

REVIEWER 1:

Dr. Jaiswal (Referee)

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General comments - The paper uses a dense traveltimes refraction dataset to map lithology. Model development part of the paper is strong. Quantitative interpretation part of the paper (Fig. 6 onwards) is weak. Specific comments - The V_p - lithology relation has been built using a series of logs. This is not wrong, just limited in its scope. Logs have a higher resolution than the V_p model. To reconcile logs with the traveltimes V_p , authors have averaged the logs within a window and resampled it again. This is a good qualitative approach, not quantitative. Running average is not the same as Backus average, but this is just a minor issue.

Authors will appreciate averaging creates uncertainty. The sense of uncertainty in quantitative interpretation is missing. I suggest approaching quantitative interpretation in one of two ways. Either, develop a rock physics model for individual lithologies or present Fig. 7 - 9 in a probabilistic sense (what is the probability of a certain point in space to correspond to a certain lithology). Authors have everything they need for both approaches.

- All the best

The main goal of this manuscript was to reveal the 3D distribution of seismic velocities and to test the capabilities and the limitations of the guided interpretation of the tomographic model to define structural features such as lithological boundaries. This guided interpretation was mainly based on logging data which was used to define the different lithotypes to be upscaled to the 3D tomographic velocity model. Unfortunately, one of the main problem was the incompleteness of the velocity logs in most of the boreholes (except SVC-6) in their upper part. This fact basically affected the gypsiferous lutites (LT) underestimating the velocity range given to this lithology and introducing a high ambiguity in the LT-Ytr boundary definition but also to differentiate. In addition to that, the bias imposed by the boreholes location, most of them located in the central part of the survey, had also a significant impact in the velocity range definition and mismatch observed between the geological interpolated model and the tomography. The fact of the layers are dipping to the west impose changes in velocity in this direction with increasing depth, being the shallow lutites the most affected lithology. The lack of wells in this area cannot account of these changes in physical properties of this lithology.

For these reasons, the guided interpretation presented in this manuscript is following a qualitative approach. We believe that a rigorous uncertainty analysis is difficult to carry out taking into account the inconsistency in the velocity log data and this approach is beyond the scope of this manuscript. To show the ambiguity associated to the boundary definitions we changed the re-imaging of the final velocity model introducing the gaps between velocity ranges which corresponds to seismic velocities that could not be assigned by the well log interpretation. This approach simplifies the understanding of the paper discussion and better supports it.

Reviewer 2

M. Majdanski (Referee)

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General comments

- The manuscript presents an analysis of very dense 3D seismic dataset to characterize the shallow subsurface. The authors suggest that use of a simple first-breaks traveltime tomography method can lead to high-resolution image of the studied area. I have already seen presented data and an initial interpretation at a conference presented by Ramon Carbonell. The data are indeed of high density and good quality, and supported with some boreholes information, so reflection imaging should be a natural interpretation technique. Unfortunately, authors do not discuss this possibility focusing on the simplest possible technique, claiming that reflection imaging is not needed.

In the first part of the manuscript authors present clear description of traveltime inversion supported with the uncertainty analysis (checkerboards). In the second part they try to combine smooth velocity model from traveltime tomography with sparse borehole data. This is very difficult and questionable part, and would be much easier with reflection imaging.

The manuscript is well written, and easy to read and understand. In the second part it is also a bit long and unconvincing.

The results presented are part of a more extensive seismic acquisition experiment carried out in Villar de Cañas (Spain). The experiment included four 2D seismic reflection profiles (Figure 1 in the manuscript) and also the 3D seismic survey presented in this manuscript. The acquired data aimed different targets according to the interests of the contractor company. The 2D seismic profiles were designed to obtain a more structural regional information focused on fault network. On the other hand, the 3D seismic survey was planned to characterize the very shallow subsurface at the future storage facilities location. The main objective of this survey was the distribution of the physical properties of the very shallow surface including the definition of the upper lithological contacts (only the upper sedimentary sequence corresponding to the 2nd Neogene Unit) which directly interact with the ongoing construction works. Taking into account the constraints imposed by the approved project itself we designed the most dense 3D seismic survey possible with different data processing options. In this manuscript we only present the results derived from the travel time tomography which pursued to provide a 3D distribution of physical properties of the very shallow surface and its geological interpretation. This is very valuable for the company to correlate with other physical properties obtained by means of other geophysical techniques (for instance, electrical resistivity tomography) that can be very useful to define the needs in the future construction process. In this manuscript we only focus on velocity models and we also tried to provide structural information using the joint interpretation with borehole data and geological mapping.

According to the reviewer comments, it seems that it is not clearly stated in the manuscript. The authors do not want to claim the seismic reflection is not needed and we agree that this method is the most suitable for the structural imaging. The presented results show the capabilities and the limitations of traveltime tomography to image the evaporite sedimentary sequences in a very shallow location. The interest in obtaining a 3D distribution of the very shallow subsurface physical properties of the site and the need of obtain a geological interpretation of this volume was the main motivation of this paper. For this reason, we have changed the abstract and the introduction of the manuscript to clearly state the objectives of the paper and to avoid

Specific comments

- Use of the first breaks only. In the near-surface data the first breaks are difficult to pick, especially in the near field. What was the data quality for those short offsets? Fig.3 present only mid-offset arrivals. What data processing (filters, agc) has been applied to the data. What is presented in Fig.3, it is definitely not raw recordings.

The data quality was also pretty good for short offsets. Every shot point was shot five times with

different geophone lines configuration. The closest offsets obtained were around 10 m (shot points close the active geophone line). For this reason, most of first arrivals corresponding to short offset are pretty clear and it was possible to include them in the tomographic inversion.

For display purposes and only for that, a trace balancing of 1500 ms was applied to the data. No band filters or any other processing was applied to the data showed in Figure 3.

- Line 170 – what do you mean by suitable did you mean “very smooth initial model”?

The existing equipped boreholes and the detailed surface geology carried out in the site, previous to our seismic acquisition, made really easy to built a proper initial tomographic velocity model. This was essential to achieve a very fast convergence of the tomographic inversion. For this reason we changed “suitable” for “proper” to provide the correct meaning to the sentence.

- Line 211: it is more like in the first 40 m, as shown in Fig.4, not 20-30

This sentence is referred to the eastern sectors of the survey. This can be easily observed in Figure 9 in the EW profiles (C-2i and C5i). The gypsum is outcropping in these areas and the transition between the surface weathered layer to most consolidated gypsum is taken place in 20-30 m with a very high velocity gradient.

- Figure 5 caption – there is no need to explain what is the checker-board test in the figure caption. It is described in the text.

We removed the checker-board explanation from the figure caption

- Also references to methodology in figure caption is unnecessary. Moreover, reference to Rawlinson et al. 20154 (should be 2014) is missing

Rawlinson, N. and Fichtner, A. and Sambridge, M. and Young, M.K. (2014) *Seismic Tomography and the Assessment of Uncertainty*. In: *Advances in Geophysics*. *Advances in Geophysics*, 55. Elsevier, pp. 1-76. ISBN eBook ISBN: 9780128003718 Hardcover ISBN: 9780128002728

Reference has been removed from the figure caption.

- Figure 5 – a-e marks and all labels are tiny; values in colour scale are missing; what are those black dots in a and b? What parameters (velocity in anomaly) has been used for checkerboard test?

The figure has been modified according to the comments of the reviewer. The size of the labels are bigger than before. The values of the color scale have been added to the figure. Those values show percentage of velocity perturbation. The “black dots” corresponds to the location of the shot points . This provides a reference to check the checkerboard recovery in depth. This information has been included in the figure caption.

- The checkerboard results shows that the first 25 m has not been resolved at all. I assume this is because of usual problem with picking the first breaks at very short offsets in the near field. In the article no short offset arrivals are presented. Could you comment on that?

The software used do not allow to introduce the topography as a reference for the velocity grid. Therefore the inversion grid is a regular cube referred to a maximum elevation. Those areas above the topography line (black dots in the checkerboard test) are not covered by ray path and thus no anomaly recovery can be obtained. This is specially significant in the western part of the survey in which lower elevation is observed. The velocity model located above the topography have been

covered and some explanations have been added to the figure caption.

- *4.1 Is this sub section necessary? There is no 4.2*

Sub section 4.1 has been removed in the manuscript and it has been included directly to Results section.

- *Profile c-2i in figure 9 shows no correlation between tomographic velocity and extrapolated surface geology. The only consistency might be found with ray penetration. I would avoid writing “matching is very consistent” (in line 348)*

The sentence has been changed to “matching is quite consistent”. The lower boundary between transition layer to gypsum is very consistent in all the area, even in profile c-2i. The mismatch occurs between the lutites layer and the transition that is difficult to constraint due to several reasons explained in the manuscript.

- *Figure.1 b small inlet has tinny font, but there is space to change legend to two column text*

The size of the legend has been increased in the geological map

- *Figure.2 a b c marks are not needed, as they are not mentioned anywhere*

The a,b and c marks have been removed and the labels of the location map are now bigger than the previous version.

- *Figure.3 what processing has been applied to this data? No information in caption nor in text*

Trace balancing was applied to the data for display purposes only. This information has been added to Figure 3 caption.

- *Figure 9 half of markings are tiny*

Figure 9 has been modified according to the reviewer suggestions

Minor editorial corrections

- *Line 86 – double dot (.)*

Dot removed from the text

- *Line 133 – unnecessary comma after .*

Comma removed from the text

- *Line 151 – missing space “releaseof”*

The space was included in the manuscript

- *Line 157 – of first breaks -> of the first breaks*

Changed in the manuscript

- *Line 441 – taking into account this -> taking this into account*

Changed in the manuscript

- *Line 451 - that does not exist any evidence of recent -> that there is no evidence of recent*

Sentence changed in the manuscript

LIST OF RELEVANT CHANGES:

- ABSTRACT and INTRODUCTION: The abstract and the Introduction have been modified slightly to clearly state the objectives of the manuscript, according to the comments of reviewer 2.
- RESULTS: The last paragraphs of the results section have been modified to explain the changes made in the presentation of the guided interpretation of the velocity models.

Related to that, Figure 7 and 9 has been modified according to the new guided interpretation. Figure 8 has been removed of the manuscript because with this new guided interpretation is not offering valuable additional information to the manuscript.

-DISCUSSION: The discussion has been rewritten according to the new figures. The discussion remains unaffected but the new figures better support the arguments used in this section

Figure changes

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Trace balancing was applied to the data for display purposes only. This information has been added to Figure 3 caption.

Figure 7 and 8 have been modified and also the figure captions

Figure 8 has been removed

Figure 9 is Figure 8 in the new version of the manuscript

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3D Seismic Traveltime Tomography Validation of a Detailed Subsurface Model: The case study of the Zancara River Basin (Cuenca, Spain)

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ABSTRACT

A high-resolution seismic tomography survey was acquired to obtain a full 3D P-wave seismic velocity image in the Zancara River Basin (east of Spain). The study area consists of lutites and gypsum from a Neogene sedimentary sequence. A regular and dense grid of 676 shots and 1200 receivers was used to image a 500x500 m area of the shallow subsurface. A 240-channel system and a seismic source consisting of an accelerated weight drop, were used in the acquisition. Half million traveltimes were inverted to provide the 3D [seismic velocity distribution up to 120 m depth](#). The project [also](#) targeted the geometry of the underground structure with emphasis in defining the lithological contacts but also the presence of cavities and fault/fractures. An extensive drilling campaign provided uniquely tight constraints on the lithology; these included core samples and wireline-log geophysical measurements. The analysis of the well-log data enabled the accurate definition of the lithological boundaries and provided an estimate of the seismic velocity ranges associated to each lithology. The final joint interpreted image reveals a wedge shaped structure consisting of four different lithological units. This study features the necessary key elements to test the traveltime tomographic inversion approach in the high-resolution characterization of the shallow subsurface. In this methodological validation test, traveltime tomography demonstrates to be a powerful tool with a relatively high capacity for imaging in detail the lithological contrasts of evaporitic sequences located at very shallow depths, when integrated with additional geological and geophysical data.

1. INTRODUCTION

Knowledge of the very shallow structure of the Earth has become a critical demand for the modern society. The shallow subsurface is the part of the Earth with which humans have the most interaction. Characterizing the subsurface is important since it hosts critical natural resources; it is used as reservoir for resources and waste, plays a key role in support of infrastructure planning and holds the imprint of the anthropogenic processes. Thus, understanding its composition and structure is a regular objective in studies such as: natural resource exploration [Davis et al., 2003; Place et al, 2015] and environmental assessment studies [Steeple, 2001; Zelt et al, 2006]. It is also critical in civil engineering practice and monitoring of underground structures [Escuder-Virue, 2003; Malehmir et al., 2007; Juhlin et al., 2007; Martí et al., 2008; Giese et al., 2009; Alcalde et al., 2013a]. In addition, the implementation of a competent subsurface exploration scheme is very valuable for assessing and ~~for~~ providing detailed site characterization for addressing natural hazards, e.g., seismic hazard [Samyn et al. 2012; Ugalde et al., 2013; Wadas et al., 2017; Bernal et al., 2018]. Typical geotechnical practice for subsurface exploration has often relied on a combination of drilling, in situ testing, geophysical surveys, and laboratory analysis of field samples [Andara et al., 2011; Kazemini et al., 2010; Alcalde et al., 2014].

Geophysical techniques provide a great variety of approaches to accurately describe the structure, and the distribution of different physical properties in the subsurface. Depending on the target depth and the required spatial resolution different methodologies can be applied [e.g. Bryś et al., 2018; Novitsky, et al., 2018; Malehmir et al., 2009 and 2011; Escuder-Virue et al 2004; Carbonell et al., 2010; Ogaya et al., 2016; Andres et al. 2016, Alcalde et al., 2013b]. Since the late 90's sophisticated geophysical techniques have been developed to estimate near-surface velocity models as a

54 proxy for subsurface stiffness in seismic applications with different targets [Bergman et al., 2004 and 2006; Heincke et
55 al., 2010]. Seismic traveltime tomography is a robust, efficient and well contrasted tool to constrain the rock's physical
56 properties at very shallow depths [Yordkayhun et al., 2009b; Flecha et al., 2004; 2006; Marti et al., 2002a; ; Baumann-
57 Wilke et al., 2012]. When seismic data is densely acquired it can provide very high spatial resolution images even in 3D
58 at a much affordable cost than conventional 3D seismic reflection surveys. In areas where the geology has not
59 particularly internal structural complexity and with moderate lateral lithological variability, traveltime tomography can
60 provide a reliable image of the subsurface [Marti et al., 2002b; 2006; Yordkayhun et al., 2009a; Letort et al., 2012;
61 Baumann-Wilke et al., 2012]

62
63 The study area, in the Loranca Bains (Cuenca, Spain), has been considered as a possible host for a singular facility for
64 temporary storage of radioactive waste. The emplacement of such a facility requires an extensive multi-scale, multi-
65 disciplinary knowledge of the site's subsurface [Witherspoon et al., 1981; IAEA 2006; Kim et al, 2011], including a
66 detailed 3D ~~image of the structure and the~~ distribution of its physical properties, specially focused on the upper hundred
67 meters which directly interact with the ongoing construction works. The available data suggests that the sedimentary
68 sequence in the study area presents certain tilting to the west, with no significant faulting and therefore no great
69 structural complexity is expected in the shallow subsurface. Following similar case studies on very shallow ~~site~~
70 characterization, traveltime tomography was ~~used considered as the most adequate geophysical method~~ to provide
71 constraints on the seismic velocities for the 3D baseline model ~~of the test site~~ [Martí et al., 2002b; Juhlin et al., 2007;
72 Yordkayhun et al., 2007].

73
74 A very dense source-receiver grid was designed to assure the necessary lateral resolution and depth coverage of the
75 seismic data, to constrain the geological features of interest beneath the construction site. The specific target was to
76 ~~build a 3D distribution of the physical properties resolve in detail the internal geometry~~ of a mostly gypsiferous
77 succession with diffuse lithological boundaries [Martinius et al., 2002; Diaz-Molina and Muñoz-Garcia, 2010; Escavy
78 et al., 2012;]. The inversion of almost half a million first arrival traveltime picks provided a ~~detailed~~ 3D distribution of
79 the P-wave velocities. This combined with borehole information allowed ~~us to infer structural features, fully~~
80 ~~characterize~~ ~~characterized by~~ three main lithological units, ~~that and~~ constrained the interpretation of the velocity model.
81 Borehole information was instrumental to define the specific 3D geometry of the different lithologies in the
82 tomographic model and, the topography of the complex boundaries.

83
84

85 2. GEOLOGICAL SETTING

86
87 The area of Villar de Cañas (Cuenca, Spain) is included in the Loranca Basin, in the southwestern branch of the Iberian
88 Chain (Fig. 1a). The Iberian Chain corresponds to a wide mostly east-southeast trending Alpine intraplate orogen in the
89 eastern Iberian Peninsula. ~~The structure consists of a thin-skinned, west-verging, mostly imbricate thrust system and~~
90 associated fault-propagation folds that deform a Mesozoic and Cenozoic sedimentary cover detached above the
91 Paleozoic basement [Muñoz-Martín y De Vicente, 1998; Sopena y De Vicente, 2004]. The thrust faults merge at depth
92 into a basal detachment located within Middle-Upper Triassic sequences [Piña-Varas et al, 2013].

93
94 The crustal structure of the Iberian Chain has gathered academic interest since the early 1990's [see Seille et al, 2015;
95 Guimerà et al., 2016 and references therein], including the acquisition of local and regional geologic and geophysical
96 studies of the Loranca Basin [Biete et al., 2012; Piña-Varas et al., 2013]. The Loranca Basin comprises syntectonic
97 Cenozoic strata [Guimerà et al., 2004]. It has been interpreted as a piggy-back basin that evolved during the Late
98 Oligocene-Early Miocene period and includes mostly fluvial and lacustrine facies sediments, organized into three major
99 alluvial fan sequences and their associated flooding plains (Diaz-Molina and Tortosa, 1996). The alluvial fans were fed
100 from the southeastern and western boundaries of the basin and were comprised of mostly sandstones, gravels,
101 mudstones, limestones and gypsum. Towards the center of the basin, in the most distal areas, mainly lakes, mud flats
102 and salt-pans sedimentary facies associations developed. The evaporitic sequences targeted in this study were deposited
103 in these distal sedimentary environments.

104
105 The three large alluvial fans that build up the sedimentary infill of the Loranca Basin have been divided into three
106 stratigraphic units named Lower, Upper, and Final Units (Figure 1). The Lower Unit was deposited during the Upper
107 Eocene-Oligocene, during the initiation of thrusting along the Altomira Range. The Upper Unit includes mostly humid
108 conditions, alluvial fan sedimentary facies at its base (Upper Oligocene-Lower Miocene), which have been described as
109 the First Neogene Unit. Up until this period, the sedimentary sequences that are now isolated within the Loranca Basin
110 were part of a much larger syntectonic Cenozoic basinal area in the center of Iberia, the Madrid Basin (Vegas et al.,
111 1990; Alonso-Zarza et al., 2004; De Vicente and Muñoz-Martín, 2013). During sedimentation of the top of the Upper
112 Unit, the Loranca basin became endorheic due to its disconnection from the Madrid Basin, related to the emergence of

113 thrusts and formation of a topographic barrier along the Altomira Range (Diaz Molina and Tortosa, 1996). The
114 endorheic sedimentary reorganization was associated with the establishment of much arid conditions in the region,
115 during sedimentation of the Second Neogene Unit sequences. This unit includes four saline/evaporitic sequences
116 including saline clayey plains and marginal lacustrine environments, well developed in the central part of the Villar de
117 Cañas Syncline, and that correspond to the area of our tomographic survey. The Final Unit of the Loranca Basin is not
118 present within the Villar de Cañas Syncline.

119
120 In the Villar de Cañas Syncline (Figure 1b), the Cenozoic sedimentary sequences are separated from each other by low
121 angle unconformities. In particular, the outcropping Lower and Middle Miocene sediments of the Second Neogene Unit
122 are surveyed by our study (Figure 1c). They are described as the Balanzas series, made up from bottom to top by the
123 Balanzas Gypsum (Y) and the Balanzas Lower lutites (LT). The Y includes several types of gypsums alternating with
124 lutites/shales that have been grouped in three units: i) macrocrystalline and laminated gypsums (Y1); ii) gypsum,
125 shales/lutites and marls (Y2); and iii) gypsum with shaly-marly levels and gypseous alabaster (Ytr) (Figure 1). The LT
126 crops out in the core of the Villar de Cañas syncline and contains red siltstones and mudstones with some gypsum
127 and/or sands (Figure 1).

128
129 According to the Second Neogene Unit sequence, gypsum rocks are the main lithological target in the study area. The
130 definition of their internal structure and the boundaries between the different sequences are often difficult, considering
131 the heterogeneity of these deposits. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is frequently affected by diagenetic processes and, as a
132 consequence, gypsum rocks include clay, carbonates and other minerals. The presence of other minerals affects the
133 purity of the gypsum rocks and this is reflected in changes of its physical properties potentially measurable with
134 geophysical methods [Carmichael, 1989; Guinea et al., 2010; Festa et al, 2016]. However, their variability in
135 composition and their complex geometry make the characterization of these deposits challenging [Martinius et al.,
136 2002; Diaz-Molina and Muñoz-Garcia, 2010; Escavy et al., 2012; Kaufman and Romanov, 2017]. In this case, the
137 high-resolution seismic characterization of the site was designed taking into account all these structural and lithological
138 constraints.

139

140 3. DATA ACQUISITION AND PROCESSING

141

142 To provide a detailed image of the target site shallow subsurface, we designed a dense 3D tomographic survey to ensure
143 a high spatial resolution. The approximately regular acquisition grid covered an area of 500x500m. Source locations
144 were distributed in a grid of 20x20 m cells. Receivers were distributed along profiles oriented east-west, with 20m
145 spacing. Along each line, 48 receivers were distributed with a receiver spacing of 10 m (Figure 2). The seismic source
146 consisted in a 250 kg accelerated weight drop. The seismic data acquisition system consisted in ten 24 channel GEODE
147 ultra-light seismic recorders (Geometrics systems) that resulted in a 240-channel system. Each channel included a
148 conventional vertical component geophone. With the available instrumentation, the acquisition scheme required 5
149 swaths to cover the entire study area. Each swath consisted in five active receiver lines (240 channels), a total of 676
150 source shot positions resulting in a total of 3380 shot gathers. The survey was acquired and completed in two different
151 time periods (December 2013 and January 2014). The acquisition program was carefully adapted to account for the
152 special circumstances associated to the acquisition of different swath at different times, with different environmental
153 conditions (e.g. different level of ambient noise, weather changes, or potential technical problems in acquisition
154 equipment). One of the main concerns was to ensure the release of enough acoustic energy for all the available offsets,
155 especially in presence of complicated weather conditions. The 250 kg accelerated weight drop source ensured high
156 signal-to-noise (S/N) ratios in most of the shot points (Figure 3). However, some of them required ~~repetition~~ repetition
157 of the shot to improve the S/N ratio by means of raw data stacking. Despite the complexity of the seismic acquisition, the
158 recorded seismic data was of high quality and high S/N ratio and allowed a well-defined picking of first arrivals (Figure
159 3) corresponding to almost all the offset range, reaching maximum offsets of almost 700 m. The high quality of the
160 seismic first arrivals favored the semi-automatic picking of more than a half million of ~~the~~ first breaks.

161

162 The algorithm used with this data (Pstomo_eq) is a fully 3D traveltimes tomographic inversion code [Benz et al., 1996;
163 Tryggvason et al 2002]. The forward modeling is a first-order finite-difference approximation of the eikonal equation,
164 computing all the time field from a source (or receiver) to all the cells of the model (two different schemes are available
165 based on Hole and Zelt, [1995] and Tryggvason and Bergman, [2006]). The traveltimes to all receiver or source
166 positions are computed from the resulting time field and raytracing is performed backwards, perpendicular to the
167 isochrons [Vidale, 1998; Hole 1992]. The inversion is performed with the conjugate gradient solver LSQR [Paige and
168 Saunders, 1982]. One of the main requirements for a successful inversion is the selection of an appropriate initial
169 model [Kissling, 1988; 1994]. A good approximation to the minimum starting model is the use of the *a priori*
170 information available for the area, based on the surface geology and ~~for~~ the geophysical data previously acquired. In our
171 case, an initial 1D model was built based on the sonic log information available for different boreholes located within

172 the study area (Figure 2). The shallow target of the tomographic experiment and the well-controlled sedimentary
173 sequence expected at these depths, with a non-complex laterally changing geology, favored the election of very
174 ~~suited~~ ~~proper~~ initial models.

175
176 The particular acquisition pattern carried out in different swaths forced to establish a careful quality control over the
177 data. These factors may introduce some bias to the first arrivals picks (Figure 3) that could affect the convergence of the
178 inversion algorithm. To avoid any potential error associated to the different conditions during the acquisition we decided
179 to invert all the swaths independently to check the data quality and their convergence. Once convergence was tested in
180 every swath, the other swaths were gradually added into the inversion. This resulted in a relevant improvement on the
181 lateral resolution and a better definition of the final velocity model. The inversion of single swaths was also used to test
182 the dependence of the result on the choice of initial models. Different initial 1D velocity models based on the previous
183 geophysical and geological information were built to analyse the consistency with the first break picks and the
184 robustness of the inversion. The best fitting 1D model chosen provided an RMS reduction of 93% showing a clear 2D
185 trending geometry in the east-west direction. Taking into account this feature, that was also observed in the surface
186 geology (Figure 1 and, 2), as well as the borehole information, an ~~initial~~ 2D velocity model was built. This initial
187 model was then used to speed up the convergence of the calculations and to reduce the number of iterations needed to
188 reach the optimal final RMS misfit.

189
190 The inversion cell size decreased during the integration of the first arrival picks corresponding to the different swaths.
191 Due to the sparse distribution of receivers in the north-south direction the cell size corresponding to this direction was
192 the most sensitive to the addition of new traveltimes picks to the inversion. Obviously, the reduction of the inversion cell
193 size was also relevant to increase the resolution of the final velocity model, resulting in a final inversion grid spacing of
194 10x20x5 m (for x, y and z).

195

196 4. RESULTS

197

198 The inverted final velocity model shows a detailed image of the shallow subsurface of the study area (Figure 4). This
199 model provides the best fitting result featuring a final RMS traveltimes residual of 2.5 ms, which is indicative of the
200 good convergence of the inversion process. According to the raypath coverage obtained during the inversion, the
201 velocity model retrieves the internal structure of the subsurface with a maximum depth of 120 m (Figure 4), especially
202 in the central and western sector of the survey. This recovering depth decreases drastically towards the east. This was
203 partly due to the usual ray coverage decrease close to the boundaries of the survey but also to other different causes. The
204 lateral changes in surface geology in this sector affected seismic source coupling reducing the overall energy injected in
205 the subsurface and affecting the seismic source repeatability. This issue hindered the identification of the first arrivals in
206 a wide range of offsets for the shot points located in the eastern part of the study area (Figure 4). Furthermore, the high
207 velocity gradient observed at very shallow surface also affects the depth of the traced ray paths.

208

209 The direct observation of the 3D P-wave velocity model reveals several interesting features about the shallow
210 subsurface and its internal structure. The tomographic model shows that the shallowest subsurface (first 5-10 m) is
211 characterized by a very low seismic velocity. This upper layer seems to have a relatively constant depth for the entire
212 study area. Beneath, there is a velocity gradient smoother towards the northwest, slightly increasing to the south and
213 significantly to the east (Figure 4). This effect is remarkable in the northeast corner of the study area, where the velocity
214 rise from 1000-1200 m/s in the shallow surface to up 4000-4500 m/s in the first 20-30 m (Figure 4). This results in a
215 wedge geometry of the velocity model, indicating a clear northwest dipping trend of the main structural features.
216 Another significant result is the lateral changes in velocity observed in the deepest part of the model which could
217 suggest the presence of lateral lithological changes.;

218

219 Different checkerboard tests were carried out to estimate the potential resolution of the final velocity models- obtained
220 in the tomographic inversion (Figure 5). These sensitivity tests provide a qualitative estimation of the spatial and depth
221 resolution and the uncertainty of the experimental design used. The main idea is to test how well the acquisition
222 geometry (distribution of sources and receivers) is able to recover a regular distribution of velocity anomalies.
223 Checkerboard tests only provide indirect evidence of these measures [Lévêque et al., 1993; Rawlinson et al., 2016].
224 These tests illustrate where, or what parts of the subsurface models are best resolved. The information that these tests
225 reveal is similar to the resolution and covariance matrix measures obtained by other conventional schemes. For
226 example, covariance matrix methods in LSQR [Yao et al., 1999] give incomplete information, especially when sources
227 and receivers are located at surface. In this case, the raypaths are strongly dependent upon the velocity gradient which
228 implies a significant non-linearity [Bergman et al., 2004; 2006]. Keeping that in mind, several tests, ~~including~~ using
229 different size of the anomalies, were applied to our data. Two different sections, one east-west and one depth slice,
230 representative of the complexity of the study area, have been selected to illustrate the results of the checkerboard

231 analysis (Fig. 5). First of all, an east-west section located at the center part of the tomographic 3D volume shows that
232 the velocity anomalies are retrieved for the first 100 m in almost all the study area, slightly reducing its depth of
233 penetration close to the eastern sector. This fact was expected, due to the lower quality of the first arrivals of the shots
234 located in this area. The traveltime picking carried out in this area were very limited in offset, which clearly impeded to
235 reach deeper exploration depths. On the other hand, a section at constant depth shows a very homogeneous distribution
236 of the anomalies recovered of the checkerboard test. At 45-50 m depth the resolution analysis assures that the ray
237 coverage is homogeneous and well distributed throughout the entire surface. The least covered area corresponds to the
238 north and the southwest part. Although these areas corresponds to the boundaries of the study areas, where lower
239 resolution is expected, technical problems with the geophone cables forced us to disconnect 24 of the 48 channels in the
240 northernmost receiver line and 12 channels in the southwestern sector in four receiver lines in a row. In spite of these
241 acquisition issues, the checkerboard analysis demonstrates the capability of our experimental system/device to image
242 with sufficient detail the shallow subsurface.

243

244 | 4.1 Velocity model interpretation

245

246 Despite the velocity model provides a detailed image of the shallow subsurface, a direct geological interpretation is
247 | difficult, especially in terms of structural features. Interval velocities from [wellsonic](#) logs are critical for a realistic
248 interpretation of the 3D tomographic model so that the internal structure of the shallow subsurface can be geologically
249 inferred.

250

251 As mentioned above, the study area was covered by an extensive borehole drilling campaign (including geotechnical
252 and geophysical boreholes with core sampling) and a very detailed surface geology mapping which provided the
253 necessary information to properly decode the geological meaning of the P-wave velocity model. Within the study area
254 only four geophysical equipped wells were available, and used to guide the interpretation of the velocity model
255 | (boreholes: SG-29, SG-30, SG-28 and SVC-6, shown in Figure 6). The [velocitysonic](#) logs, the tailings and the core
256 samples were critical in linking the different lithologies to the geophysical responses. The lithology and the
257 tomographic image were linked by correlating the velocity profiles obtained from the tomographic model with those
258 determined from the sonic logs. This correlation required a homogenization so that the scales of resolution of both
259 methods would be comparable. The 3D tomographic images are built as velocity grids with cell dimensions of
260 10x20x5m (x, y, z). This indicates that the sampling interval in the vertical (z) direction is 5 m, while the sample rate in
261 the z axis of the logs is on the cm scale. Thus, the V_p logs needed to be re-sampled to provide average interval
262 velocities in 5 m intervals, representative of the average lithology within this interval. Two resampling approaches were
263 tested. First the log was averaged using a 5 m averaging window, and then re-sampled in 5 m intervals (Figure 4);
264 window lengths from 2.5 to 10 m were also tested, but provided similar results. A median filter approach, that avoids
265 extreme values, was also evaluated, providing a similar response, so the 5m interval average method was finally
266 selected. This homogenization step assured that scale-lengths of the features observed in both data sets were
267 comparable.

268

269 The information derived from the well logs provided constraints to interpret up to nine lithological sub-units (Figure 6).
270 However, the relatively reduced overall depth coverage of the tomographic image makes that only four of these units
271 may be identified in the velocity model (Figure 4, and 6). Characteristic lower and upper limits as well as average
272 seismic propagation velocities for P-waves were estimated for each different lithological unit using the sonic log
273 measurements, resulting in the table scale shown in Figure 6.

274

275 The gamma ray logs are the most complete logs in the available boreholes, which makes them crucial to define the first
276 lithological boundary at depth (Figure 6). The velocity data is sparser than the gamma ray data, and only the borehole
277 SVC-6, located in the center part of the study area (Fig. 2), provides an almost complete velocity log as a result of the
278 combination of the downhole data and the sonic log. The analysis of the well data differentiates a first upper layer that
279 according to the core samples corresponds to the Balanzas Lower lutites (LT). This sedimentary rock consists mostly of
280 clay minerals with large openings in their crystal structures, in which K, Th and U fit well. This fact makes the gamma
281 ray measurements ideal for its identification because they are very sensitive to the presence of natural radioactivity. A
282 sudden decrease of the gamma ray values clearly defines the transition to a new lithology (Figure 6). The direct
283 observation of the SVC-6 velocity log shows two well distinguished sections characterized by different seismic
284 velocities. The recorded values are relatively low (< 2000 m/s) for the first 10-12 m, with a sudden increase at this depth
285 up to 2200m/s, keeping this velocity relatively constant until the transition zone (~24 m) (Figure 6). The boundary with
286 the deeper formations is observed in V_p with an gradual increase in the velocity values close to 3000 m/s, that takes
287 | place in a few meters indicating a smooth transition in terms of velocities. From the log analysis it can also be derived
288 that the thickness of the LT layer is almost constant in north-south direction in the central part of the study area (around
289 20 m depth in SG-28, SG-30 and SVC-6)), increasing its thickness to 32 m in the western sector in which SG-29 is
290 | located. The lack of logging information in the [eE](#)astern part of the study area forces the interpretation to rely solely on

291 the information from the surface geology (Figure 2) The geological map shows the presence of this lithological
292 interface located in the eastern sector of the study area, with an approximate orientation N-S being sudden moved to the
293 ~~w~~West in the middle part of the study area. This interface puts in contact the lutites layer with the next lithology
294 identified in the core samples. This fact suggests that the layers dip gently to the ~~w~~West supporting the wedge geometry
295 observed in the tomographic model and following the regional scale geologic interpretations [Biete et al 2012; Piña-
296 Varas et al., 2013].

297
298 Just beneath the LT layer, the core samples show the presence of a gypsum-lutite transition layer of nearly constant
299 thickness in most of the study area (at least ~~where the~~according to the logging information ~~is~~-available) with a local
300 increase in thickness in the ~~w~~Western sector. This unit, called Ytr, belongs to the Second Neogene unit and is
301 characterized by mainly gypsum with centimetric to metric intercalations of shaly/marly levels. These lithological
302 changes are characterized by a high variability in the recorded sonic and gamma ray log values. The presence of these
303 gypsiferous shales are clearly observed in the gamma ray logs, featuring high peaks related to the shaly intercalations.
304 In the sonic logs, the velocity seems to increase in the upper part of the unit with a decrease that coincides with higher
305 presence of the shaly-marly levels (increase in the gamma ray log): Close to the transition to the next lithology, t~~h~~e
306 sonic log seems to recover the velocity values observed in the upper part.

307
308 A great increase in the velocity together with a sudden decrease in the gamma ray values indicates the transition to a
309 thick lithological sequence of gypsum in depth. In terms of borehole logging several subunits can be inferred according
310 to the different signatures observed. However only two of these gypsum units, defined in the geological setting, can be
311 observed/~~correlated~~ in the tomographic model taking into account the depth achieved with the acquisition geometry
312 used. The upper unit (Y1) is defined by higher values of seismic velocities (~4250m/s) than the deeper unit (Y2)
313 (~3800m/s).

314
315 The identification of the main lithological units by means of the logging data and the core samples provides a solid link
316 between the geology and the physical properties that allow us to lay out a structural interpretation the 3D tomographic
317 volume. The standard deviation of every averaged velocity value was used to estimate ~~a~~ rough velocity range
318 corresponding to each lithology but also provided a ~~qualitative measurement uncertainty measure of the quality~~ of the
319 assigned velocity to the different lithologies. This criterion was then used to correlate each P-wave velocity value of the
320 mesh to the defined lithologies (Figure 7). Looking at the velocities table, the LT layer seems to be the most well-
321 established value, according to the standard deviation obtained, which is the lowest (90 m/s). Nevertheless, that this
322 layer was defined only by using the deeper portion of the log data corresponding to this section, which probably
323 corresponds to the higher velocities for this formation neglecting the low values that should be expected at shallow
324 depths ~~due to weathering, unconsolidation etc.~~ which ~~would~~it significantly increase the standard deviation. This is the
325 case of the Ytr layer which features a standard deviation of 400 m/s which clearly reflects the high variability of the
326 seismic velocities observed in the sonic logs.

327
328 This velocity analysis allowed us to re-image the tomographic models based on the ranges of velocities defined from
329 the well log data. In this way, we could map the defined lithologies in the velocity model defining their respective
330 boundaries. As a result of this interpretation, different velocity ranges had no direct assignment of lithologies, result of
331 the lack of overlap in the guided interpretation. These observed gaps mainly affects to the definition of the limits
332 between units which introduce a qualitative measure of their ambiguity (Figure 7)

333
334 ~~This velocity analysis allowed us to re-image the tomographic velocity model, this time assigning the different~~
335 ~~lithologies to the assigned velocity ranges observed in the well log data (Figure 7 and 8). In this way, we could map the~~
336 ~~four lithological units within the velocity model, clearly defining their respective boundaries and other structural~~
337 ~~features which characterize the shallow subsurface of the test site.~~

338

339 5. DISCUSSION

340
341 The direct observation of the guided interpreted tomographic model allow us to provide geological meaning to the main
342 features previously described. The defined upper boundaries presents an undulating character that reveals a channel like
343 structures with an east-west orientation. Note that the sedimentary environment during the Upper Oligocene-Lower
344 Miocene was meander set up [Diaz-Molina, 1993]. Furthermore, the LT and the Ytr layers appear to increase their
345 thickness towards the west keeping it constant in the north-south direction (Figure 7, and 8) which indicates that the
346 gypsum layers are dipping towards the west. This coincides with the wedge geometry clearly observed in the
347 tomographic velocity models (Figure 4). The latter was also suggested by the regional scale geology and other
348 geophysical studies [Biete et al., 2012; Piña-Varas et al., 2013].

349

350 | ~~The direct observation of the different lithological domains identified in the guided interpretation reveals several~~
351 | ~~interesting general features (Figure 8). The defined upper boundaries feature an undulating character that reveals~~
352 | ~~channel-like structures with an east-west orientation. Note that the sedimentary environment during Upper Oligocene-~~
353 | ~~Lower Miocene was meander set up [Diaz-Molina, 1993]. Furthermore, the LT and the Ytr layers appear to increase~~
354 | ~~their thickness towards the west keeping it constant in the north-south direction (Figure 7, 8 and 9) which indicates that~~
355 | ~~the gypsum layers are dipping towards the west. This coincides with the wedge geometry clearly observed in the~~
356 | ~~tomographic velocity models (Figure 4 and 7). The latter was also suggested by the regional scale geology and other~~
357 | ~~geophysical studies [Biete et al., 2012; Piña-Varas et al., 2013].-~~

358 |
359 | In order to validate the accuracy of the logging guided interpretation of the tomographic model, several 2D velocity
360 | sections in depth were extracted following different existing east-west and north-south geological profiles. Those
361 | selected profiles corresponds to geological cross-sections based on data collected at surface and the interpretation of the
362 | core samples of the existing single boreholes. Besides, the interpreted boreholes used in this study were also projected
363 | to the closest profiles, thus providing additional information to compare and evaluate the final structural interpretation
364 | of the 3D velocity grid. In addition to these wells (SG29, SG30, SG28 and SVC6), two more interpreted wells were
365 | projected (SVC4 and SVC3) to provide geological interpretation to the uncovered areas. Unfortunately, in these two
366 | wells there were no available velocity logs.

367 |
368 | ~~The definition of the different lithological boundaries was one of the main objectives of this study~~
369 | ~~The definition of the~~
370 | ~~different lithological boundaries was of great interest in this study.~~ In this sense, the resulting images show a general
371 | good agreement between the geological cross-sections, the interpreted boreholes and the tomographic models, in terms
372 | of boundary definitions, geometry and depth throughout all the 3D volume (**Figure 89**). The matching between hard
373 | data (surface geology plus well-log data) and soft data (seismic tomography) is quitevery consistent taking into account
374 | the different criteria used and resolution to define the lithological changes in depth. The correlation between both
375 | interpretations is particularly significant in the central part of the study area, where the lithological boundaries defined
376 | in the geological cross-sections even show changes in dip and undulating geometries also retrieved by the seismic
377 | velocity models. In those areas, the comparison between the interpreted boreholes projected to the velocity profiles is
378 | also in good agreement (**Figure 89**). Nevertheless several discrepancies are observed in specific areas, specially located
379 | on western and eastern ends, affecting to different lithological layers, which need to be addressed in detail to finally
380 | validate the tomographic models.

381 | From depth to surface the first units identified are Y1 and Y2 (~~Figure 8~~)(**Figure 6**). From the previous geological
382 | analysis, this gypsum units are characterized by a complex internal structure with no clear defined boundary, continuous
383 | lateral changes and the presence of widely disperse massive gypsum bodies. The tomographic model seems to
384 | corroborate this by showing a quite complex distribution of these two units in the 3D velocity volume. Unfortunately,
385 | the depth resolution of the tomographic model together with the velocity inversion observed between the Y1 and Y2
386 | (Figure 4) makes very difficult to provide a reliable retrieval of the seismic velocities associated to each lithology. This
387 | issue is well described in the literature, such as in the one described in Flecha et al. (2004). These aspects together with
388 | the smooth character of the seismic tomography leads to consider these gypsum units as a unique lithology, focusing in
389 | the upper boundary definition and avoiding the definition of the complex internal structure. Besides, this objective was
390 | beyond the scope of the study and from an engineering point of view, both lithological units can be considered as one
391 | unit in terms of mechanical response.

392 |
393 | The upper limit between Y1+Y2 (Y) and Ytr is relatively well constrained in almost all the area, especially when
394 | compared with the log interpretation. Changes in dip and variable geometries in depth observed in the geological cross-
395 | sections are also imaged by the guided interpretation of the 3D velocity model (**Figure 89**). The well contrasted seismic
396 | velocities between both lithologies observed in the well logs help in the boundary definition which does not show too
397 | much ambiguity. Nevertheless, the limitations of the seismic tomography mentioned before, , although the previously
398 | mentioned limitations of seismic tomography for these lithologies makes impossible to reach the seismic velocity
399 | ranges expected for the gypsum units according to the logging data (Figure 4).The tomography velocity model clearly
400 | suggests the velocity inversion in some of the profiles (i.e. profile c9i in **Figure 89**) at this lithological level showing
401 | the complex distribution that can be inferred from the velocity logs interpretation.-

402 |
403 | ~~The tentative interpretation of the Y1 (Gypsum 1 in **Figure 8**) clearly does not correspond to this lithology which should~~
404 | ~~be the unit defining the upper boundary of this gypsum sequence; however it is presented in the results because is~~
405 | ~~indicative of the presence of these isolated massive gypsum bodies that are observed and well defined especially in the~~
406 | ~~eastern sector of the study area, some of them very close to the surface.-~~

407 |
408 | Quite different is the LT-Ytr boundary definition which seems to be underestimated in depth location as we move to the
409 | western sector of the survey area (**Figure 89**). Several considerations can be taken into account to understand this

410 mismatch observed between different interpretations. First, this lithological boundary is relatively diffuse because of the
411 presence of the gypsiferous lutites as intercalations distributed within the gypsum rock. This fact is the cause of the
412 appearance of peaks of higher velocity in the sonic logs which are responsible for the increase in the average velocity
413 for the Ytr unit. Unfortunately, due to the acquisition geometry, the resolution that characterizes the tomographic model
414 is not able to differentiate between these intercalations/~~interfingering~~ (lenticular shape layers of centrimetric to metric
415 scale) within Ytr which would have helped to define this boundary in greater detail. As mentioned above, we resampled
416 the velocities from sonic logs to correlate their velocities to the tomography results As a result, the averaged velocity
417 associated to Ytr is characterized with a high standard deviation (**Figure 6 and 8**). This increases the uncertainty of Ytr
418 identification in the whole tomographic 3D volume which induces some mismatch in the unit identification.

419
420 On the other hand, the location of the boreholes used for the guided interpretation of the tomographic model also can
421 account for these observed discrepancies. Most of them (SG-28, SVC-6 and SG-30) are located in the central part of the
422 study area and besides they are aligned in the north-south direction. Thus, the weight of these three boreholes in the
423 estimation of the velocity intervals in both lithologies involved is significant and introduces a bias for the rest of the
424 tomography guided interpretation. According to these wells, the lutites have a quite similar thickness placing the
425 lithological boundary at a relatively shallow depth (around 20 m) compared with the same boundary in the western area
426 which is located at a deeper level. This implies that the velocity derived from the boreholes for the LT layer is most
427 probably underestimated in relation to the expected velocities for this lithology at this part of the survey. The effects of
428 the soil compaction, due to the layer thickening in this sector, could increase the velocity of the lutites at depth. This
429 fact and the incompleteness of logs at shallow depths are responsible of the low standard deviation associated to this
430 lithology which, together with the high values associated to the Ytr unit, This fact but also the standard deviation
431 associated to the Ytr unit seems to be a strong effect in the delimitation of this upper boundary when moving to the
432 west. All theseBoth factors introduce a high ambiguity in some areas of the model which lead to a mismatch between
433 the different interpretations: This can be observed in the velocity sections presented in Figure 9: In general, the east-
434 west velocity sections show a better match between geological and tomographic delineation as we move eastwards.
435 Profile c5i shows a clear example of the impact of all these mentioned factors. The mismatch between models and the
436 interpreted wells is very high in the western sector decreasing close to well SVC4 in which a high uncertainty in
437 lithological boundary is observed. In the east-west velocity sections there is also a similar effect, although showing a
438 better match between geological and tomographic delineation of this boundary as we move eastward. On the other hand,
439 the north-south sections also show definitive evidence of this. Profile c-9i presents a general good agreement between
440 both interpretations. Note that this profile is practically aligned with boreholes SG-28, SVC-6 and SG-30.
441 Conversely, section c-8i shows a clear discrepancy since it is located further to the west in relation to the c-9i profile
442 (Figure 8):-

443
444 The tomographic velocity model suggests the presence of a shallow weathered layer (warm colors in Figure 4). This
445 layer is clearly observed on the field, the surface mapping and the core samples recovered in most of the geotechnical
446 boreholes. These observations show that this very shallow layer have two different lithologies that correspond to lutites
447 (LT) at the northern and western sector of the study area and also transition gypsum (Ytr) in the eastern sector (Figure 2
448 and 6). This upper weathered layer seems to be characterized by low velocity values though, from a seismic velocity
449 point of view, both lithologies are barely distinguishable. Furthermore, the guided interpretation of the tomographic
450 model is also unable to retrieve this layer basically due to the incompleteness of the sonic logs at shallow depths (only
451 downhole data in available for SVC-6) (Figure 6). This is specially significant for the weathered Ytr unit which has no
452 recorded data to estimate its seismic velocity at shallow surface. For this reason, in the guided interpretation this
453 identified weathered layer has not been considered as a differentiated boundary. However, the surface geology offers a
454 perfect way to define the boundary associated between both lithologies in this upper weathered layer (Figure 8).
455 Methodologically it indicates that the direct mapping/correlation between velocity and lithology might not be applicable
456 when the influence of other factors is relevant. Weathering affects the physical properties of the lithology that is
457 outcropping, decreasing velocities characteristic of the Ytr to values below 2100 m/s, the upper limit criteria used to
458 identify the LT.

459
460 The imaging of the LT-Ytr transition cannot be accomplished using only the tomographic velocity model, according to
461 the borehole logging data available. More borehole logging data in representative locations of the velocity model are
462 needed to better constraint the velocity range assigned to each lithology, which in turn would enable to improve the
463 velocity ranges and reducing the standard deviations for each unit. A complete sequence for the sonic logs, from surface
464 to the maximum depth, will be very useful to further constraint the weathered layer and maybe it could offer a clue to
465 differentiate at surface lutites from gypsum from a seismic velocity point of view. Nevertheless, seismic velocity alone
466 seems to have some limitations to clearly define both lithologies or at least there is no a clear and unique distinctive
467 signature for these two lithologies. For this reason, we believed that adding other physical properties (e.g. resistivity or
468 porosity) could improve the definition of the LT-Ytr transition.

470 One of the main concerns is the presence of dissolution cavities within the evaporitic sequence, especially taking into
471 account the possible host of a singular infrastructure. In this sense, traveltimes tomography is very limited in recovering
472 the location, geometry and velocity values expected for a cavity. Besides this is particularly more difficult if only
473 surface seismic data are used in the inversion (Flecha et al., 2004). In case of the presence of a cavity, the wavefront do
474 not propagate through it and the first arrivals are only capable to record the perturbation due to the large velocity
475 contrast at the edge of the velocity anomaly. Fortunately, the density ray diagrams revealed as an appropriate tool to
476 define the presence of cavities which is characterized by a very low or a lack of ray coverage. Taking [this](#) into account
477 [this](#), the analysis of the ray coverage diagrams derived from the traveltimes inversion do not show any evidence of this
478 fact which implies that no cavities are characterized, at least at decametric scale (Figure 4, 5 and 7). Furthermore, the
479 extensive borehole campaign carried out on site also showed no evidence of the presence of cavities in the shallow
480 subsurface.

481
482 On the other hand, the presence of potentially active faults in the area is also a main issue in hazard analysis and risk
483 assessment. For this reason, the study of the presence of any non mapped minor fault and the characterization in depth
484 of mapped ones was also of interest. The study of instrumental and historical seismicity showed that the area was
485 tectonically stable with a very reduced amount of seismic events in the area and of very low magnitude. Furthermore
486 the paleoseismic studies by means of trenches revealed that [there is no does not exist any](#) evidence of recent seismic
487 activity related to any fault system. In the same way, the analysis of the tomographic velocity model supports these
488 statements about evidences of recent faulting responsible of any seismic activity that it could constitute any risk. The
489 lithological units imaged by the velocity models [do](#) not show any evidence of faulting which indicates that this
490 sedimentary package has not been affected by any recent activity (Figure 7, [and 8-and-9](#)). This fact supports the
491 evidences showed by other studies carried out in the area.

492
493

494 6. CONCLUSIONS

495

496 The detailed 3D structure of an evaporite sequence in the Villar de Cañas syncline (Cuenca) has been revealed by using
497 high resolution shallow seismic tomographic inversion of first arrival traveltimes. The local tomographic image of the
498 evaporite sedimentary sequence allows observing undulating structures in the base of the boundary layers. The
499 tomographic Vp velocity model interpreted with the aid of additional geological and geophysical observations, such as
500 Vp measurements from sonic logs and core description from boreholes provided a detailed mapping of the different
501 lithologies that build up the sedimentary evaporite sequence. Additional constraints coming from sonic and gamma ray
502 logs were proven to be critical in the interpretation of the inverted velocity model, allowing identification of the detailed
503 features and geological structures at depth. Well logs and surface geology data allowed interpreting the different
504 lithologies in the seismic image. The constraints used consisted in average Vp values and Vp ranges for the different
505 lithologies identified from the description of the core samples extracted from the boreholes. This provided the basis for
506 a pseudo-automatic (geophysically-driven) interpretation, where model cells were assigned to a specific lithology
507 according to the Vp value of the corresponding node of the mesh. Despite the relatively complex structure and
508 composition of the target area, the guided interpretation scheme presented in this study results in a very powerful
509 procedure to extract structural information from velocity models. However, the consistency between the model and
510 interpretation reduces its effectiveness when trying to resolve areas characterized by a high uncertainty in the guided
511 interpretation. This is particularly true for the uppermost layers where discrepancies can be accounted for by different
512 factors including: the irregular distribution of the boreholes and logging information; overlapping Vp values for
513 different lithologies/composition; the influence of physical conditions (pressure, temperature, water content). Therefore,
514 in those areas the direct mapping/correlation between velocity and lithology might not be applicable without the help of
515 other constraints, e.g. other geophysical parameters that can provide additional information to distinguish specific
516 lithologies.

517

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519

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731

732 Figure Captions

733

734 Figure 1. (a). Simplified geological map of the Iberian Range in eastern Iberian peninsula, with the location of the study
735 area marked in black box, (modified from Guimerà et al. (2004)). (b) Local geological map of the Villar de Cañas
736 syncline. The target area is marked by a blue rectangle. The 2D seismic reflection profiles acquired in this experiment
737 are also located in the map. (c) Detailed stratigraphic columns describing the main units observed in both flanks of the
738 syncline.

739

740 Figure 2. Geometry of the acquisition experiment. Red dots are position of the source, white dots are the position of the
741 receivers. Receivers consisted in single vertical component exploration geophones connected to an array of 10 GEODE
742 (Geometrics) data acquisition system. Light blue dots indicate drilled boreholes. Weight drop (250 kg) used (from the
743 Inst. Superior Tecnico Lisbon, Portugal)

744

745 Figure 3. Example of shot gather recorded by the array of 10 GEODES, 24 channels each. The red ticks indicate the
746 traveltime picks of the firsts arrivals used as inputs for the tomographic inversion. [Trace balancing \(window times: 0-
747 1500 ms\) has been applied to the data for display purposes.](#)

748

749 Figure 4. (a) 3D Seismic compressional wave velocity model (V_p) derived from the over 500.000 traveltime picks of
750 the first arrivals in the shot gathers. The velocity range goes from nearly 900 m/s (reds) to over 4500 m/s (blues). (b)
751 Comparison between the smoothly resampled V_p log derived from the sonic at borehole SVC-6 (light blue) and the
752 vertical V_p profile extracted from the block at the location of the SVC-6 indicated by a black arrow in the block. The re-
753 sampling of the log was carried out so that it would be comparable to the grid size used for the parametrization of the
754 velocity model which in this case is of 10x10x5m.

755

756 Figure 5. Checker-board tests; [synthetic recovery test](#) taking into account the real acquisition geometry on a model
757 involving velocity anomalies of dimensions [50x75x25m](#), [75x50x25m](#), [approximately and 10% velocity perturbation](#).
758 [Checker-board analysis is a conventional](#)
759 [scheme to assess the resolution of the tomographic inversion approaches \[Leveque et al., 1993; Rawlinson et al.,](#)
760 [20154\] \(a\) Cross-section of the input synthetic velocity model consisting of box anomalies. -Corresponds to a cross-](#)
761 [section of the input synthetic velocity model consisting of box anomalies. \(b\) Cross-section across the recovered](#)
762 [velocity model. The shot points \(black dots\) define the topography, with respect to the reference level of the inverted](#)
763 [model, below which velocity recovery takes place - Corresponds to a cross-section across the recovered velocity model.](#)
764 [The best resolution is between 25 and 75 m depth. \(c\) Depth slice \(map view\) across the input model showing the](#)
765 [synthetic velocity anomalies. Corresponds to a depth slice \(map view\) across the input model showing the synthetic](#)
766 [velocity anomalies \(squares\). \(d\) Depth slice across the recovered velocity model at a 45-50 m depth with respect the](#)

767 | reference level of the inverted model. Corresponds to a depth slice across the recovered velocity model at a 50 m depth.
768 | (e) Acquisition geometry showing the location of the vertical section of (a and b). Is the acquisition geometry, the red
769 | line near the top corresponds to the location of the depth section of (a). In the cross sections and depth slices red
770 | corresponds to low seismic velocity and blue high values of seismic velocities.

771 | -
772 | Figure 6. Drill-holes in the target area with the borehole geophysical logs used in this study. This reveals the correlation
773 | between the rock samples, its description and the values of the physical properties, Gama ray (GR), sonic logs (Vp).
774 | The top part of the figure reveals the logging data with the correlation between the available boreholes. The bottom
775 | table defines the summary criterion used for the interpretation of the different lithologies. The Vp value should be
776 | representative of the corresponding lithologies. This criterion is used later in the text to differentiate between the
777 | different lithologies in the velocity cube obtained from the tomographic inversion. The left box illustrated the location
778 | of the boreholes within the acquisition geometry of the seismic survey, with the outcropping geology of the target area.

779 | -
780 | Figure 7. a) 3D seismic velocity model grid of the shallow subsurface color coded according to the interpreted
781 | lithologies derived from Figure 6. Four different units has been identified LT, Lutites; Ytr the gypsum-lutite transition
782 | layer; Y1 and Y2, Gypsum units. b) Diagram showing the velocity ranges established and the gaps between them. These
783 | gaps correspond to seismic velocities that do not have lithologies assigned.

784 | Figure 7. Velocity model grid of the shallow subsurface, it has been color coded according to the lithologies indicated in
785 | the included scale/table which is the one derived in Figure 6. LT, Lutites; Ytr the gypsum-lutite transition layer; Y1 and
786 | Y2, Gypsum units.

787 | -
788 | Figure 8, 3D Volume representations of the different lithologic units. LT, Lutites; Ytr the gypsum-lutite transition layer;
789 | Y1 and Y2, Gypsum units.

790 | -
791 | Figure 89. Resulting shallow subsurface structure represented as detailed cross-sections. Cross-sections integrate the
792 | velocity model derived from the tomography, the constraints provided by the boreholes and the extrapolation of surface
793 | geology data (in discontinuous drafted lines). Four different east-west and north-south cross-sections are showed with
794 | their locations within the study area. Note that towards the east (in the geological map), the Ytr outcrops at surface, as
795 | well as the Y unit. This revelas that the entire layered sequence dips to the west.

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