Dear Dr. Bergmann,

Thank you for reviewing our paper and for your positive and useful comments. Please find enclosed the answers to your comments on behalf of all the co-authors and myself.

Kind regards,

Juan Alcalde

-Referee's comments are italicized, bold and addressed; manuscript text follows with changes tracked; new text added to the manuscript is attached in red for the discussion.-

MAJOR COMMENTS

Given several redundancies to Alcalde et al. (2013), the authors must specify more clearly what is essentially new here, e.g. which parts of the interpretation were exclusively available from the revised processing.

The earlier article by Alcalde et al. (2013) is part of a Special Issue resulting from the 2012 EGU Conference. The article aimed at presenting the reflection seismic experiments carried out in Hontomín. In order to provide a first general image of the Hontomín's subsurface, a standard processing flow was implemented. Furthermore, a preliminary data examination including noise sources, acquisition and subsurface issues, etc. was included in that paper. Our current article is a revised processing work and took into consideration some of the observations from the initial processing in order to go into greater depth with the processing steps and parameters to obtain a refined final image. This resulted in changes in processing parameters, but also in removal of ineffective processing steps or addition of new ones. Examples of these are: the first break picking was enhanced and the resulting static model is more accurate; the phase matching of the wavelets was carefully studied and approached by adding phase and time shifts selected from the study of the two sources used, resulting in a better matching and therefore an increase in coherency; spectral equalization was implemented in both pre- and post-stack stages, so the frequency content is more balanced and higher frequencies are enhanced.

In order to make the difference between the two articles clearer, one paragraph has been modified and one new added to the text. These are (in red):

-In Introduction

> The revised processing scheme used in the present study was adapted to the characteristics of the Hontomín subsurface. The resulting final image features higher coherency than that presented in Alcalde et al. (2013) throughout the entire seismic volume. The improvement is mainly due to the calculation of a more precise static model, the improved noise reduction and the source wavelet matching method applied.

-In Seismic data processing

> The swath acquisition provided a well-sampled azimuthal coverage (Fig. 5c), which assures the three-dimensionality of the data. The available well-log data indicate that the lithologies with higher impedance contrast are located above 1400 ms two-way traveltime (twt) in most cases. Taking this into account the data were processed down to 1500 ms. The processing flow was designed and implemented in order to enhance the S/N ratio and image the target structures.
>
> Alcalde et al. (2013) applied a standard processing to the 3D dataset. A review of this preliminary processing was conducted to identify some key data/noise issues associated with the dataset. These issues included the identification of the noise sources present during the acquisition, the shadow zone related to a near surface velocity inversion and the source wavelet matching issue. The new processing workflow presented in this paper and described below addresses these issues and takes a more detailed look at the signal processing in order to obtain a final image suitable for subsequent detailed interpretation.

Taking into consideration that the presented data (or at least portions of it) constitute the baseline for further time-lapse surveys, the value of the manuscript could be enhanced, if the

authors point out what the encountered issues imply for repeat surveys? For instance, could the static corrections be improved by adding shallow refraction seismic surveys? Or, given the statement that the presented data are "final fully-processed" it should be indicated which parts of the workflow appear useful for a time-lapse processing. For example, the application of an AGC will compromise the utilization of the workflow for amplitude-based 4D analyses.

In this manuscript we describe the problems related to the acquisition (e.g., the use of two different sources) and to the characteristics of the Hontomín site (e.g., heterogeneous near-surface geology, steep velocity inversion, mixed carbonate-siliciclastic media). These factors were studied in detail and oriented the selection of parameters for the processing. We also emphasize the processing steps that influence the quality of the final image to the greatest extent. Thus, we consider these aspects to be of great interest for the design of future seismic surveys, and the subsequent data processing.

Nevertheless, we acknowledge that there is still room for improvement regarding the data processing used. In example, the static corrections, which showed to be one of the most critical steps in the processing, could be refined by obtaining a more precise near-surface velocity model. This could be achieved by adding shallow refraction seismic data (as Dr. Bergmann kindly suggested in his review), and also by well-log data, surface-wave tomography etc. This has been mentioned in the Discussion, as follows:

> However, there is still space for improvement in the field static estimation. New information about the near-surface velocity field (e.g., sonic-log data, shallow refraction seismic data, surface wave tomography etc.) could help to constrain and refine the near surface velocity model.

We agree with Dr. Bergmann that AGC can compromise the use of quantitative interpretation methods based on amplitude variations. In this work, the major effort focused on obtaining a good quality image suitable for interpretation. We also considered that the processed volume could be used as a seismic baseline in a hypothetical CO_2 injection scenario. In such a case, the AGC should be removed from the workflow and be substituted by true amplitude recovery methods, such as linear balance, spherical divergence etc. In order to clarify this, a new paragraph was added to the discussion:

> The use of AGC within the workflow helped to obtain a good quality final image. However, it does not preserve the original amplitude character of the dataset. This

> could jeopardize the use of amplitude variation methods for monitoring. Modifications to the processing flow should therefore be made before this dataset can be used as a baseline to a repeat survey as part of a time-lapse seismic monitoring study.

We also have changed the sentence "Our final fully-processed seismic volume allows…" for a more realistic "Our final processed seismic volume…", in order to stress that this is not the final result, but the best approximation to obtain a seismic image suitable for interpretation.

Although the shots were just realized in relatively shallow holes, were uphole traveltimes recorded? If so, have they been considered for the static corrections?

Uphole traveltimes were not recorded during the acquisition. In most of the cases, the borehole depths were shallower than 1.5 m. Besides, most of the survey lies in Upper Cretaceous carbonate rocks. These limestones are characterized by relatively high propagation velocities (probably over 2000 m/s). Therefore, we should not expect static shifts of over 1 ms associated to the borehole depth, and thus the final image should not vary noticeably.

The interpretation closes with a figure on the storage capacity of the saline aquifer formation which is based on the formation's areal extent, average thickness, and porosity. Although such a capacity estimate is reasonable in first order, it makes the assumption that the entire reservoir thickness can be exploited also in the edge regions. However, this is misleading for gently dipping structures. Hence, this figure should be supplemented by one for which the input volume is truncated by the deepest occurrence of the reservoir top. Further, it must be clarified whether the porosity of 8 % refers to the effective porosity

The calculation of the storage capacity of the Jurassic dome in Hontomín is based on three assumptions. First, its boundaries were selected subjectively. The Jurassic dome resembles a pseudo-triangle in plan view with the two main faults, the Eastern and Southern faults, representing two sides. The third side was determined by looking at the dome shape: the boundary was selected at the time that the dome changes from symmetric to elongated, i.e., approximately 850 ms. The extent and shape of the considered area has been highlighted in Fig. 15. This explanation has been introduced in the text as follows:

> The geometry of the dome is almost symmetric up to 850 ms. From this point, the dome develops into an elongated shape in the NW-SE direction. It maintains this

> geometry until ~725 ms. The crest of the dome (at 650 ms) is found at the Eastern side of the H2 well, in an area between inlines 1270-1300 and crosslines 1130-1160 (Fig. 15). The Jurassic dome resembles a pseudo-triangle in plan view with the two main faults, the Eastern and Southern faults, representing two of the sides. The third side was determined from analysis of the dome geometry: the boundary was selected subjectively at the two-way-time that the dome changes from symmetric to elongated, i.e., approximately 850 ms. The calculated area of the dome is $9.4 \cdot 10^6$ m^2.

The two other assumptions made were the average thickness and average effective porosity of the Jurassic layer (80 m and 8.5%, respectively). They were extrapolated from the available well-log data, and therefore they do not consider local heterogenities. It is a hypothetical estimation and it should not be assumed that the entire region could be considered as suitable for CO2 storage. It is just a rough estimation intended to give an idea of the scale of the site. The last paragraph of the discussion has been rewritten to show this:

> In spite of this lack of internal definition, we have calculated a theoretical CO_2 capacity of the reservoir unit within the Jurassic structure. The surface geology indicates that Jurassic units are relatively homogeneous and their thicknesses are relatively constant. The calculation takes into account the characteristics of the top of the interpreted dome, and extrapolates it downwards. Assuming an average thickness and effective porosity of the reservoir unit of 80 m and 8.5 % (obtained from the well-log data), respectively, the calculated total pore volume in the dome reservoir is $1.6 \cdot 10^6$ m^3. At the expected average reservoir conditions (41^o C and 15.3 MPa), the density of CO_2 is 745.558 kg/m^3. Thus, a maximum storage capacity of 1,2 Gt of CO_2 is expected in the Hontomín Jurassic structure. This value is a rough estimate, but provides an overall idea of the scale and potential of the Hontomín site for CO_2 storage.

The porosity value presented in this manuscript corresponds to the effective porosity, and it was remarked in the text. It was calculated from the porosity-neutron log with a correction applied based on the gamma-log.

In order to highlight the capacity estimation carried out in this paper, a new sentence was added at the end of the abstract:

> Preliminary capacity estimates indicate that about 1.2 Gtons of CO2 can be stored in the target reservoir.

Remove inconsistencies between text body and bibliography. Improve the graphics quality in figures 8, 10, and 13.

These changes were applied as requested by Dr. Bergmann.

SPECIFIC COMMENTS AND STYLISTIC RECOMMENDATIONS

The style changes were applied following the suggestions of Dr. Bergmann. Here are the replies to the comments that require more explanations.

In Geological setting and seismic data acquisition:

Apart from the occurrence of oil in the structure, is there any evidence about the permeability characteristics of the faults obtained from the wells? At least the H-3 well seems to penetrate the Ubierna-related Southern fault and the H-4 well the Central fault, respectively.

There is no permeability information from the wells, and core information is not available. The only information about this issue is provided by Ogaya et al. (2013) and Nisi et al. (2013). Ogaya et al. (2013) observed a more conductive region interpreted as the Southern fault, and that could be linked to fluid circulation. Nisi et al. (2013) conducted hydrogeochemical experiments in the region and more specifically near the Southern fault. Based on the concentration of Cl^-, SO_4^{2-}, As, B and Ba, they suggested that the origin of these waters is rather deep. This information has been added to the text, as the following paragraph in the Discussion:

> The fault also contains branches that are only observable in certain sections of the seismic cube (Fig. 13). This fault could be an important conduit for fluid circulation, as observed by Ogaya et al. (2013). In addition, hydrochemistry studies in fluids derived from surface springs conducted by Nisi et al. (2013) in the eastern part of the Southern fault suggest that these fluids could have a deep origin, supporting the idea of the fluid circulation and, thus, a leaky fault. The Eastern fault presents the largest vertical offset of the study area (up to 380 m, Fig. 15b).

As a result, a new reference was added:

Nisi, B., Vaselli, O., Tassi, F., Elío, J., Delgado Huertas, A., Mazadiego, L.P., Ortega, M.F., 2013. Hydrogeochemistry of surface and spring waters in the surroundings of the CO_2 injection site at

Hontomín-Huermeces (Burgos, Spain). International Journal of Greenhouse Gas Control 14, 151-168, http://dx.doi.org/10.1016/j.ijggc.2013.01.012.

Figure 4: Discard the high-cut filter in the spectrum of the Vibroseis data when presenting it as a result of "raw" data.

The high-cut filter was applied in the field by the acquisition company in the field. Thus, this is the rawest data that we have. This information was added to the figure caption as follows:

> **FIG. 1:** Frequency spectra of the shot gathers shown in Fig. 3: shot gather 1820, acquired with Vibroseis source (dark grey) and shot gather 1158, acquired with explosive source (light grey). The high-cut filter in the spectrum of the Vibroseis data was applied in the field.

1584, 19-20: "New velocity analysis was performed after every major processing step..." Table 1 shows just one occurrence for velocity analysis.

This sentence has been removed from the final text.

1585, 17-19: „The lateral continuity of the reflections is limited in the whole seismic volume, due to the influence of the shallow velocity inversion, as well as to the existence of heterogeneities associated with small scale fracture zones." (1) Point out an example for this in Figure 11 or 12. (2) If the velocity inversion is jointly responsible for the lateral reflector discontinuity, it should be relatively variable in a lateral sense. Provide a comment whether this was inferred from the velocity analyses. (3) Provide details on the occurrence and characteristics of these "small scale fracture zones".

1 An example of this was added to the text, as follows:

The lateral continuity of the reflections is limited in the whole seismic volume (e.g., sets E and F in Fig. 12). This could be due to the influence of the shallow velocity inversion, as well as to the existence of heterogeneities associated with small scale fracture zones.

(2) We are not completely sure that the velocity inversion is responsible for the lateral reflector discontinuity. We think that this issue could be produced by the velocity inversion in the near-surface, jointly with heterogeneous fractured areas. The velocity inversion produces a loss of first arrivals (Fig. 3) and this could lead to a static problem that compromises the lateral continuity. Further studies should be performed in order to get to the root of the static problems, but we consider this is out of the scope of this paper.

(3) The Hontomín area has been the subject of different deformation stages during the Mesozoic and Cenozoic (Tavani et al. 2013). It is reasonable to assume that these major deformation events have produced certain small-scale fractures in the Mesozoic and Cenozoic sediments. These fractures can be observed in the outcrops of the different sediments, and it is believed to be the main cause of permeability in the target reservoir. The fractures have a size far below the seismic resolution and it is not our purpose to describe them, but they can still cause disturbances in the wave propagation that could explain part of the limitations on the lateral continuity.

1588, 16-17: "However, it was unexpected to find a sharp velocity inversion so close to the surface." Have there been no indications from the vintage data?

No vintage sonic-log was available for the first 400 m, and therefore the velocity field was unknown. This issue prevents obtaining an appropriate seismic-to-well tie, reducing the quality of the 3D interpretation.

1589, 24-25: I generally agree with this statement, because the reflector definition is visibly enhanced and the overall noise level is lower. However, there seem to be some

portions where the previous workflow performed better, e.g. in Fig. 11 halfway between H2 and beta' at 700-800 ms twt. Discuss this and add a distance scale to the horizontal axis of Fig. 11.

In general terms, the new processing produces a better image as compared with the processing presented in Alcalde et al. (2013). The set of reflections mentioned by Dr. Bergmann (Fig. 11, halfway between H2 and beta' at 700-800 ms twt) seem to be clearer in the previous processing. However, we would like to remark that this set of reflections shows an overestimated dip and that its lateral continuity is limited, giving the impression of being an artifact probably produced by a wrong velocity model used in the NMO and DMO steps. Besides, that area corresponds to the major Eastern fault, and a loss of continuity around this area is rather expected.

Nevertheless, we understand that there could be some parts of the volume that could not be improved with the new processing. In any case, we tried to look for an equilibrium between the parameters selected that provide a better global improvement, and this could have some drawbacks in certain small portions of the seismic volume.

A distance scale was added to the horizontal axis in Fig. 11, as requested by Dr. Bergmann.