Response of the Authors to Anonymous Referee #1:

The authors would like to sincerely thank Anonymous Referee #1 for his/her very useful comments. 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.

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

Anonymous Referee #1

P1 abstract:

L16: unclear... please rephrase The models correlate well in the surroundings of the CO2 injection area with [the major structural observed related to the presence of faults].

The sentence has been rephrased as suggested.

L18 : defining their structural -> geometry ?

The word 'structural' has been replaced by *'geometry'.*

L21: The derived velocity model is compared to both the [predicted ? from surrounding wells and seismic] and logged velocity in the injection and monitoring wells

The paragraph has been rephrased as suggested (P1 Ln21): *'The derived velocity model is compared to both the predicted and logged velocity in the injection and monitoring wells, for an overall assessment of the computed resistivity-velocity relationships. The major differences observed are explained by the different resolution of the compared geophysical methods. Finally, the derived velocity model for the near surface is compared with the velocity model used for the static corrections in the seismic data.'.*

L25: unclear, between what & what ?? The good correlation of the velocity models, one being derived from log base Vp/R relationship demonstrates the reliability of a joint interpretaion, based on petrophysical relationship.

The sentence has been rephrased as suggested (P1 Ln26): *'The good correlation of the velocity models derived from the R/Vp relationships and the well-log data demonstrate the potential of the*

combination of the two methods for characterising the subsurface, in terms of its physical properties (velocity, resistivity) and structural/reservoir characteristics.'.

L28: joint interpretation in reservoir characterisation you may write "near surface and reservoir", no ?

The last sentence of the abstract has been modified following the suggestions (P1 Ln29): *'This work explores the compatibility of the seismic and magnetotelluric methods across scales highlighting the importance of joint interpretation in near surface and reservoir characterisation.'.*

P2

L6: pore fluid 'nature'..

The sentence has been rephrased as suggested.

L27: magnetotellurics, from [respectively] a structural and petrophysical point of view.... petrophysics is not applied to seismic data?

This sentence has been rephrased to:

(P2 L29): 'In this paper, we carry out a joint interpretation of the structural model from seismics and the geoelectrical model from magnetotellurics.' '

L28: and [to] compute velocity

The word 'to' has been added to the above mentioned sentence,

L29: for [the] first time

The word 'the' has been added to the above mentioned sentence.

L29-30: and its correlation ... is used to better characterize etc..

The sentence has been rephrased as suggested (P3 L1).

P3

L5: three shallow hydrogeological wells (provide depth range for nfo...)

The depth of all boreholes has been specified in subsection 2.1. The text of the subsection has been modified to include them (P3 Ln5): *'The study area has been explored for hydrocarbon resources and contains four hydrocarbon exploration wells (depths up to 1769 m TVD) drilled between the late nineteen-sixties and 2007 (H1, H2, H3 and H4, Fig. 1). However, their overall production never*

exceeded 3000 bbl (Permanyer et al., 2013). In 2012 three shallow hydrogeological wells (depths between 150 m and 405 m TVD) were drilled in the framework of the CO_2 storage project to carry out groundwater studies (GW1, GW2, and GW3 - Benjumea et al., 2016, Fig. 1). Finally, in 2013, the injection (Hi) and the monitoring (Ha) wells (Fig. 1) were drilled as a part of the CO_2 storage plant (depths up to 1580 m TVD). The resistivity logged data of the H4, Hi and Ha wells is presented for the first time in this work.'

L12: well as the entire target dome structure. This is the first time you write about the reservoir structure, you could indicate before (in intro for instance) it is an anticlinal.

We have added 'a Jurassic domed anticline structure' in P2 Ln19 in the new version of the manuscript, which corresponds to Section 1: Introduction. The new sentence is: *'Hontomín, a Jurassic domed anticline structure located in the SW portion of the Basque-Cantabrian basin (N of Spain, Fig. 1), hosts the first pilot site in Spain for CO_2 geological storage in a deep saline aquifer.'.*

L14: 1) what is briefly the geological reason for velocity inversion You explain P8, but could suggest the answer here..

(P3 L17): 'This velocity inversion is mostly originated in the transition from high-velocity Upper Cretaceous carbonates to low-velocity Lower Cretaceous siliciclastic sediments, as well as in the shallower marlstone-limestone transition within the Upper Cretaceous layers.'

in fig2, "X-faults" in yellow are almost invisible... could you find another color...

Following Referee #1 comments we have changed the background colour of Figure 2 to enhance the contrast and improve the visibility of the X-Faults.

fig 3. a depth given in terms of m.a.s.l. is not depth, but altitude ??

The caption in fig. 3a has been rephrased to: *'From bottom to top (elevation in m.a.s.l.) […]'.*

P5

L7: The geoelectrical structure of the F region revealed an important conductive fluid circulation along the fault zone, which was unknown until the MT survey was conducted. I would suggest first a description of observed resistivity (permute with the next phrase in the text: a conductive zone is observed, and interpreted as due to intense fluid circulation..)

The above mentioned sentence has been rephrased following the suggestions of the Referee (P5, Ln13): *'In the southern part of the model, a conductive zone is observed and interpreted as a fault region ("F region").'*

In addition, a "Fault zone" of > 1km thickness (in NS direction perpendicular to the fault direction EW)... is at least a FaultS or multi-Faulted zone...? could you precise a bit..

We think the reviewer is making reference to the multi-branched expression of the South fault.: 'The F region is observed to be more conductive in the eastern part than in the western part, where it seems to unfold in different faults (Fig. 16 in Ogaya et al., 2014)' For clarity, this sentence has been replaced by the following (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 (Fig. 16 in Ogaya et al., 2014).'.*

L18: I think the use of the term "1D resistivity model" is tricky because one could read it as the result of a 1D inversion or the averaging of 3D model in 1D model... whereas it is the cells resistivity along the mesh of the 3D model.. I would suggest to consider rephrasing.. not mandatory, but, could be clearer..

We have rephrased the sentence avoiding the use of '1D' to prevent misunderstandings (P5 Ln29): *'The resistivity models displayed in red represent the resistivity values of the column of the 3D geoelectrical model located at each well position. The resistivity models of both wells are very similar to each other because they belong to adjacent lateral cells of the 3D mesh (the distance between the Hi and Ha wells is 50 m).'.*

The figure caption of Figure 4 has been also modified accordingly: *'Comparison between the resistivity log data (in black) and resistivity model provided by the column of the 3D geoelectrical model located at the well position (in red) for the Hi (a) and Ha (b) wells.'.*

P6:

L2 to 5 Interpretation of conductive / resistive zone along fault is only interpreted in terms of fluid circulation... S fault = high flow, E fault: sealed... but, what about clay? and alteration effect on resistivity signature ? Do you have arguments to neglect the clay effect on the resistivity here? (perhaps ref to your previous work ?)

In the geoelectrical model, the F region (linked to the S fault interpreted in the seismics) is imaged by low resistivity values whereas the E fault is imaged by high resistivity values. As suggested by Referee#1, a more conductive signature along a fracture region could be either due to (i) clay content variations or (ii) conductive fluid circulation. Ogaya et al. (2013) concluded that the conductive

signal along the F region was too powerful to be generated by a thin accumulation of clays along the fault zone, suggesting that the observed resistivity distribution was produced by conductive fluid circulation along the fault. In order to clarify this point, we have added a sentence to neglect the clay effect on the resistivity variations observed in the F region and we have referenced to this previous work Ogaya et al. (2013). (P5 Ln16): *'Ogaya et al. (2013) concluded that the electrical resistivity variation imaged in the F region was too high to be produced by the presence of clay in the fault zone'.*

References:
Ogaya, X., Ledo, J., Queralt, P., Marcuello, Á., and Quintà, A.: First geoelectrical image of the subsurface of the Hontomín site (Spain) for CO2 geological storage: A magnetotelluric 2D characterization, International Journal of Greenhouse Gas Control, 13, 168–179, 2013.

Effect of E fault on the higher values of eastern part of the resistivity model... interpreted as a side effect? I suppose not, else interpretation in terms of velocity model should fail then... So, could you precise what you call E fault effect on the resistivity?

The East fault is located outside the coverage of the MT survey. However, its structural effect is very significant, producing about 150 m of difference between the Eastern and the Central blocks at the Jurassic levels. In spite of being offset from the MT survey area, we think that the more resistive behaviour of the R2 layer in the eastern part of the model might be a consequence of the structural changes produced by the East fault. We can state that this more resistive behaviour in the eastern part is not an artefact of the inversion as it is certified by the resistivity log data of the H3 well (Fig. 4). Furthermore, the addition of the structural information extracted from the seismic data allowed establishing that the origin of the resistive layer corresponded to the East fault. We have modified the text to make this point clear:

(P5 L21): 'In general, the R2 layer is more resistive in the eastern part of the model (Fig. 3c,d,e). This more resistive behaviour in the eastern part is certified by the resistivity log data of the H3 well (Fig. 4).'.

(P6 Ln15): 'The East fault interpreted in the structural model (plotted in orange in Fig. 5 and called EF in the geoelectrical models) is out of the MT survey region modelled by the MT method. However, the joint interpretation of the two models seems to indicate that this fault could be the responsible of the more resistive behaviour of the R2 layer on the eastern part of the model. We have associated the resistive characteristics of this area to a potential sealing of the East fault.'

L8- L12: I think i understand what you mean, but I propose another way to wirte it: There are 2 ways to detect faults by resistivity: displacement and fluid circulation. If displacement is not sufficient, MT see nothing (but seismic resolution could). If no displacement(or no reflector to indicate displacement) seismic may see nothing but resistivity could still detect water circulation... You may use this approach to re-phrase L8 to 12 (you use this way later in the discussion chapter paragraph)

This paragraph has been rephrased to make clear the limitations in detectability of the two methods:

(P6 Ln20): 'For the joint interpretation of the minor faults, it is worth to bear in mind that faults are imaged as resistivity variations caused by displacement of the layers and/or fluid circulation along fractures in geoelectrical models. If the displacement is below the MT resolution, the faults may still be detected by the seismic method. On the other hand, faults with null displacement might be below the seismic resolution while still being detectable by the MT method if there exists certain fluid circulation.'.

P7

L1-4: could you relate ER1 and ER2 to a petrophysical model, and provide reference. That would help to explain why ER1 seems more "physically explainable" but ER2 show a good fit "mathematically a good fitter" with limitation in terms of applicability..

ER1 and ER2 are local resistivity-velocity relationships stablished 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. 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 awarded 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 stablished 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.'.*

In reference to relationship ER2, the excellent fit displayed could be relatively artificial because the resistivity is in both the dependent and independent variables. In the submitted version of the manuscript, we aimed to explore the behaviour of the data with different kinds of relationships between the variables through: (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 are aware that the underlying relationship for the ER2 relationship can be also expressed by 1/V vs 1/R as also pointed out by Reviewer#2. In the previously submitted version of the manuscript, 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. However, in this new version we have recalculated the 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, which shows that the coefficient of determination R^2 of the two relationships is very alike. The new V_{R2} velocity model is very similar to the previous V_{R2} model and there is no substantial change in the results, but the new model is statistically more correct. Table 2 and the corresponding figures have been updated accordingly.

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.

Just a comment: It is hard to compare the fit quality of the 2 relationships, you could have used centered / reduced data, check "gaussian distribution" and validity of relationship to explain the data... I recognize that the fig 7 shows pragmatically the accuracy of the models with well data...

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' (coefficient of determination) column in order to give a better idea of the lineal correlation of the two variables of the regression. We have also detailed the statistically significance of the different constants (p-value).

L21: are nosier,

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.'* .

P8

L3-4: Thus, we associate the differences between the VR models and the prognosis to the lower resolution of the MT method at that depth: that's the major point ! may be hihlighted in abstract / ccl ..

As suggested by the Reviewer, this point has been highlighted in both the abstract and the conclusions of the manuscript. In order to do so, two sentences have been added: (P1 Ln23): *'The major differences observed are explained by the different resolution of the compared geophysical methods.'*

(P13 Ln26): *'The major differences observed between the velocity model derived from the resistivity model and the predicted and logged velocity in the injection and monitoring wells are attributed to the lower resolution of the magnetotelluric method.'.*

L12-14: please rephrase This method uses the differences in travel-time of the firstbreaks to calculate the [replacement velocity = define please] of a nearsurface layer, based on traveltime inversion (Lawton, 1989).

The "Replacement velocity" concept is a well-established term in reflection seismics and the interested reader is referred to a comprehensive description of the process in the supporting reference (Lawton, 1989). Therefore, we do not believe it is critical to define this concept in full here.

This velocity model is then used to calculate the time-shifts in the [needed ?] to minimise the travel-time difference, usually enhancing considerably the coherence of the reflections.

This sentence has been rephrased to (P9 Ln24): *'This velocity model is then used to calculate the time-shifts in the needed to minimise the travel-time difference, usually enhancing considerably the coherence of the reflections.',*

P9

L6: The static correction model displays the replacement velocities for the first 40 m (Fig. [9] -> 10a).

The reference to the figure has been modified.

L8: subsurface (Fig. 10[a] -> b).

The reference to the figure has been modified.

The high noise recorded means that the resistivity model R and all the models generated from it have also lower quality in that region. I suppose the black dashed line in fig 10 indicate the wind mill line and low R quality.. should write it in the text and in the fig 10 legend

The black dashed lines displayed in figure 10 indicate the windmill line and the centre of the area with low quality of the magnetotelluric data. The meaning of this black dashed line has been explained in the text (P10 Ln24): *'The high noise recorded means that the resistivity model R and all the models generated from it have also lower quality in that region (black dashed line in Fig. 10 indicates the windmill line, centre of the area with low quality MT data).'.*

In the figure caption of Figure 10, we have also added: *'Black dashed lines indicate the windmill line and the centre of the area with low quality data.'.*

P10

L3: to the north [to -> of] the South Fault

This sentence has been rephrased as suggested (P11 Ln19).

L15: As commented before, states clearly if this it could be due to artefact of MT imaging or not "Outside this area, the presence of the South and the East faults alter the geoelectrical behaviour of the different layers and produces the major differences observed between the models"

See comment above.

L26: resolution of the MT method is different [than -> from] in the other two techniques

This sentence has been rephrased as suggested (P12 Ln24).

L29: again... "than in those areas where the existence of the South and the East faults strongly alter the geoelectrical behaviour of the different layers."

See comment above.

P11

L13: the [used -> use] of more than one empirical

'Used' has been replaced by 'use' (P12 Ln11) as suggested.

In the end of the discussion, you state that this work provide a good basis for future work on joint interpretation in the hontomin area, which I fully support.

I think you should emphasize the need for petrological constraint: theoretrical model ? and perhaps sample work varying water saturation, salinity... to refine the relationship R / V

This sentence has been rephrased to emphasize the need of petrophysical constraint as suggested (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..'.*

By the way, I did not see written that it is Vp which is considered in this paper.. it is almost evident, but not written..

We have added this information in P7 Ln10 in the new version of the manuscript: *'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).'.*

P12

potential joint "inversion" in the conclusion... joint interp in the discussion... both could be adressed..

We think the reviewer refers to the presence of the two methods, interpretation and inversion. In this work we have carried out a joint interpretation, which is the basis for a potential future joint inversion, as described in P13 L16: *'Facing the future, the work presented here constitutes a valuable starting point for a joint inversion of the seismic and magnetotelluric datasets.'*

And the impact of the aquifer properties in the near surface may impact the safety of the stroage, and detectability of diffuse CO2 leakages..

The last sentence of the discussion has been rephrased to (P13 Ln18): *'This could provide a more constrained understanding of the fluid circulation along the faults, which have important implications for the safety of the CO2 storage pilot site and the detectability of diffuse CO2 leakages.'.*

All figures are clear, needed, perhaps axis legends are a bit small.. but it is up to the editor to fix the rule.

Figures have been modified to make axis and legends bigger as suggested (e.g. Figure 1, Figure 6, Figure 7, Figure 8).