Dear Topic Editor of Sedimentology section, Prof. Samankasou,

First and foremost, we would like to thank you and the reviewers for the time and efforts that all of you have spent on reading and reviewing our manuscript.

We have now updated a revised version of the manuscript in which all of the reviewer's comments have been accepted or addressed.

- Technical questions on fluid migration, and alternative hypothesis on the formation of Linear Chimneys that have been brought up by Reviewer 3, have now been discussed in the manuscript in sections 5.2.3 and 5.2.4.
- A clear classification on the different types of Linear Chimneys requested by Reviewer 3 and 2 has been added as Figure 8.
- Background information about polygonal faults that has been requested by Reviewer 1 and 3, has been added in Introduction and section 3.2.3.
- Figure reordering as requested by Reviewer 2 and 3 has been updated.
- Clarification for figure citations in the main text requested by Reviewer 2 has been added.
- Figure simplification and modifications as requested by all 3 reviewers have been updated.
- A list describing the purpose for the use of figures is included in the list of corrections for both Reviewers 2 and 3.
- English language in the manuscript has been revised and corrected by our native British co-author as well as by a native American English language editor to ensure the international English writing standard.

We have addressed all the valuable comments provided by our three reviewers, and we hope that have fullfilled all the requirements, the updated and revised manuscript should now meet the publication standard.

Let us thank you again,
On the behalf of all coauthors
Yours sincerely,
Sutieng HO

List of corrections and accepted suggestions by authors regarding the comments of Reviewer 1: A. Plaza-Faverola

All suggestions and questions by Reviewer 1 are accepted and answered.

Summary of corrections

As requested by Reviewer 1, we have added background information to introduce what is polygonal faults (PFs), describing the main aspects of PF and the use of PF as stress indicators. We have added more clarity and definitions for terminologies in the Introduction as well as section 3.2.3.

We have also simplified figures and split them up to improve the illustration of Linear Chimneys as requested by Reviewer 1.

<u>Main points:</u>

The original points of Reviewer 1 are in bold, while the modifications made by the authors are described below each point.

About the formation of polygonal faults and their difference from radial faults

The following information has been added into the Introduction section:

"*Polygonal faults are considered as non-tectonic fault systems arising due to compactional-dewatering of very fine-grained sediments during the early stages of burial in passively subsiding sedimentary basins (Henriet et al., 1998). In the classic examples of these fault systems which show "polygonal" fault arrangements and also contribute to their nomenclature, they were characterized by very small differences between the horizontal principle stresses during their formation (Cartwright, 1994; Carruthers et al., 2013). The examples of polygonal faults in this case study show substantial departures from this classic "polygonal" fault pattern (so called isotropic PFs) to very polarized fault arrangements (so* *called anisotropic PFs) where the tier is deformed by salt tectonic structures or offset by their associated fault systems (Fig. 1; Carruthers, 2012). These faults can display a variety of intricate patterns ranging from tight radial systems around salt diapir to concentric systems within salt withdrawal basins and spiraling concentric patterns above buried pockmarks (Stewart, 2006; Ho et al., 2013). The preferentially aligned faults are many times longer than the regular faults segments with polygonal alignments but are often still confined to the same "tiers". The observations are consistent with a number of other reported examples of preferred fault alignments within networks of polygonal faults (Stewart, 2006; Ghalayini et al., 2016). The preferred fault alignments are indicative of horizontal stress anisotropy at the time of their formation (Carruthers et al., 2013).*"

See also authors online answers posted on 31st July 2018

Regarding foot wall or hanging wall of the reference fault plane

The following information has been added into section 3.2.3.:

"*"Lower footwall", when not specified, refers to the lower part of tilted PF blocks immediately adjacent to the fault which moved upwards, or referencing the lower part of horsts in this study area.*
"Lower hanging wall", when not specified refers to the lower part of PF graben."

See also authors online answers posted on 31st July 2018

Suggestion about Section 3.2 for adding all the relevant details about the types of polygonal faults

Suggestion accepted. See answer above.
Information added in Introduction and section 3.2.3 in the revised manuscript.
See also authors online answers posted on 31st July 2018

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

Suggestion accepted, Figure 1 has included all necessary stress vectors in the revised manuscript.

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

The following information has been added into section 3.2.3.:

"Preferred fault alignments or "anisotropic fault patterns" within polygonal fault networks have been observed in this study area. Concentric faults surround pockmarks (see fig. 2a in Ho et al., 2013) and are parallel to extensional synclinal faults (red dotted lines in Fig. S3 c; Appendix PF patterns b). Radial faults occur around salt diapirs (Appendix PF patterns c) (Carruthers, 2012) whilst ladder-like fault patterns occur in the center of concentric fault patterns above Syncline-2 (Fig. 6a-b, Appendix 3d).
The orientations of the PFs around or above the aforementioned tectonic structures are not unusual as the fault patterns mantle the expected stress state of the structures (Carruthers, 2012; Carruthers et al, 2013). The direction of maximum horizontal stress around the tectonic structures is indicated by the first-order anisotropic PFs while the horizontal minimum stress is indicated by the second-order anisotropic PFs (e.g. stress ellipses in Fig. 1), and hence different PF patterns are considered as indicators of stress state in the host sediments (Carruthers, 2012; Carruthers et al, 2013). "

See also authors online answers posted on 31st July 2018

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 fields are estmated in the region is missing.

The following information has been added into section 3.2.3.:

"The orientations of the PFs around or above the aforementioned tectonic structures are not unusual as the fault patterns mantle the expected stress state of the structures (Carruthers, 2012; Carruthers et al, 2013). The direction of maximum horizontal stress around the tectonic structures is indicated by the first-order anisotropic PFs while the horizontal minimum stress is indicated by the second-order anisotropic PFs (e.g. stress ellipses in Fig. 1), and hence different PF patterns are considered as indicators of stress state in the host sediments (Carruthers, 2012; Carruthers et al, 2013)."

““Regional stress” refers to stress states in the sub-surface driven by the primary tectonic forces which include gravity and the lateral extension and contraction occurring above the regional salt detachment.

“Local stress” refers to stress state at the scale and within close proximity of individual tectonic structures where the regional stress field may be locally perturbed.

“In-situ stress” refers to stress conditions in-place at the location of individual polygonal faults, this is particularly relevant when trying to understand the stress conditions at sites of incipient hydraulic fracture developments which lead to the formation of chimneys. “

See also authors online answers posted on 31st July 2018

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

Suggestion accepted.

The following information has been added into figure captions:

“*Palaeo-stress ellipses show relative directions and magnitudes of the horizontal principal stresses and are constructed from the planform geometry of the polygonal fault networks (see section 3.2.3 for more information). Blue axis and red axes on stress ellipses indicate the palaeo-orientation of the intermediate and minimum stresses, respectively. Location of seismic survey is indicated by a red star on insert map.*”

See also authors online answers posted on 31st July 2018

â ˘A´c Linear chimneys: Are the “linear chimneys” really chimneys? What is the definition of chimney used here?

Definition and explanation has already been provided in section 4.1.1. and 5.2.

See also authors online answers posted on 31st July 2018

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

See also authors online answers posted on 31st July 2018

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

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 new figure 9c in the revised manuscript.
See also Figure 5 which shows the 3D chimney bodies which are the 3D mapping of high amplitude anomaly columns on seismic sections.

See also authors online answers posted on 31st July 2018

It is indicated that the seismic data presented in the paper is from the near offset stack. The seismic profiles shown in figures 3 and 4 are from which stack version?

Suggestion accepted.

The following information has been added into section 2:

"The seismic data in both surveys multi-channels, near-offset and has been post-stack time migrated and zero-phased."

Figure 4 has been updated and became Figure 9.

See also authors online answers posted on 31st July 2018

â ˘A´c The PHAAs are interpreted as carbonates. Why would they always be associated with depressions rather than mounds?

See authors online answers posted on 31st July 2018

â ˘A´c The figures 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 figure 4 shows a white band braking through a high amplitude reflection. What is that feature? It is really hard to link all the different insets. In figure 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 find a way of simplifying these figures. Figure 5 could be split into 2 figures

Suggestion has been taken into account, old Figure 5 has now became Figure 6 and 7. Figures have been simplified.

The following information has been added into the figure caption:

"The linear depressions at issue are indicated by yellow arrows and locally interfere with regularly spaced furrows of likely sedimentary origin."

Please also see authors online answers posted on 31st July 2018

Please find below my notes while reading through the text; it includes a few typos. The L refers to the paragraph number and the P to the page number.

- L20/P3: minimum and maximum offsets? I assume these data sets are multi channel with long offsets? It is kind of important to provide this info before it is mentioned that the amplitudes vs. angle were used for verifying the seismic character of the observed features (a sort of undershooting?).

Modified. Please see section 2.

- L25/P3: typo: to map the linear. . .

Modified.

- L20/P4: figure 6b referenced before 3, 4 and 5? Check the flow of the figures. It is difficult to see from figure 2b what is stated here: that studies chimneys occur primarily in syncline areas. Maybe indicate the syncline structure in 2B and relate better 2a and 2b?

Modified.

- L25/P4 typo: relief instead of relied?

Modified.

- L10/P5 typo: check the unit used is it 10 to 100 s, ms or m?

Modified.

- L5/P6: **The linear features shown in figure 4a-b are indeed strange features. Are these really along polygonal faults? (PFs?). Polygonal faults usually do not have a preferred orientation, but on the contrary, they consist of fault segments oriented covering the whole azimuth range (closing polygons), right?**

Information added in Introduction and section 3.2.3 in the revised manuscript.
See answer above.
See also authors online answers posted on 31st July 2018.

- L20/P6: typo, 19% FORM

Modified.

- L30/P6: Consider making two different figures here. The figures have so many parts that it is actually a struggle to go through and understand everything. Is the statistical part of the figure really relevant? What do we do with the fact that 54% are intersecting the lower portion of PF? What seems most relevant in this paper is to get compared

the orientation of the fluid flow related features with respect to the orientation local and regional faults and fractures, right?

Suggestion accepted, the figure has been split into two parts.

Information below has been added to section 5.2.3.:

"As supported by the statistical analysis presented herein, over 54\% of chimneys stem from the region around the lower PF footwall, therefore we infer that over 54\% of the time gas accumulated in the footwall, at the base of chimneys. It is also the same for the 19\% of chimneys that stem from the lower PF grabens (hanging wall). As a result, the statistic leads us to the interpretation that 73% of the total time gas preferentially accumulated in the lower part of PF blocks, therefore we investigate the cause of this phenomenon."

Please see 4.1.2. and 5.2.3.

See also authors online answers posted on 31st July 2018.

- L10/P7: Check the use of tenses in this paragraph.

Modified.

- L20/P7: Is the evidence by Sonnenberg et al., 2016 related to the polygonal faults in this present study? In that case, it would help to see a sentence hinting what is the observation that works as evidence. I got this advice recently and I kind of see now the need for bringing into the current study the key observations rather than referring the reader too often to the previous studies. This degrades the flow of the reading and makes difficult to follow the paper.

See also authors online answers posted on 31st July 2018

- -L30/P7: do polygonal faults really reactivate? How is the accommodation of such movement if the fault planes can converge to each other rather than been parallel? Aren't these kind of faults associated with diagenetic processes and are hence a kind of one-time event?

See also authors online answers posted on 31st July 2018

- -L20/P8: 60 m deep and 4.5 m wide pockmark??? That is quite deep compare to the with, it is almost a conduit rather than a pockmark.

Typo corrected.

- -L30/P8: so there is active gas release at the seafloor at present? Or you mean active in the sense that there is gas filling the near-surface systems through the gas chimney structures?

See also authors online answers posted on 31st July 2018

- -L30/P8: this model is hard to digest here since there are so many faults and pre-existing weak planes that one would think that the fluids would find preferential path-ways without much effort and hence gas chimneys would not be favor?

Please see section 5.2.4.

See also authors online answers posted on 31st July 2018

- L5/P9: I could not find figure 6b. In general, it is difficult to find in the figures some of the observations regarding gas chimneys. Again, the figures could be simplified by selecting only key examples.

Suggestion accepted.
Figure modified.

- L20/P9: The use of appendix figures to illustrate what seems to be the main con-ceptual model of the paper is not ideal. One figure in the main text should be enough to illustrate description of the model for fluid migration and development of chimneys. Figure 8a doesn't illustrate this, or did I miss something? When you mention PF tier here is it 1 or 2? It is very easy to get lost while reading, I think it is due to the fact that there are so many figures overloaded with details.

Suggestion accepted.
Figure modified.

- L25/9: typo: the PRESENCE of. . .And please revise this paragraph. These aspects are not necessarily ruling out each other and a combination of them could be a pre-condition for explaining your observations. Consider reformulating the paragraph.

Suggestion accepted.

The aforementioned sentence in section 5.2.3. has now been rewritten as:

"*We suggest that two hypotheses in combination account for the mechanism of preferential gas accumulation in the lower PF footwalls of tilted blocks, horsts and lower hanging walls/grabens ((1) the presence of an impermeable regional seal, and (2) partial impermeable fault plane)), while two other hypotheses determine together the preferential gas migration to the lower PF footwall ((3) the differential strain in fault blocks, and (4) the stratigraphic position of permeable layers in fault blocks), and finally one for graben hanging wall ((5) the increase of local permeability).*"

- L30/9: where do we see the gas accumulating at the foot wall? The foot wall of a major tectonic fault or are you referring to small faulted compartments resulting from the polygonal faulting? If so, is it really meaningful to talk about footwall if the blocks are somehow both footwalls and hanging walls with respect to each other?

Definition and explanation added in section 3.2.3. in the revised manuscript.

- L5-10/P10: Why would these areas be subjected to "relative" compressional strain? What do the authors mean here? Would it be more appropriate to say "less" compressional state rather than relative? In analogy with the particle motion maps for earthquakes (focal mechanisms) one would expect that the lower part of the hanging wall and the upper part of the footwall would experience more compression while dilation would dominate the upper hanging wall and the lower footwall (which is indeed consistent with Barnett et al.,)

Suggestion has been taken into account.
We have removed "relative".

- L10/P10: again, no figure 6d and also the interpretation that the gas is accumulated in the footwall of polygonal faults is not easy to digest. A block can be considered a footwall or a hanging wall, depending on which fault plane is used as reference. I can see high amplitudes in both hanging and footwalls in figure 6c for example.

Modified.
Please see definition and explanation added in section 3.2.3. in the revised manuscript.

- L20/P11: Typo: BY. . .
- L20/P12: Again, the model of shear stress distribution through the four quadrants of the faulted blocks is very sounding for explaining the distribution of gas into more permeable zones. However, where these more permeable zones are entirely correlated with footwalls and hanging walls in these polygonal fault system is hard to assimilate. Is it really necessary to use this terminology? See main comment.

Please see definition and explanation added in section 3.2.3. in the revised manuscript.
See also authors online answers posted on 31st July 2018

- L25/P12: So the chimneys grow episodically? You foresee that the growth occurred in several episodes of reactivation of the system? It is important to describe this more explicitly in order to be able of comparing to systems from other margins with comparable settings.

Please see also authors online answers posted on 31st July 2018

- L5/P13: typo: may BE because..

Modified.

- L10/P14: typo: blocks

Modified.

- L25/P14: point 6 in the discussion. Check the grammar here. The sentence has a problem. When are the chimneys circular in isotropic stress fields? And when are they linear, isotropic and anisotropic? Clarify.

Modified.

- Figure 1: great figure. The use of a dip map to show all the elements of the study works extremely well, we can see the flanks of the salt domes and even the fine scale faults and fractures. However, isn't the present day bathymetry important to understand the stress regime?

Please see also authors online answers posted on 31st July 2018

- Figure 2b – typo: linear positive high amplitude. . .It is a bit difficult to read through the symbols of this figure.

Suggestion accepted.

Figure modified.

- Figure 5: Can you really tell that the high amplitude analogies in inset ii are gas accumulations, without any clear sign of polarity change?

Figure modified.

- Figure 6: Not convincing with the positive and negative bright spots interpretation. If you think it is key to differentiate between carbonates and gas for the discussion you may need to show a better indication for this, perhaps using wiggles and zooming into the anomalies?

Figure modified as suggested.

- Figure A7 typo: Gas MIGRATION into the hanging wall apex WAS likely because of the increase (check the sentence in any case)

Modified.

List of corrections and accepted suggestions by authors regarding the comments of Reviewer 2

Majority of suggestions by Reviewer 2 are accepted.

Summary of correction

As requested by Reviewer 2, we have reordered all figures, as well as simplified and improved them to be easier to read. We have clarified the figure citations among the main text.

Our British co-author has checked through all of the English vocabulary in the main text and we have called for a native American English editor to perform proof reading to make sure there is no conflict between the British and American English writing standards.

1. Main point:

The original points of Reviewer 1 are in bold while the modifications made in the manuscript by authors are described below each point.

- **About English language**

We have applied all the English corrections given by the reviewers. Our native British co-author has gone through the entire script , we have also asked for English editing services of a native American English editor.

- **Figure reference in the main text**

We have improved all of the figure citations with updated text body.

- **Figure**

We have made improvements for figures by following most of the suggestions of all three reviewers.

1.1. Figure modifications

- Figures of appendix 2, 4, 5, 7 have been modified and moved into key figures as requested.
- All labels of figures have been checked and raw data is not covered by interpretation.
- The amplitude scale bar has been annotated in a clearer way.
- Seismic lines showing the three types of chimneys have been added as Figure 8.
- Seismic lines show the three different ways that chimneys intersect polygonal fault plan have been added as Figure 8.
- Images which show the three types of anisotropic PF arrays have been modified and are available as Appendix 2.
- Figure 2 has been updated, and no features of interest are not obscure.
- New Figure 5 has been added to show the 3D morphology of Linear Chimney's, which is issued from the 3D mapping of the high amplitude anomaly columns on seismic sections.

1.2. Figure orders

Figures have been reordered as requested by other reviewers. The new figure order is the following:

Fig. 1 has been updated

Fig. 2 has been updated

Appendix 5 became Fig. 3

Fig. 3 became Fig. 4

New Fig. 5

Fig. 5a became Fig. 6

Fig. 5b became Fig. 7

New Fig. 8

Fig. 4 became Fig. 9 and has been simplified

Fig. 6 became Fig. 10 and has been updated

Appendix 4 became Fig. 11

Fig. 7b became Fig. 12

Fig. 8 became Fig. 13

Appendix 7 became Fig. 14

Fig. 9 became Fig. 15

Fig. 10 became Fig. 16

Fig. 11 became Fig. 17

Fig. 12 became Fig. 18

Appendix 1

Appendix 3 became Appendix 2

Appendix 2 became Appendix 3 and has been simplified

Appendix 6 became Appendix 4

1.3. Purpose of figures

The list below is the purpose for the use of each figure:

Fig. 1 is a base map of a key seismic horizon in the study area showing the distribution of the relevant structural elements and fluid flow features.

Fig. 2 shows a regional cross section through the study area and seismic-stratigraphic framework illustrating where the different fluid features are situated,

Fig. 3 shows the stratigraphic relationship of polygonal fault tiers with one of the salt diapirs in the study area.

Fig. 4 shows a montage of maps and seismic sections which provide insight into the timing of polygonal faulting.

Fig. 5 illustrates geometry of linear chimneys using a 3D horizon map with geobodies of linear chimneys, and seismic sections.

Fig. 6 uses maps and sections to illustrate the complex, flame-like geometry of PHAAs at the upper termination of linear chimneys

Fig. 7 uses a map and a seismic section to illustrate the geometry of depressions at the top of linear chimneys shallow depressions.

Fig. 8 gives a summary of the three types of Linear Chimneys and their major intersection positions with PFs.

Fig. 9 uses maps and seismic sections to illustrate the relationship of linear chimneys with concentric, synclinal faulting and gas accumulations relative to an impermeable regional horizon.

Fig. 10 shows parallel and non-parallel chimney-fault relationships comprising parallel and non-parallel.

Fig. 11 shows examples where linear chimneys are parallel to second-order polygonal faults.

Fig. 12 shows the percentage abundance of different chimney-PF faults intersecting positions which provides an insight into the formation of chimneys and gas migration history and pathways.

Fig. 13 Images of Syncline-0 show exceptional occurrence of Linear Chimneys in the interval devoid of PFs. Linear Chimneys with the scale of a kilometer in lateral length occur in parallel with tectonic syncline-related faults (For demonstrating the influence of tectonic stresses on the propagation direction of hydraulic fractures).

Fig. 14 shows hypothesis for the location of gas accumulations before the nucleation of chimneys, as well as the hypothesis of what is the cause of gas accumulation in lower grabens.

Fig. 15 shows the hypothesis for the preferential location of gas accumulation in the lower PF tiers and footwalls.

Fig. 16 Demonstrates a conceptual model for the formation of Linear Chimneys.

Fig. 17 Senarios show formations of Linear Chimneys during PF's development in Plio-Quaternary.

Fig. 18 shows different styles of fluid migration in two different geological contexts, in polygonal faulted sediment, and tectonic faulted interval without polygonal faults.

Appendix 1 Relates to the seismic surveys used in this study, as well as the location of zones which have been previously studied and published.

Appendix 2 Shows different types of anisotropic PF patterns within the study area.

Appendix 3 Shows seismic lines and maps for each group of Linear Chimneys and their statistics as well as the percentage of various intersecting positions which occur within the PF's.

Appendix 4 Shows fault traps which induce gas accumulations at the base of the PF tier as well as the bottom of the PF tier with respect to the geometry of PFs cells.

2. Other points

All the comments below have been accepted and requested modifications have been made:

P1 L2: "Angola. These features are termed "Linear Chimneys"."

P1 L3: "Hydrocarbon migration"

P1 L4: Remove "the" (second word in line)

P1 L7: Replace "e.g." with "such as"

P1 L11: "The initiation of polygonal faulting occurred 40 to 80 m"

P1 L12 "The majority of Linear Chimneys nucleated in the lower part of the PF tier below an impermeable layer within the tier. The filling of lower parts of the polygonal fault tier demonstrate the presence of pore space within the lower part of the tier. The PF gas traps restrict the leak points. . ." NOTE it is possible to have porosity / gas without significant permeability

P1 L17 ". . .polygonal faults coupled with. . ."

P2 L3 “flow directions in the subsurface and the distribution. . .”

P2 L5 “. . .structures formed during fluid leakage records the style. . .”

P2 L8: Replace “leakage” with “leak”

P2 L23: “. . . documented chimneys having elliptical cross-section and described the planform ratio of these chimneys for the first time.”

P2 L25 replace “orientations” with “orientation”

P2 L26: Reference in brackets

P2 L28 “. . . align parallel to these”

P2 L32 “However, neither factors that determined the linear planform of these chimneys nor the reason why gas charged fluid migrated into the PF tier have been investigated.”

P3 L1 “It has been documented that”

P3 L5: “interactions between the orientation of magna fluid conduits and tectonic stresses. Nakamura established”

P3 L6: “. . .different tectonic regimes, noting, for instance, that aligned. . .”

P3 L11: Delete “Based on seismic observations”

P3 L12: “in shallow buried sediments based on seismic observations, thereby”

P3 L18-19: Statement not supported by fig. 1

P3 L19 “The seismic data has a”

P3 L21 “The dominant frequency is slightly”

P3 L24: Please describe which angles are covered by the near, mid and full stack

P3 L26: “rule out whether the studied features are”

P3 L29: “. . . to map the linear fluid venting structures as accurately as possible”

P3 L30 “are present on the near, mid and far offset volumes”

P4 L4: Fig.ures cited do not support text

P4 L8: Add reference

P4 L14: Which figure in Ho 13?

P4 L20 Ho et al 2012a, fig 6a in this paper OR Fig. 6a in Ho et al 2012a?

P4 L26 Replace “Relied” with “Relief”

P4 L27: Replace “Isopach” with “Constant”

P4 L 28: “Below which a large number of gas accumulations are interpreted” (also explain why these are interpreted to be gas accumulations)

P5 L2: Spell out that PHAAs are acoustically hard (increase in acoustic impedance) and NHAs are acoustically soft (decrease in acoustic impedance). Use PHAA and NHAA or PHA and NHA, don’t use what you currently have (PHAA and NHA). Section 4.1.1 I struggled to find the observations in the text in the figures - some figure references may be wrong. See my separate comments on how to tidy up the figures to make things easier for the reader Section 4.1.2 I struggled to find the observations in the text in the figures - some figure references may be wrong. See my separate comments on how to tidy up the figures to make things easier for the reader

P7 L30: Do not see the described feature on the referenced figure

P8 L2: Same comment as P7 L30

P8 L19: Sentence does not make sense to me

P8 L30: Replace “Some might hypothesize” with “It could be argued” Section 5.2.2 Explain why strong soft anomalies are interpreted as gas. Has the seismic been balanced correctly?

P9 L28: “1) the presence of an”

P9 L33: Fig.ure reference incorrect

P10 L14: Fig. 6D does not exist

P12 L23: Sentence does not make sense

P13 L8: “. . .. Study area may be because” The notes which follow on the figures are some observations, these may or may not be relevant given my recommendation to reorder and rearrange the figures.

Figure 1: A multi-segment seismic line showing the labelled geometries would be helpful

Figure 2: Features of interest on the seismic line obscured by illustrations

Figure 3: “A few faults propagate above the Tiers-2 (interval A)": This is confusing, interval A is above Tier 1, not Tier 2

Figure 4: Please center amplitude maps on 0. It is difficult to tell which parts of the amplitude maps are negative or positive at the moment.

Figure 5: (A) (i)/(ii) and (iii) should be swapped around (show seismic line first, and then maps of given horizon). Likewise for figure 5B

Figure 6: Labelling of maps is confusing, please label the horizon used for figure 6b on Figure 6c. Amplitude limits of inset to figure 6a are not labelled.

Figure 7: Figure caption does not match figure, check this.

Figure 8: Cannot see location of seismic line on figure 8b. Amplitude map should be centred on 0.

Figure 9: “Low permeable layer” should be “low permeability layer”

Figure 10: Poor grammar in figure caption, suggest rewriting. Not sure what middle block diagram between block diagram to left and seismic line to right adds in a, b and c?

Figure 11: I like this figure, but no caption for figure 11d.

Figure 12: I like this

Figure A1: It is good to have a summary map like this, however I cannot see the grey C8area this study is based on.

Figure A2: This seems to be a key figure, not sure what it is doing in appendices. Ensure amplitude maps are centred on 0 so it is clear what is anomalous.

Figure A3: Would a reference to Ho 2013 suffice instead of reproducing this here?

Figure A4: This seems to be a key figure, not sure why it is in appendices. Ensure amplitudes centred on 0

Figure A5: Where is “appendix A”? Do you mean “Appendix 1”? This seems to be a key figure, why is it in appendices?

Figure A6: The amplitude map sin a(ii) shows PF cells filled by amplitude anomaly which IS INTERPRETED to represent gas fill. Ensure amplitude maps centred on 0.

Figure A7: I like this, is this a key figure?

List of corrections and accepted suggestions by authors regarding the comments of Reviewer 3

All suggestions and questions by Reviewer 3 are accepted and answered.

Summary of correction

As by requests, we have added in clarification for the conceptual model of fluid migration in polygonal fault tier in section 5.2.3.
A hypothesis for the formation of a sub group of Linear Chimneys has been added in section 5.2.4.
A brief introduction about PF and their usage as palaeo stress indicator has been added in Introduction and section 3.2.3.
Figures have been reordered and updated as requested by the reviewers.
A figure for the classification of different types of Linear Chimneys has been added as Figure 8.

Main points:

The original points of Reviewer 1 are in bold while the modifications made in the manuscript by authors are described below each point.

Regarding the request of adding a brief introduction for polygonal faults

We have accepted the suggestion and the following information has been added into the Introduction section:

"*Polygonal faults are considered as non-tectonic fault systems arising due to compactional-dewatering of very fine-grained sediments during the early stages of burial in passively subsiding sedimentary basins (Henriet et al., 1998). In the classic examples of these fault systems which show "polygonal" fault arrangements and also contribute to their nomenclature,* *they were characterized by very small differences between the horizontal principle stresses during their formation (Cartwright, 1994; Carruthers et al., 2013). The examples of polygonal faults in this case study show substantial departures from this classic "polygonal" fault patterns (so called isotropic PFs) to very polarized fault arrangements (so called anisotropic PFs) where the tier is deformed by salt tectonic structures or offset by their associated fault systems (Fig. 1; Carruthers, 2012). These faults can display a variety of intricate patterns ranging from tight radial systems around salt diapir to concentric systems within salt withdrawal basins and spiraling concentric patterns above buried pockmarks (Stewart, 2006; Ho et al., 2013). The preferentially aligned faults are many times longer than the regular faults segments with polygonal alignments but are often still confined to the same "tiers". The observations are consistent with a number of other reported examples of preferred fault alignments within networks of polygonal faults (Stewart, 2006; Ghalayini et al., 2016). The preferred fault alignments are indicative of horizontal stress anisotropy at the time of their formation (Carruthers et al., 2013).*"

Regarding the explanation of use of polygonal faults as palaeo stress indicators

The following information has been added into section 3.2.3.:

"*Preferred fault alignments or "anisotropic fault patterns" within polygonal fault networks have been observed in this study area. Concentric faults surround pockmarks (see fig. 2a in Ho et al., 2013) and are parallel to extensional synclinal faults (red dotted lines in Fig. S3 c; Appendix PF patterns b). Radial faults occur around salt diapirs (Appendix PF patterns c) (Carruthers, 2012) whilst ladder-like fault patterns occur in the center of concentric fault patterns above Syncline-2 (Fig. 6a-b, Appendix 3d).*
The orientations of the PFs around or above the aforementioned tectonic structures are not unusual as the fault patterns mantle the expected stress state of the structures (Carruthers, 2012; Carruthers et al, 2013). The direction of maximum horizontal stress around the tectonic structures is indicated by the first-order anisotropic PFs while the horizontal minimum stress is indicated by the second-order anisotropic PFs (e.g. stress ellipses in Fig. 1), and hence different

PF patterns are considered as indicators of stress state in the host sediments (Carruthers, 2012; Carruthers et al, 2013). "

In the proposed conceptual model, the authors have suggested that gas could not mi-grate further upward the PF plane, the reason for that could simply be the regional seal retains the gas in the lower part of PF tier but has nothing to do with the permeability of PFs? Could it be purely some lithological effects, such as permeable layers occur rather in the lower part of the PF tier and layers in the upper tier layers are less permeable or impermeable?

Information below has been added in section 5.2.3. of the revised manuscript:

"*It can be argued that, more permeable deposits preferentially occur in the lower PF tier and lead to preferential occurrence of gas accumulation in such place. This possibility is disregarded because of the indifference between the lithologies in the upper and lower part of the PF tier as indicated by Total's internal well reports, regardless the permeability measurement of the host sediments is unavailable.*"

See also authors online answers posted on 31st July 2018

In the statistics there are 7% of Linear Chimneys which are not intersecting with any PFs and occur in the middle of the tilted PF blocks. Is the conceptual model of impermeable faults intersecting impermeable layer to form fault bound trap still work for these chimneys?

Answer to this question has been added in section 5.2.4. of the revised manuscript:

"*For chimneys that do not intersect with any fault i.e. occur in the middle of PF fault blocks, the illustrated model by Løseth et al. (2009) can be used as a referential analogue (see fig. 21 in Løseth et al., 2009); a lateral contact point between the edge of the gas accumulation and the* *upper limit of the tilted storage-layer, in the middle of the tilted block, formed a hydrocarbon spill point from where gas chimney nucleated and propagated upward (Løseth et al., 2009). This type of spill point is commonly occurred in structural traps.*"

Figure modifications

- Figures have been simplified as requested.

- As requested classification for the three types of chimneys has been added as Figure 8.

- As requested the old Figure 7a has now been integrated with the classification of the three types of chimneys as a whole Figure 8.

- Figures of appendix 2, 4, 5, 7 have been modified and moved into key figures as requested.

- Figures have been reordered as requested by other reviewers. The new figure orders are the following:

Fig. 1 has been updated
Fig. 2 has been updated
Appendix 5 became Fig. 3
Fig. 3 became Fig. 4
New Fig. 5
Fig. 5a became Fig. 6
Fig. 5b became Fig. 7
New Fig. 8
Fig. 4 became Fig. 9 and has been simplified
Fig. 6 became Fig. 10 and has been updated
Appendix 4 became Fig. 11

Fig. 7b became Fig. 12

Fig. 8 became Fig. 13

Appendix 7 became Fig. 14

Fig. 9 became Fig. 15

Fig. 10 became Fig. 16

Fig. 11 became Fig. 17

Fig. 12 became Fig. 18

Appendix 1

Appendix 3 became Appendix 2

Appendix 2 became Appendix 3 has been simplified

Appendix 6 became Appendix 4

Purpose of figures

The list below is the purpose for the use of each figure:
Fig. 1 is a base map of a key seismic horizon in the study area showing the distribution of the relevant structural elements and fluid flow features.

Fig. 2 shows a regional cross section through the study area and seismic-stratigraphic framework illustrating where the different fluid features are situated.

Fig. 3 shows the stratigraphic relationship of polygonal fault tiers with one of the salt diapirs in the study area.

Fig. 4 shows a montage of maps and seismic sections which provide insight into the timing of polygonal faulting.

Fig. 5 illustrates geometry of linear chimneys using a 3D horizon map with geobodies of linear chimneys, and seismic sections.

Fig. 6 uses maps and sections to illustrate the complex, flame-like geometry of PHAAs at the upper termination of linear chimneys
Fig. 7 uses a map and a seismic section to illustrate the geometry of depressions at the top of linear chimneys shallow depressions.

Fig. 8 gives a summary of the three types of Linear Chimneys and their major intersection positions with PFs.

Fig. 9 uses maps and seismic sections to illustrate the relationship of linear chimneys with concentric, synclinal faulting and gas accumulations relative to an impermeable regional horizon.

Fig. 10 shows parallel and non-parallel chimney-fault relationships comprising parallel and non-parallel.

Fig. 11 shows examples where linear chimneys are parallel to second-order polygonal faults.

Fig.. 12 shows the percentage abundance of different chimney-PF faults intersecting positions which provides an insight into the formation of chimneys and gas migration history and pathways.

Fig. 13 Images of Syncline-0 show exceptional occurrence of Linear Chimneys in the interval devoid of PFs. Linear Chimneys with the scale of a kilometer in lateral length occur in parallel with tectonic syncline-related faults (demonstrating the influence of tectonic stresses on the propagation direction of hydraulic fractures).

Fig. 14 shows hypothesis for the location of gas accumulations before the nucleation of chimneys, as well as the hypothesis of what is the cause of gas accumulation in lower grabens.

Fig. 15 shows the hypothesis for the preferential location of gas accumulation in the lower PF tiers and footwalls.

Fig. 16 Demonstrates a conceptual model for the formation of Linear Chimneys.

Fig. 17 Senarios show formations of Linear Chimneys during PF's development in Plio-Quaternary.

Fig. 18 shows different styles of fluid migration in two different geological contexts, in polygonal faulted sediment, and tectonic faulted interval without polygonal faults.

Appendix 1 Relates to the seismic surveys used in this study, as well as the location of zones which have been previously studied and published.

Appendix 2 Shows different types of anisotropic PF patterns within the study area.

Appendix 3 Shows seismic lines and maps for each group of Linear Chimneys and their statistics as well as the percentage of various intersecting positions occuring within the PF's.

Appendix 4 Shows fault traps which induce gas accumulations at the base of the PF tier as well as the bottom of the PF tier with respect to the geometry of PFs cells.

Formation of linear planform chimneys controlled by preferential hydrocarbon leakage and anisotropic stresses in faulted fine-grained sediments, Offshore Angola

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Abstract

A new type of ~~chimneys~~ gas chimney exhibiting unconventional linear planform ~~have~~ has been observed on the 3D seismic data offshore Angola~~, and~~. These features are termed “Linear Chimneys”. ~~They~~ These chimneys occur in a shallow hemipelagic succession deformed by syn-sedimentary remobilisation processes related to hydrocarbon migration. Linear Chimneys are oriented parallel to ~~the~~ adjacent faults, within preferentially oriented tier-bound fault networks of diagenetic origin (also known as anisotropic Polygonal Faults, PFs~~)~~), in ~~the~~ salt-deformational domains. These anisotropic PFs are parallel to salt-tectonic-related structures indicating their submission to horizontal stress perturbations generated by the latter. Only in ~~anisotropic PF~~ areas with these anisotropic PF arrangements do chimneys and their associated gas-related structures ~~show~~, such as methane-derived authigenic carbonates and pockmarks, have linear planforms. In areas ~~without anisotropic PFs where the~~ with the classic “isotropic” polygonal fault arrangements, the stress state is isotropic, gas expulsion structures of the same range of sizes exhibit circular geometry. ~~In areas experiencing a transitional stress field, linear chimneys follow the trend of weak anisotropic PFs rather than the nearby tectonic structures. therefore, development of linear chimneys is interpreted to have been predominantly affected by the anisotropic stress field of PFs.~~These events indicate that chimney’s linear planform is heavily influenced by stress anisotropy around faults. The initiation of polygonal faulting ~~formed~~occurred 40 to 80 m below the present day seafloor and predates Linear Chimneys. The majority of Linear Chimneys nucleated ~~at~~in the lower part of the PF tier below the impermeable~~, upper~~ portion of ~~PFs, where gas accumulation was facilitated by~~ fault planes and below a

regional impermeable barrier within the PF tier. The ~~permeable part of~~ existence of polygonal fault-bound traps in the lower part of the PF tier is evidenced by PF cells filled with gas. These PF gas traps ~~restrict~~restricted the leakage points of overpressured gas-charged fluids to occur along the lower portion of PFs and hence, controlling the nucleation sites of chimneys. Gas leaking along the lower portion of PFs pre-~~configures~~configured the spatial organisation of chimneys. Anisotropic stress ~~fields of~~condition surrounding tectonic and anisotropic polygonal faults ~~couple~~coupled with partial impermeability of PFs determined directions of gas migration, linear geometry of chimneys, long term migration pathways and successive leaking events. Methane-~~derived~~ related carbonates that precipitated above Linear Chimneys inherited the same linear planform geometry, both structures record the timing of gas leakage, the orientation of palaeo stress and thus can be used as a tool of stress reconstruction in sedimentary successions.

1~~.~~ Introduction

Hydrocarbon migration is directly impacted by structures such as faults and salt diapirs (Roberts and Carney, 1997; Talukder, 2012; Plaza-~~Favorela~~Faverola et al., 2012~~;~~, 2015). Consequently, flow directions in the subsurface and ~~ultimately~~ distribution of hydrocarbon leakage sites at the sea floor~~,~~ are affected by such pre-existing structures (Thrasher et al., 1996; Moore et al., 1990). The morphology of structures formed during fluid leakage records the style and intensity of fluid expulsion and thus, is useful for deciphering the fluid-migration history (Roberts et al., 2006; Blouet et al., 2017). 3D seismic reflection data has played an increasingly important role in ~~visualisation~~visualization, classification and evaluation of fluid flow features (Heggland, 1997). By conducting seismic analyses for vertical successions of fluid leakage expressions around faults, such as gas chimneys feeding pockmarks and seep carbonates, it is possible to unravel the timing and pathways of migrating fluids and the sealing efficiency of faults (Ligtenberg, 2005; Plaza-~~Favorela~~Faverola et al., 2012; Ho et al., 2016).

Recent studies from the upper slope of the Lower Congo Basin have revealed the existence of a new type of chimney~~s: In contrast to the~~. Chimneys are usually ~~observed~~ circular in planform, however the chimneys~~, they~~ observed in this study are distinctly linear and display an extraordinary parallelism with ~~tier-bound fault planes with polygonal organisation (~~adjacent faults in map view (Ho, 2013; Ho et al., ~~2013;~~ 2016). ~~Polygonal networks of discontinuities affecting discrete intervals of fine-grained sediment have been linked to diagenetic processes by Berkson and Clay (1973), were first identified as tiered fault systems by Henriet et al. (1982; 1988; 1991)~~ Chimneys with non-circular planforms were first observed in the 1980's. Hovland

(1983) documented chimneys on high-resolution 2D-seismic data from the North Sea exhibiting irregular and ~~investigated in detailed by Vershuren (1992). They were later called polygonal fault (PF) systems by Cartwright (1994) (see Clausen et al., 1999; Goulty, 2008), although these faults can also be circular in map view (c.f. Chopra and Marfurt, 2007).~~

~~Hovland (1983) documented chimneys on high-resolution 2D-seismic data from the North Sea, exhibiting irregular~~ elongate planform geometries with rounded summits, and variable widths and lengths ranging between several hundred meters to more than one ~~kilometre.~~kilometer. They were interpreted as a result of gas escaping ~~gas~~ along fractures/faults from the apices of underlying sedimentary ~~undulations~~folds (Hovland, 1983~~;~~, 1984). ~~Later, on~~ On modern 3D-seismic data, Hustoft et al. (2010) documented chimneys having elliptical cross-~~section~~ sections, and ~~they~~ were the first ~~commenting on~~to analyse the planform ratio of chimneys. Hustoft et al. (2010) suggested that the preferred ~~orientations~~ orientation of the long axis of horizontal sections of elliptical chimneys were caused by local stress perturbations associated with adjacent tectonic structures. In contrast to the chimneys described by Hovland (1983), the Linear Chimneys occurring in the Lower Congo Basin are string-like in plan-view~~. Furthermore, they~~, which vary little in width and have blunt terminations often with sharp tips~~. The Linear Chimneys are~~ as well as being rooted along ~~polygonal~~ the parallel to fault planes ~~and align parallel with these~~. This geometrical arrangement suggests that the near-fault stress field affected the formation of the Linear Chimneys (Ho et al., 2012a). Previously, Ho (2013) and Ho et al. (2016) used intersecting positions of Linear Chimneys and ~~PFs~~ faults to determine the fault's permeability ~~of PFs, and~~ , they suggested that overpressured gas-charged fluids cannot migrate further ~~up~~upwards of the fault plane to produce chimneys to escape~~. However,~~ , however, the factors that determine~~d~~ the linear planform of these chimneys and their collective orientation have not yet been investigated~~, either why gas-charged fluid migrated particularly into PF tier have not been explained.~~ .

~~It has been known that stress-controlled~~The role of stresses in controlling orientations of venting structures ~~and~~, hydraulic fractures ~~can redirect~~and redirecting fluid flow ~~(~~has been well documented (cf. Nakamura, 1977; Plaza-Faverola et al., 2015). Detailed studies of the relationship between stress state, ~~polygonal~~ fault orientation, tectonic structures and injectites have been carried out by Bureau (~~2013~~2014); who demonstrated that sand injectites preferentially intrude pre-existing ~~PFs~~polygonal faults along the extensional direction of adjacent tectonic structures. Nakamura (1977) studied interactions between orientation of ~~magma~~ magmatic fluid conduits and tectonic stresses. ~~He~~Nakamura established a conceptual framework relating the orientation of magmatic dykes to regional stress perturbations generated under different tectonic regimes; for instance, aligned zones of eruptions occur parallel to fault lines under extensional tectonic regimes, while zones of eruptions form at high angles with faults in compressive tectonic areas (Nakamura, 1977). Consequently, faulting and ~~the~~ near fault stress state can play an important role on ~~fluid migration and,~~the fluids migrations hence, ~~on~~ the formation and geometric development of fluid-flow generated structures.

Based on seismic observations, the objective of this study is to constrain the timing and evolution of faulting versus fluid flow features thereby offering a fluid migration model for tier fault interval in the study area. In this case study, Linear Chimneys are associated with networks of tier-bound, small densely-spaced normal faults which have a polygonal organization in map view. Polygonal networks of discontinuities affecting discrete intervals of fine-grained sediment have previously been linked to diagenetic processes (Berkson et al. 1973). They were first identified as tiered fault systems by Henriet et al. (1982; 1991; 1998) and being investigated in detail by Verschuren (1992). They were later called polygonal fault (PF) systems by (Cartwright, 1994) (see Clausen et al.; 1999; Goulty, 2008), although other observations show that these faults can host a whole range of different plan form geometries including concentric patterns (c.f. Stewart, 2006; Chopra and Marfurt, 2007).

Generally, Polygonal faults are considered as non-tectonic fault systems arising due to compactional-dewatering of very fine-grained sediments during the early stages of burial in passively subsiding sedimentary basins (Henriet et al., 1998). In the classic examples of these fault systems which show "polygonal" fault arrangements and also contribute to their nomenclature, they were characterized by very small differences between the horizontal principle stresses during their formation (Cartwright, 1994; Carruthers et al., 2013). The examples of polygonal faults in this case study show substantial departures from this classic "polygonal" fault pattern (so called isotropic PFs) to very polarized fault arrangements (so called anisotropic PFs) where the tier is deformed by salt tectonic structures or offset by their associated fault systems (Fig. 1; Carruthers, 2012). These faults can display a variety of intricate patterns ranging from tight radial systems around salt diapir to concentric systems within salt withdrawal basins and spiraling concentric patterns above buried pockmarks (Stewart, 2006; Ho et al., 2013). The preferentially aligned faults are many times longer than the regular faults segments with polygonal alignments but are often still confined to the same "tiers". The observations are consistent with a number of other reported examples of preferred fault alignments within networks of polygonal faults (Stewart, 2006; Ghalayini et al., 2016). The preferred fault alignments are indicative of horizontal stress anisotropy at the time of their formation (Carruthers et al., 2013).

Based on seismic observations, the objective of this study is to constrain the relative timing of fluid flow and polygonal faulting thereby offering a fluid migration model for the affected interval. This model will be used as a platform to discuss the interactions between fluid flow, faults and local stress states. In particular , particularly the following questions are addressed; why are chimneys linear in planform and not circular or elliptical as observed elsewhere?, and why do they occur specifically along certain parts of PF planes?

2 Data and methods

Two 3D seismic surveys acquired in 2006 on behalf of Total over The seismic data presented in this study extends across the outer shelf and upper slope of the Angolan continental margin (Lower Congo Basin) (Fig. 1). Two 3D seismic surveys acquired in 2006 on behalf of Total have been used (Appendix 1). The larger of the two surveys covers an area of 1310 km² at about 1,000 m water depth (Fig. 1). The seismic data was obtained by usingwith a dominant frequency of 55-60 Hz withand a vertical resolution of approximately 7 m down to about 1s TWT below seafloor. The smaller survey within this area covers approximately 530 km² (Appendix 1). The with the dominant frequency was being slightly higher (70-80 Hz) allowing to reach to an improved vertical resolution of 5 m.

Both 3D surveys have a bin size of 6.25 x 6.25 m and a map resolution of 6.25 m. The seismic data in both surveys multi-channels, near-offset and has been post-stack time migrated and zero-phased. The data is displayed in SEG normal polarity where a downward increase in acoustic impedance is represented by wavelets of positive amplitude, as shown on the figures in red. Near In addition, middle, and far-offset volumes (representing the amplitude of the signal received at different angles of incidence) were all used for verifying the presence of studied features, and to rule out whether theyor not the studied features are seismic shadows of shallow anomalies or not. Here, data from the near offsets are shown as they yield the highest vertical resolution and are optimal for mapping the details of small fluid venting structures. Local horizons intersected by fluid venting structures were analyzed line-by-line and on arbitrary lines orthogonal to the structures to more accurately map out the linear fluid venting structures most accurately. Furthermore, the studied chimneys were screened for potential artefacts, combining cross-section and map views, and were which are present in the aforementioned three types of seismicon the near, middle and far offset volumes.

3 Geological setting

3.1 Regional setting

The Lower Congo Basin formed during rifting and breakup of western Gondwana followed by the opening of the central South Atlantic (Mascle and Phillips, 1972). Two main phasephases of sedimentation can be distinguished: an Albian-Cenozoic passive margin sequence detached from a Neocomian-Aptian which broadly correspond to the rift and sag sequences by Late drift components of the basins evolution. The rift sequence comprises extensional tilted fault blocks filled with Neocomian-Aptian siciliclastic sediments and overlain by a succession of evaporates (Fig. 2; Duval et al., 1992; Broucke et al., 2004).
Sénna and Anka, 2005). The drift sequence is composed of Albian carbonates and a Late Cretaceous-

Cenozoic succession of siliciclastic sediments. Since the end of evaporite (salt) deposition the passive margin sequence has been gravitationally unstable, incrementally translating seaward on Late Aptian evaporites (Duval et al., 1992). Translation was accommodated by upper slope extension and lower slope compression of the post-salt sediment cover (Sénna and Anka, 2005). The 3D seismic survey is situated above the seaward end of this zone of extension comprising an assortment of minibasins and salt diapirs. This paper ~~focusses~~focuses on the relationship between fluid flow and geological structures in the Neogene-Quaternary, upper ~~passive margin~~drift sequence ~~(Neogene-Quaternary)~~. The principal units are summarized in Figure 2a.

3.2 Structural setting of the study area

3.2. ~~Local tectono-stratigraphic framework~~ 1. Salt-related structuration

A large seaward-dipping listric growth fault rooted in the crest of a NW-SE trending salt wall (dashed pink line on Figure 1) divides the study area into a landward footwall domain and a seaward hanging wall domain (Fig. 2a; Ho, 2013). On the seaward side of the fault, the Albian to early Cenozoic strata ~~thicken~~, capped by purple Horizon 23.8 Ma, thickens into a turtle-back anticline (Fig. 2a). These thickness changes mark the first stages of salt-detached extension within the area.

Four, late Tertiary depocentres named Syncline 0, 1, 2, 3 occur ~~on the NW, NE, SE and S sides of the anticline, respectively~~ along the strike of the salt wall, situated in the hangingwall of the large listric growth fault (Fig. 1~~).~~; 2a). These synclines developed during late-stage salt-detached extension in which the NW-SE trending salt wall collapsed forming the large listric growth fault which transects the survey. Synclines 0, 1 and 2 are located adjacent to two salt diapirs (D1 and D2; Fig. 1), which are rooted in the salt wall at depth. Syncline-0 subsided from the Early Miocene (c. 20 Ma) to Messinian (Ho, 2013). Synclines-1, and -2 subsided since approximately ~~since~~ the early Middle Miocene (c. 16.4 Ma) until the Miocene-Pliocene (Ho, 2013). Some extensional faults in the SW side of Syncline-2~~,~~ next to ~~some~~ chimney structures were still active during the Quaternary (see fig. 6b in Ho et al., 2012a~~, fig. 6b~~). The roll-over Syncline-3 in the south of the study area was induced by salt deflation during the Early Pliocene and became inactive in the Late Pliocene (Ho, 2013).

3.2.2. Miocene to Quaternary stratigraphy and elements

The ~~intervals containing~~ fluid flow structures are located within the Middle Miocene to Quaternary strata being composed which is mainly composed of hemipelagic mudstonemudstones (Philippe, 2000), and intercalated with mass transport complexes (Fig. 2b). ParticularlyIn particular, the studied chimneys primarily occur within the Upper Miocene and Pliocene deposits and in syncline areaswithin synclines (Fig. 2b). These intervals are both deformed by arrays of polygonal faults faulting which conform to two distinct tiers, named here as Tier-1 and Tier-2 (Ho et al., 2012a, 2013, 2016).; Ho, 2013).

The deepest tier (Tier 1) ranges from 70-130 m thick and contains the Late Miocene units whilst the shallower Tier 2, contains the Pliocene units and has a maximum thickness of c. 250 m. Tier-1 has a thicker pinch out toward Diapir-1 while Tier-2 shows a thinner pinch out where polygonal faults become undetectable below 60ms TWT (Fig. 3). These PFs often extend into strata above (e.g. interval A in Fig. 3a). StrataThe strata immediately overlying the PF intervals covercovers the reliedrelief of the underling horst and graben structures with an isopach thickness (e.g.below and show constant thicknesses (e.g. interval B-C in Fig. 3a).

Pockmarks associated with circular PF hosts can often be observed at the base of PF tiers (e.g. Fig. 3b-c; Carruthers, 2012, Ho et al., 2013). In Tier-2, a regional impermeable barrier calledof Intra-Pliocene age has been identified by its geophysical character and immediately below which a the vast distributionpresence of gas accumulations is observedimmediately below (Ho, 2013). The) the stratigraphic position of venting structures is summarizedas summarised in Figure 2b.

3.2.3. Organisation of PFs in the study area

In this study area, PFs are organized into different patterns in map view, such as the isotropic polygonal fault pattern gradually reorganizes to a system comprising of longer faults in a certain direction (i.e. referred as anisotropic PFs) with shorter faults orthogonally intersecting them. The shorter faults are the same length as the standard "polygonal" fault segments whilst the longer ones are up to 20 times longer (Carruthers, 2012). These long and short polygonal fault segments are referred to as first and second order PFs throughout this paper.

Preferred fault alignments or "anisotropic fault patterns" within polygonal fault networks have been observed in this study area. Concentric faults surround pockmarks (see fig. 2a in Ho et al., 2013) and are parallel to extensional synclinal faults (Appendix 2b; see also red dotted lines on all maps of Syncline-3 hereafter). Radial faults occur around salt diapirs (Appendix 2 c) (Carruthers, 2012) whilst ladder-like fault patterns occur in the center of concentric fault patterns above Syncline-2 (Appendix 2d).

The orientations of the PFs around or above the aforementioned tectonic structures are not unusual as the fault patterns mantle the expected stress state of the structures (Carruthers, 2012; Carruthers et al, 2013). The direction of maximum horizontal stress around the tectonic structures is indicated by the first-order anisotropic PFs while the horizontal minimum stress is indicated by the second-order anisotropic PFs (e.g. stress ellipses in Fig. 1), and hence different PF patterns are considered as indicators of stress state in the host sediments (Carruthers, 2012; Carruthers et al, 2013).

Throughout this paper we will show that stress conditions and polygonal faulting in this area has had a profound impact on the subsequent phases of fluid flow by defining a number of interim traps. Consequently, it is important to outline the nomenclature used when referring to different scales of stresses and specific parts of the fault planes in this study.

"Regional stress" refers to stress states in the sub-surface driven by the primary tectonic forces which include gravity and the lateral extension and contraction occurring above the regional salt detachment.

"Local stress" refers to stress state at the scale and within close proximity of individual tectonic structures where the regional stress field may be locally perturbed.

"In-situ stress" refers to stress conditions in-place at the location of individual polygonal faults, this is particularly relevant when trying to understand the stress conditions at sites of incipient hydraulic fracture developments which lead to the formation of chimneys.

"Lower footwall", when not specified, refers to the lower part of tilted PF blocks immediately adjacent to the fault which moved upwards, or referencing the lower part of horsts in this study area.

"Lower hanging wall", when not specified refers to the lower part of PF graben.

4 Observations

Evidence for fluid flow around salt structures is provided by the occurrences of chimneys, pockmarks, depressions, positive high amplitude anomalies (PHAAs) which are acoustically hard (increase in acoustic impedance) interpreted as methane-derived authigenic carbonates, and negative high amplitude ~~(NHA)~~ anomalies (NHAAs) which are acoustically soft (decrease in acoustic impedance) interpreted as free gas (Coffeen, ~~1986~~ 1978; Petersen~~ et al.~~, 2010; Plaza-~~Favorala~~Faverola et al., 2011; Ho et al., 2012a).~~ ~~ These structures are characterised by a linear-to-circular geometry in plan view (Fig. 2b).

4.1 Linear Chimneys

4.1.1 Acoustic properties of Linear Chimneys and terminations

~~On seismic records, chimneys~~ Chimneys have been ~~identified in~~ observed worldwide ~~locations~~in seismic data (cf. ~~Løseth~~Loseth et al., 2011; Berndt et al., 2003; Hustoft et al., 2010; Plaza-Faverola et al., 2010; Ho et al., 2016). Seismic chimneys are represented by narrow vertical zones ~~characterised~~characterized by either stacked amplitude anomalies, pull-up, push-down or distorted reflections (Heggland, 2005; Hustoft et al., 2007~~;~~, 2010; Petersen~~ et al.~~, 2010; ~~Løseth~~Loseth et al., 2001~~;~~, 2011). In the study area ~~Linear Chimneys~~chimneys are often associated with high-amplitude patches and ~~flat-bottomed~~ shallow depressions, all of these pile up to form vertical successions (see Ho et al., 2012a). Linear Chimneys are typically expressed as "squeezed elongate columns" of acoustic distortion zones in seismic data (Fig. 5a), in plan-view they appear as linear ~~low-~~amplitude anomaly zones being 10s to 100s m wide and having an aspect ratio of 1:4 (Fig. ~~4a-b~~5a; Ho et al., 2012a). Linear Chimneys may terminate up- or ~~downward~~downwards into ~~NHA patches (see map view and section in~~NHAA (e.g. Fig. ~~4c-e),~~ 5b-c), or upward into linear flame-like patterns of PHAA (see ~~map view and~~ seismic section ~~in~~ and amplitude map Fig. ~~5a), or~~6). They may also terminate upwards into linear, elongate or sub-circular shallow depressions on the modern seafloor (Fig. ~~5b~~7). These three elements can be combined to form 3 key variations of vertical stacking sequences (Fig. ~~2b):~~ 8; see also Appendix 3):

Type-1 Linear Chimneys terminate upwards into linear, PHAAs within depressions, which are shallow flat-bottomed with relief in the range 3-5 ms TWT (Fig. ~~5a-iii~~8). The acoustic columns defining the chimneys are often associated with velocity pull-up effects~~ (Appendix 2)~~.

Type-2 Linear Chimneys terminate upwards into columns of ~~NHA~~linear NHAAs (Fig. ~~4c, d; Appendix 2~~8). The chimney body is also characterised by push-down reflection zones.

Type-3 Linear Chimneys terminate upwards into linear PHAAs with depressions and downwards into ~~a NHA column (Fig. 6; Appendix 2~~ linear NHAA columns (Fig. 8). Linear Chimneys of this type are usually not represented by any reflection distortion zone.

The ~~NHA~~NHAA columns in Type-2 and Type-3 are situated in the lower part of the ~~fault~~PF tier and are capped by the Intra-Pliocene regional barrier~~.~~ (see seismic lines in Fig. 9 and 10).

The topmost termination of a chimney is ~~easy to distinguish~~easily distinguishable when ~~it is~~ associated with pockmarks or PHAAs (cf. Heggland, 1997; Judd and Hovland, 2007; Cathles et al., ~~2011); while~~2010); whereas identifying the lower termination is challenging due to signal perturbations that increase with ~~depth~~depths (Hustoft et al., 2007~~;~~, 2009). Apart from the downward terminations of Type-3 ~~chimney~~chimneys that can be clearly distinguished due to the ~~NHA~~NHAA column, the ~~two~~ other two types are poorly constrained. (Hustoft et al~~. (~~., 2007, 2010) suggested that the base of the chimney is marked by the disappearance of distorted seismic reflections. In this study, the lower tip of chimneys is considered to be located at the level where columns of distorted seismic reflections start to branch out in opposite directions ~~(Fig. 4d)~~ or where distortions disappear (Fig. ~~4c~~9a).

4.1.2 Linear Chimneys and fault patterns

In the study area, Linear Chimneys mainly occur within the Pliocene PF ~~tier (~~Tier-2~~;~~ (Fig. 2b, Ho~~ et al.~~, 2013~~). They~~) which are parallel to PFs that have preferential directions (Fig. 5a). Both elements are often parallel to adjacent tectonic faults or salt structures (Figs. ~~1, 4a-b~~1; 9c).

~~PFs that follow the trends of tectonic structures and are several times longer than these smaller ones between them, are anisotropic; they are termed first-order PFs while the latter are second-order PF (Fig. 4a; Carruthers, 2012; Ho et al., 2013). There are three main groups of anisotropic PF arrays (see Appendix 3; Ho et al., 2013):~~

~~1) Concentric faults surrounding pockmarks (Ho et al., 2013, fig. 2a) or paralleling extensional faults of synclines (red dotted lines in Fig. 4c).~~

~~2) Radial faults occurring around salt diapirs (Appendix 3c) (Carruthers, 2012)~~

~~3) A ladder-like fault pattern occurring above Syncline-2 (Fig. 6a-b, Appendix 3d), found inside the area bounded by a set of concentric faults.~~

~~Although Linear Chimneys are often parallel to the first-order PFs (Fig. 4a, b) some linear conduits do not show preferred orientations at the NNE edge of Sycline-2 (Fig. 6a) where concentric and uni-directional PF~~

arrays intersect. At this location PFs are more isotropically arranged (Fig. 6b). Another exception occurs above Syncline-1, where linear venting structures are parallel to the second-order PFs (see Appendix 4).

Although Linear Chimneys are often parallel to the first-order PFs, some do not show preferred orientations close to the NNE edge of Sycline-2 (Fig. 10a) where concentric and uni-directional PF arrays intersect. At this location PFs are more isotropically arranged (Fig. 10b). Another exception occurs above Syncline-1, where linear venting structures are parallel to the second-order PFs and the eastern edge of Syncline-1 (Fig. 11).

Few types of gas-charged -fluid migration features are found within anisotropic PF networks. In the interval of PF Tier-2, in map view, a kilometric-scale PF area is filled by negative high amplitude patches in Syncline-3 (Fig. 4e9b), where NHA anomalyNHAA lumps are observed to reminiscent the PF pattern. The whole NHANHAA area is limited laterally by the extensional fault of Sycline-3 and vertically by the Intra-Pliocene horizon, below which Linear Chimneys of Type-2 are observed (Fig. 4d). 9a).

Linear Chimneys are observed to intersect fault planes in different positions within PF Tier-2. A catalogue and a statistical analysis comprising counts of how common each intersection position, has been made by examining 209 detected chimneys (Fig. 7a 12; see also Appendix 2catalogue; sourced from Ho, (2013;), 2013; (Ho et al., 2016)). The Linear Chimneys intersecting PFs can be split into threetwo main populations based on the number of their positions (Fig. 7b12): (1) The first population (54% intersect%) have downward terminations intersecting the lower part or basal tips of a single or a conjugate PFs, and rise from the lower footwall/horst of tilted PF blocks or horsts, (2) the second population (19%%) stem from (around) the intersection of pairs of conjugate PFs, and occur along the middle of the PF grabens (hanging wall/grabens, and (3) 9% intersect the middle to upper portion of PFs, across both footwall and hanging wall).

Population (1) and (2) represents 73% of the total number of chimneys, and are the majority. (see right column in Fig. 8 for summary). In the case of population (2), the Linear Chimneys may also intersect the lower part of the PFs, but the seismic resolution and distortion prevents an accurate determination of their position. Smaller populations include chimneys whose body intersects the middle to upper portion of PFs footwall and hanging wall (9%); and chimneys occur in the middle of PF blocks (7%). The remaining 17%10% of chimneys intersect atat other various positions (Fig. 7b12; Appendix 23). Furthermore, among the 73% (Fig. 7b12), 23% and 8% of the chimneys terminate downwards into negative bright spots in the PF's footwall or hanging walls, respectively; these sub-populations all of them belong to Type-3 linear vents. Consequently, one-third of the chimneys are associated with free gas stored in the lower part of PF blocks, while the rest only have apparent roots in the lower part of the PF tier or deeper.

4.1.3 Radial high-amplitude depression networks along saltsyncline-related faults

Although most linear venting structures occur in PF Tier-2, some exceptions occur. For example, a radial network of a leakage system at a kilometer-scale was found along syncline-related extensional faults in a deeper Late-Middle Miocene interval devoid of PFs (for details see Fig. 813). This complex network is composed of interconnected linear depressions associated with PHAAs that overlie a Linear Chimney network of big Linear Chimneys (Fig. 8a13a-b). TheThese Linear Chimneys are characterised by push-downs (Fig. 8c). The 13c) of which most have horizontal lengths around or in excess of a kilometer with the longest linear features occurones occuring along the strike of extensional faults. (Fig. 13a).

5 Interpretation and discussion

The geometrical coincidence of Linear Chimney and PFs implies a relationship between both of these structures. To decipher the genetic relationships the following aspects need to be discussed: 1) the timing of PFs and Linear Chimney formationformations in respect to each other, 2) the gas-charged fluidfluid migration pathwaypathways to the nucleated location of chimneys, 3) the mechanisms of preferential gas accumulation location locations, 4) and the factors that control the linear planform of the chimneys. Then a A conceptual model for Linear Chimney formationformations will be proposed, followed by a demonstration of using Linear Chimneys for application in hydrocarbon exploration.

5.1 Timing of polygonal faulting

Analysing timing of polygonal fault's formation is essential for the discussion of whether pre-existing PFs affected fluidfluid migration pathways, i.e. chimneys. The relationship between the timing of PFs and Linear Chimney formation can be constrained by several lines of evidence. Polygonal fault nucleation is widely considered to occur during the early stages of finefine-grained sediment compaction (see Goulty, 2008). Authors like Berndt et al. (2012), Ostanin et al. (2012) and Carruthers (2012) sug-gested that PFs formed in shallow sub-seafloorseafloor sediments and ceased propagating when they tip out on the seafloor.seafloor. Polygonal faults in the Neogene-Quaternary deposits of Lake Superior, Hatton Basin and Vøring Basin, demonstrate indicate that their growth is very recent and could even occur to the present day seafloorseafloor (Berkson et al., 1973; Jacobs, 2006; Berndt et al., 2012; Laurent et al.-, 2012-). Recently (Sonnenberg et al. ,(2016) confirmedconfirmed that PFs grew close to the seafloorseafloor with evidence of fault scarps filledfilled by onlapping strata, syn-sedimentary strata. The non-uniform topmost terminations of PFs indicate upward propagation after PF initiation (Berndt et al., 2012).

Within the study area, new evidence was found has shown to support that PFs grew in sedimentsediments very close to the palaeo seafloor.seafloor. A previous study (Ho et al., 2013) documents that in the syn-sedimentary growth wedge of Tier-2, buried ca. 50 ms below the modern sea floorfloor (see Appendix 5Fig. 3; Ho, 2013), in which PFs disappeared progressively toward the pinch-out where as the thickness decreasedecreased below 60ms.60 ms TWT toward the pinch-out. This means that PFs started to grow below seafloorseafloor at shallow depth: minimum 60 ms TWT (faulting during the tier deposition), or, maximum 110 ms TWT (faulting at present day). Similarly, the timing evidence of PF faulting is shown in Tier-1. Onlapping reflectionsreflections in the sedimentary layer covering a dome underlain by a circular PF-bounded horst (interval C in Fig.3C 4a, see also 4b-c) indicates the syn-sedimentary formation (or reactivation) of the PFs. Knowing that the onlapping strata are located 80 ms above Tier-1, this dates the latest activity of the PFs subsequent to Tier-1 deposition. It can be observed that the particular PFs bounding the circular horst are significantlysignificantly longer than most other PFs, and propagate largely above Tier-1 (into interval A in Fig. ~~3C~~4a). Thus, it is likely that most PFs formed during Tier-1 deposition, and some were reactivated once after the tier was buried (below interval A) at shallow depth (15ms below the ~~seafloor).~~seafloor). To conclude, based on literature and our seismic observations, the top-most boundary of both PF tiers represent ~~approximately the~~the approximate timeline of when the main tier ~~cessed~~ceased to form.

5.2 Formation of Linear Chimneys

Seismically recorded "gas chimneys" are commonly considered to be the result of hydraulic fracturing of an impermeable interval (Pyrak-Nolte, 1996; Heggland, 2005; Loseth et al., 2011; Hustoft et al., 2007, 2010; Cevatoglu et al., 2015). Hydraulic fractures develop when pore pressure exceeds the sum of the minimum lateral stress and the tensile strength of the sediment above and propagate upwards perpendicular to the direction of the minimum lateral stress (Phillips, 1972; Cosgrove, 1995; Hustoft et al., 2010; Loseth et al., 2009, 2011). Because the geological ~~signification~~ significance of chimneys has already been well dis cussed in many previous studies (cf. Loseth et al., 2001; Berndt et al., 2003; Hustoft et al., 2010; Plaza-Faverola et al., 2010; Ho et al., 2016), we ~~are focusing~~focus here on ~~the~~ their timing ~~of chimney formation and their nucleation~~ , and geometrical development in interaction with PFs.

5.2.1 Timing of chimney formation related to PFs

The timing of chimney formation is suggested to be recorded by their associated ~~fluid flow features~~pockmarks/depressions and methane-related carbonates, which formed at ~~chimney~~ chimney's topmost terminations when hydrocarbon-charged ~~fluid~~fluid reached the palaeo ~~seafloor: 1) pockmarks/depression, 2) methanerelated carbonates.~~ seafloor.

Chimneys connected to pockmarks have been suggested to have formed during catastrophic blow-out events on the ~~seafloor (~~ seafloor (Judd and Hovland, 2007; Hustoft et al., 2010). ~~A proposed modern~~ An analogue of a modern outcrop was observed when a pockmark 40 m in diame-ter and 7 m deep formed above a chimney while overpressured water was expulsed after 5 ½ months, from a deeper reservoir (~~Loseth~~Løseth et al., 2011). During an experiment on CO_2 injection in reservoirs, a 10 m long chimney terminating in a 4.5m wide and ~~60m~~6m deep pockmark on the ~~seafloor~~seafloor developed within 48 hours at ~~a~~ an onshore test-site in Scotland (Cevatoglu et al., 2015). These studies demonstrate that chimneys terminating into ~~pockmark~~ pockmarks or depressions can form within days. Similarly, PHAAs at the top of chimneys, interpreted as seep carbonates (Hustoft et al., 2007; Petersen, 2010; Plaza-Faverola et al., 2011; Ho et al.-, 2012a-) precipitate at the sea ~~floor~~floor over time spans (Regnier et al. , 2011). At geological time scale, PHAAs can be considered as a time marker for gas migration through chimneys to reach the paleosea ~~floor.~~floor. Because PHAAs and the associated chimneys extend~~ed~~ exactly from the linear gas accumulation below (see Type-3 chimney in Fig. 10a-b), and because the gas accumulations are compartmentalized by the anisotropic PF cells (see Fig. 10c); it implies that the PF networks must have formed prior to the gas accumulations, and hence, modulate the planform development of chimneys and the subsequent ~~fluid~~fluid features. ~~Some might hypothesize~~

It could be argued that the chimneys emanating from the lower part of a polygonal fault plane formed by overpressured gas expulsion at the upper tip of proto-~~faults~~PFs, which were still in their ~~development~~developmental stage. This assumption is, however, inconsistent with the fact that many chimneys are modern, and currently active (as indicated by PHAAs and pockmarks at their topmost terminations on the present day ~~seafloor~~seafloor), while the fault planes have already fully developed (at the end of the Pliocene) with their upper tip propagated above the nucleation point of the chimneys. The nucleation point of the chimneys must therefore correspond to a level from which the ~~fluid~~fluid could not migrate further along the fault plane, and hence, it forced the gas to open a new migration path i.e. chimney.

5.2.2 Level of chimney nucleation and location of gas accumulation

As the nucleation site of linear chimneys is directly linked to the site of gas accumulation, we ~~first~~first investigate the stratigraphic location of gas accumulation by tracing the gas migration pathway prior to the accumulations. This is done by analysing the chimney's downward termination. Type-3 chimneys (31%) initiated within the PF tier as indicated by negative amplitude columns at their downward termination (Fig. ~~6d~~10c). In contrast, the downward termination of the major population of chimneys (Type-1) cannot be determined with precision because of signal attenuation downward. However, they still appear to root in the lower part of the tier or its base, suggesting that overpressured gas-charged ~~fluids~~fluids occurred around the lower boundary of the tier. Most probably, the gas-charged ~~fluids~~fluids leaked through Type-1 chimneys and emptied the reservoirs leaving none or only weak seismic signals. In contrast, residual gas is still present in the reservoir of Type 3 chimneys~~. Therefore~~, therefore, Type~~-~~3 chimneys are interpreted as an earlier stage of Type-1, before their gas exhausted.

Now we investigate how gas had migrated ~~specifically~~specifically into the lower part of the PF tier or below. Because ~~PF~~ PFs root ~~levels can be variable~~at different levels of depth and the presence of bright spots occur~~s~~ at different ~~horizons~~ strata (within or below the lower fault tier) (cf. ~~profiles~~profiles in Appendix ~~6~~4), it is suggested that gas below the PF tier migrates via the long roots of PFs into different permeable layers within the tier. As the exact stratigraphic levels of gas sources and migration pathways to the base of chimneys ~~could~~ can not be ~~identified~~identified, based on the region in which chimneys are rooted, we propose the following scenarios when gas migrated upwards from deeper sources: (1) Gas was trapped in strata along sealed tectonic faults below the tier, (2) gas migrated laterally and reached certain carrier beds intersected by long PFs and accumulated at the base of the PF tier (Fig. 14 a, Appendix 7, 8a4), or (3) gas migrated along the lower portion of the PFs to reach a permeable layer inside the lower tier (Appendix 8bFig. 14b). These three processes either happened solely or in combination with each other as a series of steps. In conclusion, the rooting position of the majority of chimneys suggests that, before the chimneys nucleation, gas migrated and accumulated preferentially in the lower part or at the base of the PF tier.

5.2.3 Gas trapping in the lower part of the PF tier

As supported by the statistical analysis presented herein, > over 54% of chimneys stem from the region around the lower PF footwall. We therefore, Therefore we infer that >over 54% of the time gas accumulated in the footwall at the base of chimneys. It is also the same for the 19% of chimneys that stem from the lower PF grabens (hanging wall. Three). As a result, the statistic leads us to the interpretation that 73% of the total time gas preferentially accumulated in the lower part of PF blocks, therefore we investigate the cause of this phenomenon. We suggest that two hypotheses in combination account for the mechanism of preferential gas accumulation in the lower PF footwalls, of tilted blocks, horsts and one forlower hanging walls: /grabens ((1) the presentpresence of an impermeable regional seal, and (2) partial impermeable fault plane)), while two other hypotheses determine together the preferential gas migration to the lower PF footwall ((3) the differential strain in fault blocks, and 3(4) the stratigraphic position of permeable layers in fault blocks), and finally 4finally one for graben hanging wall ((5) the increase of local permeability.).

1) The seismic record documents that gas is present in the lower part of PF Tier-2 over a vast area, below the regional impermeable, Intra-Pliocene barrier (Ho, 2013). The Intra-Pliocene barrier corresponds to the topmost boundary of free gas accumulations, and does not parallel the seafloorseafloor (blue dotted line in Fig. 4d9a). As a result, this impermeable barrier does not likely represent bottom simulating reflectorsreflectors (BSR) and is, hence, interpreted as of purely depositional origin. The presence of an Intra-Pliocene barrier can explain why gas preferentially accumulated in the lower part of Tier-2, however, the preferential accumulation in the footwall side of the faulted compartment still needs to be investigated. may warrant further investigation.

2) Persistent occurrences of gas accumulations in the lower part of the PF tier below impermeable barrier, regardless of faulting offsetting it, likely indicate that the lower portion of PF plane is not hydraulically communicated with the upper one. Otherwise gas would use the upper fault plane to migrate further to the upper fault tier (Ho et al., 2016). Therefore, the upper portion of PF fault plane above the regional impermeable barrier is likely impermeable (Ho et al., 2016). This hypothesis is well demonstrated, for example, by the vast distribution of gas accumulation below the Intra-Pliocene barrier in Sycline-3 (Fig. 9a).

It can be argued that, more permeable deposits preferentially occur in the lower PF tier and lead to preferential occurrence of gas accumulation in such place. This possibility is disregarded because of the indifference between the lithologies in the upper and lower part of the PF tier as indicated by Total's internal well reports, regardless the permeability measurement of the host sediments is unavailable.

3) Shear strain resulting from extension and normal faulting affects the hydraulic properties of rocks adjacent to the fault surface (-Barnett et al., 1987). Extensional faulting induces significantsignificant shear strain and dilatancy (Zhang et al., 2009) which consequently enhances the porosity and permeability of the wall rocks (Barnett et al., 1987). Numerical modeling demonstrates that the lowest shear stresses occur in the footwall block near the basal tip of a normal fault and that the greatest shear stresses occur in the upper part of hanging wall blocks (Fig. 9a15 a; Zhang et al., 2009; Welch et al., 2009). These results match the conceptual model of Barnett et al. (1987) which shows that the lower parts of footwalls and the upper part of hanging walls are in a state of relative compressional strain, compared to the top of the footwall and base of the hanging wall (Fig. 9b15b). As Tier-2 was buried only a few tens of meters when PFs formed, it was very likely not lithifiedlithified and the lower part of the footwall blocks could have experienced dilatation (Barnett et al., 1987). Therefore, the highest permeabilities would be expected to occur in the footwall of a normal fault near the basal fault tip where gas accumulation is expected to occur. In fact, the majority of Linear Chimneys emanate from the lower parts of the footwall, where gas columns (NHAA) are observed (Fig. 6d). 10c).

34) An alternative explanation for the preferential accumulation of gas in the footwall blocks of the faults is purely geometric: with normal faults, the footwall block is upthrown with respect to the hanging wall, and its series usually raise or tilt upward along the fault (Fig. 9c15c). As a result, upward migration of gas tends to fill the footwallfill the footwall side of the faults.

45) For the second major population of chimneys (19%) that stem from the middle of grabens (PF hanging wall), it is likely that the outbreak point of overpressured fluidfluid is located in the lower part of the graben, where gas is likely to have accumulated before exceeding the lithostatic pressure. In the hanging wall, deposits are likely under a compressional regime (Barnett et al.-, 1987; Welch et al., 2009). Thus, gas will not preferentially migrate into such a location. However,, however a controlling factor is suggested being needed to guide the direction of gas migration: fracturing in grabenthe bottom areas lead to permeabilityof graben leads to an increase and facilitate forin permeability facilitating the trapping of gas (Ho et al., 2016, Appendix 8; Fig. 14b-ii). This phenomenon happens when graben sediment moves downward along curved, steepening upward faults during extensional faulting (Cloos, 1868; Fossen and Rørnes, 1996; Bose and Mitra, 2010). In the upper parts of a graben, extensional phenomena dominate, while the lower parts of the graben are subjected to compression where a compressional fold forms a structural trap.

The above elements are suggested to induce the formation of PF fault-bound traps in the lower part of a PF tier.

5.2.4 Nucleation of Linear Chimneys

Based on seismic observations and the hypothesis of gas migration into the ~~specific~~specific part of a PF interval, as established above, a conceptual model for the formation of Linear Chimneys is proposed ~~in~~ below. The majority of Linear Chimneys stem from the lower PF footwalls (Fig. ~~7b~~12) suggesting gas-charged ~~fluids~~fluids could not migrate along the upper portion of PFs while impermeable. The permeability of small faults in ~~fine~~fine-grained marine sediments varies upon the changes in stress and resultant strain around faults (cf. laboratory experience of Kaproth et al., 2016). Therefore, the impermeability along the upper part of PFs can be explained by the stress state around the fault. In literature, numerical models of Nunn (2013) show~~s~~ that ~~fluid~~fluid pressure might not be high enough to maintain low effective stress in the upper fault zones~~. Therefore,~~ , therefore, the upper part of the fault remains closed. Other modeling results show that it is possible for the lower part of PFs to appear permeable and critically stressed in the contemporary stress ~~field~~field while the upper parts are neither permeable nor critically stressed (Wiprut and Zoback, 2000; Zoback~~.~~, 2007~~.~~). In the anisotropic stress area (salt tectonic area), ~~the fact that~~ stress generated by the overpressured ~~fluid-generated stress~~ fluid in host rocks leading to propagation of planar fractures in PF hanging walls, this likely indicates that ~~fluid~~fluid pressure was not high enough to open the upper fault plane, but only high enough to overcome the minimum horizontal stress plus the fracture strength of the fault blocks (Delaney et al. , 1986; Kattenhorn et al., 2000). Therefore, once the gas trapped in the lower part of the PF footwalls ~~(Fig. 10a-b)~~ became overpressured (Fig. 16a-b), hydraulic fractures propagate from the footwall to pierce the overlying strata and breach the impermeable barrier~~. As~~ , and as a result, the chimneys were initiated and originated along the lower part of polygonal fault planes.

Apart from overpressured ~~fluid~~fluid (gas) creating new fractures, overpressured gas may also pass through, ~~filling~~ filling pre-existing sub- vertical cracks/fractures in the hanging wall bottoms along the main fault surface (~~fig.~~fig. 2~~,~~ in Gaffney et al., 2007). Fluids may also open and extend pre-existing sub-vertical cracks/fractures in the hanging wall bottoms along the main fault surface (Gaffney et al.~~.~~, 2007~~.~~). This happens only if the pressure required for ~~fluid enters~~the fluid entering into the hanging wall ~~fractures~~ fracture was less than the one for creating a new fracture (Gaffney et al., 2007). Pore pressures in the PF bound traps decrease after the fractures propagate or extend, and the residual gas in the traps may re-equilibrate with lithostatic pressure (Zoback, 2007). Consequently, some free gas can remain in the lower part of the PFs at the downward termination of Linear Chimneys (Fig. ~~6c).~~ 10c).

For chimneys originating within the lower part of PF grabens, gas might be compartmentalized in the damaged graben by the impermeable portion of the PF, therefore, not ~~flow~~being able to flow into the adjacent horsts (~~Appendix 7).~~Fig. 14b-ii). Consequently, hydraulic fractures initiated in the graben centre and propagated upward along the central axis (Fig. ~~10c).~~ 16c).

For chimneys that do not intersect with any fault i.e. occur in the middle of PF fault blocks, the illustrated model by Løseth et al. (2009) can be used as a referential analogue (see fig. 21 in Løseth et al., 2009); a lateral contact point between the edge of the gas accumulation and the upper limit of the tilted storage-layer, in the middle of the tilted block, formed a hydrocarbon spill point from where gas chimney nucleated and propagated upward (Løseth et al., 2009). This type of spill point is commonly occurred in structural traps.

5.2.5 Result ~~Chimney's~~ chimney's linear planform geometry and fault orientation

The linear planform of chimneys and their evident spatial relationship to anisotropic polygonal faults suggest that gas migration and hydraulic fracture propagation are controlled by~~BY~~ the alignments of anisotropic PFs. Anisotropic PFs follow the orientation of salt tectonic structures indicating that the PFs are controlled by the stress states resulting~~field generated by the~~ from salt activities~~structures~~ (Carruthers, 2012).~~;~~ ~~while t~~The presence of faults alone can perturb the surrounding stress ~~field~~field and affect the adjacent fracture propagation (Rawnsley et al., 1992). Thus, degree of horizontal stress ~~fields~~anisotropy and dominant direction of sigma-2 play a determinant role in both formation and geometry of anisotropic PFs, and the planform geometry of chimneys.

In ~~the stratigraphic interval where PFs are devoid, the parallelism between the deep tectonic~~ Syncline-0 polygonal faults ~~and~~ are absent, yet the kilometric-scale Linear Chimneys ~~in Syncline-0 (Fig. 7a), clearly demonstrate that chimneys propagate toward the direction that resulted from the perturbation of horizontal anisotropic stresses induced by the tectonic faults (cf. Nakamura, 1977).~~are still present (Fig. 13a). Here, Linear Chimneys are parallel to deep-seated tectonic faults resulting from salt movement. In such location, the horizontal stresses are not equal as the intermediate ~~horizontal~~ principal stress exceeds the minimum one (Cosgrove, 1995). ~~Thus, the~~ The gas pressure was likely not strong enough to overcome the intermediate ~~horizontal~~ stress so the hydraulic fractures opened in parallel with it, and against the direction of the minimum horizontal stress (Cosgrove, 1995). As a result, the ~~final~~final chimneys are linear in planform and follow the strike of adjacent faults. This example clearly demonstrates that chimneys propagate towards the direction that resulted from the perturbation of horizontal anisotropic stresses induced by the tectonic faults (cf. Nakamura, 1977).

In the smaller scale of polygonal faulted blocks, Linear Chimneys and anisotropic PFs are often aligned, such as in Synclines-2 and 3 (Fig. ~~4a; 6a).~~10a; 9c; 5). However, in a particular location above the ridge of Syncline-2, Linear Chimneys are aligned with a pseudo isotropic (less anisotropic) PF network enclosed in a zone between two (strong) anisotropic PF patterns, one is parallel to the edge of Syncline-2 and the other has a "ladder"-like pattern in the center of Syncline-2 (Fig~~s 4a, 6a, ~~. 10a-b~~; Appendix 3a~~). In this ~~specific~~specific location although the PF pattern is similar to isotropic polygonal faulted areas~~ but~~, the stress magnitude remains greater because of the tectonic extension (Carruthers~~-~~, 2012). Given that in such an enclosed (pseudo) isotropic PF area, chimneys are still linear~~,~~ and all aligned parallel to their rooted PF and do not show strong preferred orientation (Fig. ~~6a~~10a). We therefore conclude that at tier-fault scale, the in-situ anisotropic stress of the nearest PFs has major ~~influence~~influence on the orientation of Linear Chimneys than the local tectonic fault stress ~~field.~~field. The combination of both anisotropic stress ~~fields~~fields of tectonic and polygonal faults is suggested to be the main cause of linear planform chimneys with preferential orientations, as Linear Chimneys do not occur in areas where isotropic PFs are solely present.

Finally, the lateral ~~propagation~~propagations of the kilometric-scale Linear Chimneys rarely impeded by faults are oriented roughly parallel to them and the chimneys can reach much greater lengths (Fig. 13). In contrast, chimneys within polygonally faulted areas are much shorter horizontally (> 300m) (~~Fig. 8~~Appendix 3). This is because the distance for which hydraulic fractures can propagate laterally along a ~~specific~~specific trajectory is limited by faults. This example likely demonstrates that the planform and orientation of chimneys can be affected simply by the stress ~~field~~field of a tectonic fault. In conclusion, tectonic stress controls the orientation of anisotropic PFs, and the in-situ stress of the PFs ~~control~~controls the orientation of Linear Chimneys.

5.2.6 Model of ~~fluid~~fluid migration and Linear Chimney formation

Linear Chimney formation can be summarized in 6 steps (Fig. ~~11).~~ 17).

1. During the Pliocene, anisotropic PFs formed and developed under the ~~influence~~influence of an anisotropic stress ~~field~~field induced by adjacent (salt-) tectonic structures~~, and developed during the Pliocene.~~ .

2. Gas-charged ~~fluids~~fluids migrated vertically from deeper intervals along tectonic faults, and laterally into the permeable beds below or at the base of ~~a~~the PF tier (Fig. ~~11a).~~ 17a).

3. Gas-charged ~~fluids~~fluids migrated ~~upward~~ upwards along the ~~lower~~ root of PFs, then ~~flowed~~flowed into the lower part of the tier, and ~~filled~~filled the highest permeable layers in the horst or the fractured apex of grabens where the permeability was higher than in the undamaged sediment (Fig. ~~11a~~17a-b). The pressure of gas-charged ~~fluid~~fluid was not strong enough ~~for allowing it~~ to allow gas to intrude the upper part of ~~PFs.~~PF plane. Further upward migration of the gas-charged ~~fluids~~ fluids within strata was prevented by the Intra-Pliocene impermeable interval.

4. Overpressure of gas-charged ~~fluids~~fluids attained the threshold value for hydraulic fracture propagation but ~~insufficient~~was insufficient to reactivate the fault.

5. Hydraulic fractures (i.e. chimneys) ~~grew~~propagated upward from the lower part of the PF footwall or hanging wall (Fig. ~~11c~~17c), throughout the end of the Pliocene to the Quaternary. These fractures were affected by the stress ~~field~~field around the closest fault and developed ~~into~~ a linear ~~planforms and~~ planform parallel to adjacent faults (along the direction of the intermediate ~~horizontal~~ principal stress).

6. The linear outlet of chimneys on the ~~seafloor~~seafloor was eroded by gas venting, producing a linear depression~~,~~ in which methane~~-~~ derived authigenic carbonates precipitated and are expressed by PHAAs ~~on~~ in seismic ~~records~~data (Fig. ~~11d).~~ 17d).

5.3 Implications for petroleum exploration

5.3.1 Reconstruction of hydrocarbon leakage history by using Linear Chimneys

~~The~~This analysis of Linear Chimneys ~~allows access to~~ has revealed information about palaeo activities of buried hydrocarbon systems, especially how gas-charged ~~fluid~~fluid interacted with pre-existing geological structures while migrating upward to the subsurface. Based on the analysis of linear venting structures, we attempt to reconstruct the hydrocarbon leakage regime in ~~the~~this study area. ~~The occurrence of linear~~ Linear venting structures and gas concentrations occur predominantly in the synclines ~~indicate that synclines~~ indicating they are sites of active ~~fluid flow~~fluid flow (Fig. ~~4d, 6b).~~9b; 10b). The reason why gas preferentially concentrates within syncline in the Pliocene PF interval in this study area may because of coarse~~-~~r grained sediments trapped in the syncline depocenters during that period. It is also known that ~~syncline~~synclinal faults cut down to deep turbidite channel reservoirs in this study area (Monnier et al., 2014). Venting structures occurring around the extensional faults of synclines suggest that these faults served as initial leakage pathways for gas-charged ~~fluids~~fluids to migrate upwards. If the amount of gas exceeds the accommodation volume of the faults, gas will migrate horizontally into shallow carrier beds beneath ~~the~~ PF Tier-2 and then use the deep-rooted PFs as further leakage pathways into the PF tier (Fig. ~~12a~~18a). This explains why gas accumulations occur within PF Tier-2 above the center of Syncline-3, mimicking the geometry of the polygonal cells (~~=~~ traps) (Fig. ~~4e~~9b). Within the anisotropic PF network in all syncline location (e.g. Fig. ~~4e, 6b~~10b; 9c), the preferential orientation of linear gas accumulation and hydraulic fractures (i.e. Linear Chimneys~~)~~)) suggests that the direction of gas ~~flowing~~flowing and escaping within the tier was likely guided by anisotropic stress ~~fields.~~conditions. In contrast, where anisotropic PFs are absent no Linear Chimneys occur. Therefore, gas-charged ~~fluids~~fluids are likely ~~not being~~ unaffected by ~~anisotropic~~the surrounding stress state because the horizontal principle stresses ~~and~~are too weak or too similar and instead may migrate in random directions, until they reach a permeable bed or mechanically weak zone to break through (Fig. ~~12b~~8b). To ~~summerise~~summarise, the direction of ~~fluid~~fluid leakage in areas of anisotropic ~~PF~~ PFs can be predicted by analyzing fracture and fault directions (Ho, 2013; Ho et al., 2013).

5.3.2 Reconstruction of palaeo stress directions

~~While linear fluid conduits originate from perturbation of the stress field, they can be used as indicators of the palaeo stress field.~~We have shown that the propagation and resulting morphology of chimneys are receptive to perturbations in magnitude, directions and differences of the horizontal principle stresses. The ability to date the formation of such systems makes them potential indicators of palaeostress conditions. Normal faults propagate parallel to the intermediate principal stress, while hydraulic fractures open in parallel to the ~~plane~~ direction of the maximum and intermediate principal stresses and against the minimum principal stress (Cosgrove, 1995). For example~~,~~, in Syncline-1, the orientation of the ~~first~~first-order PFs implies that the direction of the intermediate compressive stress initially followed the curvature of the northern edge of Syncline-1 (~~Appendix 4~~Fig. 11). However, the Linear Chimneys rather formed parallel to the curvature of the eastern edge. Therefore, at the moment overpressured gas-charged ~~fluids~~fluids escaped via hydraulic fractures, the intermediate stress direction switched from a northern curvature to an eastern curvature. Thus, the horizontal stress ~~field~~field re-oriented during leakage of gas-charged ~~fluids~~fluids after PF formation. Next to the NE side of Syncline-1 an extensional fault set that is observed to parallel the Linear Chimneys (~~Appendix 4~~Fig. 11), was re-activated during Plio-Quaternary (red ~~starts~~stars in Fig. 2a; Ho, 2013). Because these tectonic faults were active during the same time as the linear conduits formed (~~see Fig. 11b~~in Pliocene to the beginning of Quaternary), it is plausible that the re-orientation of the stress ~~fields~~fields in Sycline-1 resulted from the movement of these faults. In conclusion, comparing the direction of ~~first~~first-order PFs and the direction of Linear Chimneys is useful for diagnosing the evolutional history of stress ~~fields~~fields in the past.

We have shown that the formation and orientation of gas chimneys was modulated by the stress ~~field~~field of faults, and that the ~~kilometre~~kilometer-scale Linear Chimneys are parallel to the tectonic faults in Syncline-0 (Fig. ~~8a~~13a); these chimneys with ~~their~~ lateral tips connect to each other and constitute a complex Linear Chimney network at 9 Ma. Their top is marked by a radial-depressional network formed due to further leakage. Methane-related authigenic carbonates that precipitated within the depressional network, formed another complex PHAA network and ~~highlighting~~highlighted the radial geometry of underlying chimney ~~network~~networks (Fig. ~~8b).~~ 13b).

Therefore, the subsequent ~~flow~~flow structures associated with the chimneys that have the same planform also appear to be useful to determine the palaeo principal stress directions.

6 Conclusions

The anisotropic stress attributed to perturbations of the regional stress ~~field~~field by faults and salt diapirism, control~~s~~ the orientation of PFs, which in turn impacts gas-charged ~~fluid~~fluid migration, leakage pathways and ultimately the geometry of gas leakage conduits and associated expulsion features at the ~~seafloor.~~seafloor. The mechanism of Linear Chimney formation is summarised as follows:

1) PF ~~blocs~~blocks form fault-bound gas traps in the lower part of PF tiers.

2) The location of these traps determines the site of gas leakage and hence, the nucleation site for vertical chimneys.

3) ~~Linear~~Linear Chimneys nucleating along the lower part of polygonal fault planes document that gas-charged ~~fluids~~fluids did not migrate along the upper portion of PF planes, which, therefore, appear to be impermeable.

4) Fluid expulsion features making the upper termination of chimneys at the palaeo sea ~~floor~~floor (pockmarks, depressions and seep carbonates) date chimney formation from the End Pliocene to the Present. Polygonal faulting initiated in the shallow depth range from 50 to 100 ms TWT below the ~~seafloor~~seafloor during Early Pliocene pre-date Linear Chimneys.

5) Orientation of chimneys is mainly determined by the orientation of the intermediate principal stress around the closest fault. Overpressured gas-charged ~~fluids~~fluids break through the host rock by pushing aside the host rock towards the direction of ~~lowest~~minimum principal stress, consequently Linear Chimneys developed aligned and parallel to the intermediate ~~horizontal~~ principal stress, and hence tectonic and/or polygonal fault strike.

6) ~~Under~~In (strongly) isotropic stress fields, under the same spectrum of ~~venting~~ fluid expulsion dynamics, the morphologies of chimneys and associated ~~fluid~~fluid expulsion features at the sea ~~floor~~floor (depressions, pockmarks, seep carbonates bodies) are circular~~. In (strongly) isotropic stress fields~~, while they are linear in anisotropic stress ~~fields~~fields surrounding tectonic faults, salt structures and in anisotropic PF networks.

7) In-situ stress ~~fields of~~fields of isotropic PFs alone are not ~~sufficient~~sufficient to induce ~~preferential orientated~~ Linear Chimneys,~~ but~~ anisotropic tectonic stress ~~fields~~fields must be involved.

8) In areas experiencing a transitional stress field, Linear Chimneys follow the trend of weak anisotropic PFs rather than the nearby tectonic structures. Therefore, the development of Linear Chimneys is interpreted to have been predominantly affected by the in-situ stress field of anisotropic PFs (which are dominated by

the anisotropic tectonic stress).

9) Linear Chimneys can be used as a tool to reconstruct previous stress directions in the same way as using preferential orientated PFs.