in the response of the MT stations?
- *Q03:* Do you expect differences between the forward responses of the magnetotelluric stations? Explain and predict the expected behavior of the apparent resistivity and phase curves of the forward MT responses for both the *xy* (TE) and *yx* (TM) modes. (Hint: also consider whether the MT responses are characterised by 1-D, 2-D or 3-D dimensionality).

Open the 'GeocapExercises' database in Geotools™ and open 2D Model 'P 01: Model 01 Layered' in the 'Items' pane. If not already enabled, select '2D Inversion' and 'Parameters' and select 'TM', 'TE' and 'Tzy' between 0.001 Hz and 100 Hz. Run the forward model (click the triangle below 'Launch').

Examine the forward station responses (apparent resistivity and phase) of the magnetotelluric stations in Geotools™. Click the station in the 2-D model, uncheck the 'Masked Data' box, check the 'Synthetic Curve' box and select the corresponding model (2D > P01 Model 01 Layered – Current Model). The forward responses of stations MT002 and MT004 are shown here.



Q04: At what period do you see the forward responses first become sensitive to the deeper resistivity structure? Knowing the resistivity values in the corresponding cross-section and using the skin-depth calculation of *Q03*, can you explain the shape of the apparent resistivity of the forward responses? Is there a relation between the apparent resistivity and phase response?

1-D Inversion

The forward stations responses can be inverted in 1-D using a smooth and a layered inversion approach in Geotools™. Open the map 'StatCoord Layered' in the 'Documents' tab. Open station MT002 in the 'Data Analysis' mode.

Q05: Examine apparent resistivity, phase, Tipper, induction arrows and polar diagrams of the station response of station MT002. Describe and explain the behavior of both components of the Tipper, of the induction arrows and of the polar diagrams.

Q06: Based on the observations made in *Q05*, can you give an estimate of the number of layers you would need to use for the (layered) 1-D inversion of this station repsonse?

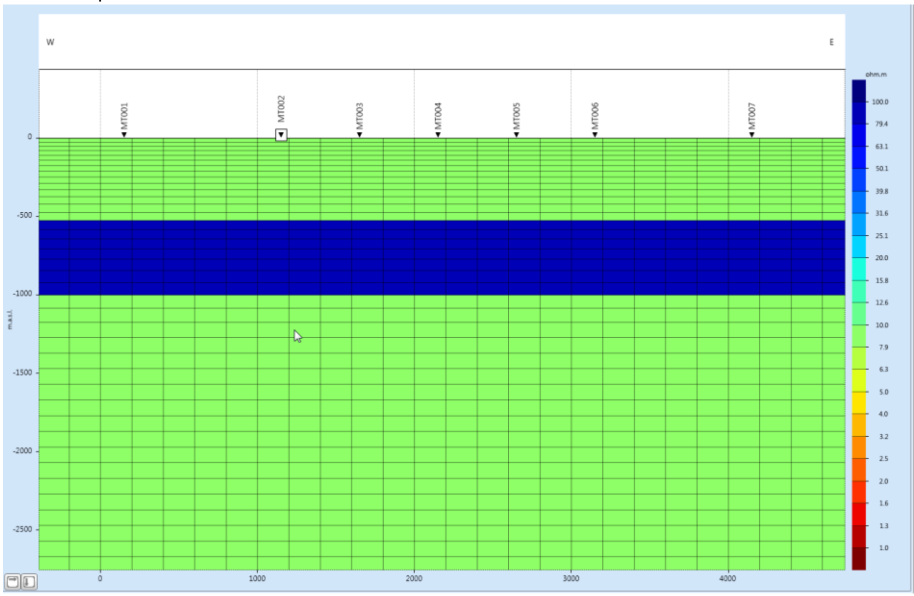
Q07: Which curve (TE, TM or invariant) is the best choice for inversion? Motivate your choice.

Go to the '1-D modeling' mode and run the 1-D inversion of station MT002 using an inversion strategy based on the answers of questions *Q05* and *Q06*. Do this by appropriately adjusting the number of layers of the layered model and the mode to be inverted. Save the result as a *.png using 'Copy' and report the RMS misfit of the 1-D layered inversion.

Q08: Is the resistivity structure of the resistivity cross-section properly recovered and resolved by the layered model? And is it properly resolved by the smooth model? Describe the similarities between the original resistivity cross-section used for the forward model and the 1-D inversion results.

2. Sandwich model

Another layered resistivity model is defined for the subsurface. The corresponding resistivity cross-section for profile P 01 is shown here.



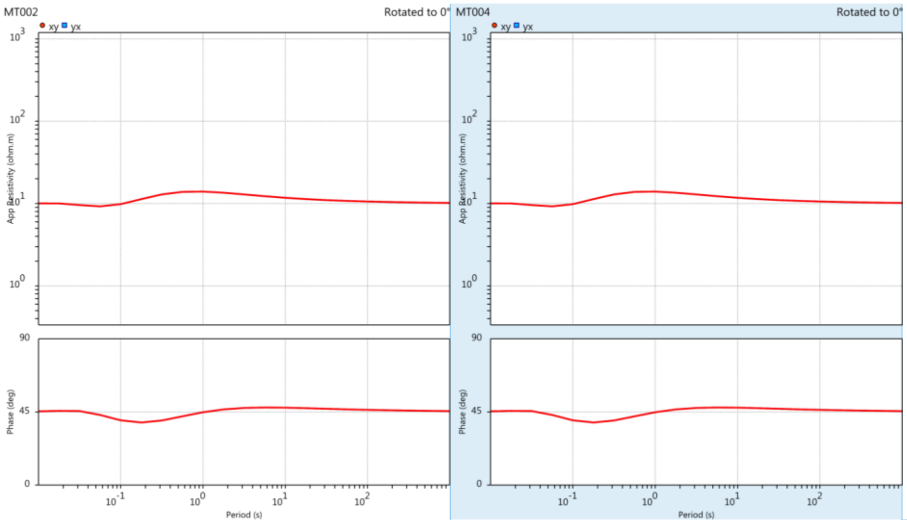
Q01: How might the geological setting of this resistivity cross-section be described?

Q02: At what period will the top of the resistive layer be visible in the response of the MT stations?

Q03: Is it possible to utilize the skin-depth equation to estimate the sounding period of the response of the MT stations corresponding to the depth of the base of the resistive layer? Motivate and explain your approach to calculate the sounding period.

Q04: Can you predict the apparent resistivity and phase curves for the *xy* and *yx* components of the forward response of the magnetotelluric stations of this model? Describe them.

Open 2D Model ‘P 01: Model 01 Sandwich’ in the ‘Items’ pane. Select ‘2D Inversion’ and ‘Parameters’ and select ‘TM’, ‘TE’ and ‘Tzy’ between 0.001 Hz and 100 Hz. Run the forward model and examine the station forward responses (apparent resistivity and phase) of the magnetotelluric stations. The forward responses of this model for stations MT002 and MT004 are plotted below.



Commented [M1]: The responses are quite subtle. I think you might illustrate a clearer response using a much greater resistivity contrast for the middle layer.

Q05: Knowing the corresponding resistivity cross-section, is the resistivity of the model fully represented in the forward responses. Do the forward responses match with the skin-depths calculated at *Q02* and *Q03?*

1-D inversion

Open the map 'StatCoord Sandwich' in the 'Documents' tab and open station MT002 in the 'Data analysis' mode.

Q06: Based on the observations made in *Q02-Q05*, can you give an estimate of the number of layers you would use for the layered 1-D inversion of this station?

Go to the '1-D modeling' mode and run the layered 1-D inversion for all stations using a strategy based on the answer to question *Q06*. Hint: you can batch invert the MT data in the ' MT Surveys' section of the 'Items' pane. Export the result as a *.png using 'Copy' and report the RMS misfit of the layered model inversions. (Invert the stations individually if the batch function is not working properly.)

Right-click profile 'P 03 Sandwich' in map 'StatCoord Sandwich' and select 'Create Section' > 'Cross Section'. (Note that create section is opened as the last tab and doesn't appear on top) In the new 'Untitled Cross Section' tab, click '+' in the 'Layers' pane on the right and add the smooth and layered models to the cross section. 'Invert colors' of the color range and set the limits to 1 and 100 Ωm. Use the 'Copy' tab to export the cross section as *.png.

Q07: Is the resistivity structure of the resistivity cross-section well recovered and resolved by the 1-D layered models? If not, give suggestions about how to manually improve the model and how to carry them out in Geotools™. Create a new cross-section of the results and save the result as a *.png.

2-D inversion

Select in the 'Items' tab, profile 'P 03 Sandwich' and create a 2-D inversion starting (or "*a priori*") model. Make sure that the MT stations are included in the model. Select 'Mesh' and change the Geometry Parameters to 'Cell Width = 200', 'Left = -800' and 'Right = 4800'. Select 'Properties' and change the *a*

Commented [W2]: Check this!

priori resistivity to 10 Ωm by changing the ‘uniform value’ and the ‘property value’ accordingly. Invert the colors of the color bar and set the resistivity range to 1-100 Ωm. Select ‘2D Inversion’. Make sure the inversion frequency range matches the frequency range covered by the MT data in the ‘Parameters’-window. Use the default values for the remaining parameters.

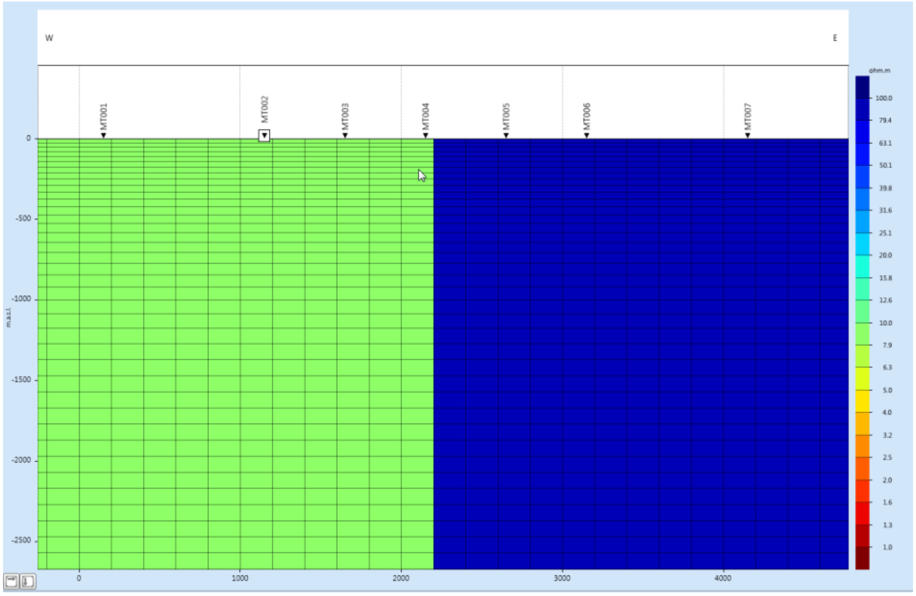
Q08: Launch the forward model and report the RMS misfit value. Interpret the reported RMS value. Examine the forward responses generated for the starting model and consider whether this starting model mesh be used reliably for the 2-D inversion of the MT data? If not, which settings (e.g., mesh, TE- or TM-mode, inversion parameters) would you change? Motivate your answer.

Q09: Run the 2-D inversion using a maximum of 50 iterations. Report a screenshot (*.png) of the model and the RMS misfit after the 50^{th} iteration. Describe the resulting 2-D resistivity model. Does the inversion result correspond well with the initial 2-D resistivity model used for the forward model?

Q10: Open station MT004 and describe the match between the observed data and the modelled data curves for the 2-D inversions carried out. (You can find the modelled data under the ‘Synthetic Curve’ button).

3. Vertical boundary model

A resistivity model comprising a vertical contact between different resistivity structures is defined for the subsurface. The corresponding resistivity cross-section for profile P 01 is shown here.

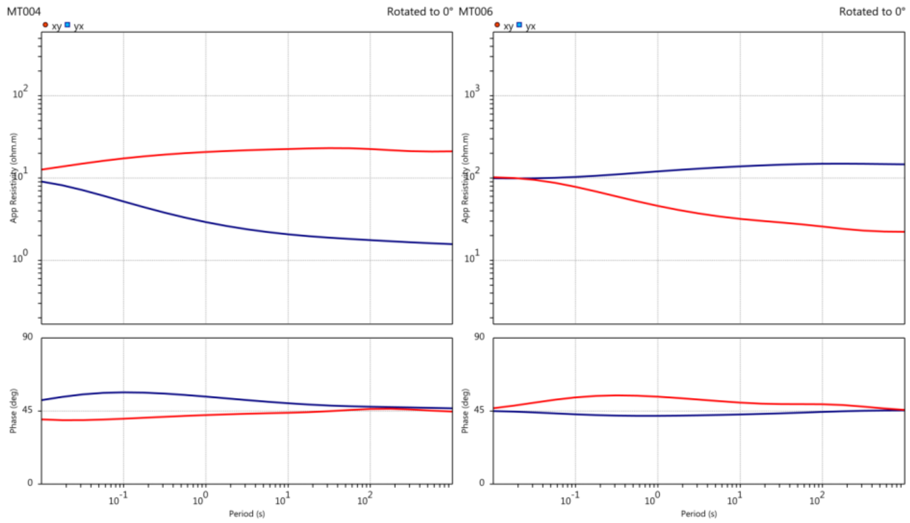


Q01: How might the geological setting of this resistivity cross-section be described?

Q02: The lateral distance from the station MT001 to the resistivity boundary is approx. 2,000 m. At what period will the vertical resistivity contact be visible in the MT response of station MT001? At what period will the vertical resistivity contact be visible in the MT responses of stations MT004 (lateral distance of approx. 50 m to the vertical contact) and MT006 (lateral distance of approx. 1,000 m to the vertical contact)? Hint: use the skin-depth equation.

Q03: Can you describe the *xy* and *yx* components of the expected forward responses of the magnetotelluric stations MT001, MT004 and MT006? (Hint: also consider whether the MT responses are characterised by 1-D, 2-D or 3-D dimensionality).

Open 2D Model ‘P 01: Model 01 Boundary’ in the ‘Items’ pane. Select ‘2D Inversion’ and ‘Parameters’ and select ‘TM’, ‘TE’ and ‘Tzy’ between 0.001 Hz and 100 Hz. Run the forward model and examine the station forward responses (apparent resistivity and phase) of the magnetotelluric stations. The forward responses of stations MT004 and MT006 for this model are plotted below.



Q04: Knowing the corresponding resistivity cross-section, can you explain the shape of the apparent resistivity and phase of the forward responses of the two MT stations? Describe how well the forward responses match with the skin-depth calculations made in *Q02?*

Q05: Describe the apparent resistivity curves of stations MT004 and MT006 in terms of how closely they (intuitively) resemble the resistivity cross-section used to generate the forward responses? (Hint: consider the differences and similarities between the *xy* and *yx* modes).

Q06: Can you explain the shape of the apparent resistivity and phase of the *yx* component? Which of the *xy* and *yx* components corresponds with the TE- and which with the TM-modes? (Hint: consider the directions of electrical current flow through the models. Consider which of the *xy* and *yx* components corresponds with current flow along the profile direction and which perpendicular to the profile direction?)

1-D inversion

Open map 'StatCoord Boundary' in the 'Documents' tab and open station MT005 in the 'Data analysis' mode.

Q07: Examine apparent resistivity, phase, Tipper, induction arrows and polar diagrams of the station response of station MT005. Describe and explain the behavior of both components of the Tipper, of the induction arrows and of the polar diagrams.

Q08: Which curve (TE, TM or invariant) is the best choice for 1-D inversion? Are any of the curves in fact suitable for 1-D modelling? Explain.

Commented [W3]: Wouter, I can't remember if we've discussed this before (and rejected the idea or not for various reasons!), but I think this might be quite a good place also to look at apparent resistivity and phase pseudo-sections. Considering the appearance of the pseudo-sections would be quite informative for the students (i.e., pseudo-sections for 2-D MT responses). If it would be helpful for the students to have looked at a simpler pseudo-section first (i.e., pseudo-sections for 1-D MT responses), the students could also look at them in the Sandwich Model of Section 2.

Go to the '1-D modeling' mode and run the layered 1-D inversion for all seven stations using a strategy based on the answers to questions *Q07* and *Q08*. Export the result as a *.png using 'Copy'. Create a cross-section of the smooth and layered 1-D inversion models. Save the cross-section as *.png.

Q09: Is the structure of the original resistivity cross-section well recovered and resolved by the profile of 1-D layered models? If not, explain why not and consider whether it is possible to improve the modelling result (e.g., by using a different data component, TE, TM or invariant, to the one used initially)? If so, describe how and re-run the 1-D inversion. Save the 1-D inversion results as *.png and create a new cross-section. Save the cross-section as *.png as well.

2-D inversion

Select in the 'Items' tab, profile 'P 04 BoundaryModel' and create a 2-D inversion starting model. Select 'Mesh' and change the Geometry Parameters to 'Cell Width = 200', 'Left = -800' and 'Right = 4800'. Select 'Properties' and change the *a priori* resistivity to 10 Ωm. Invert the colors of the color bar and set the resistivity range to 1-100 Ωm. Select '2D Inversion'. Assure the frequency range matches the frequency range covered by the MT data in the 'Parameters'-window. Use the default values of the remaining parameters.

Commented [W4]: Check stations

Q10: Run the 2-D inversion using a maximum of 50 iterations and save the results. Report a screenshot (*.png) of the model and the final RMS misfit. Describe the resulting 2-D resistivity model. Does the inversion result correspond well with the original resistivity model used for the forward model? Describe the similarities and differences. Is the 2-D inversion result a better match with the original resistivity model than the 1-D inversion results?

Change the *a priori* resistivity to 100 Ωm and save as a new model.

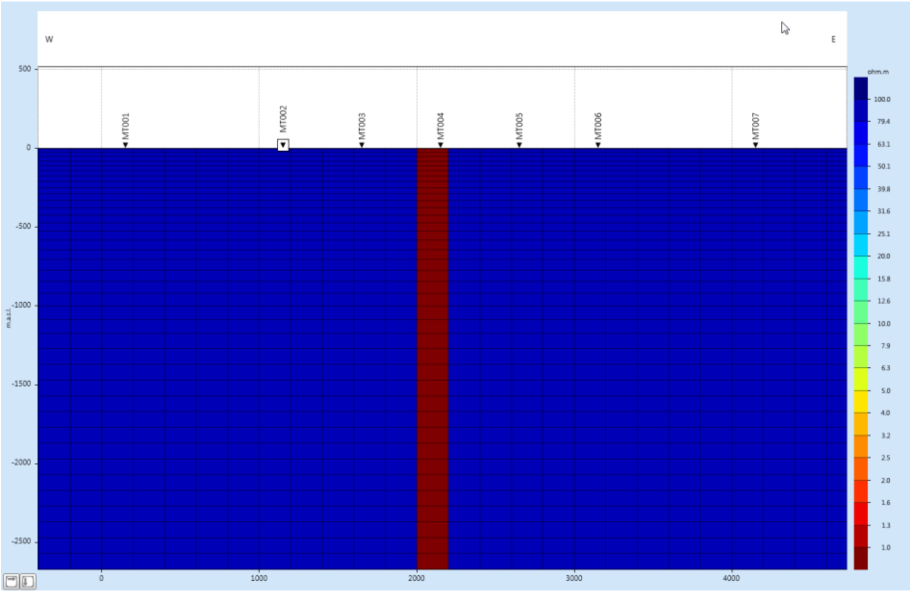
Q11: Run the inversion. Report a screenshot of the model and the final RMS misfit. Describe the resulting 2-D resistivity model. Does this inversion result correspond better with the original resistivity model used for the forward model in comparison to the inversion model derived from the 10 Ωm *a priori* model? Describe the differences, if any.

Q12: Experiment with TE- and TM-mode only inversion. Describe the similarities and differences between the inversion results.

Q13: For all 2-D inversion models, open station MT004 and describe the match between the observed data and the modelled responses (curves).

4. Vertical conductive fault model

A resistivity model comprising a vertical conductive anomaly in a resistive basement is defined for the subsurface. The corresponding resistivity cross-section for profile P 01 is shown here.

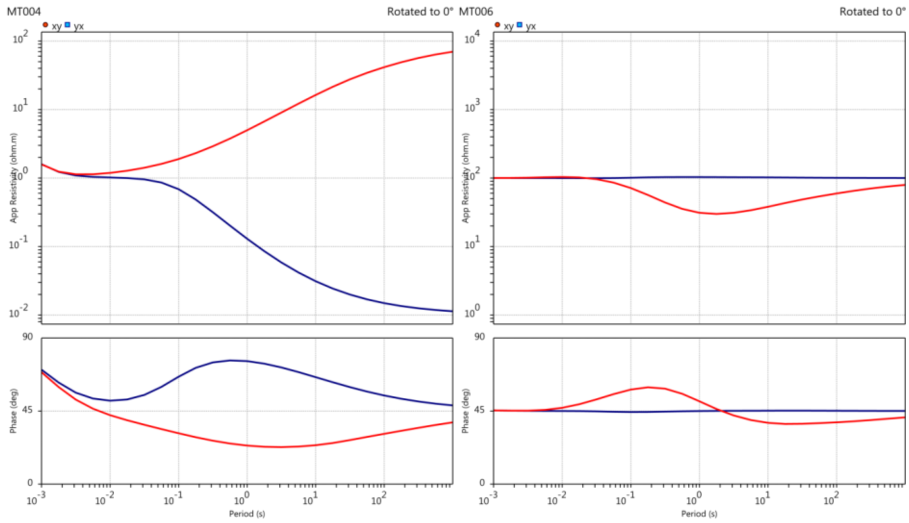


Q01: How might the geological setting of this resistivity cross-section be described?

Q02: The lateral distance from the station MT001 to the conductive fault is approx. 1,850 m. At what period will the vertical resistivity contact be visible in the MT response for station MT001? And for stations MT004 (at 0 m from the fault) and MT006 (at approx. 1,200 m from the fault)?

Q03: Can you predict and describe the *xy* and *yx* components of the apparent resistivity and phase in the expected forward responses of the magnetotelluric stations?

Open 2D Model ‘P 01: Model 01 ConductiveFault’ in the ‘Items’ pane. Select ‘2D Inversion’ and ‘Parameters’ and select ‘TM’, ‘TE’ and ‘Tzy’ between 0.001 Hz and 1,000 Hz. Run the forward model and examine the station forward responses (apparent resistivity and phase) of the magnetotelluric stations. The forward responses of stations MT004 and MT006 for this model are plotted below.



Q04: Knowing the corresponding resistivity cross-section, can you explain the shapes of the apparent resistivity and phase of the forward responses? Do the forward responses match with the skin-depth calculations made in *Q02?*

Q05: Describe the apparent resistivity curves in terms of how they (intuitively) resemble the resistivity cross-section used to generate the forward responses. Describe the similarities and differences between the two components (xy and yx) and the forward-model resistivity cross-section.

1-D inversion

Open 'StatCoord ConductiveFault' in the 'Documents' tab and open stations MT002, MT004 and MT006 in the 'Data analysis' mode.

Q06: Examine apparent resistivity, phase, Tipper, induction arrows and polar diagrams of the station response of stations MT002, MT004 and MT006. Describe and explain the behavior of both components of the Tipper, of the induction arrows and of the polar diagrams.

Go to the '1-D modeling' mode and run the layered 1-D inversion for all seven stations. Create a cross-section of the smooth and layered 1-D inversion models and save the cross-section as *.png.

Q07: Describe and motivate the strategy used for the 1-D inversion.

Q08: Is the structure of the original resistivity cross-section well recovered and resolved by the 1-D inversion layered and smooth resistivity models? If not, is it possible to improve the 1-D inversion model results? If so, describe how and re-run the 1-D inversion. Save the 1-D inversion results as *.png and create a new cross-section. Save the cross-section as *.png as well.

2-D inversion

Select in the 'Items' tab, profile 'P 05 ConductiveFault' and create a 2-D inversion starting model. Select 'Mesh' and change the Geometry Parameters to 'Cell Width = 200', 'Left = -800' and 'Right = 4800'. Select 'Properties' and change the a priori resistivity to 100 Ωm. Invert the colors of the color bar and set the resistivity range to 1-100 Ωm. Select '2D Inversion'. Make sure the inversion frequency

Commented [W5]: Check MT stations

range matches the frequency range covered by the MT data in the ‘Parameters’-window. Use the default values for the remaining parameters.

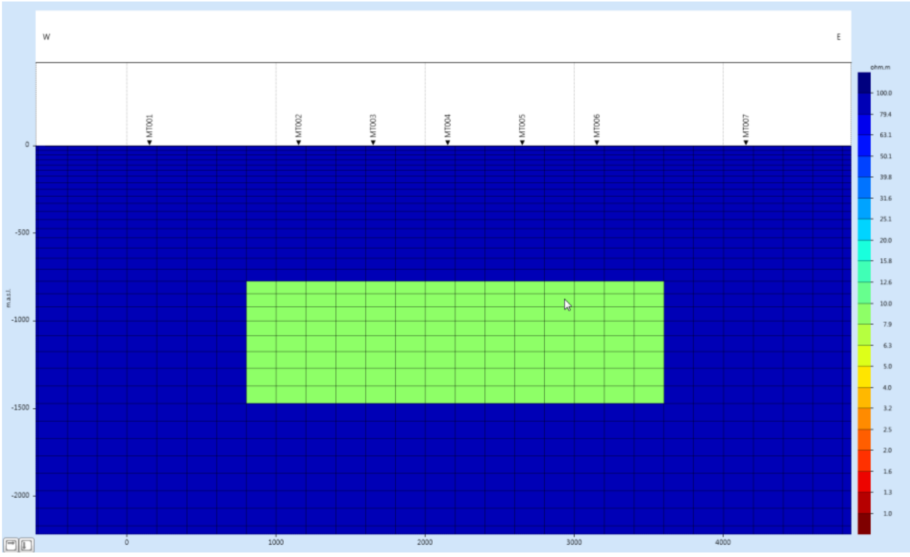
- *Q09:* Run the inversion and save the results. Report a screenshot of the model and the final RMS misfit. Describe the resulting 2-D inversion resistivity model. Does the inversion result correspond well with the original 2-D resistivity model used for the forward modelling of the MT responses? Describe the similarities and differences.
- *Q10:* Can you think of any strategies to improve the fit of the inversion model? Describe them.
- *Q11:* Try the alternative inversion strategies that might improve the inversion resistivity models and report the results (again in a *.png output of the station responses, the models and the RMS misfits).

Change the *a priori* resistivity to 1 Ωm and save as a new model.

- *Q12:* Run the inversion. Report a screenshot of the model and the final RMS misfit. If necessary, try different inversion strategies. Describe the resulting 2-D inversion resistivity models. Do these 2-D inversion results correspond better with the original 2-D resistivity model used for the forward model in comparison to the inversion models generated with the 100 Ωm *a priori* model? Describe the differences, if any.
- *Q13:* For all inversion models, open station MT005 and describe the match between the observed data and the modelled responses (curves).

5. Shallow anomaly model

A resistivity model comprising a conductive body in a resistive basement is defined for the subsurface. The corresponding resistivity cross-section for profile P 01 is shown here.

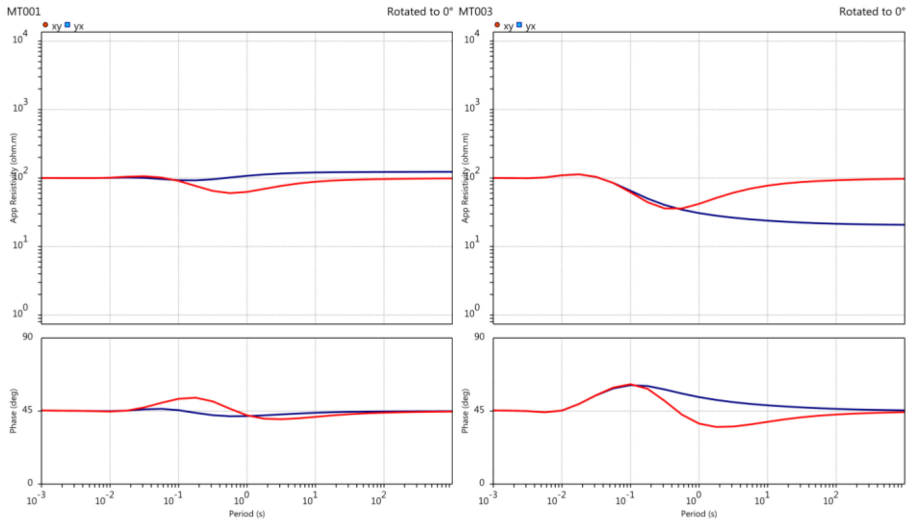


Q01: How might the geological setting of this resistivity cross section be described?

Q02: At what period will the conductive body first be visible in the response of station MT001? And in station MT003? What about the period for the bottom of the conductive body in the response of station MT003 – can this period be predicted or defined? (Hint: go back to your answers to the questions about the Sandwich Model)

Q03: Can you describe the *xy* and *yx* components of the apparent resistivity and phase in the expected forward responses of magnetotelluric stations MT001 and MT003?

Open 2D Model ‘P 01: Model 01 ShallowAnomaly’ in the ‘Items’ pane. Select ‘2D Inversion’ and ‘Parameters’ and select ‘TM’, ‘TE’ and ‘Tzy’ between 0.001 Hz and 1,000 Hz. Run the forward model and examine the station forward responses (apparent resistivity and phase) of the magnetotelluric stations. The forward responses of stations MT001 and MT003 for this model are plotted below.



Q04: Knowing the corresponding resistivity cross-section, can you describe and explain the shape of the forward responses? Do the forward responses match with the skin-depth calculations made in *Q02?*

Q05: Describe the apparent resistivity curves in terms of how they resemble the original resistivity cross-section used to generate the forward responses? Describe and explain the phase responses.

1-D inversion

Open 'StatCoord ShallowAnomaly' in the 'Documents' tab. Go to the '1-D modeling' mode and run the layered 1-D inversion for all seven stations. Create a cross section of the smooth and layered 1-D inversion models and save the cross section as *.png.

Commented [W6]: Check data in this model

Q06: Describe and motivate the inversion strategy used.

Q07: Is the structure of the original resistivity cross section well recovered and resolved by the 1-D layered and smooth inversion resistivity models? If not, is it possible to improve the models? Save all the model results as *.png outputs and report the RMS misfits.

2-D inversion

Select in the 'Items' tab, profile 'P 06 ShallowAnomaly' and create a 2-D inversion starting model. Select 'Mesh' and change the Geometry Parameters to 'Cell Width = 200', 'Left = -800' and 'Right = 4800'. Invert the colors of the color bar and set the resistivity range to 1-100 Ωm. Select '2D Inversion'. Select 'Properties' and change the *a priori* resistivity to 100 Ωm. Make sure the frequency range matches the frequency range covered by the MT data in the 'Parameters'-window. Use the default values for the remaining parameters.

Commented [W7]: Check MT stations and data

Q08: Run the inversion and save the results. Report a screenshot (*.png) of the model and the final RMS misfit. Describe the resulting 2-D inversion resistivity model. Does the inversion result correspond well with the original 2-D resistivity model used for the forward model?

Q09: Can you think of any strategies to improve the fit of the inversion model? Describe them.

Q10: Try some or all of the alternative inversion strategies that might improve the resistivity models and report the results (in *.png outputs for 2 to 3 representative station responses, the inversion resistivity ~~y~~ models and the final RMS misfits).

Q11: For all inversion models, open station MT005 and describe the match between the observed data and the modelled responses (curves).