Proceedings of the Pakistan Academy of Sciences:
A. Physical and Computational Sciences 54 (3): 311–317 (2017)

ISSN: 2518-4245 (print), 2518-4253 (online)

Pakistan Academy of Sciences

Research Article

Magnetotelluric Data Analysis using Swift Skew, Bahr Skew, Polar Diagram, and Phase Tensor: a Case Study in Yellowstone, US

Erick Pranata[1*], Selvi Misnia Irawati[1], and Sintia Windhi Niasari[2]

[1]Geophysics Study Program, Universitas Gadjah Mada, Sekip Utara BLS 21, Yogyakarta 55281, Indonesia
[2]Geophysics Laboratory, Universitas Gadjah Mada , Sekip Utara BLS 21, Yogyakarta 55281, Indonesia

Abstract: Magnetotelluric (MT) method is a passive electromagnetic (EM) technique for measuring fluctuations of the nature electric (E) and magnetic (B) fields at the Earth surface, which correspond to apparent resistivity. Prior to MT data modeling, to convert apparent resistivity to true resistivity, analyzing the dimensionality of MT data is needed. In this study, the MT data were taken from US Array in Cascadia Subduction Zone, particularly around the Yellowstone National Park, US. The MT data analysis used four parameters, *i.e.*, Swift skew, Bahr skew, polar diagram, and phase tensor. Additionally, 1D modeling for XY and YX components was performed. Thus, correlations between the model and the dimensionality data in the study areas were revealed. Data analysis from Swift skew parameter indicated the 3D character of MT data (*i.e.*, Swift skew value more than 0.3). The majority of the polar diagrams were peanut shaped, and a lot of phase tensors had an ellipse shape with large β value, indicating 3D character. Although 3D inversion modeling for these data was more proper (because the data exhibited 3D character) than 1D inversion, the 3D inversion algorithm was computationally expensive. Thus, in this study, we performed 1D inversion MT modeling which revealed that in some cases, 1D and 3D inversion results exhibited similarities.

Keywords: Bahr skew, dimensionality, magnetotellurics, phase tensor, polar diagram, swift skew

1. INTRODUCTION

Activity in MT method divided onto five stages, *i.e*., data acquisition, data processing, data analysis, modeling, and interpretation. In this study, stage three was emphasized because data analysis affects the modeling result. The model of MT can be ambiguous if the dimensionality data are different from the dimensionality model. Thus, MT data analysis can reduce the ambiguity model. In this study, 11 MT data sites at Yellowstone area were used. These are located in Idaho State and Wyoming State, North America. In the west of North America, there is a subducting plate named Juan de Fuca, which is a part of Pacific microplate and is considered as one of the smallest plates on earth. It moves toward North America plate and subducts below that plate. In their research, Xue and Allen [1] mapped the Juan de Fuca plate with seismic. It shows that Juan de Fuca plate disappears at 400 km to the east from the western coast. The plate discontinues when it reaches Yellowstone area.

The four components in 1D modeling have a different result when it begins to model the 3D data area. If they have the same trend of response, these components are valid and can be interpreted. But if each of them has different trend of responses, only some of them are valid and can be interpreted or none of them is valid.

From the 3D model [2], YX components is the most similar response from three other components at (12 to 14) km and (31 to 37) km depth. However, YX component does not have as much similarity to other components than XY components. YX component is used as a reference due to the similarity with 3D modeling.

Received, April 2017; Accepted, September 2017
*Corresponding author: Erick Pranata; Email: pranata_erick@yahoo.co.id

2. METHODS

Eleven MT data sites at Yellowstone area were used. These are located in Idaho State and Wyoming State, North America (Fig.1). MT data have impedance parameter [3] consisting of several components that represent the dimensionality. In this study, Swift skew, Bahr skew, and polar diagram were used to determine the dimensionality of MT data. Moreover, we use phase tensor to determine the geoelectrical strike.

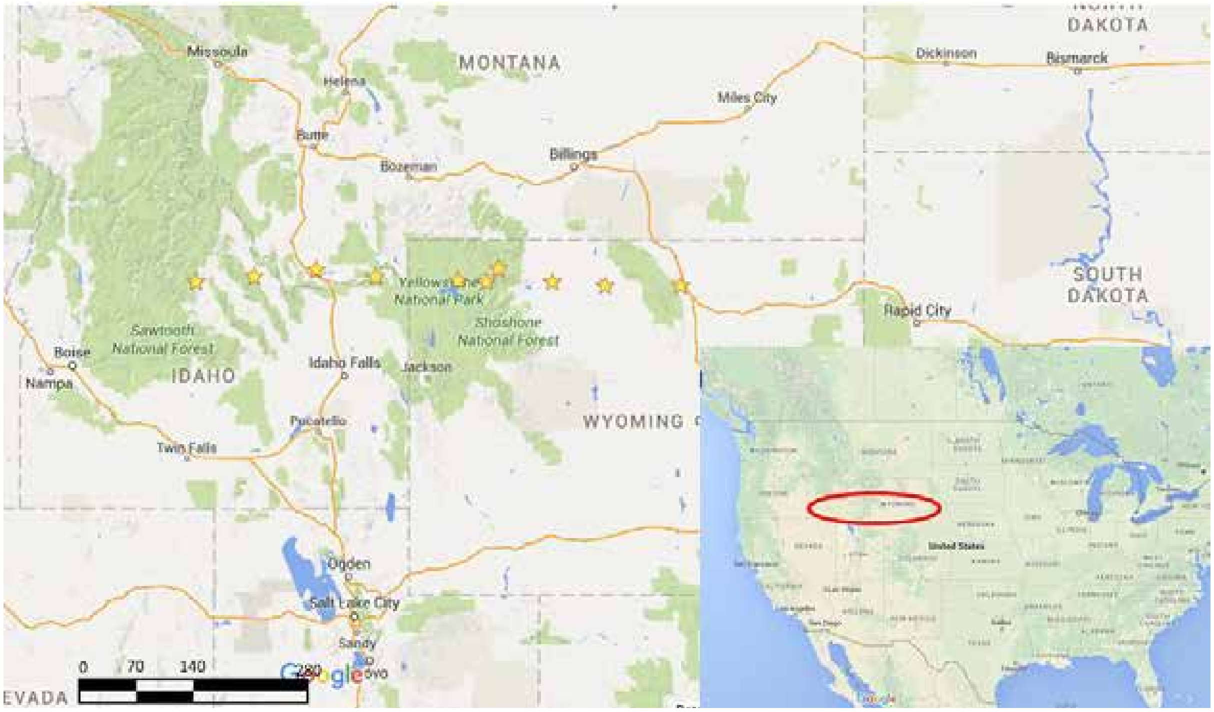


Fig. 1. Yellow stars denote MT sites. Four MT sites are located in Idaho state and six others are in Wyoming state. The space between locations is about 70 km. Inset: The study area location is marked by red ellipse.

Skew is one of dimensionality data MT analysis [4]. Swift skew is a ratio of diagonal components (Z_{xx} and Z_{yy}) to the off-diagonal components (Z_{xy} and Z_{yx}) [5]. If the value of $Skew_{Swift}$ > 0.3, it has 3D character. If $Skew_{Swift}$ < 0.3, the data has 1D or 2D character [6].

$$Skew_{Swift} = \left|\frac{Z_{xx} + Z_{yy}}{Z_{xy} - Z_{yx}}\right| \tag{1}$$

Bahr skew is known as phase-sensitive or regional skew [7]. If $Skew_{Bahr}$ < 0.1, it indicates 1D or 2D character. If 0.1 > $Skew_{Bahr}$> 0.3, indicates 2D or 3D character of MT data. If $Skew_{Bahrr}$ > 0.3, it indicates 3D character of MT data.

$$Skew_{Bahr} = \frac{\sqrt{|Im(Z_{xy}Z_{yy}^{*}+Z_{xx}Z_{yx}^{*})|}}{|Z_{xy}-Z_{yx}|} \tag{2}$$

Polar diagram is one of dimensionality data MT analysis that has not structural or frequency limitations [7]. If polar diagram drawn as a circle, it shows 1D character. The polar diagram ellipse-shape indicates 2D character while the peanut-shape represent a 3D character.

$$|Z_{xy}(\gamma)| = \left|Z_{yx}\left(\gamma + \frac{\pi}{2}\right)\right| = |Z_1 + Z_3 \cos 2\gamma - Z_4 \sin 2\gamma| \tag{3}$$

Phase tensor is a ratio of real and imaginary part of impedance tensor [8]. If the phase tensor is acircle and small β, the conductivity structure is 1D [9]. If phase tensor is drawn as an ellipse with small β, it has 2D character. If the phase tensor is drawn as an ellipse with large β value, it belongs to the 3D characteristic of MT data.

$$\boldsymbol{\phi} = \boldsymbol{X}^{-1}\boldsymbol{Y} \qquad \text{and} \qquad \beta = \frac{1}{2}tan^{-1}\left(\frac{\phi_{xy}-\phi_{yx}}{\phi_{xx}+\phi_{yy}}\right) \tag{4}$$

The 3D data in straight line in North America are processed with 1D software. The 1D Software uses the Bostick algorithm which in turn uses resistivity in a period function to get resistivity in depth function [10]. Ten magnetotellurics location is used for this research. The locations were in North America in Idaho state and Wyoming state. The distance between one data location to another was about 70 km. There are only six from the east are inside the Yellowstone area.

The data chosen visualize the geology of Yellowstone in resistivity. With four data outside the Yellowstone area and six inside, it will visualize the area that is affected by Yellowstone. The purpose of using ip2win is because everyone does not have the 3D processing software. From each magnetotelluric component, a resistivity model will be obtained. Not all components are reliable because it is in 1D. By using the ID software, this paper reveals the advantages and disadvantages of using lD software for 3D data.

The modeling process with ip2win is to make the model as close as possible to the data. The quality control is the RMS value. To decide how many layers, depends on how many gradients the data have. If only one gradient then the layer should be two (1 gradient +1). If two gradient then there must be three layers.

3. RESULTS AND DISCUSSION

Based on MT data analysis using four parameters, i.e. Swift skew, Bahr skew, polar diagram, and phase tensor, we can determine the dimensionality of the data. In this discussion, we explain the dimensionality of MT data for each parameter.

Swift skew is simply calculation from impedance tensor. Due to the calculation, most of the data have Swift skew value more than 0.3 (blue dots on Fig. 2) which indicates 3D character of MT data.

Bahr skew is modern skew calculation using impedance tensor. From the calculation, MT data dominated with the Bahr skew value 0.1 to 0.3 (orange dots on Fig. 2). That value indicates 2D or 3D character of MT data.

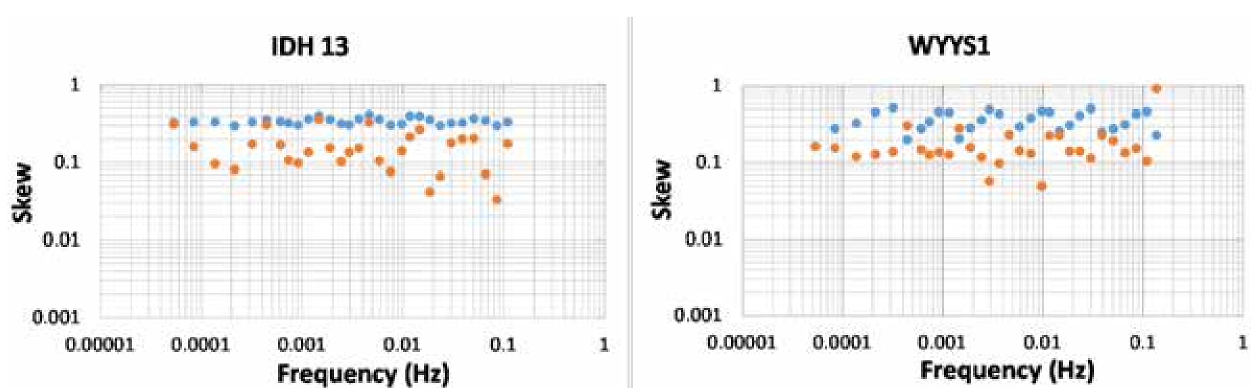


Fig. 2. Swift skew (denoted by blue dots) and Bahr skew (denoted by orange dots). a) IDH13 b) WYYS1 Swift skew dominated with value > 0.3 that indicated 3D data MT. Bahr skew had values 0.1 to 0.3, indicating 2D or 3D data.

Due to skew analysis (Swift and Bahr), this MT data has two possible dimensionality, 2D or 3D. Therefore, further data analysis using polar diagram and phase tensor parameters is needed to obtain more accurate dimensionality of MT data.

Polar diagram can determine the dimensionality of MT data. For resistive materials, major axis of the polar diagram is perpendicular to the strike direction. Meanwhile, on conductive medium, major axis of the polar diagram is parallel to the strike [7].

Polar diagram was drawn in Fig 3. Polar diagram dominated by peanut shape. That shape indicates 3D MT data. However, at sites IDH13, WYH19, and WYH20 have ellipse polar diagram which indicates 2D MT data. It happens at high frequency (> 0.066 4 Hz).

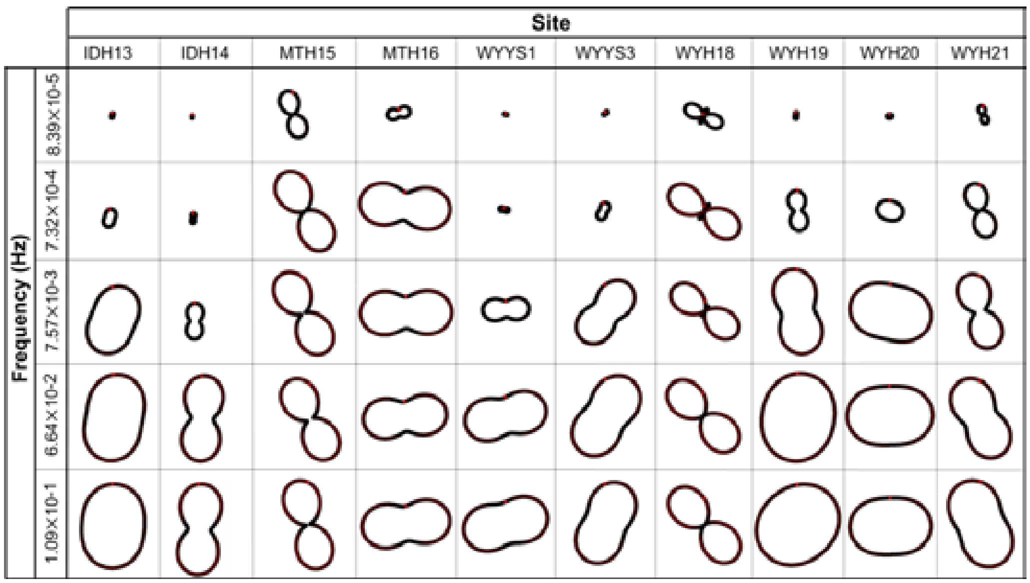


Fig. 3. Polar diagram of MT data. It was dominated by peanut shape which indicated 3D MT data. Therefore, 3D modeling inversion were proper to these data.

Based on geological condition, these sites are in different lithology margin. Thus, it affects the dimensionality of MT data. Therefore, polar diagram shape from high frequency and low frequency of these sites had different dimensionalities.

Phase tensor is one of data analysis parameter [7]. Phase tensor can be illustrated as circle or ellipse [8]. Major axis of phase tensor represents the geoelectrical strike [11]. Phase tensor shape for certain periods described the lateral conductivity structure changes. This changes showed different ellipticity phase tensor for each period (Fig 4).

In this data, phase tensor is dominated by the ellipse shape. Furthermore, β values of the phase tensor are high ($\beta > 3^{\circ}$ and $\beta < -3^{\circ}$). This indicates 3D MT data.

From the data analysis using four parameters (Swift skew, Bahr skew, polar diagram, and phase tensor), MT data in Yellowstone area reveal 3D character. Thus, if the data are 3D then 1D modeling is improper. Furthermore, MT data are important to get lower ambiguity model due to incorrect data characterization.

From this 3D layer model (Fig. 5), the majority of the data have high resistivity. In a deeper zone (284 – 341) km, the data has lower resistivity than the higher. The 3D data represent all four components merging together. The deeper zone can be interpreted as earth mantle that has lower resistivity than earth crust.

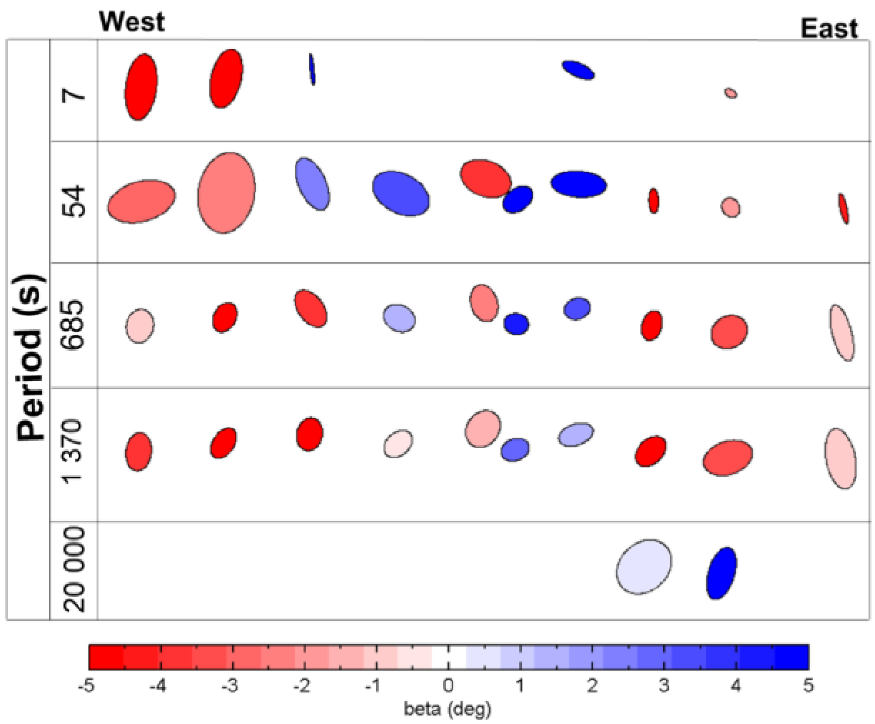


Fig. 4. Phase tensor for each period. It was drawn as an ellipse and has high β value, *i.e.*, > 3° and < -3°. That indicated the 3D MT data. Therefore, 3D modeling was proper to these data.

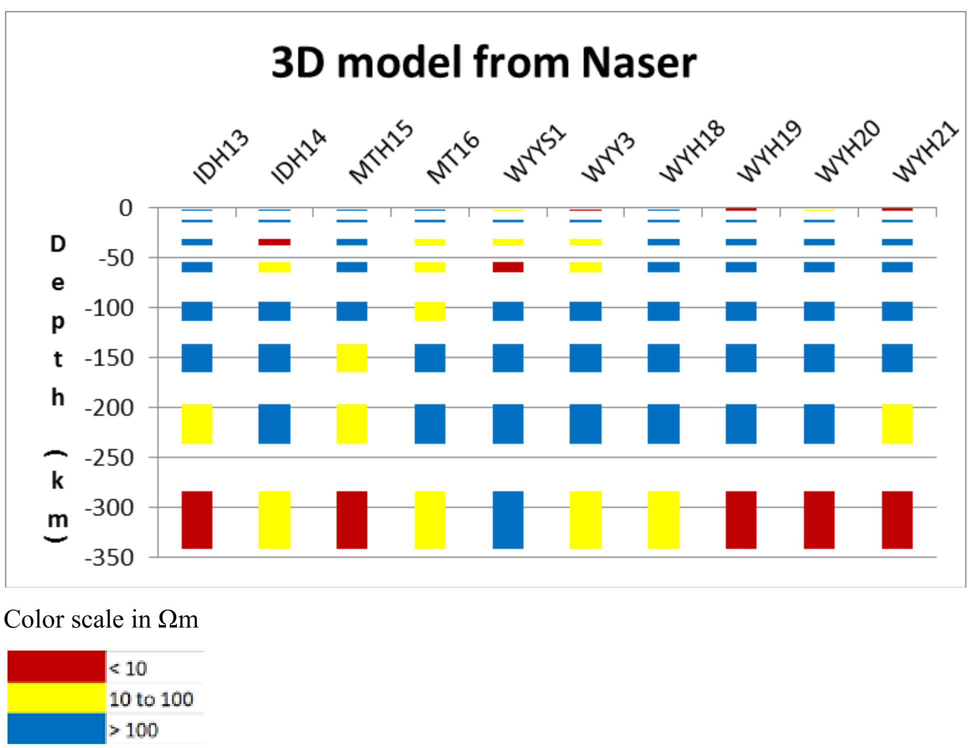
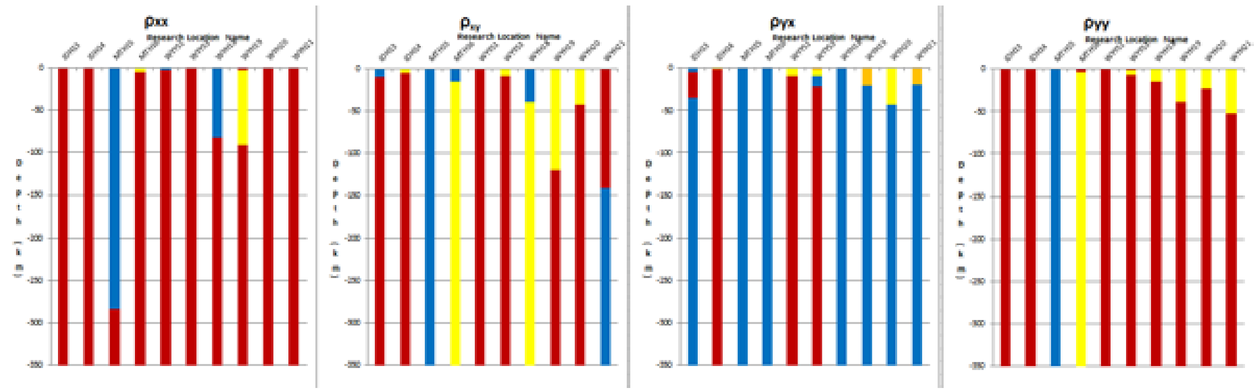


Fig. 5. Reconstruction of 3D model, reconstructed from Meqbel et al. layered model [2]. Depth 1.1 to 1.5 km, 12 to 14 km, 31 to 37 km, 54 to 65 km, 94 to 113 km, 136 to 164 km, 197 to 236 km, and 284 to 341 km. Majority of the data had high resistivity value.



Color scale in Ωm

Fig. 6. 1D ρ apparent modeling at research location; from west to east, depth in km. From left to right: IDH13, IDH14, MTH15, MTH16, WYS1, WYYS3, WYH18, WYH19, WYH20, and WYH21. a) ρxx; b) ρxy; c)ρyx d)ρyy each component has 350 km depth. YX component was used as reference to resemble other components.

From Fig. 6, YX component had the most resemblance with 3D model than three other components; the resemblance was 38 out of 80 (about 47.5 %). The RMS error from XX component is 10.577 %, XY component is 6.072 %, YX component is 5.176 %, and YY component is 10.158 %. From the RMS error, YX model is the most similar to its data. From both RMS and manual resemblance, the most relevant model synchronizing with 3D model is the YX component. In this area, YX component has the most similarity with the 3D data. It can be used as a standard to model 3D data with 1D software in Yellowstone.

With YX as a reference, it has 29.52 % of resemblance with another component. The similarity result is obtained by matching the resistivity from each component subjectively. The total similarity is 62 out of 210 (about 29.52 %). In this area, YX component is used as a reference although XY component has more similarity with other component is because YX component is most similar to the 3D model.

4. CONCLUSIONS

In the Yellowstone area of USA which has majority 3D data proved with the skew, polar diagrams and phase tensor can be modeled with 1D software. The 1D component that is the most representable is YX component; however, the similarity between 1D inversion of YX component and 3D inversion is 47.5 %. The YX component has 29.52 % similarity with other three components but the XY component has 37.61 % similarity. The YX is picked due to the most relevance with the 3D model.

5. ACKNOWLEDGEMENTS

Special thanks to A. Schultz, G.D. Egbert, A., T. Peery, V. Clote, B. Fry, S. Erofeeva and staff of the National Geoelectromagnetic Facility. The authors thank Universitas Gadjah Mada for funding this research. The authors also thank Atria, Rakhmat, Adytya, Halim, Afta, Rachmat, and Dina for their help and support by way of reviews, suggestions and comments.

6. REFERENCES

1. Xue, M. & R.M. Allen. The fate of the Juan de Fuca plate: Implications for a Yellowstone plume head. *Earth and Planetary Science Letters* 264: 266–276 (2007).
2. Meqbel, N.M., G.D. Egbert, P.E. Wannamaker, A. Kelbert & A. Schultz. Deep electrical resistivity structure of the northwestern U.S. derived from 3-D inversion of US Array magnetotelluric data. *Earth and Planetary Science Letters* 402: 290–304 (2014).
3. Jiracek, G.R. *The Magnetotelluric Method*. San Diego State University, San Diego, CA, USA, p. 11–12 (2004).

4. Vozoff, K. Magnetotellurics: Principles and practice. *Earth and Planet Science* 99: 441–471 (1990).
5. Swift, C.M.A. *Magnetotelluric Investigation of an Electrical Conductivity Anomaly in the Southwestern United States*. [PhD thesis, Massachusetts Institute of Technology, MA, USA (1967).
6. Hoffmann-Rothe, A., O. Ritter & C. Janssen. Correlation of electrical conductivity and structural damage at a major strike-slip fault in Northern Chile, *Journal of Geophysical Research* 109: B10101 (2004).
7. Berdichevsky, M.N. & V.I. Dmitriev. *Models and Methods of Magnetotellurics*. Springer, Berlin, Germany, p. 31–33 (2008).
8. Caldwell, T.G., H.M. Bibby & C. Brown. The magnetotelluric phase tensor. *Geophysical Journal International* 158: 457–469 (2004).
9. Booker, J.R. *The Magnetotelluric Phase Tensor*: *A Critical Review*. Springer, Berlin, p. 7–40 (2013).
10. Rodi, W. & R.L. Mackie, Nonlinear conjugate gradients algorithm for 20 magnetotelluric inversion. *Geophysics* 66: 174–187 (2001).
11. Hill, G.J. Distribution of melt beneath mount St Helens and mount Adams inferred from magnetotelluric data. *Nature Geoscience Letters* 2: 785–790 (2009).