AUTHOR RESPONSE TO RC1 (Vedad Hadziavdic)

We try to summarize below the referee main comments and the authors response, along with the actions and changes done to improve the previous manuscript. We have also clarified some points when needed.

GENERAL COMMENTS:

"Awareness about significance of structural uncertainty in the subsurface models and its effects on costly decisions has risen sharply in the oil industry over the last decade. Commercial tools to model and simulate structural uncertainty have become easily available, either as stand-alone applications or fully integrated in widely used reservoir modeling software packages. However, understanding how the uncertainties affect the results, how to parametrize the models (determine priors, trends, variograms), or how to use results (which are probability distributions) remains a challenge. The bridge between statistics on one hand and geophysics and geology on the other is still not easy to cross for a typical geoscientist. The paper touches upon some of these issues in an interesting case-study. It is nicely structured. It starts with a clear motivation and a nice overview over the most important elements needed to be considered. It continues with a description of the geological setting for the reservoir.

The dataset if described very shortly and lacks some important information, which should be included when assessing the uncertainties discussed in the paper.

The paper continues to discuss specifics of the uncertainty modelling for both horizons and the faults. Fault uncertainty modelling is not often included in the structural modelling, due to several reasons. The authors demonstrate the importance of fault uncertainty on the observed differences in GRV. In the interpretation of the results, the authors show how structural uncertainty affects GRV and distribution of oil in the reservoir. They use clearly the cross-sections of the reservoir, histograms and box-plots to describe the effects of structural uncertainty.

What lacks in the paper is a more detailed discussion about two important issues.

The first one is related to the specification of the interpretation uncertainty. What type of seismic survey is used? How is the frequency content related to the width of the envelopes used in manual uncertainty picking? What is the main source of uncertainty in picking top reservoir?

The second issue is related to what affects uncertainty in top structure. It is a combined effect of uncertainty in velocity model, uncertainty in well picks and seismic interpretation. For a reservoir at this depth (time), depending on the choice of velocity model, velocity uncertainty could have a much bigger impact on the structural uncertainty than time interpretation. By including only one, and leaving all others out, what may happen is often called "ballooning effect". All the other uncertainties are squeezed and their effect pops out in an ambiguous way within the time interpretation uncertainty. This might lead to overestimating the effect of picking uncertainty on the top structure.

The paper is however interesting and shads light on an important topic which needs more investigation."

Authors comment: We are very grateful for your general comments and suggestions. We agree with the reviewer that the dataset should be presented with more details and that the discussion should be completed with regards to the relationship between the uncertainty envelopes and the type of seismic data used. It is also important to comment that the effect of the interpretation uncertainty in picking the horizons and faults could be overestimated if the others uncertainties are not included (i.e. velocity and well pick uncertainties).

Following these comments, we have tried to improve the manuscript by completing the description of the dataset and also the discussion section:

- Regarding the dataset, the seismic data used in this work is a pre-stacked time migrated seismic cube. It was acquired and processed in 2006. A conventional acquisition system with a bandwidth between 8 – 80 Hz was used. The frequency content ranges from 20 to 40 Hz and the time window for the seismic picking is 20 ms. The vertical resolution of the seismic data is 45 m.
  The velocity model for the time-to-depth conversion was built using a 3D root-mean-square migration velocity field that was calibrated with velocities from wells (using a sonic log and a check-shot survey). Interval velocities ranged from 1528 m/s to 5028 m/s.

  This information has been included in the corresponding Dataset section of the revised version of the manuscript.

- Regarding the two issues to be discussed, we have added a new discussion section ("5.3 Seismic survey and other sources of structural uncertainty"), where we have commented the relationship between the envelopes and the frequency content, and the importance of capturing the velocity uncertainty.

SPECIFIC COMMENTS:

Specific comment #1: "In Section 3.1. the authors introduce uncertainty envelopes around initial horizons. They base the uncertainty on variations in diffractions and amplitude of the data. Judging from the example and illustration in Figure 4., diffractions do not seem to play a role in the picking uncertainty. In general, it is difficult to see clear footprint of diffractions (smiles) in the seismic presented in the work. What seems to guide uncertainty picking in Figure 4. is frequency of the seismic event (Top lower BTG Lubina). The lower the frequency, the higher picking uncertainty is introduced.

It is not argued why this should be the case. In broadband surveys, which contain more low-frequency information, the seismic image displays wider reflection "bands". At the same time, increased low frequency content provides higher resolution in the seismic. This means that picking visually might seem more ambiguous. At the same time, the increased resolution will improve detection of elastic changes in the subsurface.

A counter example is a conventional survey with narrow frequency band. Such a survey will suffer from dominant side lobes in the wavelet. Visually, they seem to provide higher frequency content and narrow reflection events which are easy to pick. Typically, a geologist will prefer to pick on such seismic. However, this is an erroneous assumption, which will lead to overconfidence in picking based on events which do not represent real elastic changes in the subsurface.

More information about the seismic survey, tuning effects and frequency content should be provided to be able to specify picking uncertainty in a more confident way. As it is demonstrated in the paper, these prior uncertainties are very important away from the wells."

Authors comments: Thank you for your comment. We totally agree with you in that we have not commented properly how the manual uncertainty envelops have been defined and that discussing the relationship between the frequency content and the uncertainty envelopes has not been sufficiently considered in the earlier version of the manuscript.

Different actions in the revised version of the manuscript have been done:

- We have specified that the size of the envelopes in the manual uncertainty case vary according to frequency content events, lateral variations of amplitudes along reflectors, diffraction areas and how the reflectors terminate around fault surfaces when fault reflections are not present in the seismic image. This has been changed in the Abstract (P1L21-23); in section "3.1 Manual and constant uncertainty workflows" (P6L14-15 and P6L19-23); in section "3.2 Fault uncertainty modeling" (P7L20-23); in section "3.3 Horizon uncertainty modeling" (P8L7-8); and in section "6 Conclusions" (P16L1-2).
- Some discussion has been added in new section "5.3 Seismic survey and other sources of structural uncertainty".

Specific comment #2: "In Section 3.3. the prior model is presented in detail. For the spatial continuity of the residuals, spherical variogram is chosen, which is reasonable choice for this kind of applications. However, the variogram range was set to 500m, based on the argument that it should not be more than half the reservoir width (Section 5.3). The expected lateral continuity of the geological layering is mentioned but not further discussed. The range of 500m is very short for most of the structural settings. The kriged depth surfaces will be uncorrelated for distances larger than 500m. However, already at much shorter distances (e.g. 250m), spherical variogram will only require weak correlations. If the prior uncertainties are large, and there are few data points in the data set, the simulated surfaces will exhibit large depth fluctuations over short distances. On one hand, it is geologically questionable. On the other, it will lead significant local changes in GRV which might not be realistic or informative.

This is to some degree illustrated in Figure 6 (b) where significant changes in depth over short distances can be observed in some areas, which apparently are not related to fault transitions."

Authors comments: Thanks for this comment. We think that some clarification to this point is needed.

The variogram range does not control the correlation distance of a simulated horizon independently of other parameters like the trend uncertainty, but accounts for the correlation of small-scale variations in the depth of the horizon. These small-scale local variations are associated with differences between the position of the trend and the well data, and also with the frequency content, the amplitude of the reflectors and the presence of diffraction zones that make the picking of the horizons uncertain.

The residual is described by two components: vertically, by the standard deviation maps generally derived from the interpreted envelopes in the seismic interpretation, and laterally, by the variogram. Therefore, the variogram range only represents the horizontal continuity of the small-scale variations of the simulated horizons.

The trend controls the large-scale variations. The final position and geometry of a simulated horizon results from the sum of the trend and the residual. This is illustrated in fig. 6. In the example of this figure, the horizon represented in (c) is a simulated horizon corresponding to the sum of the trend shown in (a) and the residual shown in (b). As it can be noted, the depth and the general geometry of the simulated horizon is very similar to those of the trend, indicating that the trend uncertainty exerts an important control on the simulated horizons. In the example shown in fig. 6, the residual represent variations in the horizons depth of about 0.05%.

To clarify this in the text, we have replace the sentence "represent the expected lateral continuity of the geological layering" in line 31 of page 12 in the original manuscript by "accounts for the correlation of small-scale variations in the depths of the horizons" in the revised version of the manuscript.

*Specific comment #3: "As the uncertainty in velocity model could strongly dominate the total uncertainty in the structure, the model needs to be presented and some discussion needs to included. The uncertainty in depth can be roughly described as d(Z)=d(V*t)=dV*t + V*dt. Considering time of the event, average velocity and uncertainty in both variables, the effects of the two can be roughly compared.*

Quite often, changing the time interpretation does not change the depth surface significantly, given a large uncertainty in the velocity.

Authors comments: As commented in the manuscript, the objective of this paper is to capture the uncertainty in the seismic interpretation, although we agree with the referee that other uncertainties like the uncertainty in the velocity model or in the well data are also important structural uncertainties that deserve much attention. Following your recommendation, we have presented the velocity model in section "1.2 Dataset" (as commented in the Authors response to the General comments). We have also completed the discussion section by including some estimations of the velocity uncertainty, comparing them with the uncertainty in picking the horizons and by commenting the importance of investigating the uncertainty in the velocity model in future works. This part of the discussion has been linked to that of the "ballooning effect" (see new discussion section "5.3 Seismic survey and other sources of structural uncertainty").