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A workflow for cooperative inversion of seismic and magnetotelluric data

Eric Takam-Takougang
DET CRC, Curtin University
26 Dick Perry Avenue,
Kensington, 6151 WA
eric.takam@curtin.edu.au

Brett Harris
DET CRC, Curtin University
26 Dick Perry Avenue,
Kensington, 6151 WA
b.harris@curtin.edu.au

Anton Kepic
DET CRC, Curtin University
26 Dick Perry Avenue,
Kensington, 6151 WA
a.kepic@curtin.edu.au

SUMMARY

We present a cooperative inversion approach for acoustic impedance using seismic and magnetotelluric data. In this approach, the magnetotelluric data, sensitive to the resistivity of rocks are used to get the large scale background spatial trends of the acoustic impedance model, while the seismic data are used to get the small-scale features. The connections between resistivity and elastic properties of rocks are obtained from petrophysical relationships derived from borehole data. Structural constraints derived from seismic are used to improve the magnetotelluric inversion. We present an application of this technique to synthetic data derived from previous interpretation of seismic and magnetotelluric models in a mineral province. The synthetic example shows how an improved result is obtained using our cooperative inversion workflow.

Key words: Cooperative, Inversion, seismic, magnetotelluric, mineral

INTRODUCTION

The application of joint inversion techniques of various datasets are gaining in popularity (e.g. Gallardo and Meju, 2004; Colombo et al., 2008; Jing et al., 2011). The use of complementary datasets such as seismic and magnetotelluric has the potential to provide improved estimates of subsurface rock properties, and reduce exploration ricks, in complex areas such as basalt covered areas and subsalts, characterized by complex near surface high velocity and high resistivity variations. The propagation of seismic waves in such areas is effected by several problems such as scattering, multiples, mode conversion and attenuation, which make accurate estimates of velocity difficult. On the other hand, electromagnetic waves propagate easily through resistive bodies and provide complement rock properties information useful for improved imaging and interpretation.

Finding the appropriate link to connect different data types is a key step in join inversion algorithms (e.g. Meju et al., 2003; Gallardo and Meju, 2004; De Stefano et al., 2011). Currently, there are two main approaches to connect different data types: The petrophysical approach which uses relationships between various rock properties derived empirically or from core analysis (e.g. Meju et al., 2003; Colombo et al.,2008; Gomez et al., 2009; Gao et al., 2012), and the structural approach which is based on the assumption that both data types are sensing the same underlying geological structure (e.g. Gallardo and Meju, 2004; Colombo et al., 2008).
The simultaneous joint inversion of seismic and electromagnetic data (using a single algorithm) remains challenging due to the great difference in resolution and sensitivity, between different data types (Jing et al., 2011). The resolution of standard seismic reflection data is a few tens of meters whereas that of electromagnetic data can be several hundreds of meters, depending on frequency and depth. This difference in resolution and sensitivity tends to slow down the convergence of the inversion (Jing et al., 2011).

In this paper, we present an alternative inversion approach using seismic and magnetotelluric data (MT data). Rather than simultaneous inversion, we use a cooperative inversion scheme for acoustic impedance.

METHOD

In our cooperative inversion approach for recovery of acoustic impedance, we propose the use of magnetotelluric data to assist in establishing large-scale background trends in acoustic impedance, while seismic data provides small-scale features. Petrophysical relationship derived from borehole data are used to connect resistivity and elastic properties of rocks. In this technique the seismic and magnetotelluric data may be highly complementary for particular subsurface distributions of acoustic impedance and electrical conductivity (e.g. a highly conductive zone beneath shallow “fast” layers). An overview of the cooperative inversion workflow is provided below (Takam Takougang et al., 2014):

1. Recover a first pass conductivity distribution via inversion of magnetotelluric data.
2. Obtain a stacked seismic section that possesses true relative amplitudes. (every effort must be made to recover true relative amplitudes in the migrated seismic data)
3. Improve magnetotelluric inversion upon comparison with migrated section (i.e. adding structural constraints from migrated section into magnetotelluric inversion). This step may require many iteration as improvement of the magnetotelluric inversion by adding structural information from the seismic may not be straightforward. Great care must

be taken in using such constrains as the consequences of fixing a sharp boundary in the wrong location may be severe.

4. Estimate petrophysical constraints between velocity, density and resistivity from borehole data.
5. Convert the resistivity model from magnetolluric inversion into a background acoustic impedance model using the previously derived petrophysical relationships.
6. Use the derived acoustic impedance model as a starting model (background model) for high resolution acoustic impedance inversion using the migrated seismic data. Additional geological information from available well log can also be added at this stage.

The inversion for high resolution acoustic impedance values is conducted with an algorithm based on gradient-descent method. The source signature for the inversion is estimated using the seismic and well log data (sonic and density logs). The starting impedance model is iteratively updated to minimize the misfit between observed and computed seismic data. The misfit between field data and synthetic data is used to control the inversion. Ideally, the misfit amplitude values should be close to zero.

Petrophysical coupling

Petrophysical relationships are used to estimate acoustic impedance from the resistivity model derived from MT inversion. We use a density (d) & velocity (v_p) relationship similar to the Gardner's law which has the form:

$$d = a v_p^b , \tag{1}$$

where the coefficients a and b are to be estimated from cross-plotting the density and velocity values obtained from the well log. We also used a linear relationship between velocity (v_p) and resistivity (ρ) in the form:

$$\log(v_p) = c\log(\rho) + c \ , \tag{2}$$

where the coefficients c and d are derived after cross-plotting the velocity and the resistivity values obtained from available well logs.

Empirical relationship can also be used if well logs are not presents. The initial acoustic impedance model (*AI*) is then derived using the following equation:

$$AI = d.v_p \ . \tag{3}$$

Structural coupling

The cross-gradient can be used as a structural constraint for linking various dataset (e.g. Gallardo and Meju, 2004). This technique is based on the assumption that the various geophysical method sense the same underlying geological features. During the inversion, the models are updated only if the gradient of the velocity and conductivity are changing in the same direction, or if the gradient of one parameter is changing while the other parameter remains constant. This technique works well if there is a strong structural correlation between the direction of change of elastic properties and electrical resistivity. However, if such a constraint is applied in an inappropriate setting where elastic and electrical properties do not present a similar change in direction, the inversion may be directed away from the correct solution.

We introduce structural constraints in our cooperative inversion by updating the resistivity model obtained from the magnetotelluric inversion upon comparison with the migrated seismic data. Structural information such as horizons are added as constraints during the magnetotelluric inversion. This step of the cooperative inversion scheme is necessary to obtain a resistivity model consistent with seismic and to mitigate non-uniqueness of solutions.

SYNTHETIC EXAMPLE

We designed a synthetic test to assess the effectiveness of our cooperative inversion approach. First a model volume with velocity, density and conductivity distribution was created. Then we produced synthetic co-located seismic and MT survey dataset suitable for cooperative inversion. The model used in this test is based on previous interpretation of well log data; magnetotelluric data and seismic survey of the Getchell-Turquoise Ridge mining deposit (see Table 1 and Figure 1). The Getchell mining deposit is located on the northeastern flank of the Osgood Mountains, Nevada and is well known for hosting Carlin-type gold deposits. The host rocks for the Carlin-type gold deposits on the Getchell trend consist of Late Cambrian through Ordovician carbonates, silty carbonates, calcareous shales, and shales (Eck, 2010). The mineralization occurs as a series of discrete zones developed along the N-S trending Getchell Fault and with the NE trending Turquoise Ridge Fault. Gold deposits are found at depth along the Getchell Fault and in sedimentary units near the Getchell Fault.

Our goal in this test is to recover the true model (velocity or acoustic impedance model) after applying our cooperative inversion technique, with a focus on the mineralization lenses along and nearby the fault zone within the Carlin-style carbonate sequences.

#	Rock unit	Vp (m/s)	Resistivity (Ohm.m)
A	sediment	4400	100
B	sediment	4837	50
C	Mudstone	3966	8
D	Carbonaceous mudstone.	5489	500
E	carbonates	5273	300
F	Potential mineralised zone	3755	4

Table 1. Velocity and resistivity values for the 2D model. The density was calculated using the Gardner's law.

The synthetic seismic data were obtained using 2D acoustic modelling with 96 shots, 201 receivers per shot, a shot interval of 20 m and a receiver interval of 10 m. The source wavelet was a zero phase Ricker wavelet with a dominant frequency of 80 Hz. Kirchoff depth migration was then used to recover the reflectivity (Figure 1.7). The synthetic 2D magnetotelluric data were computed from forward modelling (Constable et al.,1987) using 49 stations with 40 m station interval and frequencies in the range 10000-40 Hz. Both TE (transverse electric) and TM (transverse magnetic) modes were used. The magnetotelluric inversion was then performed with a starting model consisting of a homogeneous half-space, with a constant resistivity of 50 Ohm.m.

The result of the inversion is displayed in Figure 1.4. This result shows that the major units (A, B, C, D) are reasonably well recover, however, the inversion has not been able to effectively separate unit C and the potential mineralized zone (F) at x=1200 m. To improve the result, we added a structural constraint within the magnetotelluric inversion. We picked the boundary between units B D and E (Figure 1.7) after superimposing the resistivity model on top of the seismic image. This new information was then added into the magnetotelluc inversion as a constraint. The result of the inversion is displayed in Figure 1.3. A significant improvement is observed in the overall result. The shape of unit F and its separation with unit C at x=1200 m has improved.

The obtained resistivity model was converted into acoustic impedance using a petrophysical relationship derived from a synthetic sonic and resistivity log located at x=100 m. The petrophysical relationship has the form:

$$\log(v_p) = 0.070928\log(\rho) + 3.5475 \qquad (4)$$

For simplicity, we assumed no density log and a constant density of d =2.7 g/cc×m/s was used to derive the acoustic impedance model (see equation 3). The derived acoustic impedance model became the stating model for model based seismic inversion (Russell, 1988; Russell and Hampson, 1991). The result of the inversion is displayed in Figure 1.5. From this Figure, it is clear that our cooperative inversion has recovered the main features of the model; i.e. all the main units, as well as the mineralized lenses. We would like to emphasize that the cooperative inversion workflow for the synthetic example was executed without any assumed knowledge of the "true" model. That is, we used a constant density and performed cross-plot of velocity and resistivity from a synthetic well to derive a relationship between velocity and resistivity, This relationship was based on a single well and does not change with depth. It is an approximation of the true relationship used during synthetic modeling and consistent with what might be available if cooperative inversion workflow when applied to field data. To highlight the value of cooperative inversion, we performed the classic model based acoustic impedance inversion (Russell and Hampson, 1991) with the migrated seismic data and the single available well log, then compare the resultant acoustic impedance image with the output from our cooperative inversion. In this case, the starting acoustic impedance model for the classic model based inversion was obtained from picking horizons on the migrated seismic section and correlating the horizons with the available well log data. The classic model based inversion result (Figure 1.6) provides good definition of units A, B, D. However the presence of the potential mineralization zone (F) and unit C are not evident and there is no boundary between unit D and E. This is not a surprise as in this case the result of the inversion depends heavily on the number of available well log data. The quality of the inversion could be improved by adding more log data, especially at x = 800-1600 m where the model is more complex.

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CONCLUSIONS

We presented a cooperative inversion workflow for acoustic impedance using seismic and magnetotelluric data. In our inversion approach, a model of resistivity distribution derived from magnetotelluric data is used to get the large scale background trends while the seismic data provide the small-scale features. Petrophysical relationships derived from borehole data are used to link velocity, resistivity and density. In the absence of well logs, empirical or known relationships consistent with the study area could still be used. Structural constraints derived from migrated seismic data are used to improve the magnetotelluric inversion. The cooperative inversion scheme provides a high resolution acoustic impedance model that provides value beyond that which independent inversion could achieve. The synthetic test shows that when using only a single well and complementary dataset (in this case seismic and magnetotelluric) it is possible to obtain improved subsurface images in complex areas such as imaging lenticular zones.

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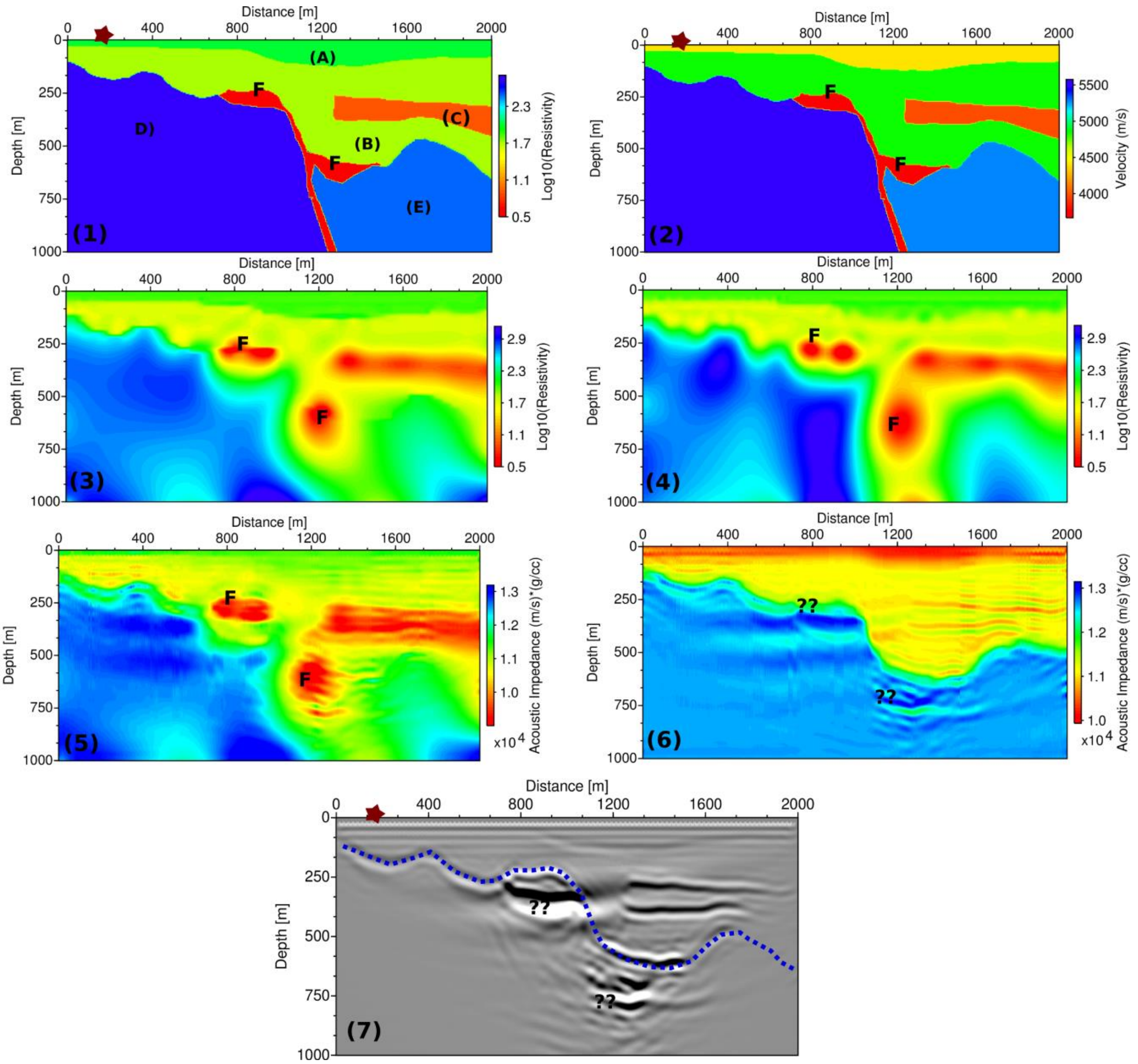

Figure 1. (1) Velocity and (2) associated resistivity model used for synthetic modelling; (3) resistivity model from magnetotelluric inversion with structural constraints and (4) rresistivity model from magnetotelluric inversion without structural constraints. (5) recovered acoustic impedance model using as starting model the converted resistivity model with structural constraints to acoustic impedance and (6) standard model based acoustic impedance inversion result. (7) Migrated seismic section. The dotted blue line in (7) indicates the picked horizon that was included to constraint the magnetotelluric inversion. The star indicates the location of the well. The identification of the potential mineralized zone (F) is obvious on the cooperative inversion result (5) but it is not evident on the standard model based inversion (6). See Table 1 for definition of units