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Interactive comment on "Formation of linear planform chimneys controlled by preferential hydrocarbon leakage and anisotropic stresses in faulted fine-grained sediments, Offshore Angola" *by* Sutieng Ho et al.

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Answers to comments of Reviewer 1 A. Plaza-Faverola

Answer Part 1

(Due to the word limitation of the online system, the answers to comments are divided into two parts)

1. Author's response to summary

The authors would like to take this opportunity to thank the reviewer's for their extensive review and helpful insights into the readability of the paper and raising specific technical questions and queries. A major theme in the reviewer's comments is on clarity of explaining the key results, summarising the main themes and simplifying and/or clarifying figures and their connection to the text. The authors propose that the manuscript now go through a revision phase to address these broader issues and in doing so complying with the reviewer's general comments. Below are specific answers to the reviewer's questions. Review questions are in bold and the authors responses are below. Hopefully the authors have addressed the reviewer's concerns with adequate responses.

2. Main points:

â ËŸA′c Polygonal faults: the core of the paper is the relation of shallow gas accumulations and chimneys with the presence of polygonal faults. Although the authors do reference key studies related to polygonal faults (identiïňĄed in the area but also globally), I think that a little bit more emphasis on describing the main aspects of such faulting is needed in the paper. I usually think of polygonal faults as those faults forming "polygons" in ïňĄne-grained sediment sequences. I realize that in this paper there are also radial faults associated with the synclines next to the salt diapirs that are as well referred to as polygonal? Are these termed polygonal faults because the mechanism of formation is similar to the other ones? How exactly do they form? Do they really reactivate?

The reviewer's questions are all valid and the authors will work to address the wider issue of clarity with regard to faulting. The classification and debate on the genesis of polygonal faults has evolved quite a bit over the last decade or so and with improvements in the resolution and coverage of 3D seismic data geoscientists have been offered atypical examples of the fault system to study and a chance to explore the finer details of these systems. One such detail is in the geometry which across a number of basins now show a departure from the classic "polygonal" pattern that has been observed previously. This has implications for understanding variations in the in-situ stress state at the time of faulting (expanded later).

At the time that polygonal faults were first mapped in 3D seismic data, for example in the North Sea (cf. Cartwright, 1994), the first question to resolve, was the origin of the faulting and the "polygonal" geometry was central to that discussion. Summarising; the presence of discrete tiers of normal faults in a passively subsiding, largely non-tectonic basin, was paradoxical since uniform 1-d compaction does not typically coincide with normal faulting. The "polygonal" geometry also suggested a non-tectonic setting as the wide range of fault strikes indicate horizontal stress isotropy which are typical of horizontal or only very gently dipping strata undergoing uniform compaction. Polygonal faults can also form where there is isotropic horizontal extension above a rising and widening, symmetrical dome but this setting clearly does not account for such vast systems in the North Sea and other places. It was later postulated that syneresis (shrinkage) caused volumetric contraction during burial and compaction of the host sediments which resulted in the next extension that produced the fault systems. Because this driver for faulting occurred in an environment of largely horizontal stress isotropy the faults developed as polygonal planforms. Other more sophisticated mechanisms have been put forward recently such as diagenetic processes. Nevertheless at the time of discovery, the name polygonal aptly described the geometry of the faults but as more systems were recognised their name was also referring to the mystery process that formed them.

There is no reason why the process generating polygonal faulting should be restricted to non-tectonic basins so what should happen in settings where there is a phase of re-

activation, diapirism or gravity tectonics? One may expect that the horizontal stresses would not be isotropic in these settings and that compaction and contraction-related faults would form with preferred alignments. A PhD study undertaken by one of the authors (Carruthers, 2012) investigated two basins where such environments exist and put forward a comprehensive list of justifications for the presence of non-polygonal, a sort of hybrid "polygonal" faults. The obvious issues that arise from this work is the usage of terminology because most geoscientists are now familiar with the fault family "polygonal faults" but the examples known to date are increasingly non-polygonal. In this paper, we acknowledge previous work on polygonal faulting on timing, genesis and interpretation but will use the revision phase of the manuscript to clarify the terminology of polygonal faults (faults having formed during early compaction and contraction of very fine-grained sediments) but which have preferred alignments. Responding to the reviewers question regarding reactivation; there is no reason to treat reactivation of "polygonal" faults as different from any other fault systems. If a stress is applied to the fault is great enough to overcome the strength of the host-media and propagate the fault tips the fault will propagate. In some of the classic North Sea examples of polygonal faults, and even here, polygonal faults are organised in tiers. The nature of tier boundaries, especially the upper ones, are still not well understood. There have been some indications in some basins to argue for an upper mechanical boundary to upward fault propagation. Most of the time, polygonal faults define the seal package in petroleum basins and rarely return detailed well information from the interval, the few that have suggest the mechanical boundary hypothesis is at least not globally applicable. There is better evidence to indicate that the uppermost tier boundary is a paleo-seabed horizon at which upward propagation of polygonal faulting ceased but because most of the system occurs in non-tectonic basins were not reactivated expect in specific locations.

Is it really meaningful to talk about foot wall or hanging wall if the faulted blocks can be one or the other depending on the reference fault plane?

Hanging wall and footwall are basic properties of faults so we believe there is no reason why they are not relevant to this particular fault family. We use "graben, horst and tilted blocks" to describe the shapes of fault blocks, and use "hanging wall and footwall" to describe the direction of displacement of the fault plane. Hanging wall and footwall can co-exist in a single titled block; for example, the side of fault juxtaposes against the adjacent down shifted block is considered as footwall, while the opposite side of fault juxtaposes again the adjacent up lifted block is considered hanging wall. Our reference to hanging wall and footwall is with respect to a particular fault so we appreciate that when discussing a specific example we should make this clearer on figures. With reference to the statistical analysis we feel this is less relevant because our findings indicate that fluid migration is sensitive to the elevation of bedding across such small-scale fault blocks.

They do not form subaerially right? Section 3.2 could concentrate all the relevant details about the types of polygonal faults observed here and what exactly are the main characteristics of such faults.

The authors acknowledge the need for a summary and overview of the faults families and their characteristics at the outset of the paper. The authors will include the necessary additions during the revision phase of the manuscript.

Answering the specific technical question from the reviewer; polygonal faults form in the very shallow sub-surface during compaction and contraction of often very-fine grained hemipelagic sediments probably in base of slope (deep-water) settings. At key phases during the propagation of faulting (usually at the end of faulting) the upper tips were exposed at the seabed.

â ËŸA′c Stress distribution at polygonal fault planes: The use of the principle of particle motion and the distribution of stress at each faulted block is great for

explaining migration pathways and leakage distribution. However, I wonder how meaningful is the terminology of footwall and hanging wall for polygonal faults. In cases where there are several parallel polygonal fault planes, one block may be the hanging wall with respect to a block on one side but it would be the footwall of the next fault. It is difiňĄcult to see that the shallow gas accumulations are exclusively at the lower part of the foot wall of polygonal faults (if I understood correctly the interpretation by the authors). I do see high amplitudes on what could be a hanging wall or a footwall depending on which fault segment for the polygonal set I choose. So I think it makes more sense to talk generally about focused regions of higher shear stress and dilation depending on the relative motion of the faulted blocks with respect to each other.

This question has been raised previously and answered previously. Blocks relative to fault plane – specific mention will be made within the text.

In general, the discussion about stresses is hard to follow. I think it would help to use only one ïňĄgure to project all the relevant stress vectors inferred at the local zones of ïňĆuid leakage, together with regional stress vectors from, for example, salt-tectonics.

Given the length of the manuscript at present we feel we can convey all the necessary points by better editing of text and fig captions rather than produce more figures. We feel the paper is already on the long side. We acknowledge the difficulties to navigate the section referenced by the reviewer and will look to improve.

Where do the blue and red vectors in ïňĄgure 4 and 6 come from? Are these measured orientations of principal stresses or inferred?

The stress ellipses are not absolute stress vectors. They are used to indicate the direction and relative changes in magnitude of the horizontal stresses (Sigma-2 and

Sigma-3). In fault systems produced during 1-d compaction and burial the largest compressive stress (Sigma-1) is vertical and the intermediate and least principal stresses are horizontal. The intermediate principal stress (Sigma-2) is parallel to fault strike. In classic examples of polygonal faults the wide-range of the fault strikes indicate over large areas there is no consistent direction of Sigma-2 suggesting overall horizontal stress isotropy. Where the same system of faults are clearly polarised in a dominant direction (such as radial or concentric around salt diapirs) the direction of Sigma-2 is predominantly in one direction.

The radial and concentric alignments of faulting here arise due to stress perturbations related to gravity salt tectonics but the dominant fault characteristics are the same as the layer-bound normal faults with polygonal geometries. We therefore, as explained earlier, consider them the same fault family and having formed by the same dominant process and at the same time but under the influence of local tectonic-driven stresses. This follows previous studies such as (Carruthers, 2013, Carruthers et al, 2013, and Ho et al, 2013).

The variations in faulting and thus changes horizontal stress isotropy to anisotropy are best shown on the regional base map which shows the most variations. We have thus taken the opportunity to show the stress ellipses here first.

We acknowledge that this could be better explained in the manuscript and on figures and will look to improve during the revision phase of the manuscript.

Figure 10 says the vectors are local + in situ. What does in situ mean in this context, how are these stresses estimated? Information about regional and local stress ïňĄelds are estmated in the region is missing.

We address some of this question above. In situ refers to the stresses in the host-sediments at the moment of and during faulting. The geometry of polygonal faults offer a basic understanding of the dominant direction of the intermediate

compressive stress. Where fault strikes converge or diverge for example toward or away from a salt diapir it may be possible to indicate that there is a relative increase or decrease in the magnitude of the Sigma-2 but this is the limit to which this technique can be used to indicate horizontal stress variations. Once a polygonal fault has formed, the regional stress state may be further perturbed by the now formed fault plane, and the perturbed stress field around polygonal fault is what we refer as in-situ stress field. We will look to clarify all references to stress in the necessary sections.

Not sure this is accurate, see comment above. Section 1, second paragraph. Also the ïňĄgure captions should explain what those vectors signify.

Agree we will change and clarify better.

â ËŸA′c Linear chimneys: Are the "linear chimneys" really chimneys? What is the deïňĄnition of chimney used here? Aren't these features fractures/small scale fault planes where the ïňĆuids literally escaped through and formed authigenic carbonate that together with trapped gas in the system creates the blanking in the seismic?

The authors feel a comprehensive classification and overview of terminology and definitions is already present in the manuscript – see specific references below. However, we will ensure this information is explained as clear as possible in the revision phase of the manuscript.

In section 4.1.1 we have described the seismic characters of chimneys while in section 5.2 we have given geological interpretation of these chimneys.

In section 4.1.1. we described that on the study seismic survey, chimneys are represented by: 1) stacked of high amplitude anomalies (either positive or negative or both), 2) pull up reflections and 3) push down reflections. These three types of features can be “or not” overlaid by positive high amplitude anomalies which were interpreted in the discussion section as authigenic carbonates.

In section 5.2. we interpreted these chimneys as hydraulic fractures created by overpressured fluid.

Since there are previous studies which have well studied the basic characters of chimneys so we did not repeat the discussion in this paper.

Is there evidence of breciation, or hydrofracturing in the regions interpreted as linear chimneys?

The relevance of the question is uncertain but we assume it refers to establishing evidence of overpressure and hydro-fracturing rather than migration through faults.

The vertical stacks of high amplitude anomalies showing a linear plan form (either with positive or negative polarity, interpreted here as seep carbonates or free gas respectively) occur at different stratigraphic levels along the same vertical axes. This supports the existence of vertical fluid migration zones and hence the Linear Chimneys.

These vertical stacks of linear fluid venting systems cross multiple stratigraphic intervals and are taller than the polygonal fault tiers suggesting these systems are not simply migrating through faults. Furthermore, their vertical form is quite different from the 40-60 degree dip range typical of the polygonal fault system (and other extensional faults here). There vertical forms are best explained by overpressure and development of linear chimneys influenced by stress anisotropy around polygonal faults.

Actually, the illustration of the chimney features is not that great in the ïňĄgures. And this brings me to the next concern. In the data section the authors mention that different stacks were produced grouping angle of incidence.

It is indicated that the seismic data presented in the paper is from the near offset

stack. The seismic proïňĄles shown in ïňĄgures 3 and 4 are from which stack version? The character of what is indicated as chimney in panel e of ïňĄgure 4 reminds me how gas chimneys look in undershooting data, namely along a stack using just a selected range of offsets. Two vertical blank regions appear to each side of a high amplitude zone; the separation between the two vertical blank regions increases with depth. The feature appears then as a double line on the maps. This is a bit confusing for a reader that is not familiar with the processing of the data. I wonder whether showing the character of the chimney on the full stack is more intuitive and straight forward. If the double pattern of the so called linear chimney is not due to processing, it would be interesting to her what causes such a particular feature (ïňĄgure 4 a and b).

All images shown in this manuscript are from multi-channel, post-stack, near-offset seismic data and were processed by the geophysical department in Total S.A. There is not any undershooting data used in this study.

In the methodology we mentioned that we also checked the presence of chimneys in the middle and far-offset surveys (all of them have different incident angles) to verify the authenticity of the studied chimneys. Since the near-offset survey best illustrates the chimneys we have used this survey in this project within Total S.A. Use of the full-stack data was beyond the scope and contract conditions of this study.

We agree that it is not easy to visualise Linear Chimneys that are parallel to PFs within the PF network due to the figure resolution in Figure 4a. That was the reason why we used Figure 4b to show the planform geometry Linear Chimneys. Regardless, the branching shadows below the chimneys are artefacts. We agree that it is can be confusing for readers who are not familiar with seismic processing. In order to show the planform geometry of Linear Chimneys, we have mapped high amplitude reflections which cross the body of bright spot chimney columns, and have superimposed it on a dip map of PF (see Figure I here).

â ËŸA′c The PHAAs are interpreted as carbonates. Why would they always be associated with depressions rather than mounds? By analogy with carbonate mounds at present day seaïňĆoor, buried authigenic carbonate concretions within chimneys can get buried and appear as mounded features in the middle of a cavity with onlap of reïňĆections at the ïňĆanks. The interpreted buried carbonate concretions don't show positive morphologies in this case? Can it be related to the resolution?

Carbonate mounds with onlap reflections on their flank do exist in this study area but they are not associated with linear planform chimneys.

We did not go into detail about the geometry of the PHAAs at the topmost termination of Linear Chimneys as it does affect the interpretation for Linear Chimney's formation and is beyond the scope of this study.

PHAAs in outcrops can take a variety of forms and shapes: nodules, slabs, cements, mounds, etc. However, the PHAAs that are associated with Linear Chimneys in this study, their geometry is not visible within single seismic reflection so we are not able to confirm which shape these PHAAs have (i.e. they are below the vertical resolution of the seismic data). Depressions at the topmost termination of Linear Chimneys, in association with PHAAs or not, are visible on the modern seafloor in some cases (fig. 5b) and no visible carbonate mounds have been observed above Linear Chimneys.

We suggest the reason why Linear Chimneys terminate upward into PHAAs with negative depressions is because the chimney exit was eroded by out-coming gas. The gas concentration or volume was insufficient to allow carbonate mounds development but nodule or cements (Blouet et al., 2017). So we think that the lack of carbonate mounds within depressions was likely related to the intensity of methane flux rather than seismic resolution.

â ËŸA′c The ïňĄgures are of high quality. However, even if they are over loaded

with insets, some times they lack explanations of features that seem relevant for the interpretation. For example, panel b in ïňĄgure 4 shows a white band braking through a high amplitude reïňĆection. What is that feature? It is really hard to link all the different insets. In ïňĄgure 5 I don't manage to identify where is the feature pointed with a yellow arrow on 5ai, on 5aiii. Is it correct that the seismic is NW to the right? It is important to ïňĄnd a way of simplifying these ïňĄgures. Figure 5 could be split into 2 ïňĄgures. I would suggest selecting 7-8 ïňĄgures to show the main observations and to illustrate the conceptual models. Despite all the ïňĄgures in the main text the authors still refer to appendix ïňĄgures for observations that are key for the paper. The ïňĄgures in the main text could be used in a more efïňĄcient way.

We will improve the organisation of figures in the revised version of the manuscript.

(For continuation please read Part 2)

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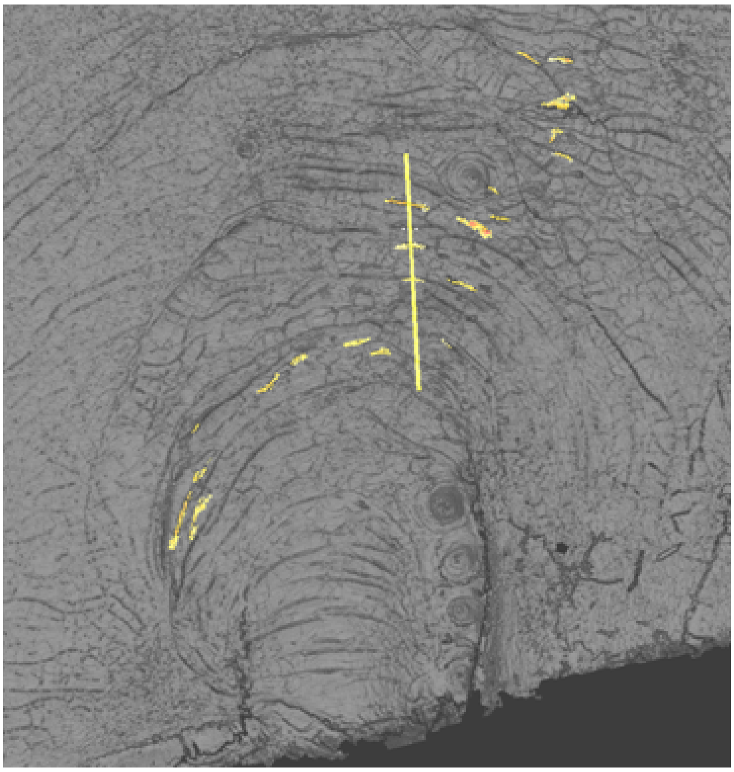

Fig. 1.