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Insights into the permeability of polygonal faults from their intersection geometries with Linear Chimneys: a case study from the Lower Congo Basin

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Abstract: Layer-bound arrays of polygonal compaction faults have long been considered as important migration routes for hydrocarbon fluids leaking to the surface across thick shale sequences. A classic example is the deep offshore of the Lower Congo Basin where numerous fluid-venting structures are present above a Pliocene polygonal fault system. In this paper we present a detailed seismic analysis of a newly recognised system of Quaternary-aged Linear Chimneys and their intersection geometries with pre-existing Pliocene-aged polygonal faults (PF). Most (73%) of the 209 chimneys analysed intersect the lower portions of polygonal faults and almost half of these are rooted in strata below the PF interval. This indicates that fluid (in this case gas) migrated vertically, cross-cutting polygonal faults as it ascended through the tier. This is a strong indicator that PFs did not provide viable migration pathways otherwise chimneys would terminate at the upper tip of the fault, which would be the most likely migration exit point. Only twice in the whole system of Linear Venting Systems did this occur. A sub-set of chimneys stems from or above PF planes but these are restricted to either the lower footwall or from the apex area of hanging wall. At best they are evidence of fluids migrating up the lower part of polygonal faults and exiting deep within the tier, then migrating through most of the tier in their own vertical leakage vents. These results provide strong indicators that at least within this part of the Lower Congo Basin polygonal faults were the least effective/favoured migration pathway and that it was more energy-efficient for migrating gas to hydrofracture its fine-grained overburden than to re-open polygonal faults.

Key Words: Linear chimneys; hydrocarbon; polygonal faults (PFs); permeability; methane-related carbonates; Lower Congo Basin; Angola.

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Résumé : ***La perméabilité des failles polygonales déduite de la géométrie de leurs intersections avec des cheminées linéaires : une étude de cas dans le bassin du Bas-Congo.-*** Les réseaux de "failles polygonales" (failles de compaction restreintes à un intervalle stratigraphique) ont été longtemps considérés comme d'importants chemins pour la migration vers la surface des hydrocarbures à travers d'épaisses séries argileuses. Un exemple classique est fourni par l'offshore profond du bassin du Bas-Congo où de nombreuses structures d'échappement de fluides sont présentes au-dessus d'un système de failles polygonales affectant l'intervalle pliocène. Ce papier présente l'analyse sismique détaillée d'un système récemment reconnu de cheminées linéaires d'âge quaternaire, ainsi que de la géométrie de leurs intersections avec des failles polygonales pliocènes (donc préexistantes). La plupart (73 %) des 209 cheminées analysées recoupent le mur des failles polygonales, et près de la moitié d'entre elles s'enracinent dans l'intervalle sous-jacent à l'intervalle faillé. Cette disposition indique que le fluide (gaz en l'occurrence) a migré verticalement, recoupant les failles polygonales lors de sa remontée ; elle met également en lumière le fait que les failles polygonales ne constituent pas un chemin de migration efficace, sans quoi les cheminées se termineraient à l'extrémité supérieure de la faille, qui serait le point de fuite préférentiel. Cette configuration n'a été observée que dans deux cas sur l'ensemble du système. Un sous-ensemble de cheminées se développent depuis la partie inférieure des plans de failles polygonales ou directement à l'apex des grabens. Au mieux ces cheminées sont l'expression de fluides ayant migré seulement le long de la partie inférieure des failles polygonales avant de s'en échapper pour migrer verticalement le long d'un chemin créé par le gaz lui-même. Ces résultats indiquent de façon nette que, dans cette partie du bassin du Bas-Congo au moins, les failles polygonales ne constituent pas un chemin de migration et qu'il est énergétiquement plus efficace pour le gaz de migrer par fracturation hydraulique de la couverture argileuse que de rouvrir les failles préexistantes.

Mots-clefs : Cheminées linéaires ; hydrocarbure ; failles polygonales (PF) ; perméabilité ; carbonates liés au méthane ; bassin du Bas-Congo ; Angola.

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Introduction

The interaction of polygonal, tier-bound compaction faults (PFs) with fluid flow has been an issue since fluid venting structures have been discovered in association with these faults (*cf.* Berndt *et al.*, 2002; Pilcher & Argent, 2007; Hjelstuen *et al.,* 2010). In some areas, PFs have been interpreted as permeable fluid migration pathways (*e.g.*, Berndt *et al.*, 2003; Gay *et al.*, 2004; Ostanin *et al.*, 2012). However, most evidence is at best conjectural and often based on qualitative assessment of spacing and proximity of shallow fluid venting structures with underlying PFs leaving the question of PF permeability very much unsolved.

In this paper we investigate the relationship between a unique system of chimneys with a linear plan form and a Neogene-aged polygonal fault system developed in the deepwater Lower Congo Basin, offshore Angola. Detailed seismic attribute maps of surfaces intersected by Linear Chimneys and polygonal faults, first shown in Ho *et al.* (2012), reveal a fascinating parallelism between the two structures strongly suggesting that development is somehow interrelated. Here, we build on these initial results and explore the relationship between Linear Chimneys and PFs further, focusing on two key aspects. Firstly we present the results of a quantitative analysis of the intersection and termination positions between Linear Chimneys and PFs (undertaken in Ho, 2013) to determine if linear venting chimneys are randomly developed within the polygonal faulted interval or if they show persistent relationships with key parts of faults or certain fault sets, and secondly, we discuss the absolute and relative timing of the two structures to understand their evolution.

Our results suggest that the leakage of fluid-forming Linear Chimneys (most likely gas in this area) did not migrate along the whole PF plane exiting at their upper tips. Gas instead, migrated along their lowest parts only before creating their own vertical migration pathways through the remainder of tier stratigraphy. These results suggest that PFs are at least impermeable in their upper parts in this part of Lower Congo Basin. We conclude this paper with a discussion of the interactions that lead to the preferred fluid migration pathways reconstructed in our analyses.

Data and method

Our analyses of fluid venting structures and PFs are derived from a 1000 km^2 3D seismic reflection survey in the deep offshore of Angola in water depths ranging between approximately 500 and 1000 m. The survey images both PFs and fluid venting structures with excellent quality and precision. The survey has a bin size of 6.5 m and a dominant frequency of about 70 Hz in the Pliocene-Quaternary interval yielding a vertical resolution of about 7 m. The survey was acquired in a NNE-SSW direction. Crucially it is not aligned parallel to the main structures in this area such as faults and linear fluid-venting structures and therefore preserves maximum image quality of the structures.

The seismic volume is pre-stack time-migrated and has been zero-phased to display seismic events in American polarity convention. That is, where downward increases and decreases in acoustic impedance are represented by symmetrical peaks and troughs shown herein as a yellow-red and grey-black reflection events respectively. Zero crossings or zero amplitude are represented by the white colour of the adopted colour pallet. Only near-offset volumes, retaining the greatest resolution, were used in this study. The seismic data has been interpreted with Sismage© software developed by Total. Seismic horizons were tracked automatically whenever possible otherwise manual picking was adopted. Arbitrary lines orthogonal to structures were chosen for interpretations and so are aligned oblique to the inline and cross-line direction. Visualization was carried out in full 3D view.

A key aspect of this work involves determining chimney-fault intersections or chimney terminations, up and down. It is thus important to state what criteria was used to define them, as well as the associated uncertainty. Chimneys have been interpreted on seismic data as narrow, vertical zones of stacked amplitude anomalies (Hustoft *et al.*, 2007, 2010; Petersen *et al.*, 2010), which may coincide with seismic pull-up or push-down (see seismic sections in Fig. 1.a-c). These characteristics are common amongst chimneys observed elsewhere in the world (*cf.* Heggland, 2005; Hustoft *et al.*, 2007, 2010; Petersen *et al.*, 2010; Løseth *et al.*, 2011). The stack of anomalies of Fig. 1.c shows a shallow anomaly at the top (at the level of the cyan horizon, 2.5 Ma), then series unaffected by acoustic perturbation over ca. 75 ms TWT, down to the Intra-Pliocene (Intra-Plio) horizon, and then about 100 ms TWT with several high amplitude anomalies. Although these are likely not fully resolved, *i.e.*, are thinner than the resolution of the seismic, they show quite variable morphologies: some make local relief (*e.g.*, the convex-up anomaly labeled "A" on the seismic section in Fig. 1.c) while others are depressed (*e.g.*, the concave-up anomalies labeled "B" and "C" on the same line, Fig. 1.c). As regards amplitudes, the column of anomalies includes several reinforcements of amplitude, either positive or negative. This is not consistent with absorption of seismic energy by the shallowest anomaly, and records instead the presence of a

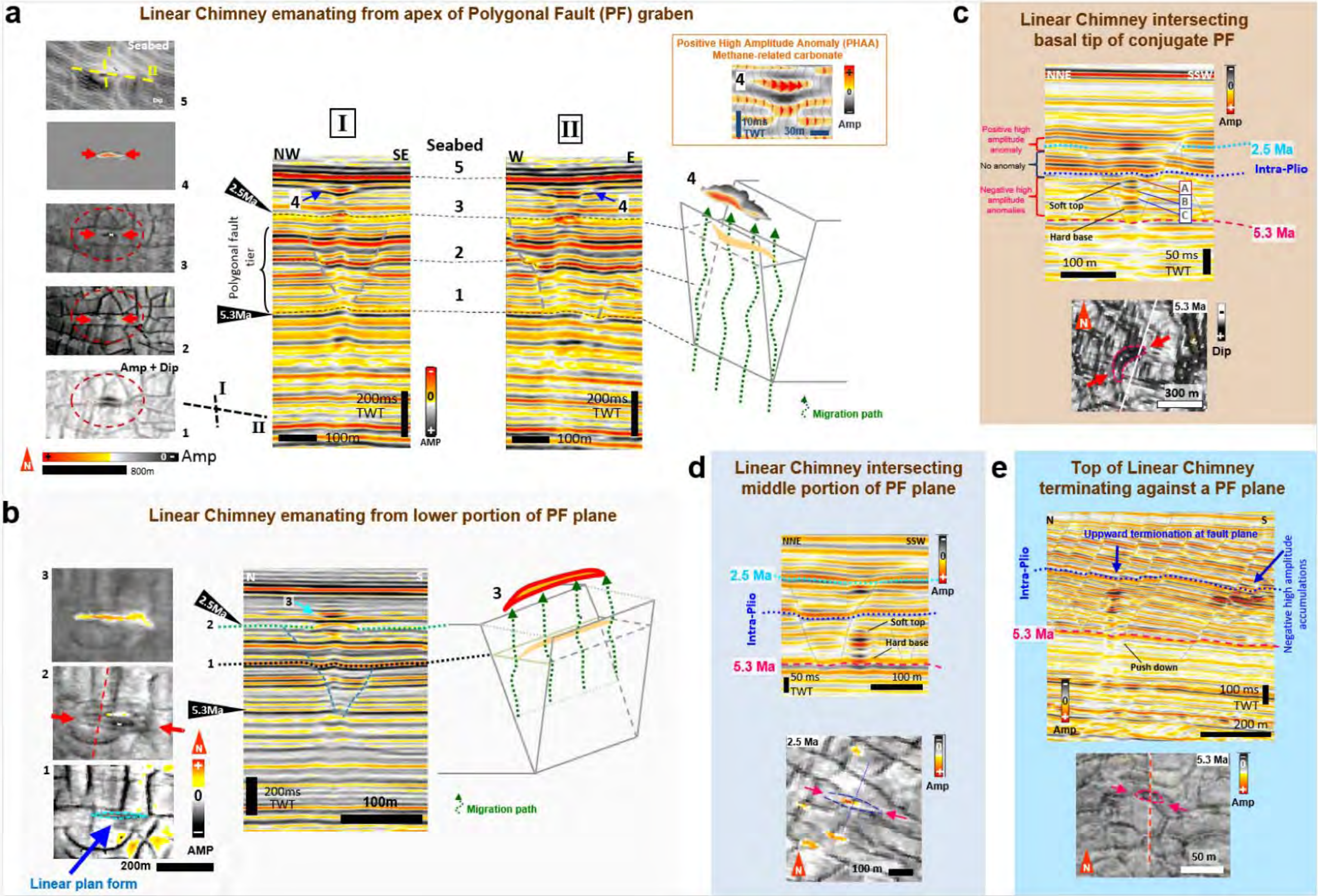


Figure 1: Linear Chimneys intersecting and emanating from different parts of tier-bound polygonal fault (PF) planes. The plan forms of the chimney are shown on inset maps in each section. **a)** The linear plan form geometry of a chimney is shown on a series of amplitude maps on the left. Seismic sections intersecting the short (panel I) and long (panel II) axis of Linear Chimneys. Note that the chimney intersects the apex of the underlying PF graben as illustrated in in the far right cartoon. Inset at top right shows seismic wavelets of positive high amplitude anomaly labelled '4' on the section. Modified after Ho *et al.* (2012). **b)** Seismic section showing chimney intersecting the basal portion of a conjugate PF. **c)** Zoomed seismic section showing bright amplitude column intersecting centre of conjugate PF graben. Label "A": convex-up anomaly, label "B" and "C": concave-up anomalies. **d)** Zoomed seismic section showing chimney intersecting middle portion of PF plane. **e)** Zoomed seismic section showing chimney terminating abruptly upwards against a PF plane. Blue arrow indicates the negative high amplitudes are bounded by the Intra-Pliocene (Intra-Plio) horizon.

succession of impedance contrasts in the column. Similar observations can be made on the section of Fig. 1.d: the stacked anomalies there occur in two separate clusters: one just below the 2.5 Ma horizon and the other in the 120 ms above the 5.3 Ma horizon. There is no way in which the upper anomaly could bring perturbation to the signal in the lower part of the tier without affecting the intermediate part between the two clusters. The 209 chimneys studied here were screened for potential artifacts, combining cross-section and map views, before being included in the set.

Location of study area and stratigraphy

The Lower Congo Basin is situated in the Central South Atlantic on the West African continental margin. The formation of the basin is intrinsically related to the rifting and breakup of Gondwana followed by opening the South Atlantic (Mascle & Phillips, 1972). The post-rift passive margin sequence of the basin which is the focus of this study has been strongly affected by gravitational collapse and translation over Late Aptian evaporates (Duval *et al.*, 1992). The study area is situated at the distal end of the upper slope extensional domain (Ho *et al.*, 2012). Extension above evaporites resulted in the development of coast-parallel salt rollers and salt diapirs and intervening minibasins (SÉRANNE & ANKA, 2005). Salt diapirs collapsed during the later-stages of extension forming a number of secondary minibasins (BROUCKE *et al.*, 2004) whose formation has subsequently influenced the orientation of contemporaneously developing polygonal faulting and fluid venting structures (HO *et al.*, 2013a). It is in this interval of shallow Pliocene-Quarternary hemipelagic sediments (HO *et al.*, 2012) that our study and analysis are focused. For detailed information on the distribution of fluid-venting structures and tectonic framework in the studied area see HO *et al.* (2013a).

Seismic observations and results

Map view geometry of chimneys and PFs

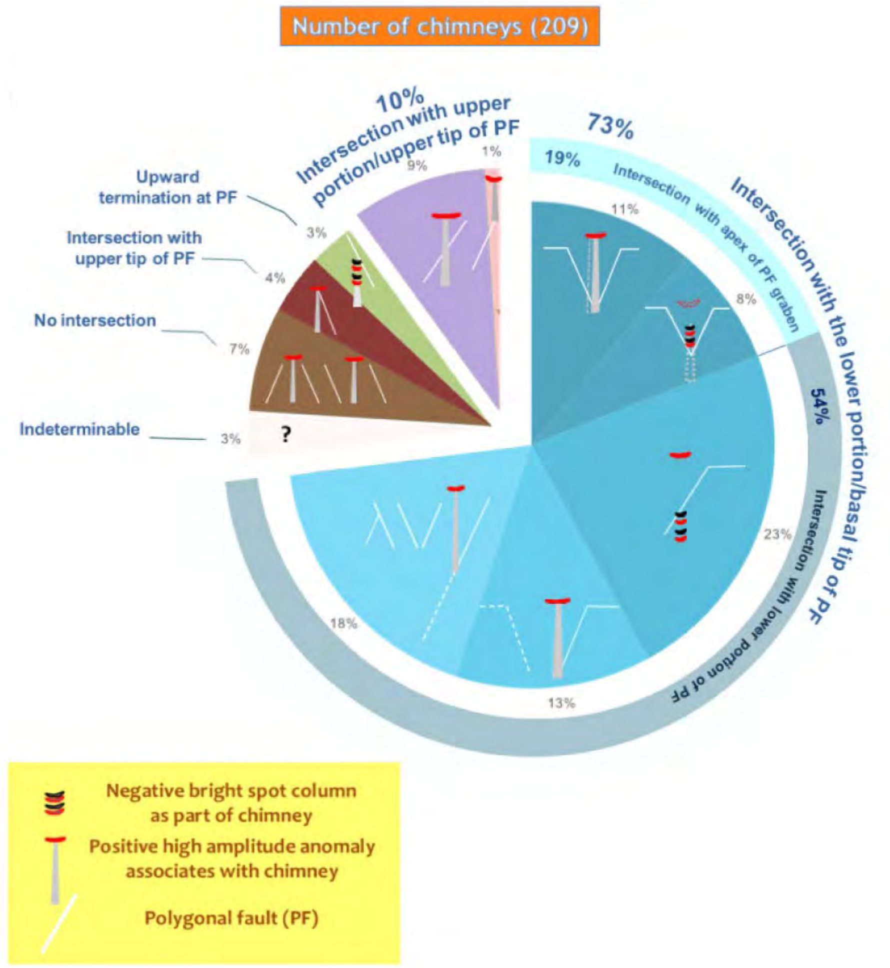
In cross-section, chimneys are vertical, narrow structures expressed in seismic data by any or one of the following: pull-up, push-down or stacked amplitude anomalies (LØSETH *et al.*, 2001; HEGGLAND, 2005; HUSTOFT *et al.*, 2007; PETERSEN *et al.*, 2010), while zones of pull-up and push-down are generally interpreted as indicators for occurrences of genuine fluid conduits, *i.e.*, hydraulic fractures on seismic (*e.g.*, PYRAK-NOLTE, 1996; LØSETH *et al.*, 2001, 2011; HEGGLAND, 2005; HUSTOFT *et al.*, 2010). On amplitude maps chimneys show up as small zones of amplitude anomalies (*e.g.*, horizon 1-3 in Fig. 1.a). In previous studies chimneys mapped in seismic data have typically been shown to be circular or elongate in map view (*e.g.*, HEGGLAND, 2005; HUSTOFT *et al.*, 2007, 2010) but here they are distinctly linear with an aspect ratio greater than 1:4 (HO *et al.*, 2012). Linear Chimneys are developed in the fine-grained Pliocene interval. They are essentially vertical, and mostly develop in an interval affected by pervasive, densely-spaced normal faulting (HO *et al.*, 2012). The faults are layer-bound (see seismic sections in Fig. 1.a-e) and define a somewhat 'polygonal' pattern in map view although a detailed inspection shows that the polygonal fault pattern is anisotropic, as opposed to truly polygonal, around salt diapirs and within minibasins in this study area (HO *et al.*, 2013a). Despite this fault pattern variation they show all the major characteristics of the 'polygonal faults' referenced in CARTWRIGHT (2011), however the exact mechanism of formation of these faults is still a matter of much debate (*cf.* GOULTY, 2008; CARTWRIGHT, 2011) but is beyond the scope of this paper.

Linear Venting Systems

Linear Chimneys commonly have upward or downward terminations characterised by linear varieties of other fluid flow features including: **1)** Shallow depressions presenting as small pockmark-like structures (feature n. 4 in Fig. 1.a-I-II), **2)** Positive high amplitude anomalies (feature n. 4 in Fig. 1.a and feature n. 3 in Fig. 1.b), which have previously been interpreted as the seismic expression of methane-related carbonate ("seismic-carbonate") in this region *cf.* HO *et al.* (2012, 2013b) and **3)** Columns of negative high amplitude anomalies (NHAAs), which, based on their soft reflection tops, hard reflection bases (Fig. 1.c-d) or underlying push-down (Fig. 1.e), are interpreted as free gas accumulations (COFFEEN, 1986). The collective name given to vertically-stacked arrangements of linear venting structures is Linear Venting Systems. Although the stacking order and presence or absence of some linear fluid flow features within these Linear Venting Systems can vary there are two persistent observations. First, if linear positive high amplitude anomalies (PHAAs) and linear shallow depressions are present they occur at the upper termination of the Linear Chimney (see seismic section in Fig. 1.a). PHAAs often occur within the fill sequence of linear shallow depressions that are restricted to the Quaternary interval (see cartoon and inset in top right of Fig. 1.a). The second observation is that, if columns of NHAAs are present, they occur in the lower part of Linear Chimneys, which is typically in the lower-to-middle part of the Pliocene polygonal fault tier (see seismic section in Fig. 1.c-e, Fig. 2.a).

Intersection positions of Linear Chimneys with polygonal faults

Seismic sections show that Linear Chimneys intersect or terminate at a variety of positions across individual polygonal fault planes ranging from the basal to upper fault tip and with no or indeterminate intersections. Besides those cases which have no termination or could not be determined, the rest fall into two broad groups: those that intersect the lower portion of fault plane beneath the Intra-Pliocene horizon, and those that intersect the upper portion of fault plane above the Intra-Pliocene horizon. Of the 209 Linear Chimneys identified in the study area (Chart), 73% stem from or intersect the lower portions of faults or basal tips (for examples seismic sections in Fig. 1.a-b), whilst only 9% intersect the upper portions (for example Fig. 1.d). In only 2 of the 209 cases (1%) chimneys stem from the upper tips of polygonal faults. Of the chimneys that extend beneath the Intra-Pliocene horizon, 54% intersect the lower PF footwall (for example seismic sections in Fig. 1.a-b); 19% apparently intersect the base of conjugate polygonal-fault grabens (for example Fig. 1.c) and 3% have upward terminations bounded by the fault planes (for example Fig. 1.e).



◀ **Chart** showing the percentage of 10 different linear chimney-polygonal fault intersection or termination positions (see labels and cartoons for description of each position).

Interpretation

Timing of fluid flow relative to faulting

Determinations of timing of each of the fluid flow structures and faults can be made to varying degrees of accuracy. The timing of chimneys are very ambiguous where they do not contain any syn-kinematic indicators (*e.g.*, containing pockmarks); only a cross-cutting relationship with stratigraphy allows the earliest possible onset to be determined (*cf.* LØSETH *et al.*, 2011). The latest possible timing is present-day because the chimney could have formed in a completely blind sense similar to blind faults (*cf.* SUGIYAMA *et al.*, 2003). In this study area we believe that evidence for timing exists in the infill sequence of overlying shallow depressions, which also contain methane-related carbonates. Shallow depressions formed during a phase of moderate fluid venting at the palaeo-seabed in the Quaternary, while methane-related carbonate was emplaced shortly afterwards before being buried not more than a few metres (PAULL & USSLER, 2009). Methane-related carbonate and shallow depressions have the same orientation and length as the chimneys that tip out directly below them (see seismic sections in Fig. 1.a-b). It is therefore very likely that they are part of the same vent through which fluid flowed. We therefore suggest that shallow depressions or methane-related carbonates are the surface expression of fluid flow through the chimney (HEGGLAND, 1997; HO *et al.*, 2012) and thus define the latest phase of chimney activity, which occurred over a short length of time from hours to a few months as suggested by LØSETH *et al.* (2011).

How does this compare to the timing of polygonal faulting? Due to the small size of the polygonal faults and magnitudes of their throws (typically between 5-15 ms) any subtle thickness variations across the fault cannot be conclusively attributed to syn-kinematic growth. This is because small thickness changes can occur during compaction of the sedimentary layers around the fault (CARTWRIGHT *et al.*, 1998). Therefore, direct evidence for the age of polygonal faulting is absent. However, there are several lines of indirect evidence. First, polygonal faults have been observed to tip out at or within very close proximity to the present day seafloor (CARTWRIGHT *et al.*, 2003; BERNDT *et al.*, 2012). Polygonal fault growths must have occurred sometime during either deposition or burial of tier stratigraphy. Because the PF tiers are only a few hundred metres thick in these examples PF genesis must have been triggered at shallow burial depths. This is likewise supported by the recognition of PF within the London Clay Formation onshore Belgium (HENRIET *et al.*, 1982) which was buried to a few hundred metres. Second, PFs are commonly developed in discrete stratigraphic layers of, termed here as tiers. The upper tips of PFs typically occur at a specific seismic horizon or horizons within a thin interval of only few 10's metres thick and this is persistent over vast areas (> 100 km^2) (*cf.* examples from the Tertiary North Sea (LONERGAN *et al.*, 1998; CARTWRIGHT *et al.*, 2003; CARRUTHERS *et al.*, 2013). There is little evidence for a mechanical explanation for this distribution of upper tips because the whole of the Tertiary succession is composed of claystone. It is thus more likely that the upper tier surface defines a palaeo-seabed at which upper tips arrested and ceased vertical propagation (CARTWRIGHT, 2011; BERNDT *et al.*, 2012; CARRUTHERS *et al.*, 2013). We consider this to be likely also for the Lower Congo PF tier and propose that faulting ceased at the end of Pliocene before the phase of fluid flow that formed overlying linear shallow depressions and chimneys.

One final piece of evidence supports PFs having formed prior to the formation of Linear Chimneys and that lies in the existence of free gas in the PF footwalls in the base of Linear Chimneys (blue star in Fig. 2.a). Almost a quarter (23%) of Linear Chimneys developed above lower PF footwalls and terminate downwards into NHAA, which represent free gas. The NHAAs are always linear (Fig. 2.b-I), parallel to the overlying carbonates and terminate upward at the PF planes, which have the same trends (Fig. 2.b-II). We suggest that this is not coincident and that NHAAs are remnants of trapped fluids in PF footwalls, *i.e.*, accumulations postdate PF formations. Because NHAAs are so similarly aligned and shaped to the directly overlying linear carbonates and depressions, we further suggest that they are remnants of the fluid involved in the formation of the Linear Chimney and the overlying venting structures.

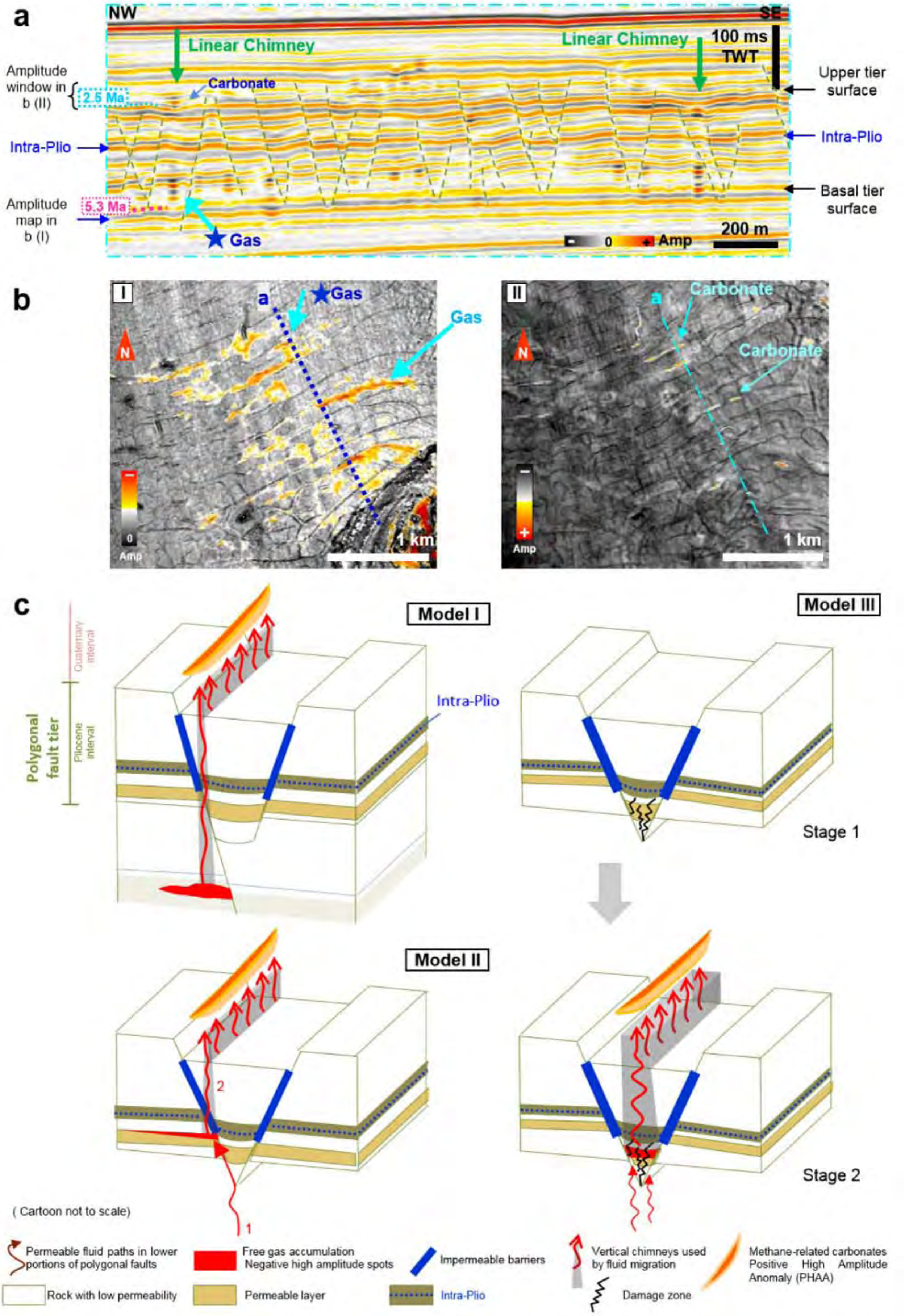
In summary our results suggest that polygonal faults formed during the late Pliocene before the phase of Quaternary fluid flow which formed Linear Chimneys and overlying depressions and methane-related carbonates (*i.e.*, PHAAs).

Fluid migration pathways

Linear Chimneys provide a clear indicator of the migration pathway that gas took on its ascendancy through the polygonally faulted stratigraphy. If polygonal faults had provided the main migration pathway we should expect Linear Chimneys to persistently terminate downward at the upper tips or at least the uppermost footwalls of polygonal faults, *i.e.*, the migration exit point of an entirely permeable polygonal fault. However, our results reveal the complete opposite. In the vast majority of cases Linear Chimneys stem from or intersect the lower footwalls.

Approximately 10 percent of the time chimneys terminate downward into the pre-PF-tier stratigraphy among the 209 cases. Gas was thus sourced from depth in these examples, attained overpressure below the PF tier after which the Linear Chimney propagated vertically, cross-cutting polygonal fault planes (red arrows in Fig. 2.c-I). Fluid migrated vertically and was relatively unaffected by the PF itself (red arrows in Fig. 2.c-I). However, in 23 percent of cases gas migrated into the PF tier and was trapped in the lower footwalls (red zone Fig. 2.c-II). It is not possible to reconstruct the migration pathway below the chimney in these cases because negative bright spot columns define the deepest part of the linear vent and there are no other obvious fluid venting structures or traces of anomalous amplitude adjoined to their base. Gas could therefore have either migrated oblique to bedding along the lower part of PFs before reaching permeable beds juxtaposed against the fault or gas could have simply migrated pervasively up through grain-to-grain permeability. In a minority of cases (8%), gas managed to migrate across PF planes only to be trapped in the overlying hanging wall.

▶ **Figure 2: a)** Seismic section intersecting Linear Chimneys showing predominantly positive bright spots ('seismic' methane-related carbonates) at the top and negative bright spots (free gas) at the bottom. Amplitude window in (a) is indicated by brackets at the left of the section. **b)** Seismic amplitude maps show high amplitude anomalies within and at the top of the polygonal fault tier; **b-I)** Amplitude map of the negative reflection just below horizon 5.3 Ma. The map shows strongly negative linear anomalies (orange/red) interpreted as free gas, overall in the trend of nearby faults. **b-II)** Root Mean Square amplitude of a 40-ms thick interval between the upper limit of the tier and the base of Quaternary. Narrow linear high amplitude anomalies, again parallel to the nearest faults, are interpreted as methane-related carbonates. **c)** Cartoons illustrating gas migration pathways through polygonal fault tier. **Model I)** Gas migration into PF footwall followed by overpressure and linear chimney formation above PF plane. **Model II)** Overpressure at depth; gas chimney nucleates below PF tier and propagates vertically upward cross-cutting PF planes. Red digits represent the chronological order for fluid migration represented by red arrows. **Model III)** Gas migration into hanging wall between conjugate intersecting PFs. Model III occurs in two stages. Stage one: The hanging wall deformed through faulting or fracturing causing a mechanically weak zone (damage zone). Stage two: Migrating gas preferentially overcomes fracture gradient and migrates across fault plane until sealed by the Intra-Pliocene horizon. Later the seal capacity of the Intra-Pliocene horizon is overcome and the linear chimney forms.


a
NW
SE
Linear Chimney
Linear Chimney
100 ms TWT
Amplitude window in b (II)
2.5 Ma
Carbonate
Upper tier surface
Intra-Plio
Intra-Plio
Basal tier surface
Amplitude map in b (I)
5.3 Ma
Gas
0
Amp
200 m
b
I
a
Gas
Gas
N
0
Amp
1 km
II
a
Carbonate
Carbonate
N
+
Amp
1 km
c
Model I
Model III
Quaternary interval
Pliocene interval
Polygonal fault tier
Intra-Plio
Stage 1
Model II
2
1
Stage 2
(Cartoon not to scale)
Permeable fluid paths in lower portions of polygonal faults
Free gas accumulation Negative high amplitude spots
Impermeable barriers
Vertical chimneys used by fluid migration
Methane-related carbonates Positive High Amplitude Anomaly (PHAA)
Rock with low permeability
Permeable layer
Intra-Plio
Damage zone

Possible explanations for temporary intra-tier sealing prior to chimney formation

Trapping of gas within PF tiers provides further insight into relative permeability or sealing capacity of PFs. Our analysis suggests the most common trapping configuration is within the lower footwalls. This is not too surprising as fluids typically migrate upward and footwalls often provide the highest structural closure across a fault making it a logical place to accumulate fluid once a seal is reached (red zone in Fig. 2.c-II).

What provided the seal? Since NHAAs are persistently bound by the Intra-Pliocene horizon the restriction of gas in the lower part of the tier may be entirely stratigraphically controlled by an Intra-Pliocene seal or sealed by the whole of the upper PF tier strata. It is also possible that the lower portion of PF planes was permeable but that the middle to upper part was impermeable. This would mean that gas migrating up PF planes stopped midway up the tier at Intra-Pliocene horizon (Phase (1) in Fig. 2.c-II). Further migration upwards along the fault plane would only be possible if sufficient overpressure could be achieved to overcome the normal stress on faults (PEDERSEN & BJORLYKKE, 1994; BJORLYKKE & HOEG, 1997). Gas trapped in the lower part of footwall might have had pressure values exceeding the overburden stress plus the tensile strength, which allows vertical hydraulic fractures to propagate in the hanging wall above (LØSETH *et al.*, 2011), hence the formation of chimneys (Phase (2) in Fig. 2.c-II).

Trapping of gas in the hanging walls of PFs is difficult to explain unless the highest structural closure was somehow sealed off (*e.g.*, blue barriers in Fig. 2.c-III) or if permeability varied sufficiently enough in some localised areas to allow discrete, less resistant migration pathways. The latter could be attributed to a greater intensity of fractures or faulting around the intersecting lower tips of conjugate PF (see damage zones on Fig. 2.c-III) or perhaps due to bending-related fractures in hanging wall monoclines.

Conclusions

A statistical analysis of the intersection and termination positions between Linear Chimneys and polygonal faults has shown that:

- The lower part of polygonal faults may behave as conduits for gas migration, as shown by the relative paucity of chimneys that cross fault planes. This is equally apparent by the absence of shallow depressions and methane-related carbonate at the upper tip of PFs.
- The upper part of polygonal fault planes does not behave as a conduit. This could mean that it was more energy-efficient for gas to create hydraulic fractures in the overlying fine-grained sediment rather than to re-open the polygonal fault planes.
- This study has therefore brought in for the first time evidence that sheds light on the permeability of polygonal faults, and could provide a better understanding of the sealing character of polygonal fault systems for hydrocarbon migrations.

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