Magnetotelluric Imaging of Sete Cidades Volcano, São Miguel Island, Azores.

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Abstract

Along a N20E striking profile at Sete Cidades Volcano we recorded broadband magnetotelluric data at 4 sites in the period range 8s – 30000s.

Robust processing and decomposition analysis followed by 2D inversion were applied to the dataset in order to unveil Sete Cidades Volcano structure. A high condutive zone was found at depth within the main crater.

Introduction

Sete Cidades is an active central volcano located on the western part of São Miguel island, Azores archipelago (Fig. 1). This volcano has approximately circular summit caldera with approximately 6000 km diameter. Inside the main caldera pumice cones, maars and domes can be observed. The dominant structure on the outer slopes are scoria cones and domes.

The first caldera-forming event took place approximately 36000 years ago, followed by two collapes phases at 29000 and 16000 years ago (Queiroz and Gaspar, 1998). Around 5000 years ago, the intracaldera activity changed from a magmatic to a hydromagmatic dominant character. Since then, at least 17 intracaldera eruption has been identified, making the Sete Cidades volcanos one of the most active central volcano known in the region. Associated to this volcanic system there is, at least, one geothermal reservoir (Forjaz *et al.*, 1993).

The Azores archipelago is located within the framework of the triple junction between European, African and North-American plates (Figure 1). The Mid-Atlantic Ridge (MAR), the East Azores Fracture Zone (EAFZ) and the Terceira Rift are the main important fault system in this area. The present knowledge of the evolution of the Azores is mainly constrained by focal mechanism of earthquakes. They show essentially a combination of WNW-ESSE normal faulting, with a E-W right lateral strike slip fault system (McKenzie, 1972; Buforn et al. 1988). This regional tectonic regime influence the main fracture systems that can be identified at the Sete Cidades volcano. The Mosteiro Graben, a pronounced NW-SE tectonic structure on the northewestern flank of the caldera, is interpreted to be a sub-aerial segment of the Terceira Rift (Queiroz and Gaspar, 1998). The positioning of several scoria cones within the caldera is cleared controled by the Mosteiro Graben. At the western part of the volcano, the E-W aligment of domes is considered to be a superficial expression of a deep oceanic fractures.

The magnetotelluric investigation shown here is within the scope of a Brazilian-Portuguese research program to study the Sete Cidades Volcano and the crustal structure of the Azores Triple junction. One of the main goals of this project is the detection of electrical anomalies which could be linked directly to volcanic activity in one of the three main volcanos in São Miguel Island (i.e. hydrothermal fluids or the hot melt).

In this paper we discuss the results from a profile extracted from a MT/GDS broadband survey done at Sete Cidades Volcano, São Miguel Island. The refered profile, striking N20E, crosses the main crater (Fig. 2). We give the interpretation of 2D inversion realized at both polarization modes sounding and discuss the significance of the shallow conductivity anomaly found in the area.

Data Acquisition and Processing

A comercial single station long period MT system (LIMS 5.0, Phoenix) was used in this study to record the five components of the eletromagnetic fields (Ex, Ey, Hx, Hy and Hz). The telluric fields were recorded in cross-configuration with 100 m dipoles, while the magnetic data were measured with one induction coil that recorded simultaneously the horizontals and the vertical components. At all sites the measurements were aligned to the magnetic North. Due to our two main goals at the joint project we employed two diferent strategies for data acquisition: Site 07, situated at a small secondary crater inside the main caldera was acquired with a sampling rate of 1 s and recording time of 7 days. The other sites were recorded with a sampling rate of 4 Hz and recording time of at least 24 hours. This strategy allowed us to have a broadband datset ranging from 8 to 30000 s.

The MT tensor elements and geomagnetic (GDS) transfer functions were estimated using the robust code of Jones-Joedick (1984). Most of sites were disturbed by noise, specially the telluric fields. São Miguel island is the most populated area of Azores archipelago, most part of the population lives in small villages within and around the crater, all of which have electricity. Prior to the robust estimation the time series were analyzed to cut off bad data segments, that generally ocurred at both ends of the registers. Figure 3 shows apparent resistivity, phase curves and induction arrows for site number four of profile P1 as an example of data quality.

Strike Determination and Distortion Analysis

The use of conventional Swift's method (Swift, 1967) has shown that the strike angle is fairly well determined for the whole frequence range at the four studied sites, with an average value of N35E. The tipper strike is also well determined with an average value of N30E. It is interesting to note that these values are nearly frequence-independent. This result is quite surprisingly as a vulcano is essentialy a 3D structure. Therefore, we should not expect to have a preferencial strike arising from the dataset. The geoelectrical strikes found are orthogonal to the strike of Mosteiro Graben fault zone. Due to the inherent 90o ambiguity in strike estimation, that could be an indication that this 2D regional structure is influentiating our long period dataset.

To investigate further the data dimensionality and determine the regional strike, Groom-Bailey decomposition (Groom & Bailey, 1989) was applied to each site. This decomposition scheme assumes that the regional response is 2D and the electric field has been distorted by a local 3D structure. The analysis of the regional impedance and the local distortion parameters (twist and shear) was done at the whole period range. The authenticity of the proposed model was tested with a chi-square test (Chave & Thomson, 1989). The obtained regional geoelectric strike, N60W, was selected as the one producing the smallest frequence-independent misfit in relation to the distortion model. The twist and shear values were fixed to a constant values at which they displayed a near independent behaviour. The fixed values of strike, twist and shear were employed to recover the regional impedances.

Induction arrows are particularly useful to unveil lateral conductivity contrasts (Ritter et al. 1998) and may be useful to constrain strike estimation. In the Parkinson convention (Hobbs, 1992), as ploted in Figure 3, the real vectors points towards the conductive bodie or a nearby conductivity contrast. In our case the real induction vectors are very large and point toward the coastline at all studied sites, indicating that the conductive ocean surrounding São Miguel Island has considerable effect on the GDS data at the studied period range.

2D Inversion and Interpretation

Based on the distortion analysis discussed before, the subsurface appears to have a great 2D contribution; therefore 2D inversion was attemped. The position of the sites were projected onto a profile oriented N20E before inversion. This direction is approximatelly orthogonal to the Mosteiro Graben. 1D models were used as the initial guess model.

We used the RRI code Smith and Booker (1991) to invert both principal impedances simultaneously . All four sites were inverted for 21 periods in the 8 –1000 s interval.

It is well known that a multiplicative static shift factor g still remains unknown after tensor decomposition, here we have chosen to estimate g as part of the inversion process using RRI, to minimize that problem we initially performed the inversion adjusting only the phases.

The final model is shown in Figure 4, that section is limited to 10 km depth because our main interest in this study is to understand the volcano system. The whole section is characterized by low to medium resistivities. A strong conductor with depths ranging from 1.6 to 2.8 km is evidenced beneath site 07. That may indicate the existence of a hydrotermal reservoir at the central-northern portion of the main caldera. Our interpretation is in accordance with the surface geological knowledge, site 07 is located over a known geothermal zone (Fig. 2) bounded by Mosteiro Graben; and several hot springs are known in the studied area.

Our results are quite similar to a previous geophysical survey done at Água de Pau Volcano (Andrade et al. 1995), another hydrothermal zone located 30 km east of the present survey.

Conclusions

High quality MT data was collected along a profile crossing Sete Cidades Volcano, São Miguel Island, Azores. Data was processed with a robust scheme to obtain the impedance and tipper tensors.

2D RRI inversion was applied to estimate the volcano structure at depth. A high condutive zone was identified between 1.6 and 2.8 km depth. A magma chamber beneath Sete Cidades volcano may be associated to the hydrothermal reservoir identified at depth.

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References

Andrade, A.; Santos, F.A.M.; Forjaz, V.H.; Mendes Victor 1995. Gravity and resistivity surveys in hydrothermal modelling (S. Miguel-Azores). Proceedings of the World Geothermal Congress, Florence, Italy, 1179-1184.

Buforn, E., Udias, A. and Bolt, B.A. 1988. Seismicity, source mechanisms and tectonics of the Azores-Gilbratar plate boundary. Tectonophysics, 152, 89-118.

Forjaz, V.H.; Serralheiro, A.; Carvalho, M.R.; Cunha, D. 1993. Carta de recursos hidrogeológicos e geotérmicos – Ilha de São Miguel, Açores. Escala 1:75.000. Universidade dos Açores.

Groom, R.W.; Bailey, R. 1989. Decomposition of the magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. *J. Geophys. Res.,* **94**, 1913-1925.

Hobbs, B.A. 1992. Terminology and symbols for use in studies of electromagnetic induction in the Earth. Survey in Geophysics, 13, 489-513.

Jones, A.G.; Jödicke, H. 1984. Magnetotelluric transfer function estimation improvement by a coherence-based rejection technique. Contributed paper at 54th Ann. Int. Met., Soc. Explor. Geophys., Atlanta, GA, Dec 2-6, Expanded abstracts, 51-55.

Lourenço, N.; Miranda, J.M.; Luis, J.F.; Ribeiro, A.; Mendes Victor, Madeira, J.; Needham, H.D. 1998. Morpho-tectonic analysis of the Azores volcanic plateu from a new bathymetric compilation of the area. *Marine Geophys. Res*, **20**, 141-156.

McKenzie, D.P. 1972. Active tectonics of the Mediterranean region. Geophys. J.R. Astron. Soc., 30, 109-185.

Queiroz, G. and Gaspar, J.L. 1998. The geology of Sete Cidades volcano, S. Miguel island, Azores. EC Advanced Study Course, volcanism hazard assesment, monitoring and risk mitigation. Ponta Delgada, São Miguel. p. 46.

Ritter, O.; Hoffmann-Rothe, A.; Müller, A.; Dwipa, S.; Arsadi, E.M.; Mahfi, A.; Nurnusanto, I.; Byrdina, S.; Echtarnacht, F.; Haak, V. 1998. A magnetotelluric profile across central java, Indonesia. Geophys. Res. Letters, 25, 4265-428.

Smith, J.T.; Booker, J.R., 1991. Rapid inversion of two and three-dimensional magnetotelluric data. J. Geophys. Res. 96, 3905-3922.

Trota, A.N. 1998. Main alignments in São Miguel island obtained from aerial photo-interpretation. EC Advanced Study Course, volcanism hazard assesment, monitoring and risk mitigation. Ponta Delgada, São Miguel. p. 91.

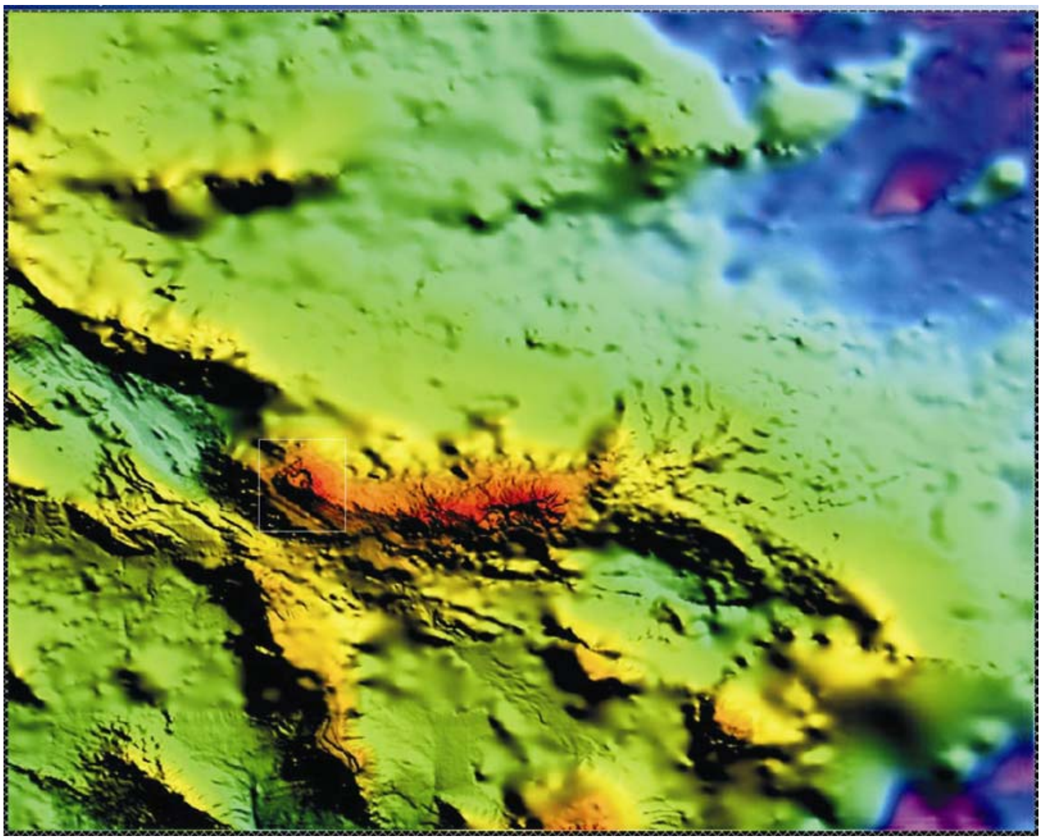

Figure 1 – Topography of São Miguel Island and batimetry of adjacent oceanic area. The white square indicate Sete Cidades Volcano position. Two main regional structure directions are evidenced: NW-SE and E-W.

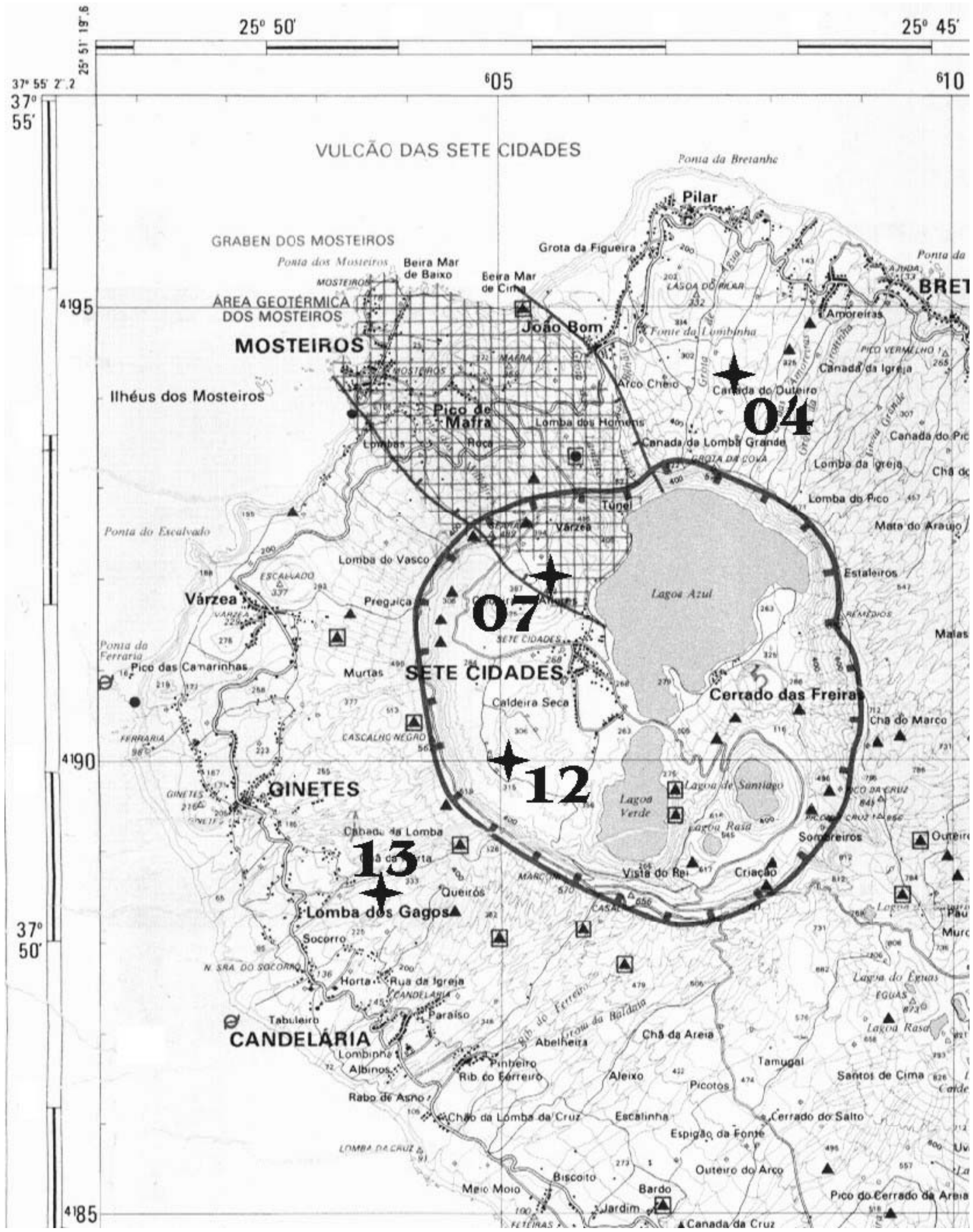

Figure 2 – MT sites colected along a N20E profile crossing Sete Cidades main caldera

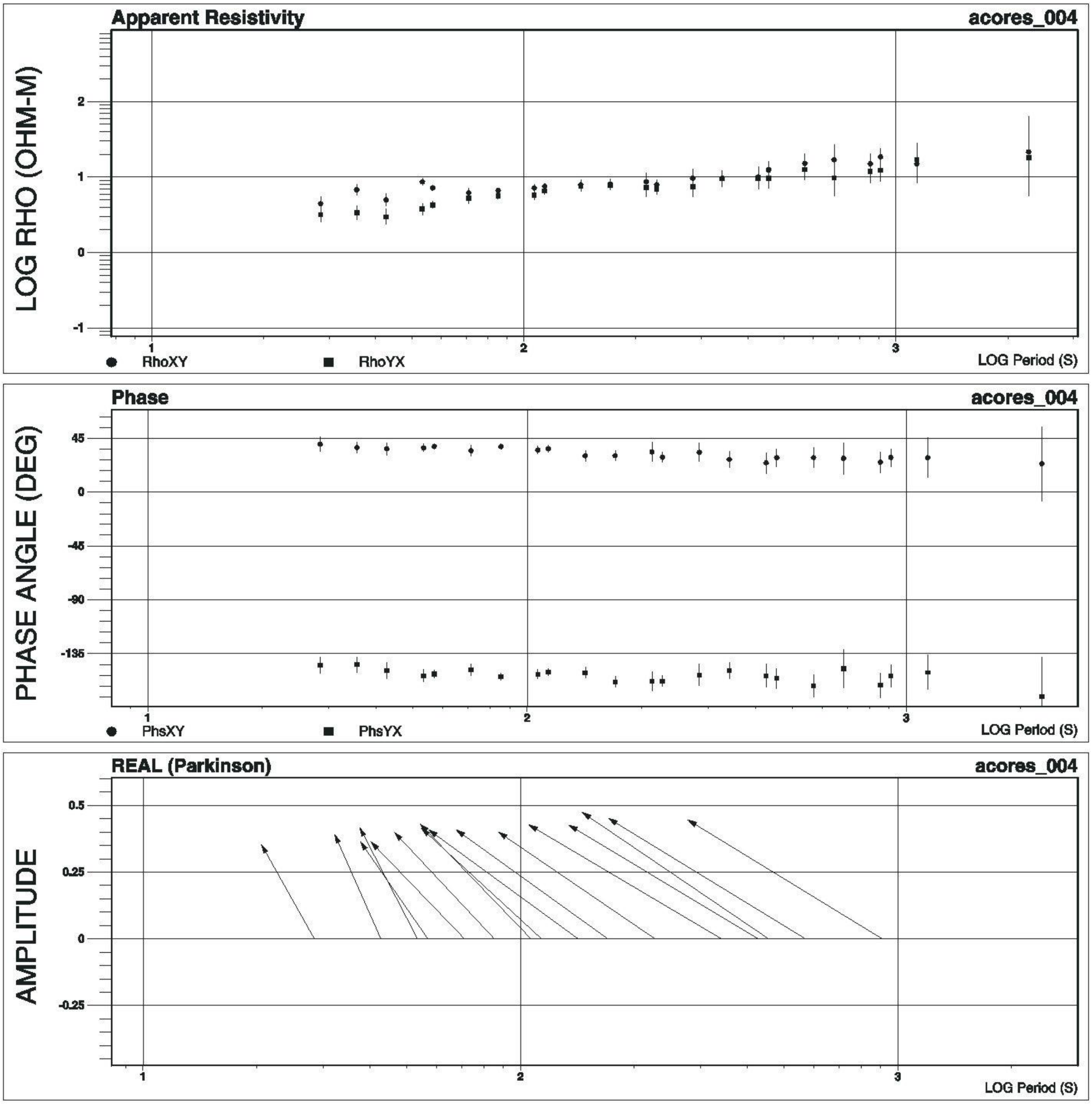

Figure 3 – MT parameters of Site 04, apparent resistivity, phase and induction angle with parkinson notation, arrows points towards the conductor.

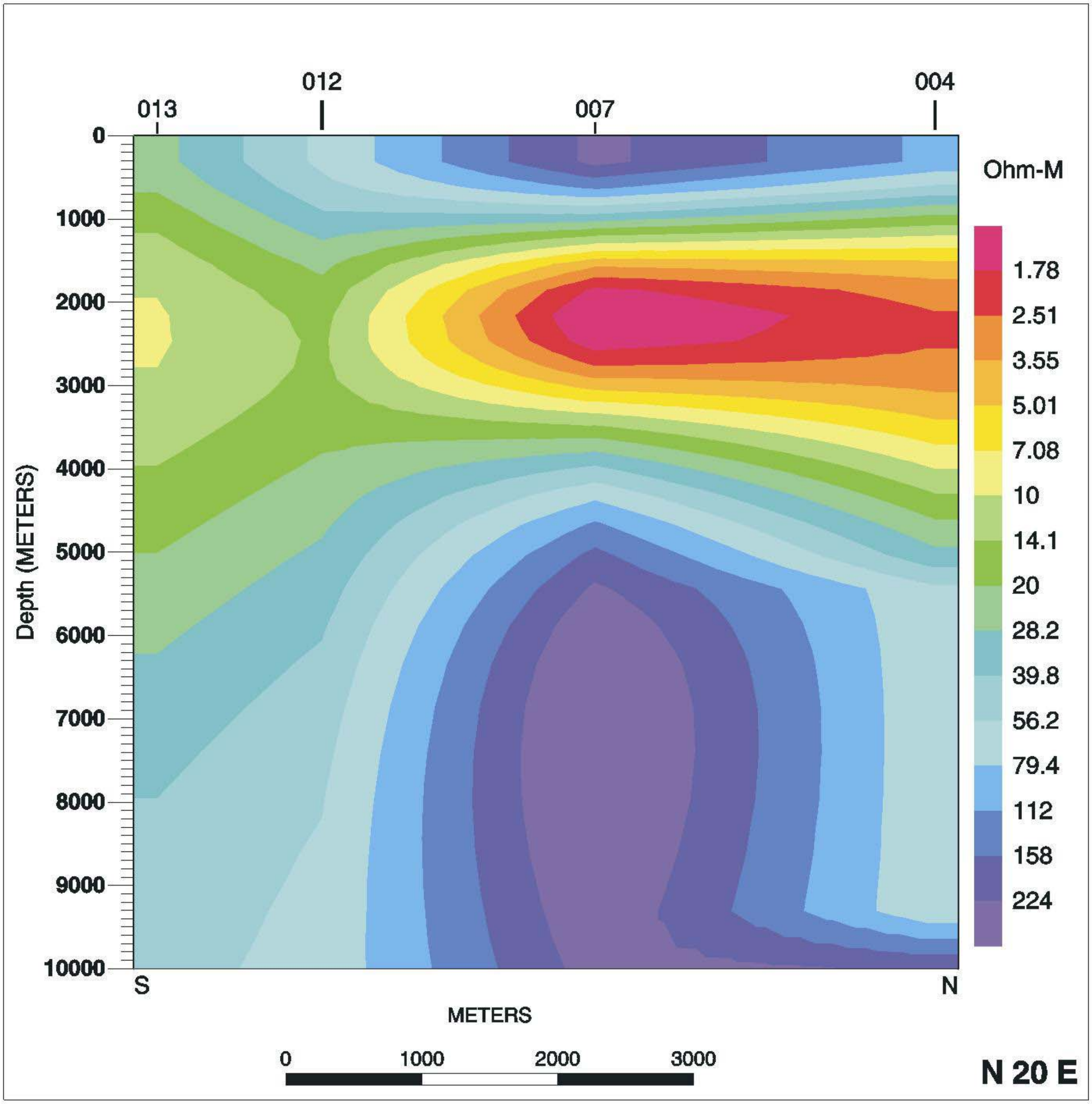

Figure 4 – RRI 2D final inverted model, note the shallow (1.6 – 2.8 km depth) high condutivity zone bellow site 07.