Workshop 2
Exploring high temperature reservoirs:
new challenges for geothermal energy
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2D inversion of a magnetotelluric profile in Travale geothermal field using invariant responses

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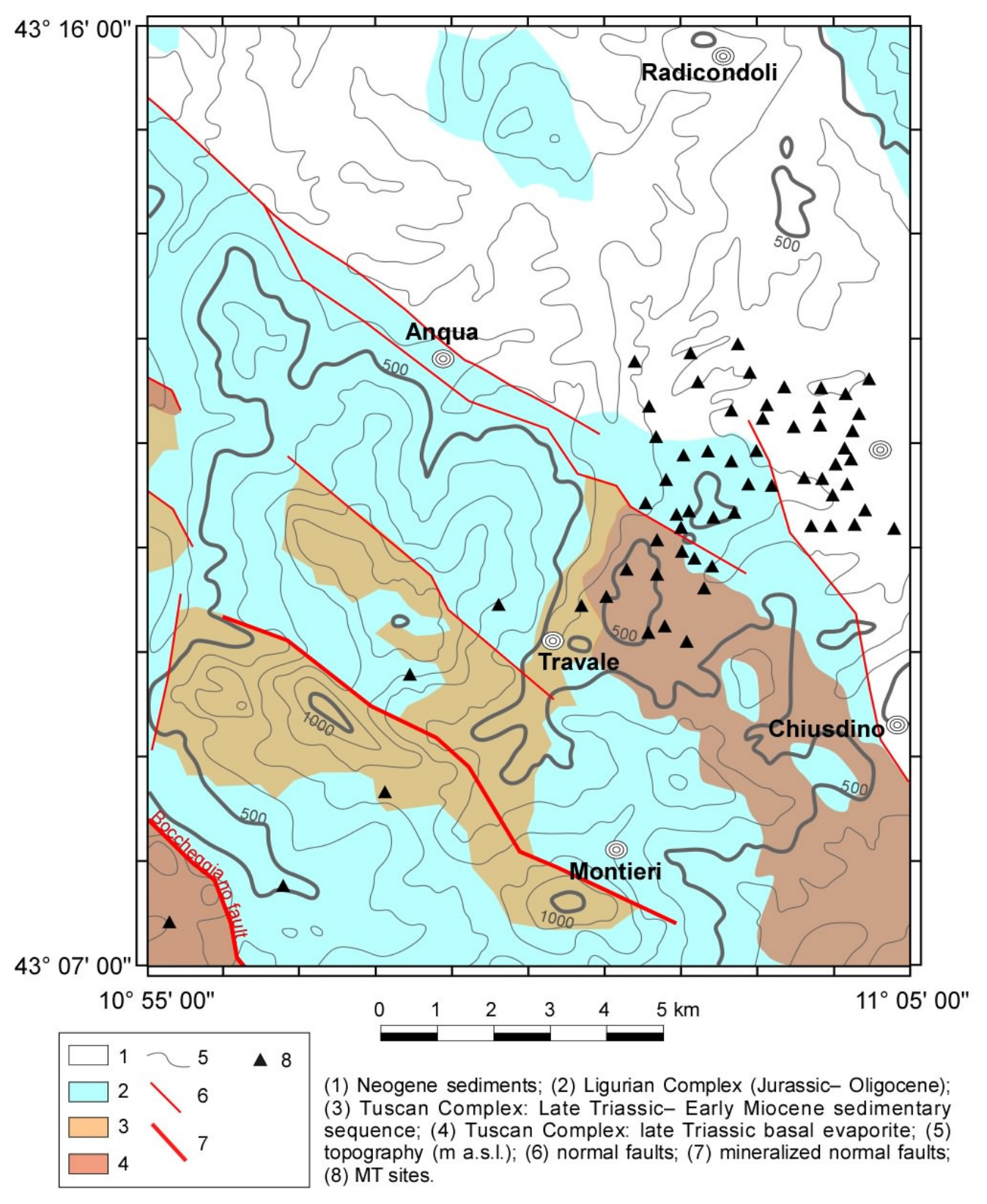
Abstract

We utilized a magnetotelluric profile in the Travale geothermal field, in Tuscany, Italy, to obtain a resistivity model using 2-D inversion of the series and parallel (S-P) invariant impedances. The aim was to compare the performance of the S-P responses with 2-D inversion of conventional TE and TM impedances. Resembling TE and TM responses, S-P are complementary, as series impedance is more sensible to galvanic effects while parallel is to inductive effects. Moreover, as both responses are rotation invariant, they overcome the trouble of selecting a rotation angle or using a tensor decomposition technique. For S-P inversion we used a Gauss-Newton algorithm designed to minimize the data misfit at the same time as the model is kept as smooth as possible. The trade-off between data misfit and model roughness is balanced by a regularization factor. We changed this factor in a search for the model with the best tradeoff between data misfit and model roughness. TE and TM impedances were inverted using the algorithm of Rodi and Mackie, after rotation of data toward the main strike direction of the area. The resulting TE-TM and S-P model shows many similarities in defining resistivity anomalies at both shallow (500 m) and deep (1-5 km) depth. The 2D models show resistivity anomalies that correlate with zones of high permeability and fluid content representing exploited geothermal reservoirs. The shallow resistivity anomalies show a good correlation with the shallow geothermal reservoir, located in carbonate units. The anomalies are particularly visible in correspondence of the faults, suggesting an increase of permeability, a pathway for fluids and possible related alteration minerals. The most conspicuous feature of the 2D models is the presence of low resistivity anomalies inside the resistive basement at a depth of 1-4 km b.g.l. This deep resistivity anomaly corresponds to the deep fractured and highly productive geothermal reservoir located in the metamorphic rocks. This deep reservoir is made of sparse fractures and hosts superheated steam.

Geological setting

Travale geothermal field, in Tuscany Italy, belongs to the famous geothermal region of Larderello. Here the permeability is usually low and heterogeneously distributed. In particular, two geothermal reservoirs are exploited: a shallow reservoir within cataclastic levels of the carbonate evaporitic rocks of the Tuscan Complex, and a deeper, more extensive reservoir defined by fractures within the metamorphic rocks, at depths of more than 2 km. In this area the exploration targets are mainly located in metamorphic rocks down to 4000 m depth, characterized by very high temperature (up to 400°C). In this area the following tectono-stratigraphic complexes have been recognized: 1) Miocene-Pliocene and Quaternary sediments, filling extensional tectonic depressions; 2) the Ligurian complex, consisting of Jurassic ophiolite rocks, its sedimentary Jurassic-Cretaceous sedimentary cover, and Creataceous-Oligocene flysch; 3) the Tuscan complex, including sedimentary rocks from Late Triassic-Jurassic evaporitic and carbonate rocks to Late Oligocene-Early Miocene turbidites; and 4) a substratum, principally known through geothermal drillings, composed of two units: the upper is referred to as the Monticiano-Roccastrada Unit, mainly made up of Triassic quartzites and phyllites (Verrucano group), Palaeozic phyllites and micaschist; the lower one corresponds to the Gneiss Complex. Details of geology may be found in the poster from Giolito et al., in this same workshop.

On 2004, in order to characterize the resistivity distribution of the geothermal area, 59 magnetotelluric (MT) sites were acquired using Phoenix systems (320-0.001 Hz).



(1) Neogene sediments; (2) Ligurian Complex (Jurassic– Oligocene); (3) Tuscan Complex: Late Triassic– Early Miocene sedimentary sequence; (4) Tuscan Complex: late Triassic basal evaporite; (5) topography (m a.s.l.); (6) normal faults; (7) mineralized normal faults; (8) MT sites.

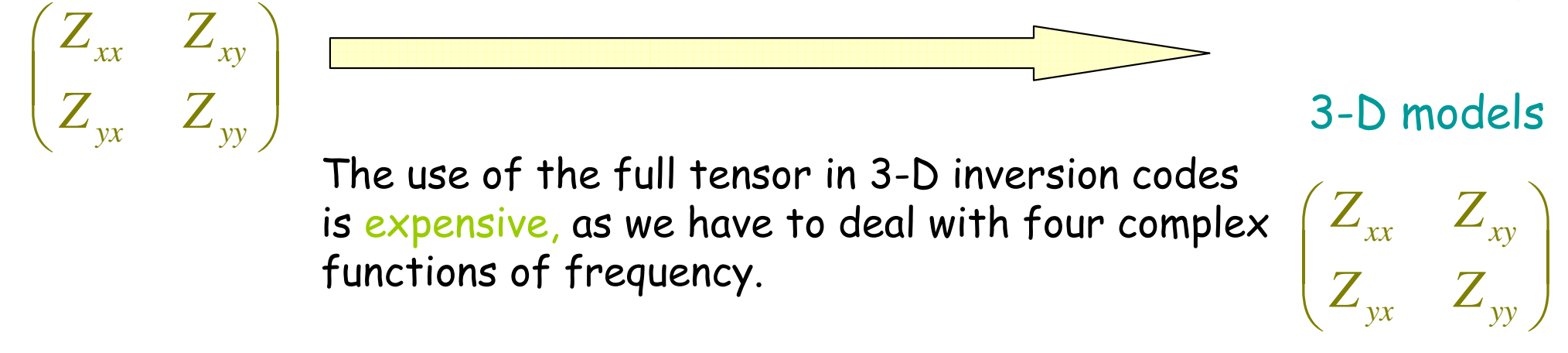
Invariant responses

In geologically complex zones, like those prevalent in many geothermal zones, the physical properties of the rocks have complicated geometrical distributions. The traditional 2-D approach for magnetotelluric interpretation oversimplify the problem and utilizes only one part of the information contained in the measured impedance tensor.

In this work we applied a transformation to the impedance tensor, which reduces the tensor into two complementary impedances and two angular response functions (Romo et al, 2005). This new representation of the MT responses is valid regardless of dimensionality and, unlike conventional TE and TM polarization modes, do not depend on rotations of the measuring reference system. In addition, the so-called Series and Parallel impedances are complementary to each other, in a similar way as TE and TM modes are complementary in ideal 2-D situations.

The 3-D problem

In a 3-D situation, a simple rotation cannot decouple the impedance tensor in two polarization modes.



3-D data

$$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

The pseudo-TE and pseudo-TM impedances resulting from ad-hoc procedures (Swift, 1967; Groom and Bailey, 1991, etc) oversimplify the data, leading to an incomplete description of the 3-D media.

2-D models

$$\begin{pmatrix} 0 & Z_{TE} \\ -Z_{TM} & 0 \end{pmatrix}$$

The use of the full tensor in 3-D inversion codes is expensive, as we have to deal with four complex functions of frequency.

3-D models

$$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

Thus, it is convenient to have a way to estimate two representative impedances, hopefully keeping most of the information contained in the measured tensor.

Following Romo et al. (2005), the transformation

$$\mathbf{R}_e\,\mathbf{E} = \mathbf{R}_e\,\mathbf{Z}\;\;\mathbf{R}_h^{\mathrm{T}}\,\mathbf{R}_h\,\mathbf{H}$$

with $\mathbf{R} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$ and $\theta = \alpha + i\beta$

Converts the measured full tensor in two impedances and two angular functions

$$\{Z_{xx},\;\; Z_{xy},\;\; Z_{yx},\;\; Z_{yy}\} \Leftrightarrow \{Z_S,\;\; Z_P,\;\; \bar{\theta},\;\; \Delta\theta\}$$

The transformed responses can be readily calculated from the original tensor by

$$Z_s = \left(\frac{Z_{xx}^2 + Z_{xy}^2 + Z_{yy}^2 + Z_{yx}^2}{2} \right)^{1/2} \qquad \bar{\theta} = \mathrm{atan}\left(\frac{Z_{yy} - Z_{xx}}{Z_{xy} + Z_{yx}} \right)$$

$$Z_p = 2\,\frac{Z_{yx} Z_{xy} - Z_{xx} Z_{yy}}{\left(Z_{xx}^2 + Z_{xy}^2 + Z_{yy}^2 + Z_{yx}^2 \right)^{1/2}} \qquad \Delta\theta = \mathrm{atan}\left(\frac{Z_{yy} + Z_{xx}}{Z_{xy} - Z_{yx}} \right)$$

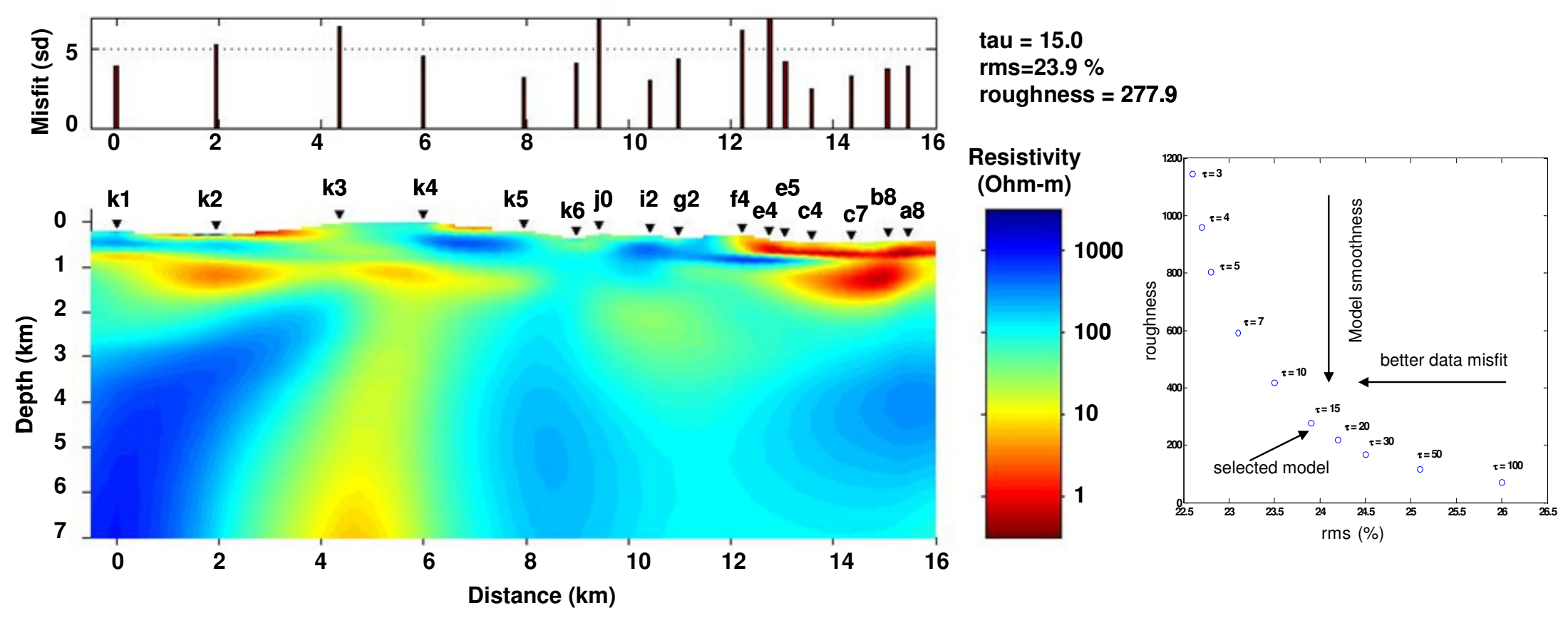
Data Inversion

We inverted Z_S and Z_P impedances using a regularized 2-D inversion algorithm, based on Gauss-Newton optimization, written by Rodi and Mackie (2001) and adapted by Romo et al. (2005) to invert the S-P responses. The optimization process minimizes the following objective function

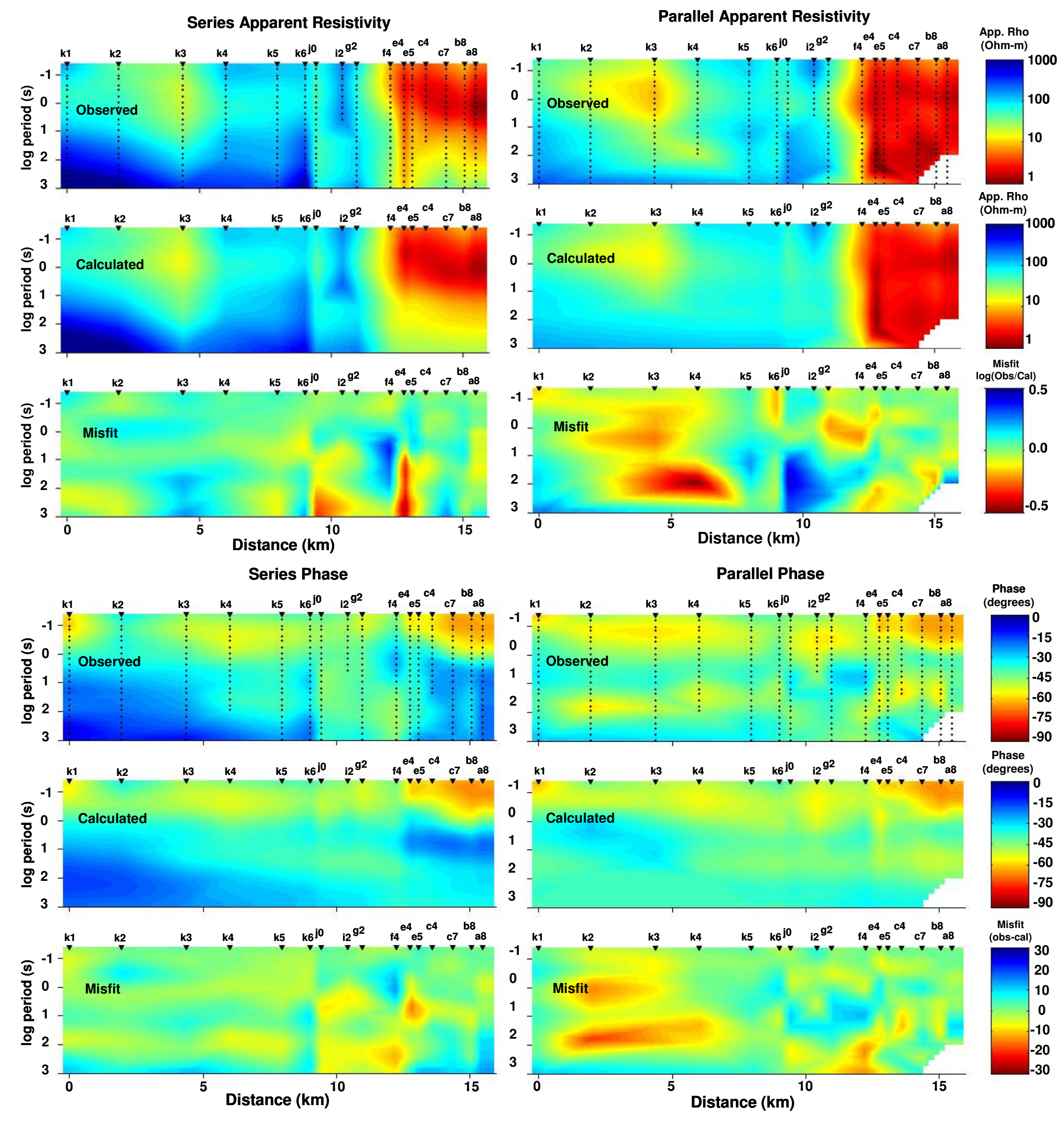
$$S(\mathbf{m}) = \underbrace{\left(d - F(\mathbf{m})\right)^T \mathbf{R}_{dd}^{-1} \left(d - F(\mathbf{m})\right)}_{\text{Data misfit}} + \tau\, \underbrace{L\left\|(\mathbf{m} - \mathbf{m}_0)\right\|^2}_{\text{Model roughness}}$$

$S(\mathbf{m})$ = Objetive function
$F(\mathbf{m})$ = Model response
d = Observed data
$\mathbf{m}$ = Model parameters
$\mathbf{R}_{dd}$ = Data uncertainty
τ = Regularization factor
$\mathrm{L}(\mathbf{m})$ = Laplace operator

The solution space was explored with different regularization factors in order to find the best tradeoff between model roughness and data fitness. This was chosen using the L curve criteria.



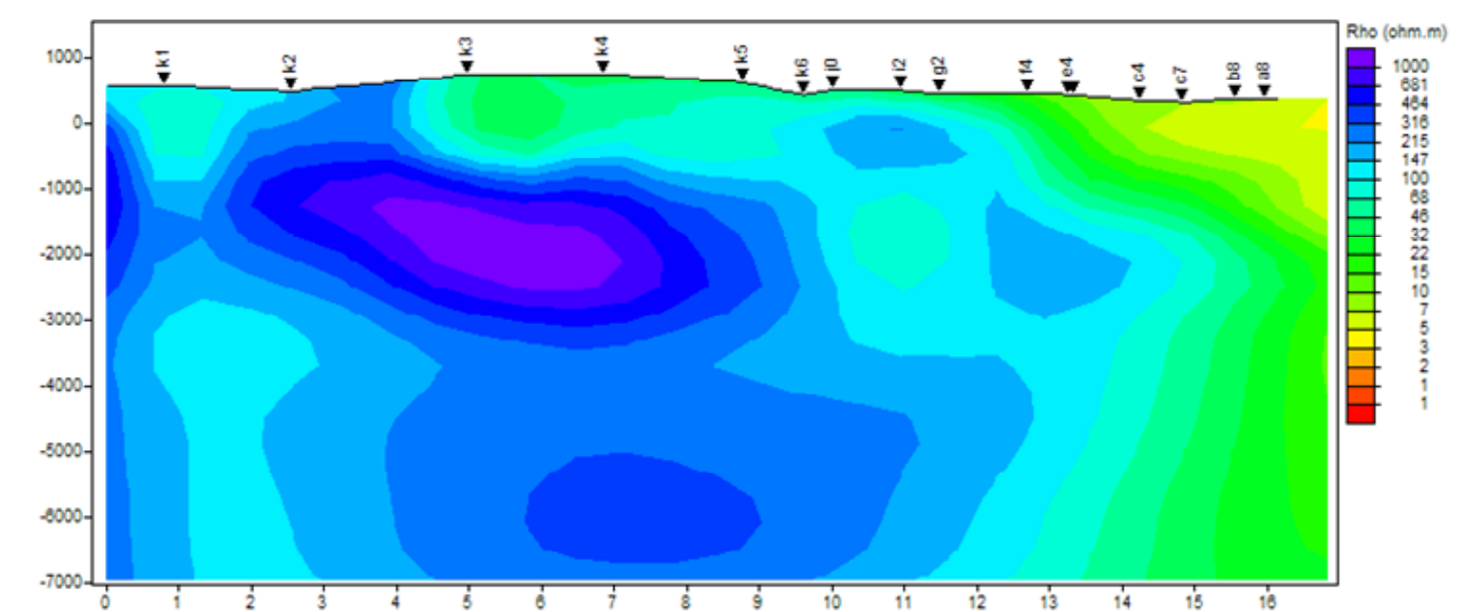
The figures below show Apparent resistivity and Phase pseudosections comparing model response with observed data. We also show the misfit pseudosection. The largest misfit corresponds to parallel apparent resistivity and phase at longer period beneath sites k3 and k4.



TE and TM data inversion

Relatively stable regional strike estimates defined a principle direction of -45° from magnetic north at most of the sites. Since the main tectonic strike in the area is in NW-SE direction, a regional 2-D structure elongated in a NE-SW direction is a reasonable first approximation. After retrieving the regional strike direction, all data were then rotated in the N45°W direction and TE and TM impedances were estimated.

Conventional TE and TM data inversion was also conducted using the complex conjugate algorithm by Rodi and Mackie (2001). The resulting model is shown below.



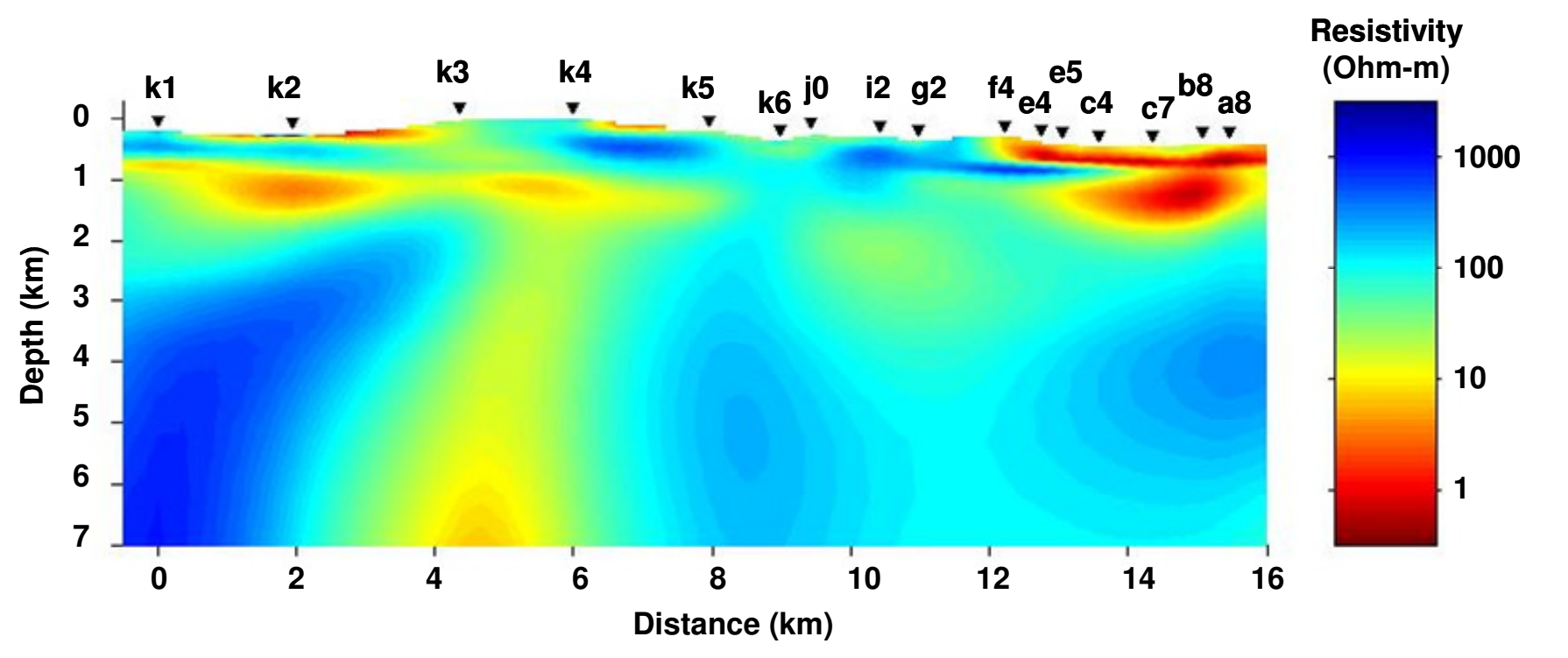
Discussion and Conclusions

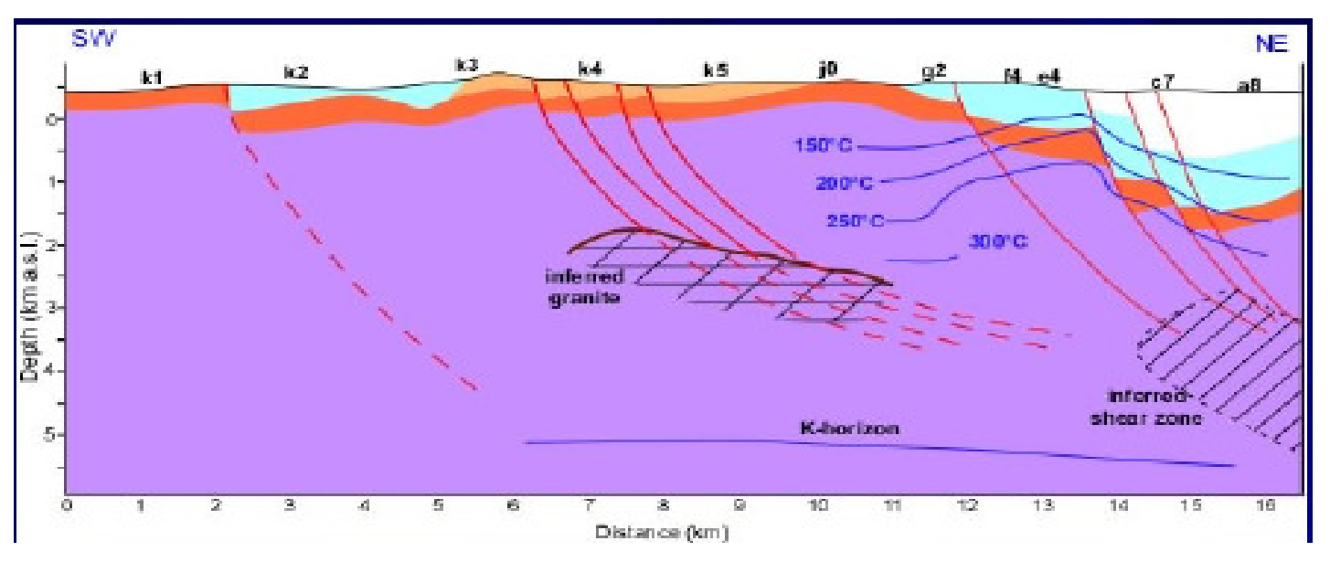
The figures below show a) S-P resistivity model, b) TE-TM resistivity model and c) geological cross section.

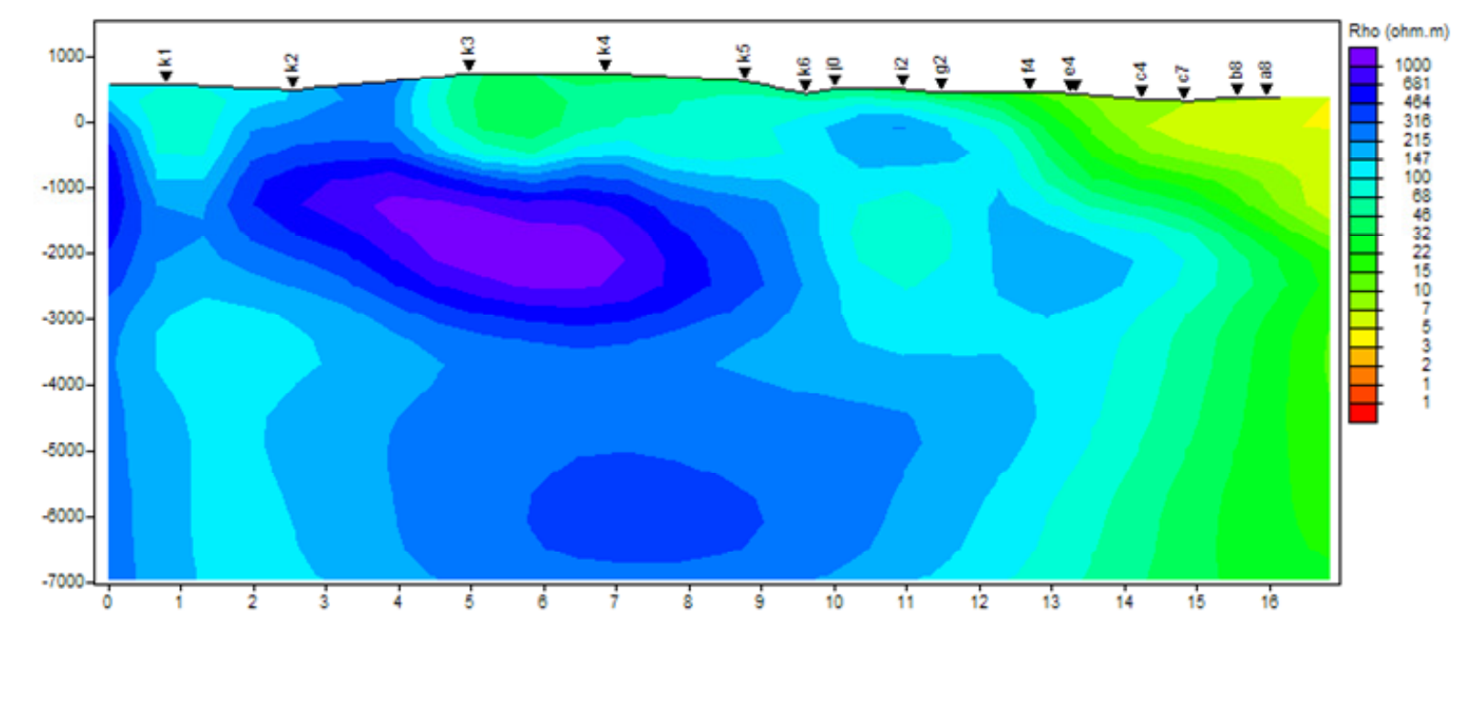
Agreements:
1) A resistive anomaly corresponding with granite uplift at the central part of the profile, beneath k5, k6, j0.
2) A conductive anomaly beneath g2 corresponding to the deep exploited geothermal reservoir (250-300°C).
3) The shallow conductive zone at the eastern end is in very good agreement with the structural attitude of the blocks dropping down toward the east and with the shallow geothermal reservoir.

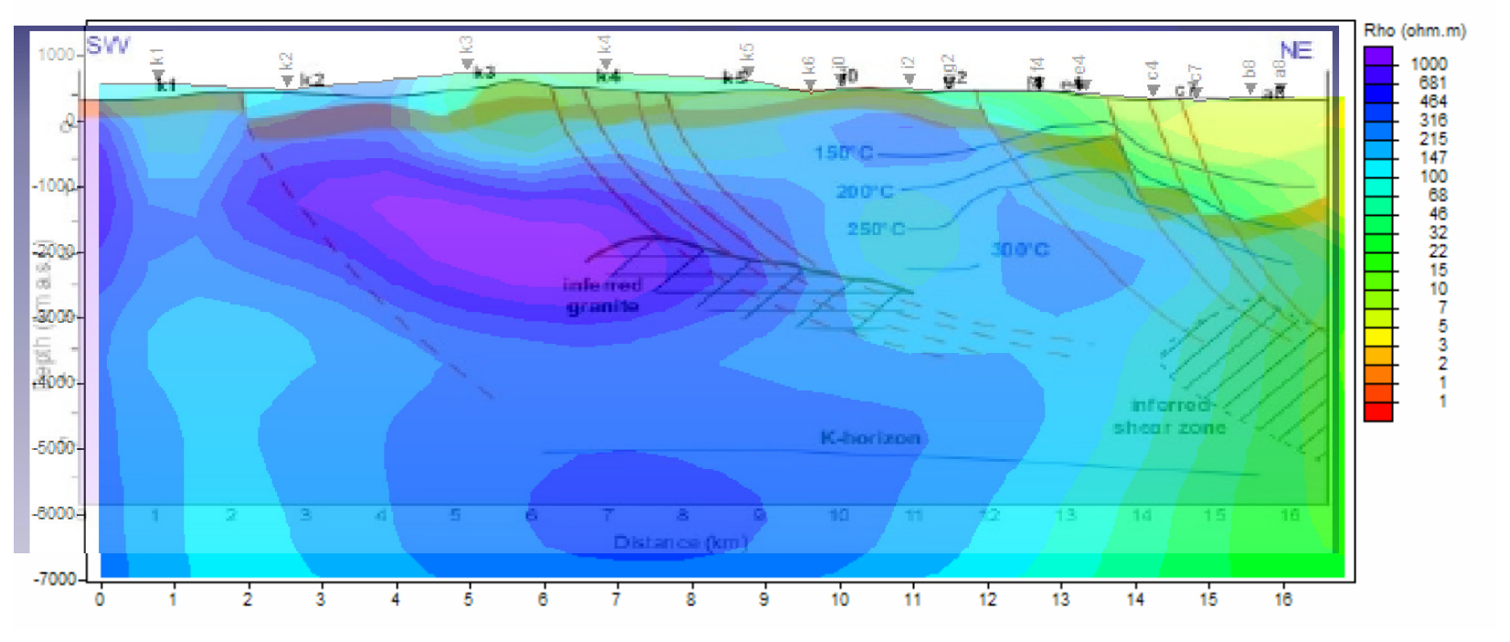
Disagreements:
1) The geological section beneath k1, k2, k3, in the western part of the profile, shows an homogeneous earth, while the S-P model images a conductive anomaly extending horizontally between 1-2 km depth. In the same area the TE-TM model shows a resistive anomaly.
2) A major fault inferred between k1 and k2 is not present in the S-P model, but it is in the TE-TM model
3) The S-P model shows a deep vertical conductive feature going up beneath k3, k4, which is no present in the TE-TM model (or may be is shifted westward to appear beneath k2?).

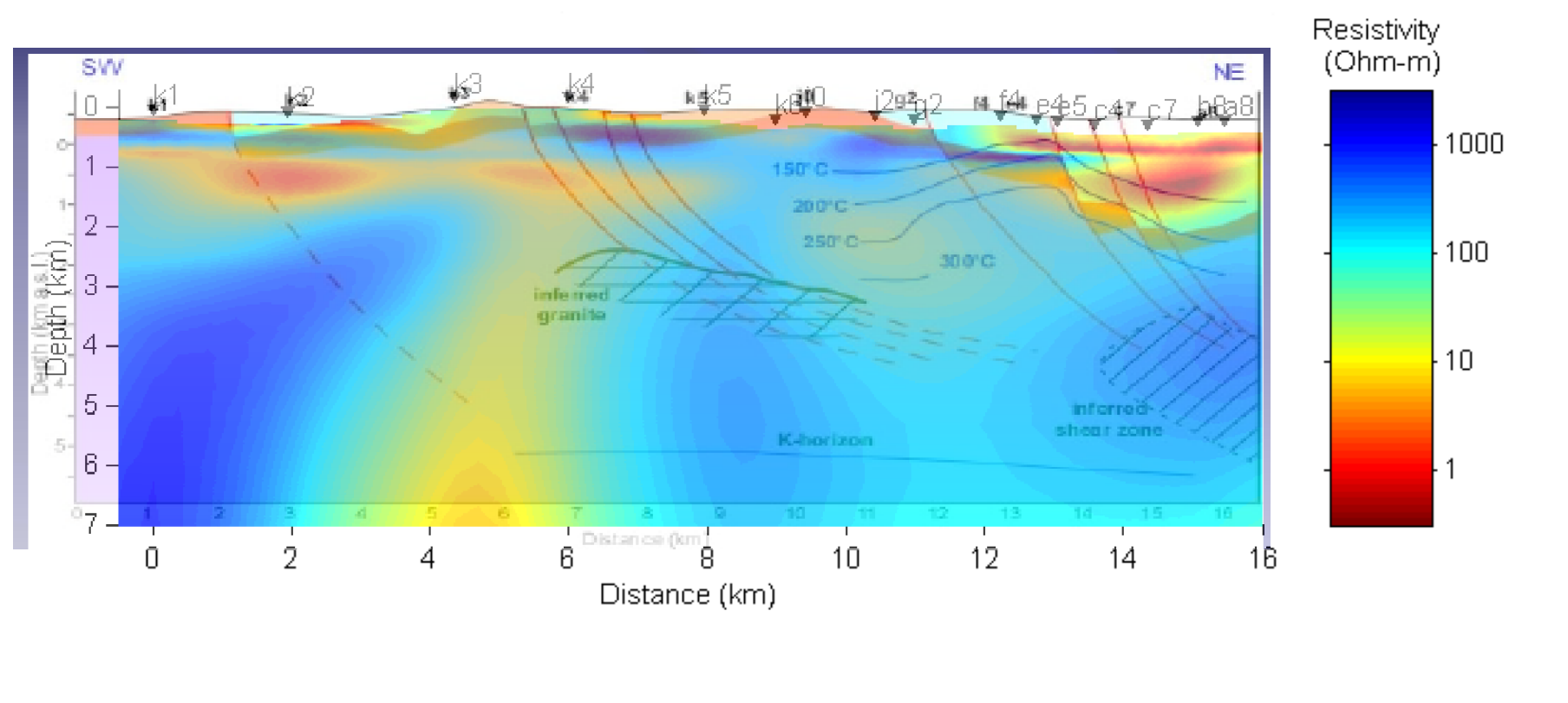
Other facts:
1) the disagreements are located in the western side of the profile, where data (k1, k2 and k3) are more spaced and with inconsistencies at long periods.
2) The deep conductive anomaly going upwards from 7 km depth, and bordering the western flank of the granite uplift, looks very suggestive of a major fluid filled zone. Is this a spurious result of the k2 k3 data inconsistencies at long periods? We need to do a sensitivity test (a future task).











References

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