

## **Response of the Authors to Referee #2: I. Ferguson**

The authors would like to sincerely thank Ian Ferguson for his interesting and useful comments, especially for the ones related to the correlation of the well-log resistivity and velocity data. All comments and suggestions have been adopted for the most part in this revised version of the manuscript. We summarised below how the changes have been addressed and implemented, indicating our answers in normal case and the sentences in the manuscript in italic. The page and line numbers (PX LXX) in the responses correspond to the new numbering in the manuscript.

The most significant change is that we have recalculated relationship ER2 as a linear relation of  $1/V$  vs  $1/R$  in the new version of the manuscript ( $\frac{1}{V} = c \frac{1}{R} + d$ ), as suggested by the Referee.

## **Interactive comment on “Joint interpretation of magnetotelluric, seismic and well-log data in Hontomín (Spain)” by X. Ogaya et al.**

The manuscript describes a valuable and interesting comparison of seismic velocity and resistivity data in the area of the Hontomín CO<sub>2</sub> sequestration site. Three-dimensional velocity and magnetotelluric (MT) resistivity models are described and compared, and these data are compared with well-log information. Statistical relationships between the velocity and resistivity are derived from the well-log data and used to convert the 3-D MT resistivity model into equivalent velocity models. These results are then compared with the actual well-log data and near-surface seismic models. The manuscript is well written and illustrated and appears to be scientifically correct. It will be of interest to a wide range of readers of Solid Earth.

I have only one significant comment on the scientific aspects of the manuscript and that is that although the relationships between the well-log seismic and velocity data are established for subsequent empirical use I think there should be a little discussion of their physical basis and a more critical assessment of their significance. There are also a number of small editorial scale corrections that would enhance the manuscript.

## **General Comments**

1. The results of the study will be valuable to many readers. The intercomparison of the seismic and MT results provides new results meaning that the overall geophysical data set provides more information than the sum of the results obtained from the individual methods. For example, the differences between the data sets provide information at depth on fluid

distributions relative to the fault locations and in shallow areas on the possible contribution of clay to the resistivity variations.

2. The comparison of the MT 3-D resistivity model with the well-logs was also of valuable and demonstrated that the surface method provided remarkably good resolution of the sub-surface resistivity.

3. I think that the aspects of the study dealing with the correlation of the well-log resistivity and seismic data could be strengthened in places.

(a) The manuscript cites other studies that have considered this correlation but it would be useful for it to include some level of discussion of the physical basis for the regressions used.

- **What is the basis for considering different depth ranges (empirical observation or accounting for the influence of confining or fluid pressures on velocity, pore connectivity)?**

The depth ranges of the different groups are based on empirical observations: The resistivity-velocity log pairs were grouped based on their relative behaviour. The direct or inverse relationship between the two properties defined the limits of the different groups. We were aiming to derive resistivity-velocity relationships without any other information or assumption apart from the resistivity and velocity logged data (not accounting for the influence of confining or fluid pressures on velocity, pore connectivity).

To make this point clearer, we have added this information in the new version of the manuscript (P7 Ln11): *'The resistivity (R)-velocity (V) log pairs were grouped based on their depth and their relative behaviour (i.e., direct or inverse relationship between resistivity and P-wave velocity). The different depth ranges were determined by empirical observation.'*

- **How do the two relationships accommodate the effect of porosity expressed in the standard Archie's Law (with or without a surface conductivity contribution from clay minerals) for resistivity and Reuss average (time-average) or other physical mixing models?**

ER1 and ER2 are local resistivity-velocity relationships established for the Hontomín dataset. ER1 ( $V = a \log R + b$ ) could be associated to the original Faust equation (Faust, 1953) and ER2 ( $V = \frac{R}{cR+d}$ ) to a recent re-evaluation of the Faust equation for unconsolidated shales (Hacikoylu et al., 2006). In Hacikoylu et al. (2006) the authors concluded that the Faust's equation is only applicable to consolidated sandstones but not to shale with high clay content. We used these two relationships to be able to reproduce the behaviour of both shale and sandstone layers. Besides we used two different

relationships to have an idea of the accuracy of the approaches for the different depths according to the discrepancies observed between the two.

Our relationships were empirically derived from cross-plots without providing much insight in their physical basis. As we mentioned before, we grouped the data according to their behaviour, hence we assumed that the different lithologies, compositions, porosity or clay content were somehow accommodated in the different groups.

We are aware that velocity and electrical resistivity are usually related to each other through porosity. However, as this work is more focus on a structural correlation between the seismic and MT results obtained at the Hontomín site, we have not approached this problem in this paper. This is undoubtedly a very interesting subject to face in future works as it is mentioned in the discussion section.

To make this point clearer, we have added this information in the new version of the manuscript (P8 Ln4): ‘

*Note that ER1 and ER2 are local resistivity-velocity relationships established for the Hontomín dataset. However, the ER1 relationship could be associated to the original Faust equation (Faust, 1953) and the ER2 relationship to a recent re-evaluation of the Faust equation for unconsolidated shales (Hacikoylu et al., 2006). The use of both ER1 and ER2 relationships can provide a different estimation of the velocity at the different depths, reproducing the behaviour of both shale and sandstone layers. This can be especially useful to evaluate the accuracy of the approach based on the discrepancies observed between the two relationships and to better estimate the velocity for those groups where the R-V relationships seem to return the mean value of the velocity of the depth range.’*

#### References:

Faust, L. Y.: A velocity function including lithologic variation, *Geophysics*, 18, 271–288, 1953.

Hacikoylu, P., Dvorkin, J., and Mavko, G.: Resistivity-velocity transforms revisited, *The Leading Edge*, 25(8), 1006-1009, doi: 10.1190/1.2335159, 2006.

#### • What is the relationship between the observed relationships and the various lithologies?

We have grouped the logged data based on their depth and the relative behaviour of resistivity and p-wave velocity log pairs thus each group represents data with similar electric and sonic properties. We have added the dominant lithologies of the S- and D- groups in Figure 6 to make the relationships between the observed relationships and the various lithologies clearer. However, as we stated in the discussion, we would need to consider other petrophysical properties for a further petrological

interpretation of the derived S- and D-groups since the relationship between them and their dominant lithologies is not obvious.

We have rearranged one of the paragraphs of the discussion to express this idea (P12 Ln16): *‘The relationships used were empirically derived from velocity-resistivity cross-plots without providing a full insight in their physical basis. Thus, future work should include exploring how these relationships accommodate parameters such as effect of porosity, water saturation, salinity or clay content, in order to refine the R/V relationships. Besides we would need to also consider other petrophysical properties for a further petrological interpretation of the derived S- and D-groups since the relationship between them and their dominant lithologies is not obvious.’*

- **The manuscript attributes differences in the near-surface velocity models in Figure 10 to the role of clay. However, I assume that the mean clay content is already accommodated in the two regression models so it is really spatial variability in clay content that is involved. What percentage contribution of clay to the bulk conductivity is required to explain the observations?**

There is an agreement between the areas with high discrepancies between the static correction model and the derived velocity models, and the quaternary unconsolidated sediments (see geological map in Figure 1). Reviewer #2 is right in suggest that the variations of clay content should be in some way accommodated in the ER1 and ER2 relationships. The observed discrepancies could be due to variations of clay or water content but could also be a consequence of the limitations of the methodology used. It is clear that the resistivity model is imaging more bodies than the velocity model in the first 40 m, in particular to the south of the South fault. However, we should improve the quality and resolution of the resistivity model in the shallow subsurface (e.g. with a high resolution audio magnetotelluric –AMT- survey) before attempting a further interpretation. We have rephrased a number of sentences to make this point clearer:

*(P1 Ln25): ‘The results allowed extracting information about the characteristics of the shallow unconsolidated sediments, suggesting possible clay and water content variations’.*

*(P11 Ln10): ‘In general, there is an agreement between the areas with high discrepancies between the two models and the quaternary unconsolidated sediments (see geological map in Fig 1). The sediments of the South block are mainly composed by Quaternary sandstones (gravel and clay) and Cenozoic sandstones (sandstones and clay)(Fig. 1). Thus the differences observed in this area could be due to variations of clay or water content.’.*

*(P11 Ln23): We have replaced ‘accumulations of clays’ by ‘presence of unconsolidated sediments’.*

(P12 Ln32): *'Hence, the correlation of the two methods gives a more complete information of the shallow sediments, suggesting possible variations in clay and water content. On the other hand, the joint interpretation of the two models provides little information about the extent and geometry of the existing karstic areas. The 3D seismic and 3D MT surveys were designed for imaging deeper structures, including the target reservoir and seal formations which are located circa 1.5 km deeper. Thus, capturing the inherent complexity of the shallow subsurface and in particular, of the karst (i.e., variable size, composition of the filling of the voids, seasonal variation of the water table, potential cementation) could be out of the limits of resolution of the methods and methodology applied in this work. An interesting task to face in the future would be to merge these results with other geophysical (e.g., Benjumea et al., 2016) and geochemical (Elio et al., 2013; Nisi et al., 2013) studies carried out in the area, to better constrain the location and geometry of the karst, and clay and water content variations.'*

(P13 Ln29): We have replaced *'highlighting'* by *'suggesting'*.

**(b) There is partial circularity in the results that has not been explicitly noted in the manuscript. For the ER1 models there are a number of fitted relationships in which the constant  $a$  appears to be not statistically significant (e.g., for S4, S5, D1, D6, D7, and D11 in Table 1) In these depth ranges the velocity is effectively independent of resistivity so the regression line essentially provides only the mean value of the seismic velocity for that depth range. The resistivity has virtually no capacity to predict the velocity in these depth ranges. When the fitted relationship is used to predict the velocity from the 3D resistivity model all it is doing is returning the mean value of the velocity for that depth range. This result will of course provide a good representation of the seismic results because it is based almost entirely on seismic constraints. The comments on the quality of prediction of the seismic results should focus to a greater extent on those depth ranges in which there is a strong resistivity-velocity correlation.**

We completely agree with Reviewer #2. The coefficient of determination  $R^2$  is smaller than 0.05 and the constant  $a$  is not statistically significant ( $p\text{-value} > 0.02$ ) in the groups S4, S5, D1, D5, D6 and D11. In our opinion, this fact could be partially explained by the small depth variations represented by the different groups and that in general, the resistivity varies in a wider range of values than the velocity. In order to overcome this limitation, in this work we have used two different R-V relationships aiming to better estimate the velocity, in particular in those cases where the R-V dependency is not clear.

We have detailed the statistical significance of the different constants (p-value) in Table 1 and Table 2, as well as added the following text in the manuscript:

(P7 Ln19): *'The groups D8, D9 and D10 are the ones better explained by the linear regression model ( $R^2 > 0.9$ ). On the contrary,  $R^2$  is smaller than 0.05 in S4, S5, D1, D5, D6 and D11. For those groups, the constant  $a$  is not statistically significant ( $p\text{-value} > 0.02$ ).'*

(P8 Ln1): *'The results of the statistical analysis show that the resistivity seems to have limited capacity to predict the velocity in some depth ranges, in particular in groups S4, S5, D1, D5 and D11. This fact could be partially explained by the small depth variations represented by the different groups and that in general, the resistivity varies in a wider range of values than the velocity.'*

(P8 Ln6): *'The use of both ER1 and ER2 relationships can provide a different estimation of the velocity at the different depths, reproducing the behaviour of both shale and sandstone layers. This can be especially useful to evaluate the accuracy of the approach based on the discrepancies observed between the two relationships and to better estimate the velocity for those groups where the R-V relationships seem to return the mean value of the velocity of the depth range.'*

(P12 Ln11): *'Based on the obtained results, the use of more than one empirical relationship is advisable because the discrepancies between the different velocity models indicate areas with higher and lower agreement, helping to constrain the error and the accuracy of the approaches. This is especially useful for those depth ranges where velocity is independent of resistivity and the derived relationships are only able to provide a mean velocity value.'*

- **I think it would also be valuable to include an assessment of the statistical significance of the regression results in Table 1 in order to address this issue. It may be hard to use a standard statistical test as the true number of degrees of freedom is unclear because of the spatial correlation of the well-log data. However, perhaps an analysis of the proportional decrease in variance could be used.**

Table 1 and Table 2 have been modified in this new version of the manuscript: 'Norm of residuals' column has been replaced by ' $R^2$ ' column in order to give a better idea of the lineal correlation of the two variables of the regression. We have also indicated the constants that are statistically significant (p-values).

**(c) The display of data in Figure 6b and c and the results in Table 2 are perhaps a little artificial. Much of apparent excellent fit of the data in Figure 6b is due to the presence of  $R$  in both variables and disguises the true level of correlation. Re-arrangement of (the second) equation 1 suggests that the underlying linear relationship is of the form:**

$$\frac{1}{V} = c + \frac{d}{R}$$

**Equation 1**

**so I think a regression of 1/V against 1/R would provide a truer indication of the fit of the underlying model. It is presently difficult to use the results in Table 2 to see if there are any similar issues to those noted in point (b) above.**

The authors are aware that the excellent fit displayed could be a little artificial because the resistivity is in both the dependent and independent variables. In the previous version of the manuscript, we aimed to explore the behaviour of the data with different kinds of relationships between the variables: (i) a linear regression of V vs log(R), to test a simple relationship between the two properties (ER1); and (ii) a linear regression of R/V vs R to explore a combination of variables different from the type 'V vs R'. We chose R/V vs R over 1/V vs 1/R in order to redefine the dependent variable and to reduce the dispersion of the data points enhancing the quality of the lineal regressions. We tried to improve the velocity estimation in those layers where the relationship ER1 seems to return the mean value of the velocity of the depth range. We discarded a plot of 1/V vs 1/R because it did not provide a noticeable improvement in the data fit.

However, we agree that 1/V vs 1/R is a truer indication of the fit of the underlying model. For that reason, in this new version of the manuscript, we have recalculated relationship ER2 as a linear relation of 1/V vs 1/R in order to show a more proper indicator of the fit between the two variables.

*(P7 Ln22): 'On the other hand, the empirical relationship ER2 is of the type*

$$\frac{1}{V} = c \frac{1}{R} + d, \quad (2)'$$

The new  $V_{R2}$  velocity model is very similar to the previous  $V_{R2}$  model. Table 2 and the corresponding figures have been updated. Some parts of the manuscript have been rephrased to include the statistical analysis of the ER2 relationship:

*(P7 Ln26): 'In general, the values of the coefficient of determination  $R^2$  are smaller than for the ER1 relationship. The groups D8, D9 and D10 are again the groups better explained by the linear regression model ( $R^2 > 0.9$ ). For the groups S4, S5, D1, D3, D5 and D11 the coefficient of determination  $R^2$  is smaller than 0.05. All the constants are statistically significant except the constant c for the groups S4, S5, D1, D5 and D11 ( $p\text{-value} > 0.02$ ).'*

### **Specific Comments**

**p. 1, line 23-24. Perhaps "... model for the near-surface is compared..."**

This sentence has been modified as suggested (P1 Ln 30)..

**p. 2, line 7. Perhaps "..., for example, the magnetotelluric method ..." (Unless you specify this is for the scale of the sequestration site investigation most electromagnetic methods can provide similar constraints on fluid characterization.)**

This sentence has been rephrased to replace ‘more especially’ with ‘for example’ in the new version of the manuscript (P2 Ln10).

**p. 3, line 14. Perhaps "The mixed lithologies (siliciclastic..."**

‘media’ has been replaced by ‘lithologies’ in the new version of the manuscript (P3 Ln19).

**Line 16. Perhaps "... together with moderate..."**

The sentence has been modified in the new version of the manuscript following the suggestions of the Referee (P3 Ln21).

**Line 26. Perhaps "...regional geological information...", "...identification of 39 subunits..."**

Both suggested changes have been implemented in the new version of the manuscript (P4 Ln2).

**p. 3. Line 29. I was not fully sure what "prognosis" meant in this context. It is a little unusual use of the word so it may be worth adding a few extra words of clarification.**

As suggested by the Reviewer, we have replaced the term “prognosis” with “prediction” throughout the text.

**p. 4. Line 17. Perhaps "The BBMT sites were..."**

‘data’ has been replaced by ‘sites’ in the new version of the manuscript (P4 Ln25).

**p. 5. Line 1. "...which has an aerial extent of circa..."**

The text has been corrected and modified as suggested (P5 Ln9).

**p. 5. Line 9. It was bit unclear what "unfold in different faults" means.**

We have rephrased this sentence to:

*(P5 Ln18): 'The F region is observed to be more conductive in the eastern part than in the western part, where it seems to split in different fault segments'.*

**Line 29. It is also not entirely clear what "bend of the resistive body" means. In the vertical plane or in the horizontal plane?**



The sentence has been rephrased specifying 'in the vertical plane' to make it clearer (P6 Ln10): *'The plane of the South fault in the structural model coincides with the bend in the vertical plane of the resistive body R2 and with the position of the F region interpreted in the geoelectrical model.'*

**p. 6. Line 4. Perhaps "... seems to indicate .."**

'certify' has been replaced by 'indicate' in the new version of the manuscript (P6 Ln17).

**p. 7. Line 21. "noisier", Perhaps "...are large (>2000 m/s)."**

This sentence has been rephrased (P8, Ln30): *'For depths shallower than 200 m, area where the log data of the GW1 well show significant dispersion related to a high heterogeneous media, the differences between the models are large (>2000 m/s). However, for depths ranging between 200 and 400 m the log data are characterised by a low variation and the discrepancies between the models are below 300 m/s.'*

**Line 28. "... ones observed ..."**

This sentence has been modified as suggested (P9 Ln5).

**p. 10. Line 26. "Although the level..."**

'Despite' has been replaced by 'Although' in the new version of the manuscript (P12 Ln24).

**p. 19. "... thicknesses of the sedimentary units."**

The figure caption of figure 2 has been rephrased in the new version of the manuscript as suggested by the Reviewer.

**p. 23. Perhaps "... velocity for the GW1 and H4 well logs"**

The figure caption of figure 6 has been rephrased in the new version of the manuscript as suggested by the Reviewer: *'Resistivity vs Velocity for the GW1 and H4 well logs. [...]'*.