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[EA]A New Method for Assessing Fault Seal Integrity by Using Intersections Between Faults and Gas Chimneys*

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Abstract

An innovative and low-cost method for assessing fault seal integrity by using the geometry of intersection between faults and gas conduits (so called chimneys, or pipes) is proposed, exemplified by 3D seismic data from offshore West Africa. A new type of gas chimney with uncommon linear planform (in contrast to the more common sub-circular chimneys), has been observed intersecting downward different parts of faults or originating from fault surfaces. Statistical analysis shows that 73% of these chimneys originate from the lower part of footwall or the lower half of fault surface. This suggests that, in ¾ of the cases, overpressured gas did not migrate all the way up the fault, but rather created preferentially vertical hydraulic fractures along the entire fault strike, or re-activated pre-existing fractures to leak upward. Thus, at least the upper half of the fault planes did not act as efficient migration pathways and was impermeable during expulsion of gas. As a result, hydraulic fractures formed wall-like structures termed "Linear Chimneys".

The top of a Linear Chimney is commonly characterized by aligned seep carbonates that formed in depressions on the palaeo seafloor and which are seismically expressed as linear positive high-amplitude anomalies. These structures are parallel to adjacent tectonic and/or tier-bound faults (i.e. polygonal faults). These faults show preferential orientation parallel to salt-related structures. The relationship between fault anisotropy and local structures suggests a control of the regional and local stress states on fault initiation and propagation. Chimneys with a linear planform only develop in areas exhibiting anisotropic arrangement of (polygonal) faults. In areas having an isotropic (polygonal) fault network, the chimneys and overlying amplitude anomalies display a circular planform.

Using spatial relationships between faults and chimneys to investigate fault seal integrity forms the base of an innovative method. So far, no other study has used fact-based statistical data demonstrating that chimneys principally emanated from below the topmost tip/the upper segment of faults to support the hypothesis that fault impermeability induces chimney formations via propagation of vertical fractures. Seep carbonates with linear planform precipitated above Linear Chimneys record the timing of gas leakage. Both Linear Chimneys and the carbonates can be used to reconstruct orientations of palaeo stresses states.

Introduction

Chimney structures, the expressions of gas conduits in seismic data, have been widely used to locate reservoirs to track hydrocarbon leakage pathways and to evaluate geohazards (cf. Heggland, 1998; Connelly et al., 2008; Løseth et al., 2011). It is a low-cost but efficient method which allows, in a qualitative way, contribution to the first-hand evaluation of the hydrocarbon potential of the targeting area by using only 3D seismic data. It is particularly useful when well data or other physical measurements are not available.

Using seismic chimneys to assess fault seal integrity has been pioneering carried out since the 1990’s by, for instance, Heggland (1997, 1998, 2005), Ligtenbert and Connolly (2003), and Løseth et al. (2009, 2011). Chimneys originating at the intersection between a fault and a closure’s flank or crest can indicate whether hydrocarbons have all spilled out or not (Heggland, 2005). Furthermore, a fault is interpreted to have been permeable if the fault itself is a chimney and if pockmarks or depressions occur at the topmost tip of the fault (Heggland, 1998, 2005). In addition, chimneys may or may not crosscut fault planes, act as pathways for transporting fluids from deeper intervals into the reservoir/trap that is bounded or offset by the faults (Connelly et al., 2008). Chimneys terminate at overlying faults, if the faults are not permeable (Connelly et al., 2008). A new method using the geometry of intersections between (tier-bound) faults and chimneys to assess whether the fault was fully, partly or not permeable during the gas expulsion has been suggested by Ho (2013) and Ho et al. (2016). This method is not only designated to assess the integrity of a unique type of fault; it can be applied to both types of fault: diagenetic, or tectonic. Tier-bound faults are interpreted to have a diagenetic origin and they are also known as polygonal faults (PFs; Henriet et al., 1991, Dewhurst et al., 1999, Verschuren, 2019).

Our previous studies addressed the relationship between a unique system of chimneys and a Neogene tier-bound fault system in the deepwater sediments offshore West Africa. Detailed seismic attribute maps of layers intersected by chimneys and tier-bound faults, first shown in Ho et al. (2012), reveal an intriguing, geometric parallelism between these two structural elements which strongly suggests their interrelated development. Statistical data on the position of chimneys intersecting faults from Ho (2013) are used to perform a quantitative analysis of fault seal integrity. It is the purpose of this study to introduce this new method to assess fault permeability by using the geometry of intersections between chimneys and faults.

Study Location and Setting

The study area is located in offshore West Africa and is heavily deformed by salt tectonic structures. The interval of interest is the Neogene-Quaternary hemipelagite, in which faults and chimneys have developed. Around the fault, the higher block/side is the “footwall” while the lower block/side is the “hanging wall”, which includes grabens.

Gas Chimneys from the 3D Seismic Survey of Offshore West Africa

The chimneys addressed in the present study are distinctly linear or string-like in plan-view and planar vertical in 3D (Figure 1; Ho et al., 2018). This geometry contrasts with the chimneys commonly reported in the literature, which typically exhibit a circular or elliptic planform and a cylindrical or columnar 3D morphology. Linear Chimneys comprise a new type (Ho et al., 2012). They have an aspect ratio > 4:1 in map view. Their horizontal length varies from a few tens of meters to a few kilometers.

Chimneys with non-circular planforms were first observed by Hovland (1983). On high-resolution 2D-seismic data from the North Sea, chimneys exhibit irregular and highly elongated planform geometries and variable widths and lengths ranging between several hundred meters to several kilometers (Hovland, 1983). They were interpreted to result from gas escaping along fractures/faults connected to the apices of underlying sedimentary folds (Hovland, 1983, 1984). In 3D seismic data, the planform ratio of chimneys having elliptical cross-sections was first analysed by Hustoft et al. (2010). They suggested that local stress perturbations associated with adjacent tectonic structures induced the preferred orientation of the long axis of elliptical planforms of chimneys.

Linear Chimneys in the study area offshore West Africa occur along and parallel to tectonic faults and/or tier-bound faults. Their planar morphology has been interpreted to result from hydraulic fractures propagating under the influence of anisotropic stress fields surrounding the adjacent faults and the local salt tectonic structures (Ho et al., 2012, 2018). Like the common chimneys reported in the literature (e.g. Hustoft et al., 2010), in this study 3 types of chimneys are distinguished (see Ho et al., 2016, 2018):

- Type I = Positive high-amplitude anomalies above pull-up reflections. They are often associated with linear depressions and linear methane-related carbonates expressed as positive high-amplitude anomalies (PHAAs) at the top.
- Type II = Negative bright spot columns. The chimneys consist of gas columns, which are associated with underlying push down reflections.
- Type III = Positive high-amplitude anomalies overlying negative bright spots.

Technique and Method

The presence or absence of pockmarks at the topmost tip of the fault indicates whether a fault was permeable or not during an overpressure phase (Heggland, 1998, 2005). Similarly, if faults provide viable migration pathways, then gas expulsion and chimney nucleation would occur at the upper tip of the fault (Ho et al., 2016). Sites of chimney nucleation in fault blocks provide insight in fluid flow efficiency along a fault. It is likely that gas did not, or did not fully, migrate along the fault (fully or partially impermeable), if the chimney emanating from the fault has its downward termination intersecting the lower portion of the fault, or the chimney is rooted in strata below the fault and crosscuts the fault (Ho et al., 2016, 2018).

Therefore, it is necessary, first, to establish the spatial relationship between faults and the downward termination of chimneys. Counting the number of intersections between faults and chimneys is essential as basis for a qualitative analysis of fluid flow efficiency of an entire fault system (Ho et al., 2016). The advantages of this method are that it can be carried out at low costs on preliminary seismic survey study and that no well data are required.

Example of Statistical Analysis

The occurrence of chimneys within a tier-bound (polygonal) fault system is statistically evaluated to analyse the fault seal integrity as outlined by Ho (2013; et al., 2016). On 3D seismic sections, chimneys intersect or terminate at various positions on individual fault planes ranging from the base to the upper fault tip. Of the 209 Linear Chimneys identified (Figure 2), 1% originates at the topmost tip of faults; and 73% stem from the basal part of faults, among that 54% intersect the lower part of footwall/fault or the strata below and 19% intersect the apex of graben (i.e. hanging wall). Another 9% of chimneys intersect the middle segment of faults, 7% occur in the middle of fault blocks without intersecting any fault, 10% intersect faults at other positions.

Fault Permeability

The vast majority of chimneys emanate from or intersect the lower portion of the (polygonal) faults. Consequently, if polygonal faults acted as main migration pathways, chimneys could be expected to persistently terminate downward at the upper tips (or at least somewhere along the uppermost portion) of polygonal faults that may represent the exit point of an entirely permeable fault (Figure 3a; Ho et al., 2016). However, the statistic results demonstrate the complete opposite.

In at least 73% of the cases, gas created its own pathway i.e. chimney to escape (Figure 3b-c). Only in 1% of the cases, gas migrated along the fault and was expelled from the upper fault tip, where the chimney nucleated (Figure 3a).

More than half of chimneys (54%) emanated from the lower part of footwall/fault or from below the footwall and suggest that gas could not migrate upward along the upper fault plane or did not use the fault plane at all (Figure 3b-c). Just like for the 9% of the cases that intersect the middle part of a fault, fluid initially migrated through the footwall then breached the fault plane and continued migrating vertically up through the hanging wall block (Ho, 2013). In one fifth of the cases (19%), gas was likely compartmentalised by impermeable faults and a horizontal barrier in the graben and escaped by creating chimneys (Figure 3d). Therefore, in most cases, fault planes above the downward termination of chimneys (above the chimney-fault intersection) were likely impermeable during overpressured events.

Fault Bound Traps and Nucleation of Chimneys

There are 23% and 8% of chimneys composed of the negative high-amplitude (NHA) columns that record free gas occurring below a regional, impermeable stratigraphic barrier (Intra-Pliocene, see blue dotted line in Figure 4a; Ho et al., 2016). Although these NHA columns below the barrier are likely residual gas as they are present-day features, the gas accumulations also possibly occurred below the barrier before the overpressure phase. This hypothesis is supported by the occurrence of actually gas-filled strata in such locations over a vast area of several tens of km^2 (Ho et al., 2018). The geometry of these gas accumulations below the impermeable barrier mimics the shape of fault cells in map view

(Figure 4b). At other locations where chimneys formed, gas accumulations might have occurred as isolated patches in the past, not necessary filling up a vast area of strata.

The gas-carrier bed below these strata was intersected by the deep-rooted tier-bound (polygonal) faults, and gas migrated via the lower tip/portion of the fault into the strata; and then accumulated below the impermeable barrier (Ho et al., 2018). The majority of chimney terminations occurring in the lower part of (polygonal) faults suggests that only the lower portion of the fault was permeable but further up it was impermeable (Ho et al., 2016). Gas might have migrated up the fault planes and stopped where it became impermeable. Further upward migration along the fault plane was only possible if the gas pressure could overcome the normal stress acting on the fault (Delaney et al., 1986, Pedersen and Bjorlykke, 1994). Gas trapped below the impermeable interval might have had a pressure sufficiently high for surpassing the overburden stress plus the tensile strength to open vertical hydraulic fractures propagating across the barrier (cf. Løseth et al., 2011; Blouet et al., 2017) and to form chimneys. Alternatively, gas did not need to create new fractures, but reactivated the pre-existing ones that were generated during the normal faulting (Gaffney et al., 2007; see also the supplementary material in Ho et al., 2018). Such a scenario likely occurred when the pressure required to open the pre-exiting fractures was less than that for opening a new one (Gaffney et al., 2007).

The impermeable stratigraphic barrier and the impermeable portion of the fault formed fault bound traps in fault blocks below the barrier (Figure 3b-d; Ho et al., 2016, 2018). Since more than half of the chimneys emanated from the lower part of the fault's footwall, the gas probably migrated preferentially into the footwall and accumulated there due to the differential strain around the fault. The footwall tends to experience some dilatation where permeability is enhanced (Barnett et al., 1987). Furthermore, gas tends to accumulate in the highest permeable strata in the footwall. Leakage of overpressured gas in such a location induced hydraulic fractures/gas chimneys that nucleated from the crest of the fault-bound trap in the footwall and thus, chimneys stemmed from the lower part of the fault, or stemmed from the gas accumulation within the strata of the footwall and crosscut the fault plane (Figure 3b and Figure 3c) (Ho, 2013; Ho et al., 2016). One fifth of chimneys terminate in the graben apex, suggesting accumulation of overpressured gas there. Such an accumulation forms if the pathway to the highest structural closure (in the footwall) was obstructed, or the hanging wall's permeability increased, for example, due to intensive fracturing during faulting (see damage zones on Figure 3d; Cloos, 1968). The impermeable portion of the fault, which could extend downward below the impermeable barrier, compartmentalised the gas in the deformed graben (Ho et al., 2018). As a result, gas chimneys nucleated from the graben apex and propagated across the graben center (Ho et al., 2016).

Consequently, impermeable barriers and fault-bound traps control the future leakage locations of overpressured fluids. The nucleation sites of vertical fractures are located at the basal tips or lower part of PF footwalls and of hanging walls. The statistical data illustrate that gas did not (fully) migrate along the (polygonal) fault planes or exit at the upper fault tips. Instead, gas created its own vertical migration pathways through the sediments above. In the studied part of the Lower Congo Basin, polygonal faults are impermeable at least in their upper parts, while the impermeable fault portion could extend deeper and vary downward (Ho et al., 2018). Our studies (also Ho, 2013; Ho et al., 2016) have brought in, for the first time, evidence that sheds light on the permeability of polygonal faults at the moment of overpressured events.

Conclusion

The downward terminations of gas chimneys in seismic data record and localise gas leakage points. The intersection between faults and chimneys reveals the fluid transport efficiency of faults during a phase of fluid overpressure and, thus, provides a new method to assess fault permeability. This study has illustrated different positions of chimney terminations occur in fault-bound blocks or along faults. The geometry of intersections between faults and chimneys indicates the starting point of the permeable/impermeable fault portion. Our study demonstrates in detail its applicability in an oil and gas province. Technical details about the chimneys and fluid flow systems can be found in Ho et al., (2016, 2018).

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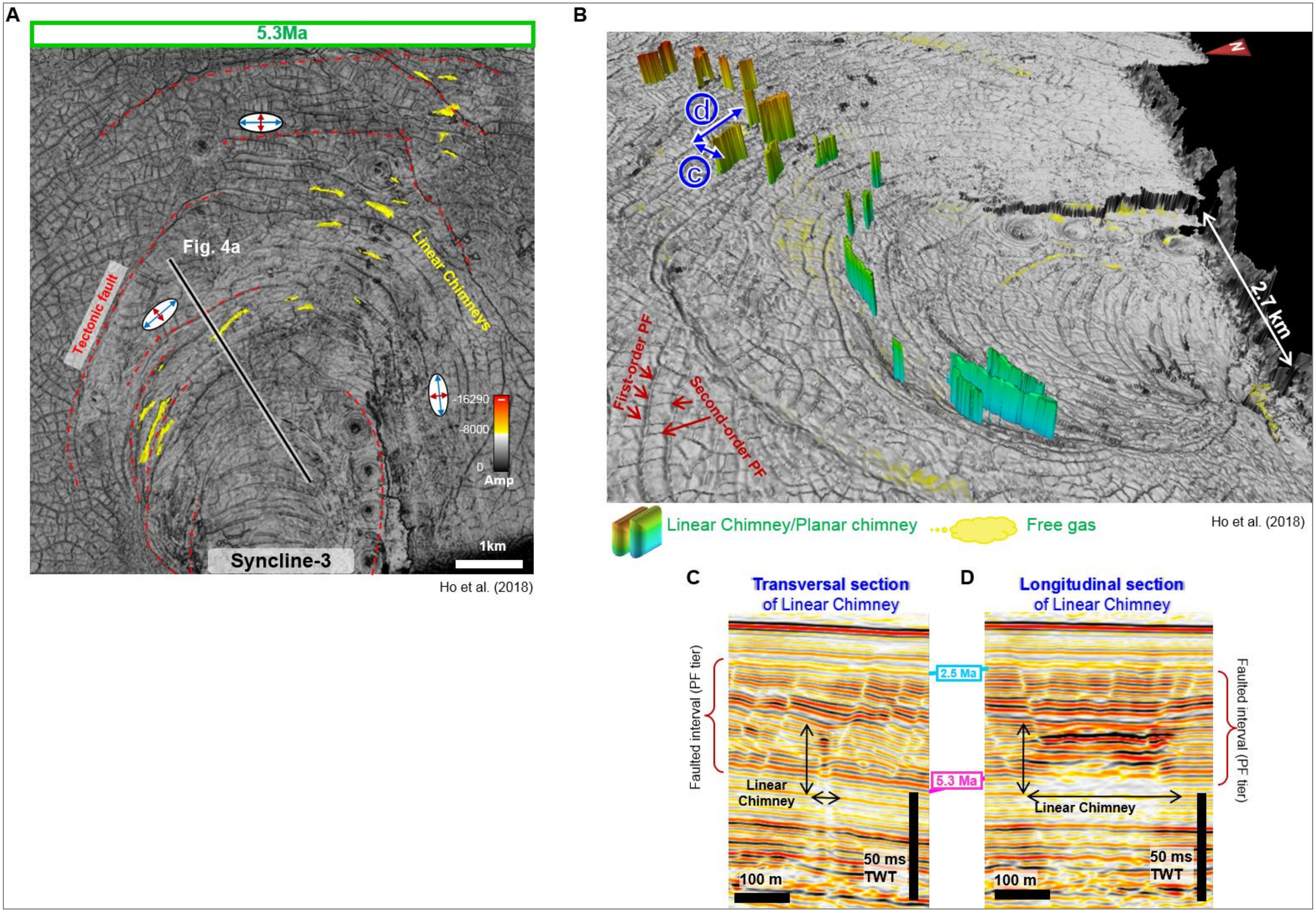

Figure 1. Planform and 3D geometry of Linear Chimneys in this part of offshore West Africa. a) Amplitude map shows Linear Chimneys parallel with preferentially orientated long faults (anisotropic polygonal faults, PFs). b) 3D view of Linear Chimneys in Syncline-3. c-d) Different sides of a Linear Chimney in (b), that is composed of a gas column.

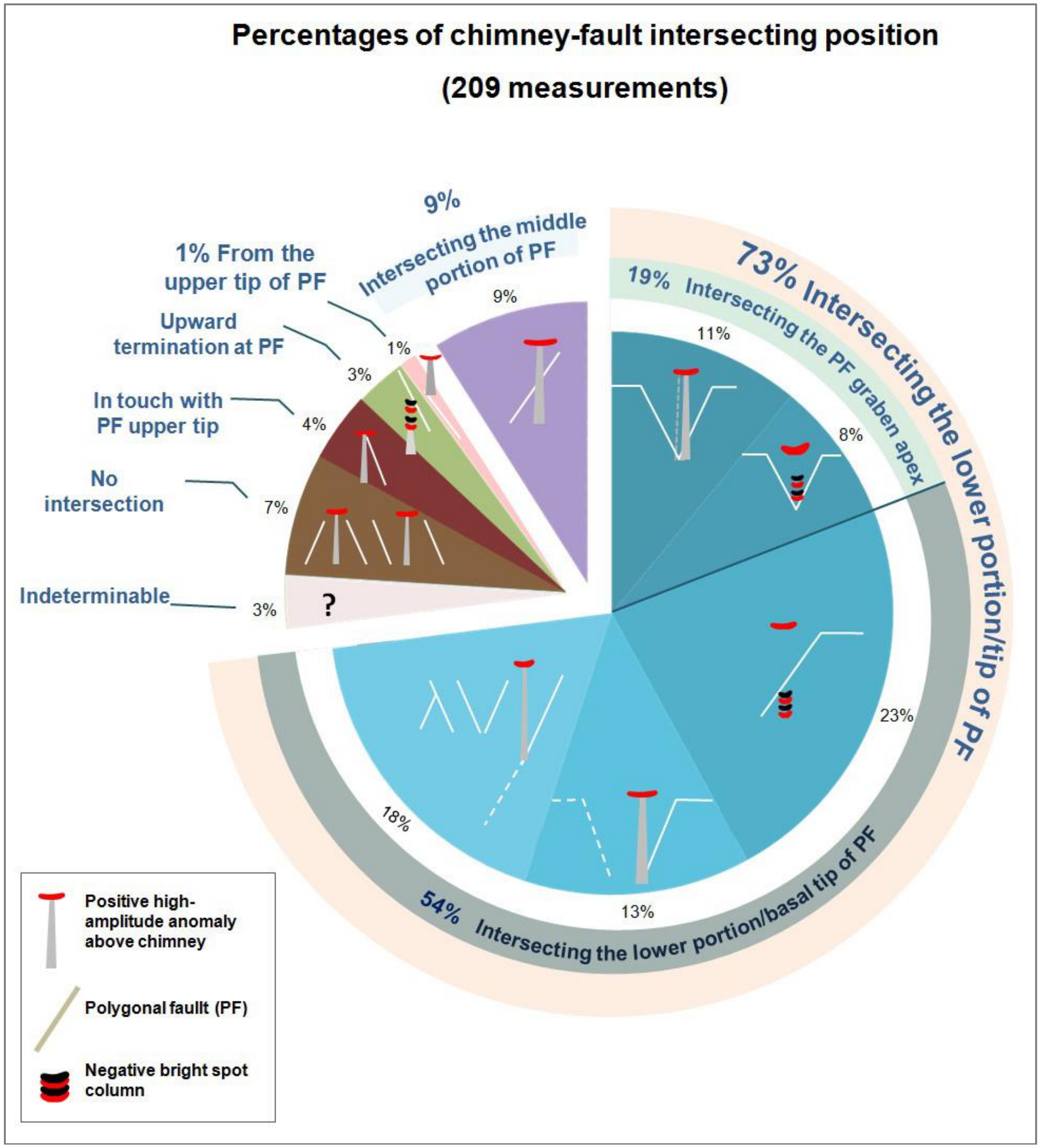

Figure 2. Pie charts showing the percentage of chimneys intersecting or emanating from different parts of fault planes or adjacent fault blocks. Image modified from Ho (2013), adapted by Ho et al. (2016).

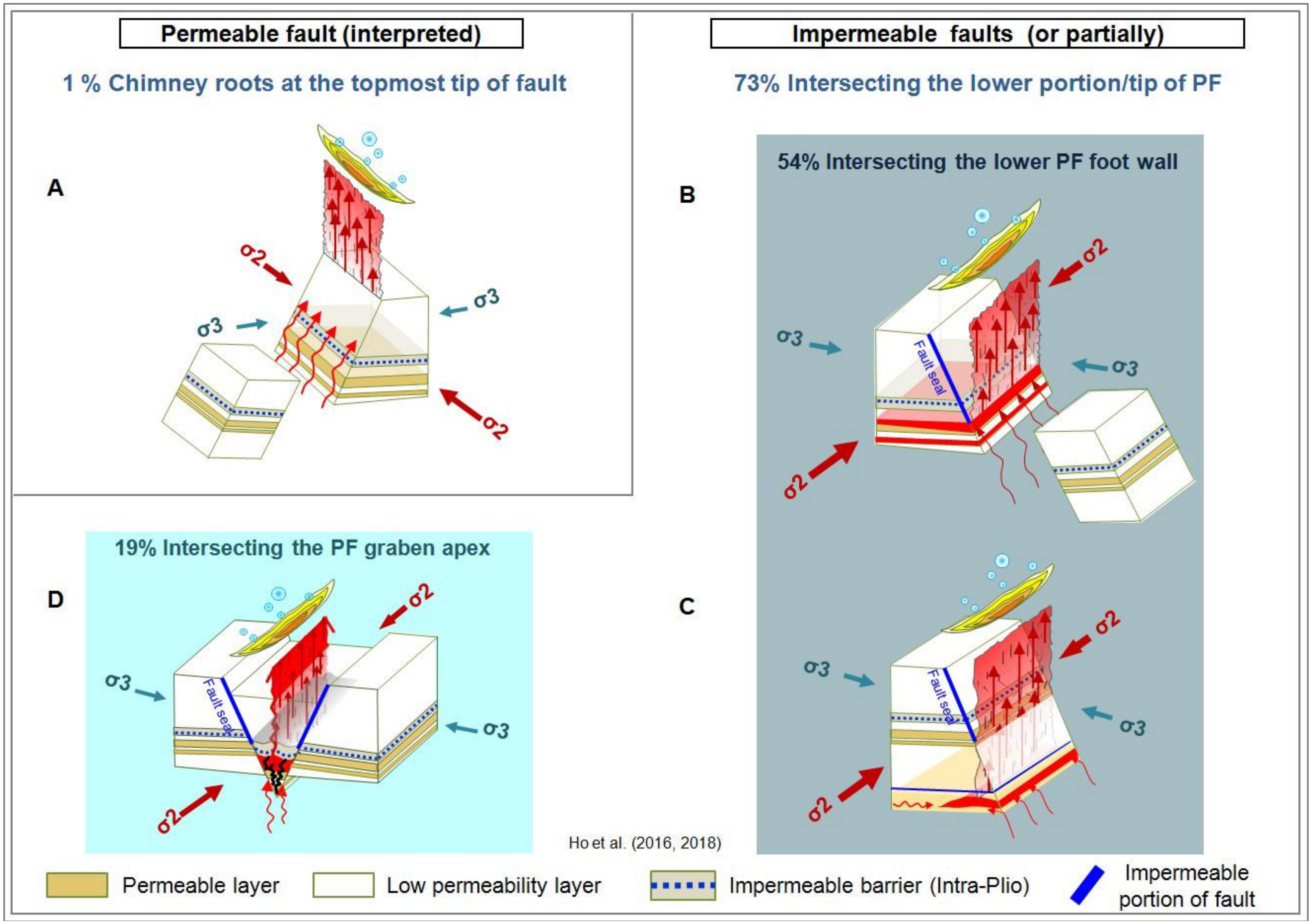

Figure 3. Cartoons illustrating spatial relationship between gas chimneys and polygonal faults (PFs). a) Chimney roots at the topmost tip of fault. Two major groups of chimneys stemming from fault-bound traps located in: footwall strata b) within or c) below the fault tier (below the blue solid line), d) the lower part of a graben/hanging wall. To notice that, in (c) gas expulsion from the crest of a (polygonal) fault-bound trap (Ho et al., 2016; 2018), is distinguished from expulsion at the cut-off point of a faulted carrier bed (Figure 16 in Pilcher and Argent, 2007), as in the latter case, the gas accumulation was prior to the faulting and was not promoted by the formation of structural traps.

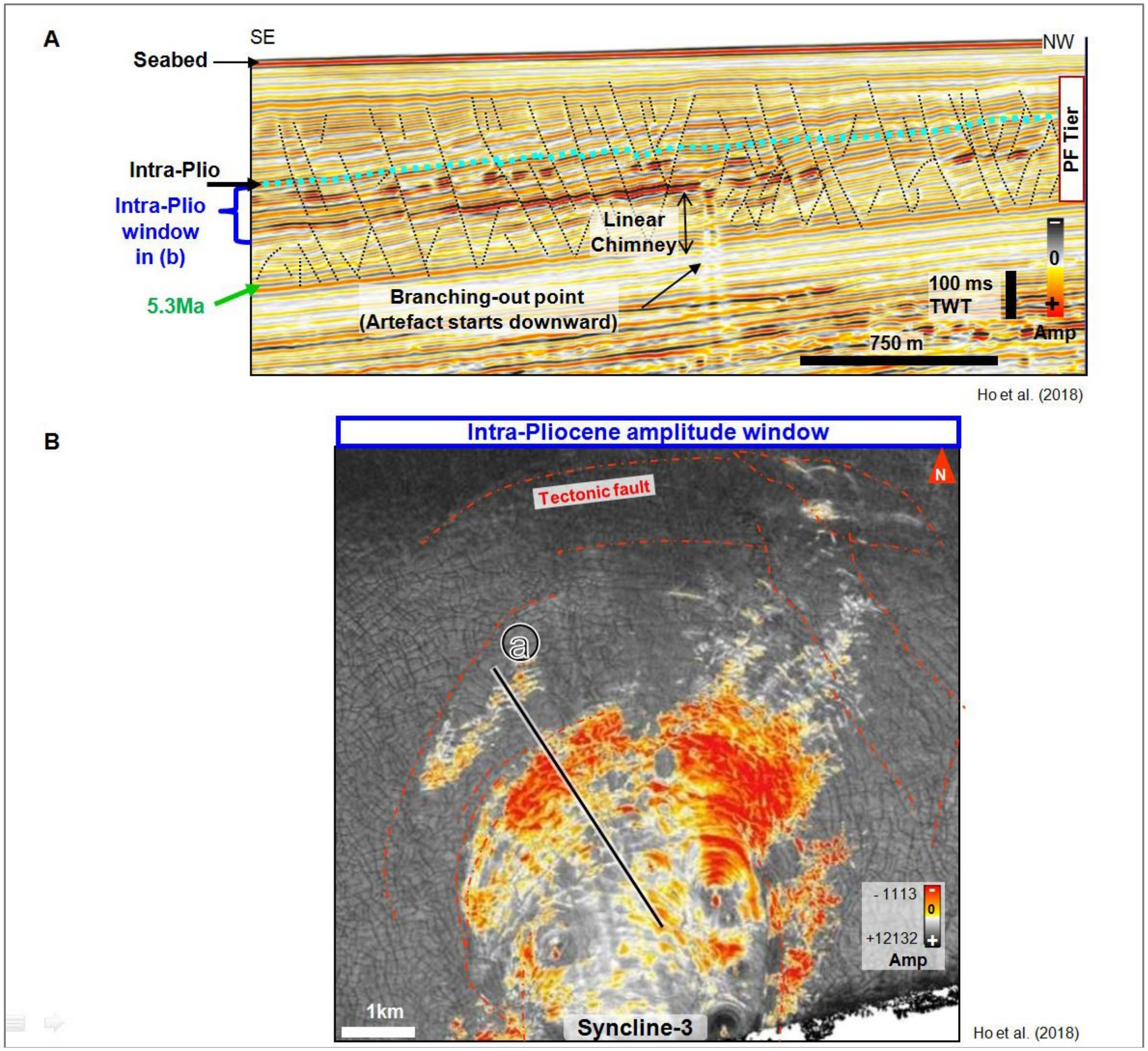

Figure 4. Gas accumulations expressed by negative high amplitude anomalies (NHAAs), occur within fault-bound traps, in the strata below the impermeable barrier "Intra-Pliocene" within the (polygonal) fault tier. a) Seismic section across the (polygonal) fault bound traps, showing the gas accumulations expressed by (NHAAs). b) Amplitude window shows gas accumulations imitate the form of (polygonal) fault blocks.