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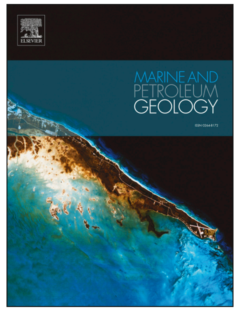

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Seismic characteristics of fluid escape pipes in sedimentary basins: implications for pipe genesis

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Abstract

Fluid escape pipes were first documented from 3D seismic data over a decade ago, and have subsequently been identified in many petroliferous basins worldwide. They are characterized on seismic data by vertical to sub-vertical zones of reduced reflection continuity that have a columnar geometry in three-dimensions. The upper terminations of these pipes commonly coincide with pockmarks or palaeo-pockmarks, signifying a close connection of pipe formation with a high flux fluid expulsion process. Dimensions range from tens to hundreds of metres in diameter, and hundreds to over a thousand metres in height, and the slenderness ratio, defined as height/diameter (Ω), ranges from 0.8 to over 20. Pipes are frequently associated with sub-vertical clustering of amplitude anomalies on seismic data, related either to the presence of free gas, or to cementation linked to the passage of hydrocarbons.

Three mechanisms have been suggested to explain pipe genesis: (1) hydraulic fracturing, (2) erosional fluidisation, and (3) capillary invasion. We suggest a further two possible mechanisms in the form of localised collapse by volume loss and synsedimentary flow localisation. We review all five mechanisms and conclude that it is unlikely that a single mechanism applies but that combinations of these processes may all occur in particular contexts. Fluid escape pipes may be far more widespread that currently appreciated, and they may play a critical role in secondary hydrocarbon migration and in providing leakage pathways for trapped hydrocarbons through overlying seals.

1.Introduction

Pore fluid expulsion at various stages in the burial and lithification of sediments can be highly localized in sedimentary basins and may occur in various forms such as sand intrusions, mud volcanoes and fluid escape pipes (Berndt, 2005; Cartwright, 2007). Fluid escape pipes as defined here as highly localized vertical to sub-vertical pathways of focused fluid venting from some underlying source region and are recognizable on seismic data as columnar zones of disrupted reflection continuity, commonly associated with amplitude and velocity anomalies, and scattering, attenuation and transmission artifacts (Fig. 1)(Hustoft et al., 2007; Moss and Cartwright, 2010a). The terminology relating to these features is potentially confusing because they have also been referred to as acoustic pipe structures, blow out pipes, seismic chimneys and gas chimneys. This wide range in terms may in part reflect a continuum in the processes involved in their genesis, and the large range in scale and seismic expression exhibited by these features. One of the aims of this paper is to synthesise the key descriptive elements of fluid escape pipes such that they can be more easily differentiated from similar features that may have contrasting origins.

Evidence of highly localized fluid escape features has been accumulating for the past two decades, as the quality of seismic imaging has improved. Vertical zones of acoustic disruption or attenuation relating to fluid escape were first identified using 2D seismic data in a number of basins in the 1990s (Baas et al. 1994; Evans et al. 1996; Hovland and Judd, 1988). However, detailed interpretation was hindered by artifacts inherent to 2D seismic imaging and spatial aliasing resulting from typical 2D seismic survey grids, the vertical orientation of pipes and the abrupt lateral velocity changes due to gas or cementation within pipes (Bouriak et al., 2000). Later developments in 3D seismic methods helped validate the true columnar geometry of pipes (Løseth et al. 2001). Nowadays, such features have been identified in a variety of basins worldwide (Table 1 – Fig. 2).

Fluid escape pipes are important to document and to understand for a variety of reasons. Due to their large vertical dimension that often exceeds hundreds of meters, fluid escape pipes may be important pathways for vertical fluid flow and secondary hydrocarbon migration in sedimentary basins (Berndt, 2005; Cartwright, 2007; Huuse et al., 2010). They may represent important venting routes for overpressured source layers at depth (Davies, 2003). They may be the pathway for supply of methane to the hydrate stability zone or allow methane to cross the stability zone and vent at the seabed (Gorman et al., 2002; Berndt et al., 2003; Netzeband et al., 2009; Davies and Clarke, 2010; Hustoft et al., 2010). Furthermore, fluid escape pipes could hinder carbon sequestration if embedded into the overburden to potential storage reservoirs; in fact, it is likely that CO_2 migration has either formed or exploited a pipe structure in the Sleipner pilot project (Arts et al. 2004).

The main aims of this paper, are to summarize characteristics of fluid escape inferred from seismic data, integrate these observations with those derived from outcrop studies and both review and suggest potential formation mechanisms.

2. Characteristics of Fluid Escape Pipes

Most of the available knowledge for fluid escape pipes (simplified to ‘pipes’ in the following sections) has been inferred from high resolution marine seismic studies. This section starts with brief comments related to inherent limitations and biases in the seismic characterization of these seafloor features.

2.1 Seismic Expression - Limitations Inherent to Seismic Characterization

Pipes manifest in seismic data as vertical to sub-vertical zones of disrupted reflectivity extending across an otherwise layered succession (Fig. 2). Stratal reflections of the host succession may be offset, deformed, attenuated, or have their amplitudes enhanced within the vertical zone. It is typical to see vertical variation from upward convex or concave bending or offset of reflections into regions of more complex deformation, layer thinning or thickening, reflection attenuation or amplitude enhancement. Amplitude anomalies are also commonly distributed within the pipe, and adjacent to the pipe.

Seismic artifacts can result in poor seismic migration, distortion due to velocity ‘pull up’ or ‘push down’, scattering and attenuation, low signal to noise ratios, reflected refractions, uncollapsed diffractions and complex multiples (Fig. 3). Near incidence raypaths are particularly distorted, so imaging must rely on the accurate migration of wider angle raypaths (Yilmaz, 2001; Bacon et al., 2007), which in turn are affected by changes in velocity anisotropy in the host layers (Tsvankin et al., 2010). In general, the imaging accuracy is less certain with increasing depth down the pipe (examples in Figs 1-5), and with decreasing pipe width (Løseth et al., 2011).

The identification of lateral margins is affected by data/imaging quality (Løseth et al., 2011). Horizontal or layer-parallel attribute slices are used to identify margins and define the horizontal cross-sectional geometry of pipes (Fig. 6). Coherence attribute slices often render sharp margins (Fig. 1b), whereas use of amplitude attributes is commonly less precise (Fig. 6).

2.2.Geometric Characteristics

2.2.1 Alignment and Geometry

Most pipes have a distinct vertical orientation with only minor lateral offsets (Løseth et al., 2011), yet, pipes with axes approaching 60 degrees to the horizontal have been observed recently (A. Maia, pers comm., 2014).

These generally vertical columnar structures can have parallel sided margins (e.g. Fig. 1), varying diameter with depth (upward or downward tapering - Figs 2 5, 7), or an irregular geometry with locally wider portions distributed at specific levels along the pipe. Whilst single pipes are by far the most common, occasionally pipes appear to have bifurcated upwards (‘conjoined pipes’ in Fig. 7) (Moss and Cartwright, 2010a).

The dimensions of pipes varies in a wide range (Table 1). The vast majority of reported pipe heights are in the range 200-to-500m (e.g. Davies et al., 2013). However, some reach ~2000m in height (Moss and Cartwright, 2010a, b), and pipe-like mud volcano conduits can exceed >5000m (Kopf, 2002). The detection of short pipes is limited by the vertical seismic resolution and they may be under-represented in compilations of pipe heights.

Similarly, there is a wide range in reported pipe diameters, from a few tens of meters (i.e. the effective lateral resolution limit for conventional petroleum industry seismic data) to over 500m (Table 1). The slenderness ratio, Ω, between the pipe height and diameter varies from Ω~0.8 to Ω> 10 (Table 1, Moss and Cartwright, 2010a).

Map or slice-based attributes (such as coherency, amplitude or dip) show that pipes are circular to weakly elliptical, with a maximum reported ellipticity ratio of 3 (Table 1). The ellipticity of neighbouring pipes may be aligned to reflect underlying structural or topographical controls (Hustoft et al., 2010 – Note: lack of ellipticity alignment is reported in Moss and Cartwright, 2010a).

2.2.2 Root Zones

The root zones of pipes are important to interpret because they allow a link to be made to the source region of the fluids involved in pipe formation, and hence potentially provide clues about fluid composition (Hustoft et al., 2010; Moss et al. 2010a). For example, shallow root zones hosted within regional aquifers might point to venting of overpressured pore fluids or potentially biogenic gas, whereas deeper root zones might involve thermogenic hydrocarbons, mud slurry or water expelled during chemical as well as mechanical compaction. Identifying the root zone is unlikely to allow unique conclusions about fluid composition without direct sampling, but it may help reduce the uncertainty in the interpretation and provide valuable constraints to any sampling strategy.

This significance of root zones was amply demonstrated by Løseth et al. (2001), who showed that pipes connected directly from a deepwater (channel) sandstone reservoir to the seabed. This allowed them to build a genetic model involving overpressure build-up and release in the channel reservoir. Subsequently, a number of other studies have been able to identify root zones quite precisely at deeply buried slope channel sand bodies by exploiting sinuous patterns in pipe clustering (Davies, 2003; Gay et al., 2007; Moss and Cartwright, 2010a), in contourite mounds with unusually low seismic interval velocities indicative of free gas accumulation (Plaza-Faverola et al., 2010), or in strong, layer-bound amplitude anomalies indicative of free gas accumulations (Davies and Clarke, 2010; Plaza-Faverola et al., 2010; Weibull et al., 2010).

Cases where the root zone can be identified unambiguously are rare. In general, the loss of imaging accuracy with depth means that root zones are generally hard to define. This can be seen, for example, in Figure 3, where scattering, attenuation and poorly migrated diffraction 'tails' all combine to reduce signal to noise ratios in the root zone to the point where it is impossible to identify the true base of the pipe. Where there is a strong contextual link to a specific reservoir, as for example in the case of buried slope channels (Gay et al. 2007), the root zones can be located at a specific horizon containing the reservoir by correlating the spatial distribution of pipes and pockmarks to the underlying geometry of the channel. It should also be borne in mind that not all pipes will be 'sourced' or rooted from a single discrete horizon, but may draw their fluid supply more broadly from a thicker zone that encompasses more than a single seismic reflection.

2.2.3 Pipe Terminus

The pipe terminus, or upward limit of the seismically visible pipe structure, provides important clues relating to pipe genesis, growth and timing, and potentially to fluid composition. Commonly, pipes terminate upwards at surface pockmarks (Fig. 8a; e.g. Løseth et al., 2001), demonstrating a clear link between formation of the pipe and formation of the pockmark, often through transport of methane (Judd and Hovland, 2007). However, some pipes terminate within the subsurface at buried pockmarks (Fig. 2a), and may have fed a series of vertically stacked paleo-pockmarks suggesting episodicity in pipe activity (Fig. 9; Andresen and Huuse, 2011). Conversely, many pipes terminate in convex upwards structures (Fig. 2d; Bouriak et al., 2000; Hustoft et al., 2010) or palaeo-seafloor mounds (Fig. 4; Hansen et al., 2005), and in these cases the nature of the mound can provide invaluable clues as to the wider significance of the structure as whole. Whether the mound is entirely authigenic or formed by material extruded from the subsurface is the key question in such cases that has a direct bearing on pipe genesis. If the mound is formed of extruded sediment, for example, then there is a strong case that the pipe feeding the mound represents a conduit for the juvenile stage of development of a sedimentary volcano, as suggested by Cartwright (2007) and Huuse et al. (2010).

Some pipes terminate abruptly at a discrete subsurface horizon with no paleo-pockmark structure where the horizon may be a barrier to upward pipe growth due to a major change of lithology (Van Rensbergen et al., 2007). Others terminate in a vertically stacked set of amplitude anomalies above the main locus of seismic disruption (e.g. Fig. 8b); that can be evidence of a protracted low flux flow regime persisting after pipe-formation.

2.2.4 Internal Structure

The internal geometry of pipes cannot be imaged when the pipe diameter is of the order of the spatial resolution limit (Brown, 2003). Even when the diameter is several times the spatial resolution, seismic modeling shows that significant imaging artifacts can mimic true deformational structures, such as a consistent upward convexity in internal reflection geometry (Løseth et al. 2011). There are only a few examples of large pipes where internal imaging is reliable. These cases show that the internal geometry can vary, in part due to potential differences in genesis and growth:

- vertically stacked reflection discontinuities; therefore, stratal reflectivity is not erased during formation inside large diameter pipes (Fig. 5)
- evidence of both thickening and depletion of layers compared to the same layers outside the pipes in the host succession (Hansen et al. 2005)
- some show tendency to 'upbending' of reflections within the pipe as genuine structures rather than pull-up artifacts (Hustoft et al., 2010); upward stratal deformation would be consistent with non-fluidized and non-erosive localized fluid flow (Bouriak et al. 2000; Hansen et al. 2005)
- others are consistently convex-downwards, with abrupt discontinuity of reflections at the pipe margins, only partially justified by velocity push down, and often accompanied by marked thinning of basal layers within the pipe (Fig. 5b; Moss et al. 2010a); downward deformation could be related to basal erosion or collapse analogous to caldera collapse observed in mud volcano conduits (Deville et al. 2003; Evans et al. 2008).

2.3 Host Formations

The occurrence of pipes indicated in Table 1 is probably a small subset of the full global distribution. It is biased by the availability of high resolution 3D seismic data, acquired mainly for petroleum exploration and it is therefore restricted to petroliferous basins or to the few cases where research cruises acquired 3D data. Active margins are thus heavily under-sampled. Hence, the following observations about pipes distribution must be considered within these sampling biases.

2.3.1 Basin and depositional context.

Fluid escape pipes have been described from 3D seismic data in more than 10 sedimentary basins, the majority of which occur on passive continental margins but with important occurrences in both active margins and intra-continental post-rift sag and back-arc basins (Table 1). Confidential seismic data show fluid escape pipes in many more basins, primarily in passive continental margin settings.

Systematically, fluid escape pipes are found in highly layered, clay-dominated marine sedimentary successions, typically of Neogene age and in the upper kilometer of the sediment column. High frequency attenuation limits imaging resolution and hinders the detection of pipes that may be present in older and deeper sedimentary formations (Yilmaz, 2001).

Most observed pipes formed in continental margin settings transect mainly clastic lithologies that range from claystones to thin sandstone units. Possible analogues for pipes transecting thicker sand bodies have been described by Huuse et al. (2004), from aeolian deposits in Utah, where considerable evidence for localized fluidization and brecciation of the host sediments is seen. Fluid escape pipes have not been observed to cross thick (> 100s of metres) sandstone units.

No pipes have been reported crossing thick limestone units except where the pipe is associated with the dissolution of the limestone unit (Storey, 2000; Bertoni and Cartwright, 2005; McDonnell et al., 2007).

2.3.2 Hydrate-Bearing Sediments

Many pipes have been reported in the context of hydrate bearing sediments, where the gas hydrate stability zone (GHSZ) is identified by free gas layers trapped beneath the base of this stability zone, with or without a seismic expression as a bottom simulating reflector (BSR). Root zones and upward terminations are highly variable but can be grouped as follows:

- pipes rooted at the BSR (Mienert and Posewang, 1998; Taylor et al., 2000; Wood et al., 2002; Berndt et al., 2003; Trehu et al., 2004; Hustoft et al., 2009; Netzeband et al., 2010)
- pipes that cross the BSR (Bouriak et al., 2000; Gorman et al., 2002; Gay et al., 2007, Hornbach et al., 2007; Hustoft et al. 2010; Moss and Cartwright, 2010a, Andresen et al., 2011); these are potentially important bypass paths for venting methane rich fluids directly to the seabed (Liu and Flemings, 2006, 2007; Cathles et al., 2010)
- deeply rooted pipes that terminate at the BSR or within the GHSZ (Davies and Clarke, 2010).

Pipes may involve hydrate-lined percolating paths that sustain high free-phase methane fluxes (Liu and Flemings, 2006, 2007; Westbrook et al. 2008). However, further research is required to clarify the relationship between pipes and hydrate formation (e.g. see discussion in Paull et al. 2008).

2.4 Spatial Distribution and Timing

2.4.1 Clusters

Fluid escape pipes rarely occur in isolation, but are more typically found in clusters (Løseth et al. 2001; Van Rensbergen et al., 2007; Gay et al. 2007; Davies and Clarke, 2010; Hustoft et al., 2010; Moss and Cartwright, 2010b). Often, pipes are aligned, either along straight paths following faults, structural or topographic highs, buried scarps or pinch outs (Løseth et al. 2001; Hustoft et al. 2010; Moss and Cartwright, 2010a,b), or along curvilinear paths following underlying channel sand bodies (e.g. Davies, 2003; Gay et al., 2006a,b; 2007). Clusters of pipes may also reflect stratal fluid migration pathways and the presence of traps, either due to underlying structure or to the presence of gas hydrate seals at the base of the GHSZ (Nyegga area, offshore Norway - Weibull et al., 2010).

2.4.2 Timing

The dating of pipe formation is poorly constrained. As image quality diminishes with depth, many pipes may have complex growth histories concealed in poor image quality at depth; furthermore, upward propagation may erase earlier evidence for pipe growth-arrest at intermediate stages. Core-based isotope dating combined with high resolution seismic data may overcome some of the present limitations in pipe dating (e.g., Plaza-Faverola et al., 2010b). Guidelines frequently invoked in dating pipes using their seismic expression include:

- a pipe termination at a seafloor pockmark suggests relatively recent pipe formation (Løseth et al., 2001; Hustoft et al., 2010; Judd and Hovland, 2007).
- mound development at the upper terminus helps constrain the later stages of fluid flow history as it contributes dateable materials at the top of the pipe (see discussion in Mazzini et al. 2006; Hustoft et al. 2010)
- the seismic horizon that defines the stratigraphic position of upward pipe termination does not necessarily define the time of pipe formation: it can instead be a sign of fluid dissipation into a subsurface reservoir (Hustoft et al. 2007).
- episodic pipe growth is inferred where stacked pockmarks can be interpreted within a single pipe structure (e.g. Fig. 9)(Andresen and Huuse, 2011); episodic formation suggests protracted growth histories.

Of the numerous studies of pipe development presented to date, only two have attempted systematic analysis of pipe formation times. Fluid escape pipes in the Nyegga area, offshore Norway, were found to exhibit three formation stages (Plaza-Faverola et al. 2010a): (1) pipes that formed ~200kyrs ago and reactivated once or twice thereafter, with a present day seafloor expression; (2) pipes that formed between 160 and 125kyrs, without any present day seafloor expression; and (3) pipes that formed after the last glacial maximum between 25 and 18kyrs ago. These periods of fluid escape correspond to the last stages of glacial maxima in the region, when thick glacial debris flow deposits led to loading-induced overpressures in the basin.

Significant diachroneity in pipe clusters was identified in the Namibe Basin offshore Namibia over a 5-10Myr long period probably associated to cyclic excess pore pressure generation and release (Moss and Cartwright, 2010b). A spatial statistical analysis of pipe distributions in an area of intense pipe occurrence with a total population of nearly 400 pipes showed no preferential clustering patterns. Instead, pipe occurrence was found to be sporadic (temporal resolution ~100-200ka), whereby pipes in one episode can form in “virgin areas” with no previous pipes, or within the same area where clusters of pipes had formed in previous episodes. However, newly formed pipes are not in close proximity to pipes formed in an immediately preceding time period, suggesting the underlying presence of an “exclusion distance” associated to fluid pressure build up.

An important consideration when attempting to date pipe formation, is the possibility that some pipes may have formed in a syn-sedimentary mode (Fig. 10). It is possible that some tall pipes may have grown by persistent or episodic fluid expulsion during continued sedimentation, and the later propagation phases may then eradicate traces of the earlier fluid expulsion (see Discussion).

3. Discussion: Pipe Genesis

Hypothetical mechanisms for pipe-genesis must be able to explain salient pipe characteristics such as formation in layered clay-dominated sedimentary successions, almost ubiquitous vertical orientation or geological ‘gravitropism,’ frequent association with overpressured root zones, apparent exclusion distance between neighbouring pipes, and varied termination conditions such as pockmarks, mounds and diffuse termination within the sediment (Table 1). This section reviews previously suggested pipe formation mechanisms, suggests two new potential mechanisms, and discusses their limitations.

3.1 Hydraulic Fracturing

Hydraulic fracture is frequently proposed to explain pipe formation (Løseth et al., 2001, 2011; Cartwright et al., 2007; Hustoft et al., 2007 and 2009; Moss and Cartwright 2010; Plaza-Faverola et al., 2011; Davies et al., 2012). In this hypothesis, overpressure in the root zone induces hydraulic fracturing in the overburden and a network of hydraulic fractures propagates towards the surface normal to the minimum stress (Fig. 11). The conditions necessary for hydraulic fracturing of 'seal' units above a source unit are generally taken to be that the fluid pressure in the source should exceed the sum of the minimum stress in the overburden plus the tensile strength (see Cosgrove (2001) for review). The minimum stress may locally approach the overburden stress for poorly consolidated, clay-rich overburden sediments with high values of K_0 (the ratio between horizontal and vertical effective stresses; Terzaghi et al. 1996). Hence, high values of fluid overpressure in potential source units are a requirement for this mechanism to apply.

Some experimental work has been undertaken to evaluate the conditions necessary for hydraulic fracturing of unconsolidated sediments as opposed to capillary invasion (Fauria and Rempel, 2011), but it is more challenging to validate these conditions in the subsurface. In this context, Seldon et al., (2003) and Reilly and Flemings (2010) both argue in favour of fluid flow via networks of hydraulic fractures and, importantly, document fluid pressures in shallow buried regional aquifers reaching the minimum stress value at crestal regions where venting is observed. Trehu et al. (2004) show that pressure in a gas column trapped beneath a vent is equal to the overburden stress, and also argue for venting via hydraulic fracture networks.

Since fluid escape pipes are universally quasi-vertical, the development of pipes by this mechanism would be favoured in regions where the maximum compressive stress is vertical. A possible exception would be the case of a pipe that formed in an inclined fracture and later migrated by gradual erosion to eventually align itself with the shortest vertical path (see Ligtenburg, 2005). This mechanism is observed in laboratory scale models, but migrating pipes erase the stratigraphy along their path.

The required overpressured zone can result from basinal hydrodynamics, build-up of gas pressure due to organic matter evolution, hydrate dissociation or gas trapping at hydrate seals beneath the gas hydrate stability zone (Flemings et al., 2003; Trehu et al., 2004; Liu and Flemings, 2006), rapid glacial sediment loading (Hustoft et al., 2009), or rapid loading by evaporate deposition (e.g. Bertoni et al. 2013)), amongst others. Presence of methane as a free gas phase is commonly linked to pipe formation, and the relatively modest gas column heights needed to fracture shallow sediments are widely found in basins and may explain the preponderance of pipes with heights less than 200-300m (Hornbach et al., 2004; Table 1). An interesting, and unresolved question however, concerns the gas saturation required to (a) represent a continuous column, and (b) to promote fracture propagation driven by the non-wetting (methane) as opposed to wetting phase (pore water)(P. Flemings, Pers. Comm., 2014). Pipe genesis as hydraulic fractures agrees with the spatial alignment of pipes relative to local structures such as hinges, folds or minor faults that may affect the stress field, and transverse pipe ellipticity in some cases (such as in Hustoft et al., 2010).

It is important to stress that there is thus far no direct evidence of hydraulic fracturing within any in situ pipe observed on seismic data, possibly because of lack of well calibration, so there may be lessons to be learned by analogy with outcropping pipes or similar structures. At least one study has identified possible analogues to subsurface fluid escape pipes on Rhodes (Greece) where circular fractures and brecciation are observed (Løseth et al., 2011). It is also possible that exposed mud volcano conduits may provide partial analogues for fluid escape pipes. It has been suggested, for example, that the initial stages of formation of mud volcano conduits may be similar to the formation of fluid escape pipes and that there may be a process continuum whereby fluid escape pipes evolve into mud volcano conduits as the composition of the fluid evolves to include solid componentsCartwright, 2007; Huuse et al. 2010). Outcropping mud volcano conduits typically exhibit increased density of fracture networks towards the central highly brecciated zone, and show evidence of mud slurry transport upwards via the fracture network (Morley, 1997; Clari et al., 2004; Roberts et al., 2010).

It is less easy to draw analogies with vertical networks of sandstone intrusions (formed by fluid pressure in a sand slurry mobilized from a highly overpressured ‘source’ sand body; Hurst and Cartwright, 2007). Outcrop studies of these networks commonly show that aspect ratios of sandstone dykes are strongly elliptical in the horizontal rather than closely grouped with vertical dimensions greater than the horizontal (Vetel and Cartwright, 2010).

Arguments against the hydraulic fracture genesis of pipes relate to source zone and pipe geometry. First, well imaged root zones show that many pipes do not initiate at pressure foci such as structural crests of large anticlines or lateral pressure transfer zones such as in updip pinchout positions (Fig. 3; Stump and Flemings 2000; Flemings et al., 2003), but emanate from synclinal topographic lows or gently dipping layers with no structural closure to build gas columns. Second, the hydraulic fracturing model is not consistent with the slender columnar geometry observed for some pipes which may reach a slenderness of **Ω**=20: it is mechanically unwarranted that individual fractures will propagate from the root zone to the pipe terminus with such high aspect ratios. From this perspective, the assumption that potential hydraulic fracture heights can be inferred from compiled pipe height data remains highly questionable (Davies et al., 2012).

Fluid-driven erosion and flow localization along the vertical plane of hydraulic fractures (Novikov and Slobodsky, 1978) could eventually evolve into a single pipe or multiple aligned pipes with a proper exclusion distance between them (Ligtenburg, 2005). Fluid-driven erosion is addressed next in the context of fluidization.

3.2 Erosive Fluidization

Fluidization is the mobilization of granular materials by seepage forces (Kunii and Levenspiel, 1969; Lowe, 1975; Mourgues and Cobbold, 2003). Fluidization is a widely observed phenomenon in geological systems (Woolsey, 1975; McCullum, 1985; Nichol, 1995), and has been invoked in association with the formation of pockmarks, mud volcanoes, hydrothermal vent complexes and kimberlite pipes (Lorenz, 1975; Brown, 1990; Nermoen et al., 2010). In fact, small-scale experimental studies have shown that the typically upwards-widening, steep, conical structure of diatremes or hydrothermal vent complexes can be reproduced in the laboratory by fluidization of a granular medium under a high pressure input jet of water or air (Fig. 12)(Woolsey, 1975; McCullum, 1985; Nichol, 1995; Nermoen et al., 2010). Pressure dependent fluid expansion (e.g., gas exsolution or steam expansion) increases the efficiency of fluidization, as observed in multiphase magmatic eruptions, diatremal structures and kimberlites (Woolsey, 1975; McCullum, 1985), and is considered responsible for the development of pockmarks (Judd and Hovland, 2007). Furthermore, fluid-pressure driven pipe formation may explain clustering patterns and exclusion distance between pipes determined by lateral drainage efficiency within the overpressured zone (Moss et al., 2010b).

While fluidization can capture some of the final characteristics of some localized flow structures, this model does not explain initiation conditions. In particular, the necessary flow velocity for fluidization will not develop in layered sedimentary columns where low permeability, fine-grained layers hinder fluid flow, even when overpressure develops in underlying high permeability reservoirs (Fig. 12c). In fact, an initiation mechanism such as hydraulic fracturing is needed prior to flow localization and fluidization pipe formation to provide the critical flow velocity needed for fluidization in the overburden. Alternative, retrogressive top-down piping can develop in a fluidized bed when the hydraulic gradient (the difference in hydraulic head between the source layer and the outlet divided by the length) exceeds 1.0 and flow localization nucleates at preferential points (Note: higher gradients will be needed in partially lithified sediments). Retrogressive erosion (from the exit to the source) is a well-known pipe formation mechanism beneath dam failures (Terzaghi et al 1996), and only requires a high hydraulic gradient across a permeable granular medium for flow localization to emerge. We highlight that flow localizes at the outlet which would be the seabed in the case of pipes from where the pipe would then propagate downwards towards the overpressured source.

Clearly, erosive fluidization cannot explain pipes with a diffuse upper termination within the sediment column (e.g. Fig. 8b). In addition, internal erosion would erase the layered stratigraphy of the host medium that is seismically observed within the pipe (Fig. 12)(McCullum, 1985; Nermoen et al., 2010). Therefore, erosive fluidization cannot explain the genesis of pipes that exhibit clear stratigraphic continuity across the full width of pipes as observed using high resolution seismic data where the wavelength is much smaller than the pipe diameter (e.g. Figs 1, 5 & 6). Top-down piping is also unlikely to explain cases where there are strong orientational controls on pipe distribution exerted by underlying source layers such as submarine channels (e.g. Davies, 2003).

3.3 Capillary invasion

Gas migrates through water-saturated sediments when the difference between the gas pressure p_g and the water pressure p_w exceeds the capillary entry pressure (similar to capillary trapping in petroleum reservoirs Schowalter, 1979; Watts, 1987; Berg, 1975). From Laplace's equation:

$$p_g - p_w \geq \frac{2\gamma\cos\theta}{r}$$

where γ is interfacial tension, θ is contact angle and r is the effective pore throat radius. The pressure difference is determined by the height of the continuous gas column H_g, and differences in unit weights γ_w and γ_g,

$$p_g - p_w = H_g(\gamma_w - \gamma_g)$$

Capillary invasion has been suggested as a mechanism for pipe formation when the root zone can generate free phase gas (e.g. Liu and Flemings, 2006, 2007). A recent model links pipe formation (although termed gas chimneys by the authors) to pockmark formation using the process of capillary invasion (Cathles et al., 2010). In this model, gas trapped at a capillary seal accumulates up to a critical thickness until the buoyancy at the top of the seal forces the gas through the pore throats at which point it forms, an upward migrating gas column that advances as a piston and displaces pore fluiden route (Fig. 13). Cathles et al., (2010) suggest that pipe growth will be controlled by capillary barriers in the overburden (bedding), which give the chimney a relatively flat topped geometry and limit its width. They argue that the diameter of the chimney will be controlled by the sediment heterogeneity and envisage that gas will saturate the pore space in the chimney and thus move easily through it with little viscous resistance. They argue that pockmarks form when the pipe extends about halfway to the seafloor from the source layer (Fig. 13a-c) and final expansion of gas at the seafloor results in a final more dramatic stage of pockmark formation (Fig. 13d).

The most positive feature of this model is that it offers a logical explanation for the classic columnar, vertical geometry of pipes, based on the buoyancy of the free gas phase. A pre-requisite of the model is therefore the existence of a gas column of sufficient height to initiate capillary failure of the seal. However, for many pipes observed on seismic, particularly those emanating from synclinal positions, or from simple monoclinal flanks, the trap configuration does not easily equate with the necessary column height requirements.

How realistic is a piston like capillary invasion, upwards through highly heterogeneous sediments typical of many successions hosting observed fluid escape pipes? Pipe growth by capillary invasion is hindered by fine-grained layers with small pore-size. In relatively homogeneous sediments, lateral spread against finer layers will control the effective diameter of pipes. However, vertical permeability heterogeneity can be several orders of magnitude between alternating layers typically found in marine hemipelagic depositional settings where pipes are observed (Yang and Aplin, 1998). In this case, gas invasion will more likely take the form of stacked ‘pancake’ or ‘Christmas tree’ topology (Fig. 14) of a type observed during CO_2 injection in the long term sequestration project in Norway (Arts et al. 2004), rather than the universally columnar geometry exhibited by pipes (Figs. 1-5). Recent observations of highly irregular vertically stacked amplitude anomalies are also good examples of what might be more typically expected from upward gas migration by capillary invasion of a multilayered stratigraphy (Foschi et al., 2014).

Note that the formation of a preferential gas migration pathway does not necessarily imply any deformation of the layered stratigraphy which are observed in high-resolution seismic images of pipes, e.g., layer distortion, pinching and sagging. While specifically excluded in Cathles et al., (2010) analysis, gas-driven opening mode discontinuities may emerge during gas invasion (Jain and Juanes, 2009; Shin and Santamarina, 2010 & 2011; Fauria and Rempel, 2011).

3.4 Localized subsurface volume loss

Localized subsurface volume loss causes a pipe-shaped collapse geometry in the overburden with slenderness ratios comparable to many pipes reviewed here (Whittaker and Reddish, 1989). Contrary to erosive fluidization, pipes generated by local volume loss preserve the initial stratigraphy, albeit layers appear down-shifted (Fig. 15; Qiliang et al., 2013). Collapse of the initial void propagates upwards in a columnar zone of fracturing that significantly enhances the vertical permeability of the overburden and promotes fluid escape preferentially via the pipe (McDonnell et al., 2007). Mineral deposits are frequently encountered in these structures which when mineralised are commonly termed breccia pipes.

Subsurface volume loss can result from the dissolution of carbonate or evaporites (Bertoni and Cartwright, 2006; Cartwright et al. 2007; McDonnell et al., 2007; Qiliang et al., 2013), hydrate dissociation (augmented by gas expansion and migration), or even organic matter degradation. Many pipes have been observed within the gas hydrate stability zone (Moss et al., 2010a; Davies and Clark, 2010). An important difference between this mechanism and that of hydraulic fracture, capillary invasion or erosive fluidisation is that no initial overpressure condition is specifically required in the 'source' unit i.e. the unit undergoing volume loss, although such overpressure may exist.

In unconsolidated sediments, these pipes may be delimited by sharp shear localization along peripheral walls, stress relaxation within the pipe, and sediment expansion and loosening within the pipe (Cha, 2012). When sediments have experienced some degree of lithification the upward propagation may evolve as successive roof collapse events. This "stoping" mechanism has been suggested for the formation of mud volcano conduits (Roberts et al., 2010).

3.5 Syn-sedimentary Formation

A compacting basin sustains upwards fluid flow. The flow field is not necessarily uniform, and often localizes into a few drainage paths as new sediments are deposited. Localized flow may be preserved during sedimentation. This is the case when sediments have a broad grain size distribution or the depositional sequence consists of successive fine-coarse grained layers: drag forces drive fine-grains away from the injection point and form an aquitard layer concentrically away from the flow field. In the meantime, coarser grains fill the space above the injection point. As sedimentation continues, a highly conductive syn-sedimentary pipe made of the coarser fraction is formed (Fig. 10).

In contrast, syn-sedimentary pipe formation is not expected in homogeneous media made of uniform grain size sediments, as the pressure field decays rapidly away from the injection point. This fluid-dependent overpressure release genesis underlies self-regulation between sedimentation and fluid pressure.

Many tall pipes may have started their evolution as short pipes, and grown upwards as sedimentation occurs. Dating of syn-sedimentary pipes should rely on detecting thickness changes or segregation attributes within the main conduit.

Syn-sedimentary pipes may end within the sedimentary column as fluids leak-off the main conduit and lower velocities cannot drag fine grains away. Similar to fluidization, syn-sedimentary pipes prevent the formation of fine grain layers within the pipe; however, grains coarser than the Stokes grain size may form layers within pipes.

4. Concluding Remarks

Pipes are remarkable features that can exert a controlling role in the overall subsurface geo-plumbing. The salient characteristics of pipes include: favoured in layered, clay-dominated sedimentary basins, development in either in a single formation event or in episodic formation; decisive vertical orientation; may exhibit pronounced slenderness ratios Ω=10 or greater; often linked to high-pressure root zones (sometimes related to gas accumulation) or collapse structures; possible regional clustering; alignment may reflect subsurface features; termination my take place at the seafloor (pockmarks or mounds) or within the sediment (paleo-pockmarks or in diffuse termination); and, the structure of the host sediment may be preserved within the pipe (at least in large pipes).

Not all pipes are made equal! Furthermore, it is important to distinguish between initiation and growth mechanisms. Indeed, field evidence suggests several genetic processes at work. Therefore, it may be unwarranted to assume that all pipes form in a single, catastrophic phase of fluid expulsion from a deep, highly overpressured source region.

Hypothetical formation mechanisms must be able to explain salient characteristics identified above. The frequently invoked hypothetical genesis by hydraulic fracture cannot explain the most common features observed in most pipes. However, it may be an initiator to pipe formation, but followed by flow localization and erosive fluidization. These processes can be augmented by capillary effects related to gas phase accumulations, gas exsolution and expansion. There is clear evidence that some pipes form as the overburden collapses above a localized zone of volume contraction. Other pipes may have developed by a syn-sedimentary process, growing vertically during prolonged joint phases of fluid escape and continual sedimentation.

Observations summarized in this review are hampered by problems related to seismic imaging of vertical structures, where lateral and vertical seismic velocity anomalies are present. This leads to considerable uncertainty in the true structure of pipes, with many potential artefacts contributing to the seismic appearance of pipes. Analogues such as mud volcano conduits may provide valuable insight into these potentially important fluid escape pathways.

This review has focused primarily on synthesising seismic observations of pipes, and assessing potential genetic mechanisms in that context. If additional constraints are available for the composition of the fluids transported through the pipe at the time of formation, e.g. from direct seafloor sampling (e.g. Smith et al. 2014), associated diagenetic phenomena at the vent (e.g. Gay et al. 2006b), or from rock physical calibrations of associated direct hydrocarbon indicators such as acoustically soft amplitude anomalies (Foschi et al. 2014), then it may be possible to narrow down the range of potential mechanisms further on a case by case basis.

Finally, it seems likely that fluid escape pipes are far more common in sedimentary basins than the current limited literature on the subject suggests. The pipe structures represent a clear manifestation of natural flow localization phenomena at a range of scales, and may be integral to many hydrocarbon plumbing systems in petroliferous basins worldwide.

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Location	Height (range in m)	Width (range in m)	Top at Surface	Buried top	DHIs	Ellipticity	Reference	Mechanism
Offshore Nigeria			Y	Y	AAs, blanking		Løseth et al. 2011	HF
Offshore Ireland	<1500	200-600	N	Y	AAs, blanking		Van Rensbergen et al. 2007	HF
Offshore Mauretania	140-340	<200m?	N	Y	AAs		Davies and Clark, 2010	
Offshore Namibia	50-1100	30-450	Y	Y	AAs, blanking	Up to 7:1	Moss and Cartwright, 2010a	HF
Offshore Norway	600-1200	200-600	N	Y	AAs, blanking		Hansen et al. 2005	
Hikurangi, New Zealand	250-600	100-300	Y	N	AAs, blanking		Netzeband et al. 2009	
Offshore Vancouver Is. Canada	100-200	<100	Y	N	AAs, blanking		Zuhlsdorff & Spiess, 2004	HF
Offshore Norway	80-700	50-915	Y	Y	AAs, blanking	Mean 2:1	Hustoft et al. 2010	HF
Offshore Angola	25-450	60-300	Y	Y	AAs, blanking		Andresen et al. 2011	HF
Offshore Angola	200-700	50-300	Y	Y	AAs, blanking		Gay et al. 2007	

Table 1: Compilation of published examples of pipes. Abbreviations are as follows: Y- yes, N- no; AAs- amplitude anomalies; HF- hydraulic fracturing.

Observed Characteristics	**Implications for Pipe Genesis**
formation in layered, clay-dominated sedimentary basins	low vertical hydraulic conductivity
either single-time formation event or episodic formation	sustained overpressure generation and sporadic release events
decisive vertical orientation	gravi-tropic guided formation mechanisms
may exhibit pronounced 10:1 slenderness	length-persistent formation mechanism
often linked to high-pressure root zones, sometimes related to gas accumulation	fluid driven mechanisms
apparent exclusion distance between neighboring pipes	drained root zone
some pipes form above collapse structures	not fluid driven
possible regional clustering	shared formation mechanism
alignment may reflect subsurface features	associated to fluid flow conduits or local strains that favor pipe nucleation
termination my take place at pockmarks or mounds on the seafloor or at similar paleo-features within the sediment	vigorous fluid flow and sediment erosion/transport
diffuse termination within the sediment	pipe genesis associated to a deep cavity collapse at the root zone, or a fluid-driven pipe formation where gradually dissipates into a highly permeable layers and can no longer sustain pipe growth
the structure of the host sediment may be preserved -at least in large pipes-	fluid driven mixing is not enough to eradicate the sedimentation structure or formation does not involve high fluid flux
intermediate layers may be missing within pipes	selective fluid-driven removal

Table 2: Salient pipe characteristics and potential implications. This table summarises the diverse observations made of pipes using seismic data, and attempts to highlight a link between each observation and some aspect of pipe genesis. It is intended more as a ‘rule of thumb’ or as a ‘primer’ for further analysis, and not as a rigorous analytical tool.

Acknowledgements

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Figure Captions

Figure 1: Seismic expression of fluid escape pipes. A: Vertical seismic profile through a series of fluid escape pipes from offshore Namibia (from Moss and Cartwright, 2010a). Arrow depicts the base of the pipe, SB- seabed. B: Coherence attribute time slice through a group of pipes showing the typical circular to sub-circular planform, with diameters of 100-300m, located offshore Namibia.

Figure 2: Seismic characteristics of fluid escape pipes (see text for full explanation). A: Seismic profile from offshore Nigeria (from Løseth et al. 2011), showing pipes emanating from a reservoir interval c.1000ms (TWT) below the seabed, terminating in buried or surface pockmarks. B: pipes from offshore Norway, emanating from a gas bearing layer, with convex upwards deformation of host strata and terminating at seafloor pockmarks (from Plaza Faverola et al. 2010a). C: Profile showing several pipes (labelled as chimneys to be consistent with the original figure) all with loss of coherence and subtle convex upwards deformation, from offshore Norway (from Hustoft et al. 2010). D: chair seismic display of two orthogonal seismic profiles and a coherence slice showing chimneys (pipes) from offshore Norway, with variable seafloor expression, but including a large mound (from Hustoft et al. 2010). E: A pipe from offshore Norway, with variable relief exhibited by the convex upwards deformed strata, terminating in a seafloor pockmark (from Hustoft et al. 2010).

Figure 3: Seismic interpretation of fluid escape pipes is made complicated by different types of seismic artifact. A: A profile from the Faeroe-Shetland Basin, offshore Scotland, showing a zone of attenuation and seismic disruption beneath the root zone of some pipes in a fluid source unit (from Cartwright, 2007). B: Seismic profile from offshore Namibia showing two prominent pipes. The left hand pipe clearly terminates downwards above a coherent reflection (CR), whereas the root of the other pipe is harder to interpret, because of scattering and distortion possibly linked to an amplitude anomaly (AA).

Figure 4: Seismic image of a large pipe from offshore Norway, showing highly variable seismic expression vertically along the pipe, from a wide root zone, badly affected by artifacts, to a narrower disrupted zone with migration artifacts (MA), upwards to a zone with convex upwards deformation across sharp inflection points (IP) to a shallow region of laterally extensive high amplitude reflections (HARs)(from Hansen et al. 2005).

Figure 5: Seismic profiles across large diameter pipes from offshore Namibia. A: profile showing a pipe with concave downwards relief and discontinuity of stratal reflections at pipe margins. Note the variable geometry evident at the horizons indicated with circles. B: profile showing thinning of the basal layers within the pipe interior close to the root zone (arrowed).

Figure 6: Amplitude display of a mapped horizon that is intersected by numerous pipes, offshore Namibia. Some of the pipes are quite sharply delineated by this attribute image (e.g. P), but in others (e.g. Q), the amplitude anomalies associated with the pipe extend laterally outside the pipe margins, blurring the recognition of the margin.

Figure 7: Seismic profiles showing variation in geometry of pipes. A: profile from offshore Namibia showing an upward tapering conical pipe geometry. B: profile from offshore Mauretania showing a downward tapering conical pipe geometry (from Davies and Clarke, 2010). C: profile from offshore Namibia showing an upwards bifurcating pipe geometry, with pipes A and B linked at a single, high amplitude reflection (see arrows).

Figure 8: Seismic profiles showing the upward terminations of pipes. A: Upward termination in of a pipe at a large seafloor pockmark (from Andresen et al. 2011). B: Upward termination with gradual reduction in concave relief and local stacking of overlying high amplitude reflections (HARs) (from Moss and Cartwright, 2010a). Note the bottom simulating reflector (BSR) crossing the pipe with no loss of continuity.

Figure 9: Seismic profile showing a pipe structure that is interpreted to feed a series of near-vertically stacked pockmark craters (P)(from Andresen and Huuse, 2011).

Figure 10: Cartoon representation of a model for syn-sedimentary, episodic pipe growth. A: step 1, initial formation of pipe at time t_0. B: step 2, no pipe growth during deposition up to layer at time t_1. C: step 3: new phase of growth of the pipe at time t_2 overprints the earlier pipe structure. D: step 4, growth continues as new layers of sediment are deposited to time t_3.

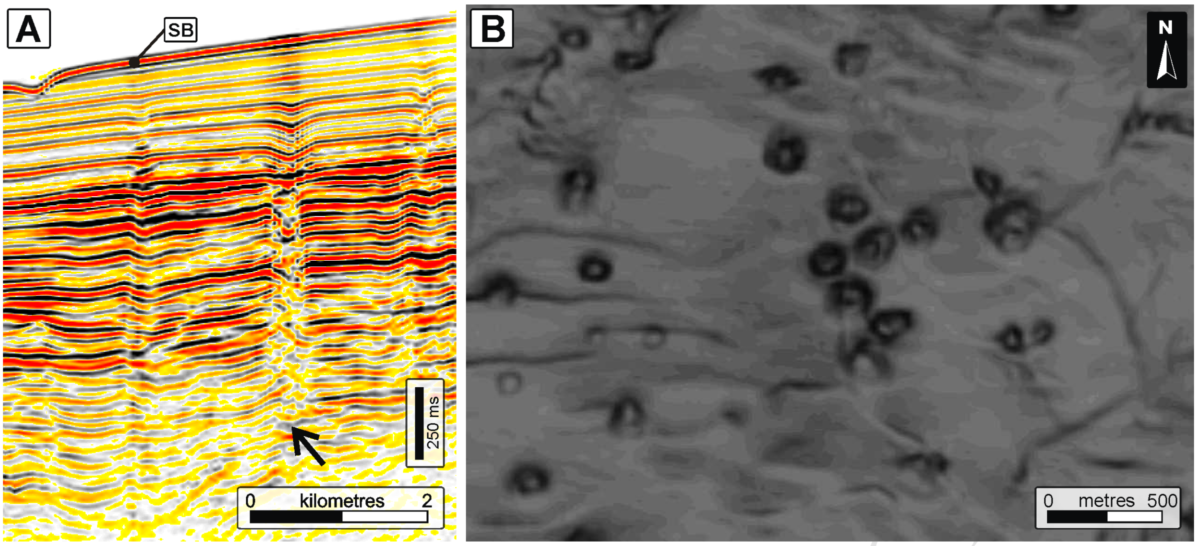
Figure 11: Conceptual model of pipe growth by hydraulic fracturing. A: an initial fracture nucleates and propagates upwards from the interface between the overpressured layer and the overlying seal (inset shows the pressure (P) – depth (Z) plot for this intitial propagation of a hydraulic fracture, at depth Zc and critical fluid pressure in the source, Pr, where this pressure intersects the fracture gradient (F)(see Watts, 1987). H is the hydrostatic gradient, and L the lithostatic gradient. B: As fluid escapes into the seal, a network of small, distributed hydraulic fractures propagates upwards, with some widening of the fractured region. C: The escape of fluid from the overpressured zone is focused into the region of fractures because of enhanced permeability of the fractured seal, and fractures selectively widen and propagate. D: A threshold is reached where fluid flow and fracture network linkage result in increased focusing of flow, higher flow velocity, and possible gas expansion to form the well established cylindrical conduit (pipe) and associated surface expulsion features (see Cartwright et al. 2007for details and original source references)

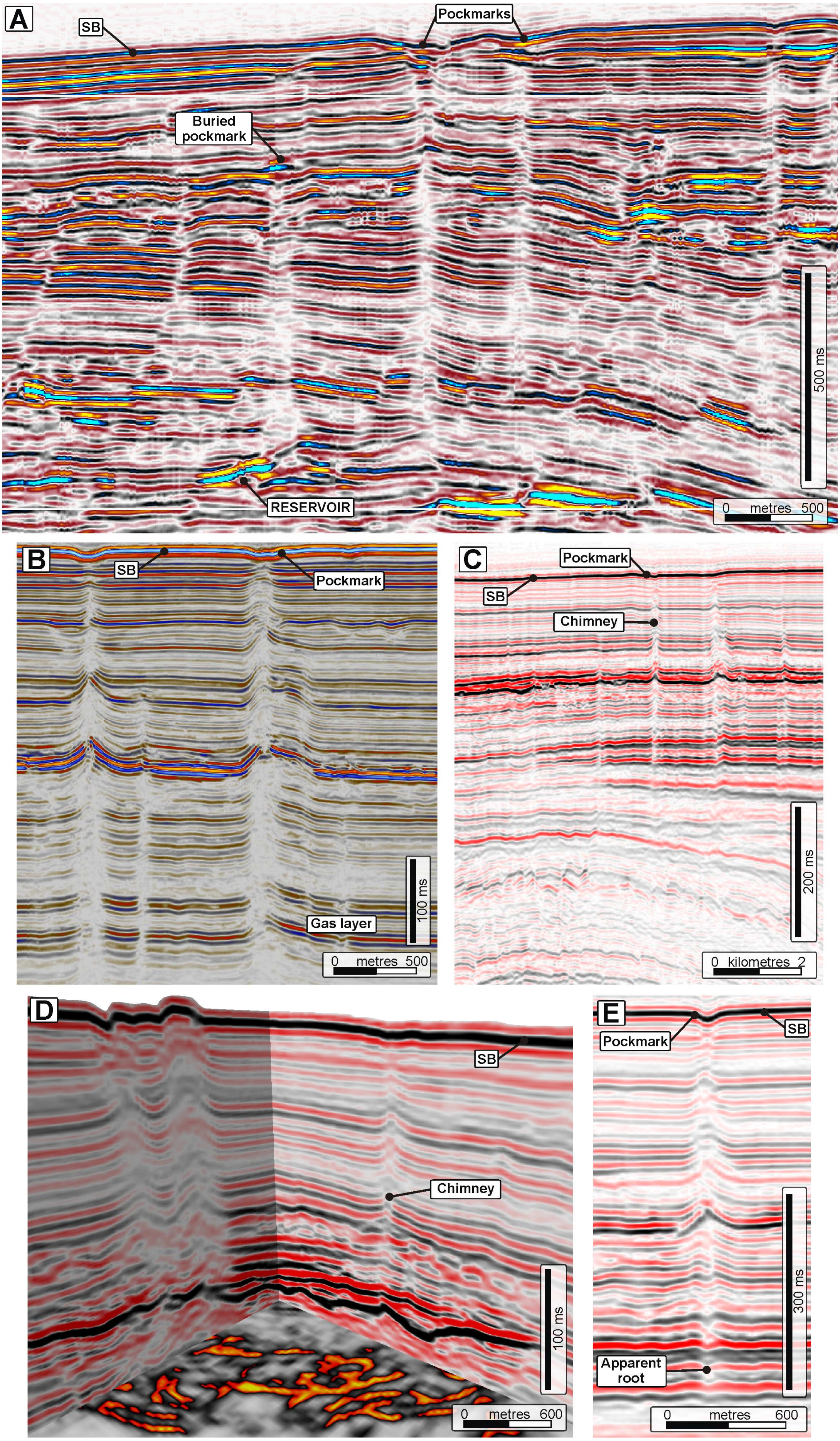
Figure 12: Simplified view of a fluidization model for diatreme formation. A: gross geometry of a sedimentary diatreme formed by fluidization. B: Details of the reservoir-seal interface, where the pressure gradient drives fluid flow across the boundary and flow in the seal fluidizes the overburden to form the pipe-like conduit. C: Enlargement of the interface to highlight the difficulty in achieving fluidization velocity within the seal when it is largely composed of clay-sized particles.

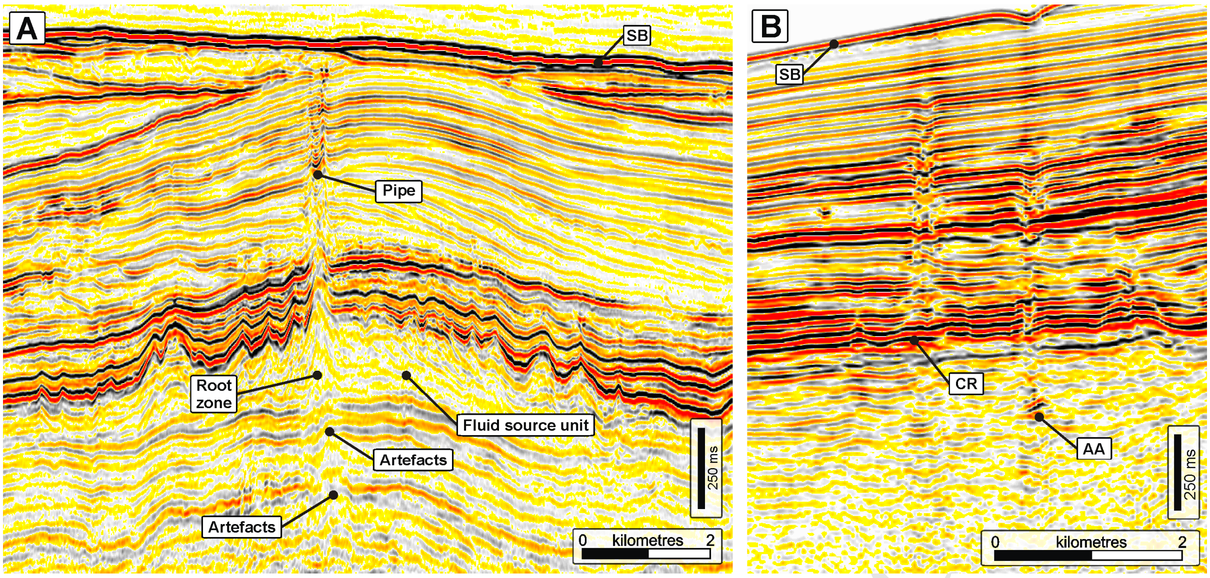
Figure 13: Schematic evolutionary cartoon of the capillary invasion model for pipe formation (after Cathles et al., 2010). A. Gas of column height d is trapped beneath a seal. B. Seal failure results, and a piston of gas rises displacing the pore fluid in the overburden (black arrows). C. When the gas ‘piston’ is about halfway to the surface, the surface begins to deform and small pockmarks form from flow routes emanating from the top of the ‘piston.’ D. When the piston approaches the surface, a large pockmark forms with diameter similar to the piston width.

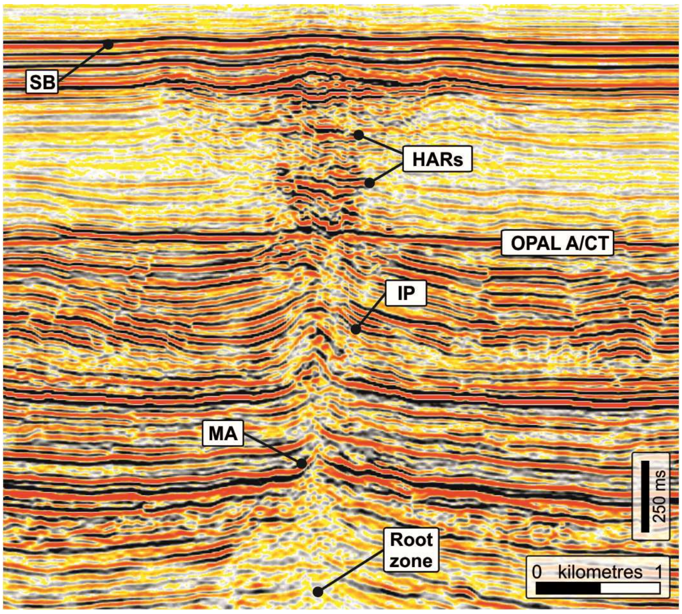
Figure 14: The ‘Christmas Tree’ mode of upward migration of gas across layers with contrasting values of horizontal permeability (Kh). Competition between vertical and lateral migration of the gas results in a highly serrated margin to the zone of gas saturated sediments (shown as dark stipple tone), and not a regular, parallel–sided columnar structure as idealized for example in Figure 13 or in seismic examples of pipes.

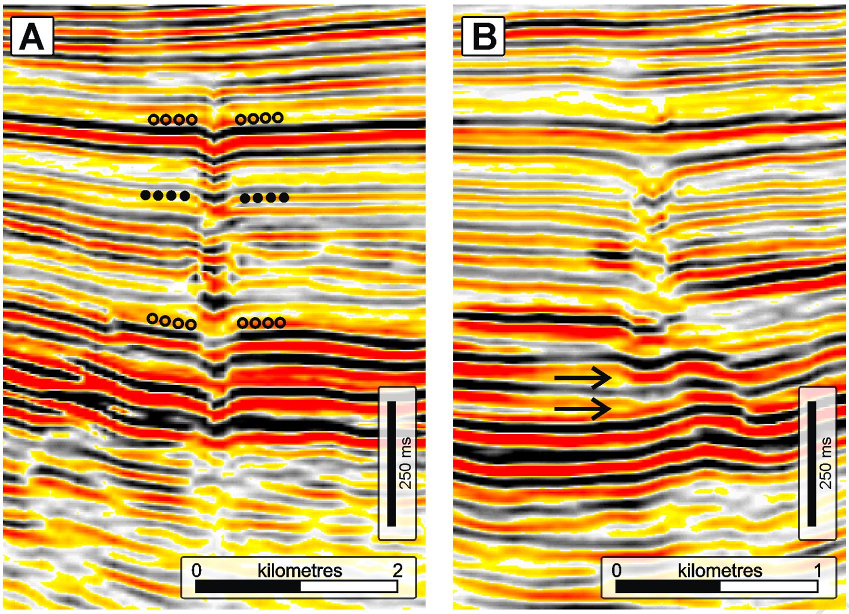
Figure 15: Seismic profile from the South China Sea, showing pipe structures formed by the dissolution and collapse of an underlying carbonate reservoir. The root zones are clearly visible in the carbonate layer. SB is seabed. From Qiliang et al. 2013.

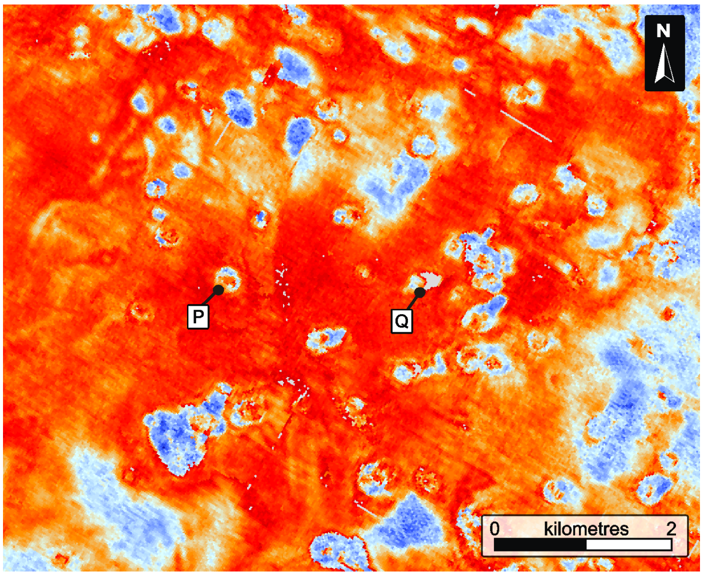

A
SB
250 ms
0 kilometres 2
B
N
0 metres 500

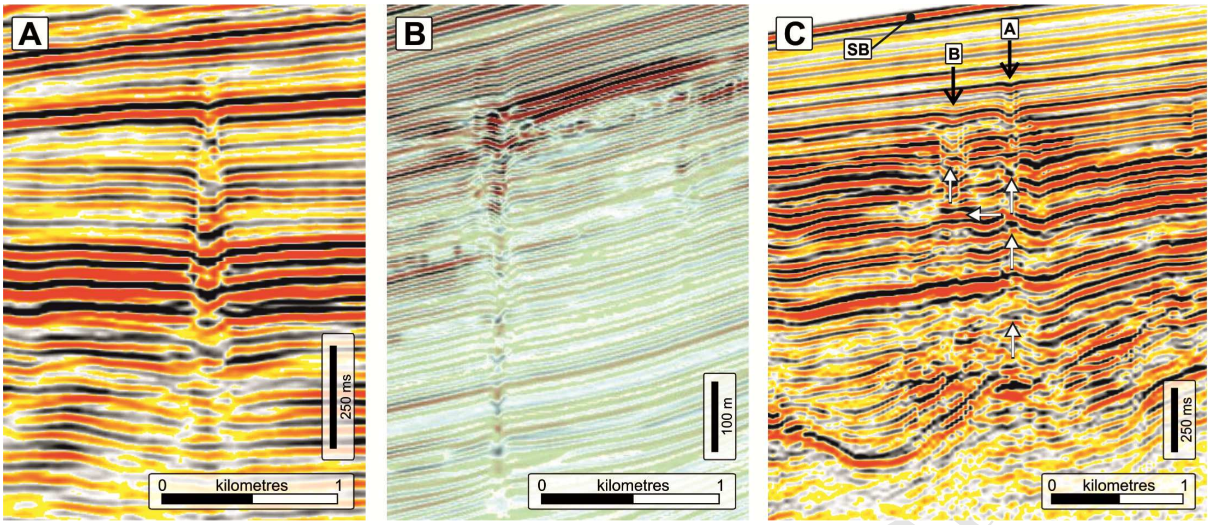

A
SB
Pockmarks
Buried pockmark
RESERVOIR
500 ms
0 metres 500
B
SB
Pockmark
Gas layer
100 ms
0 metres 500
C
Pockmark
SB
Chimney
200 ms
0 kilometres 2
D
SB
Chimney
100 ms
0 metres 600
E
Pockmark
SB
300 ms
Apparent root
0 metres 600

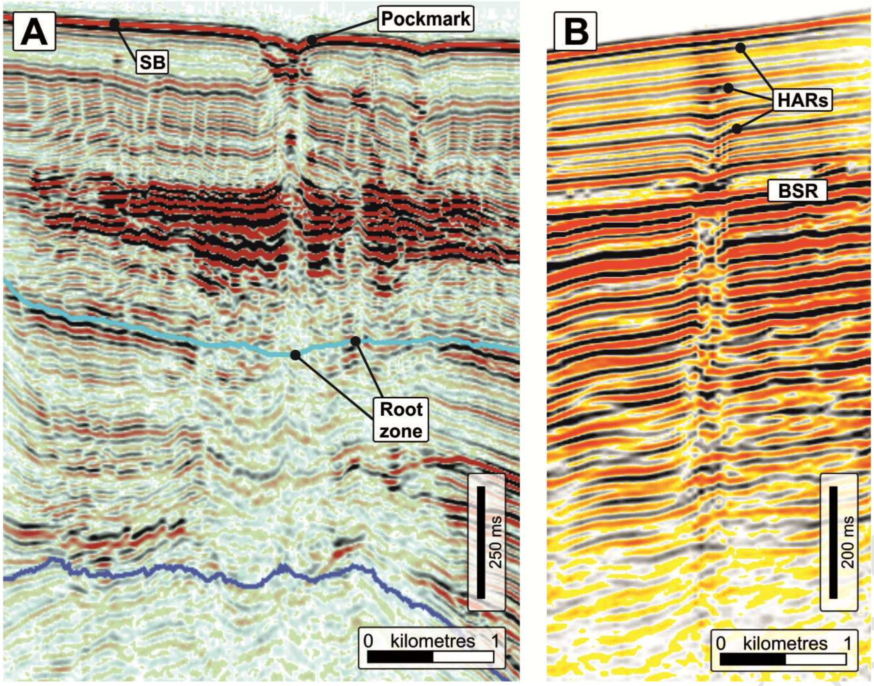

A
SB
Pipe
Root zone
Fluid source unit
Artefacts
Artefacts
250 ms
0 kilometres 2
B
SB
CR
AA
250 ms
0 kilometres 2

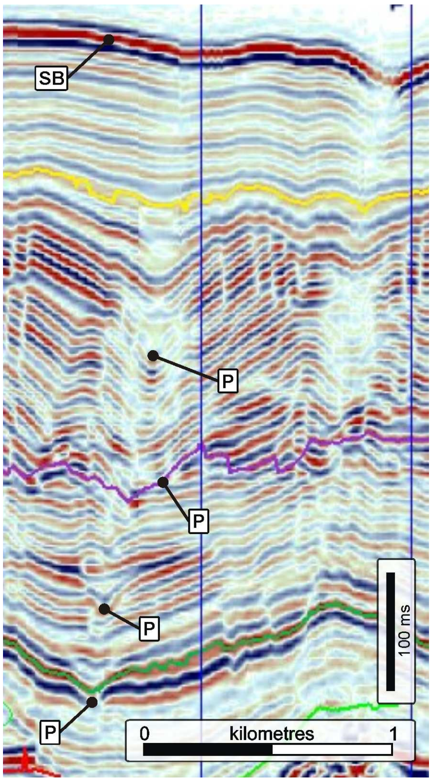

SB
HARs
OPAL A/CT
IP
MA
250 ms
Root zone
0 kilometres 1


A
250 ms
0 kilometres 2
B
250 ms
0 kilometres 1

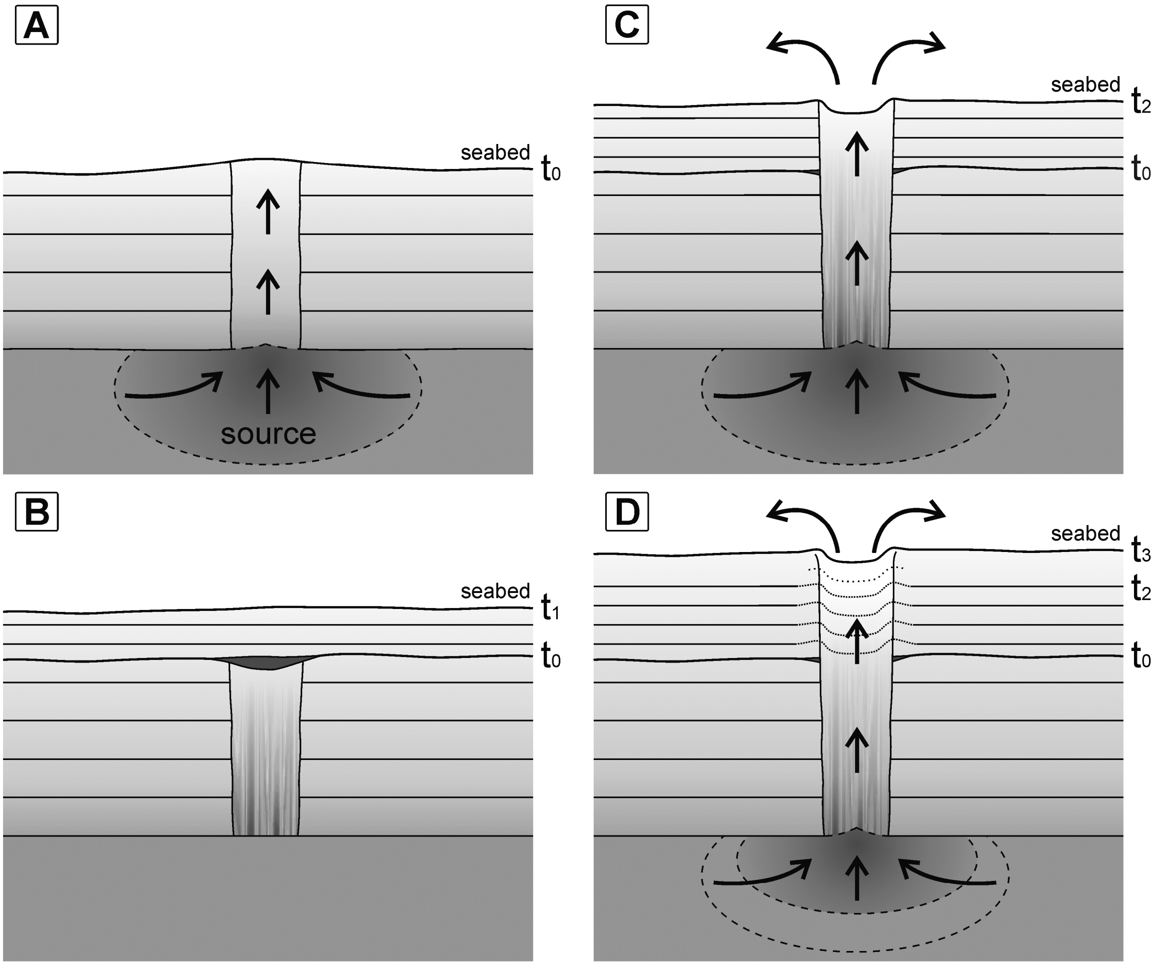

N
P
Q
0 kilometres 2

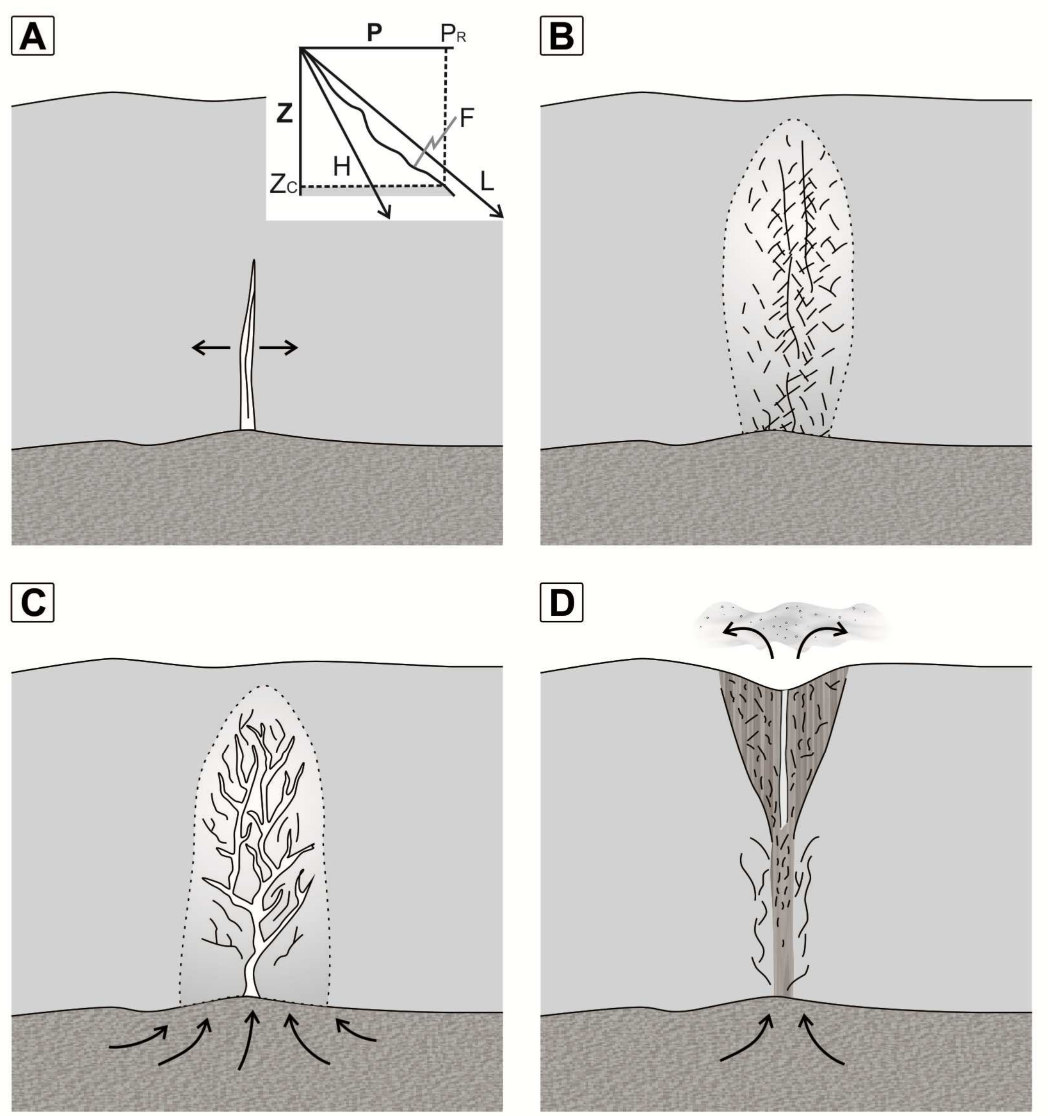

A
250 ms
0 kilometres 1
B
100 m
0 kilometres 1
C
SB
B
A
250 ms
0 kilometres 1

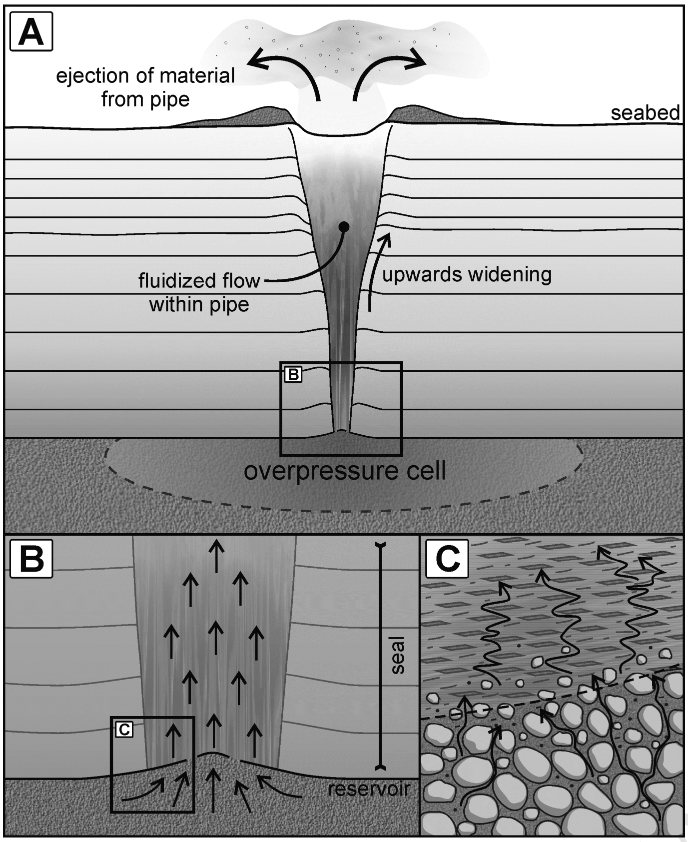

A
Pockmark
SB
Root zone
250 ms
0 kilometres 1
B
HARs
BSR
200 ms
0 kilometres 1

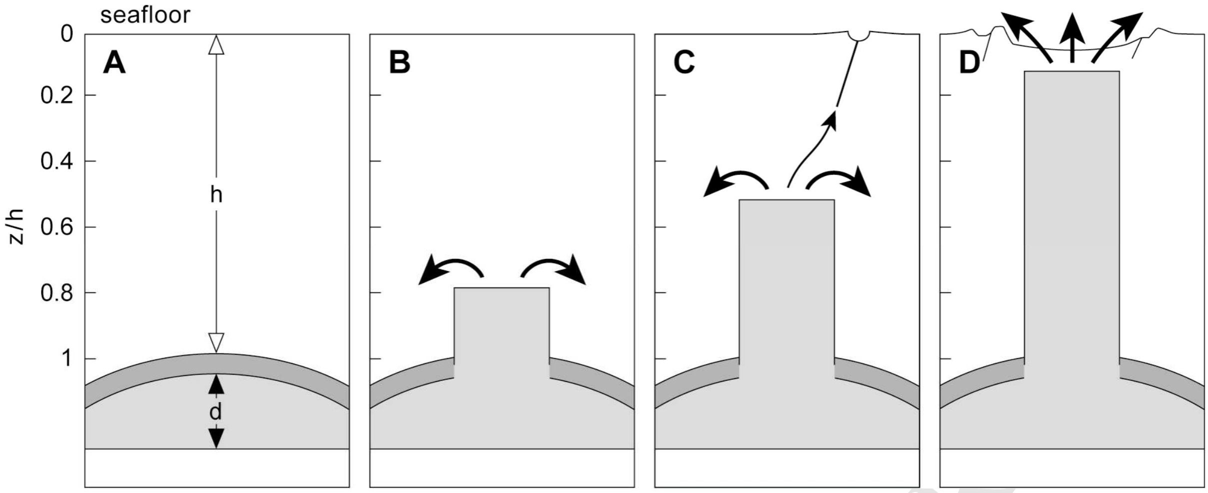


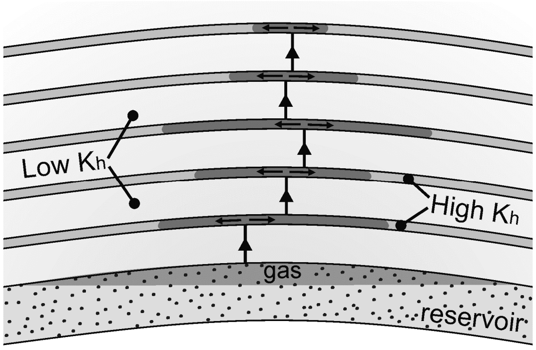
SB
P
P
P
P
100 ms
0
kilometres
1

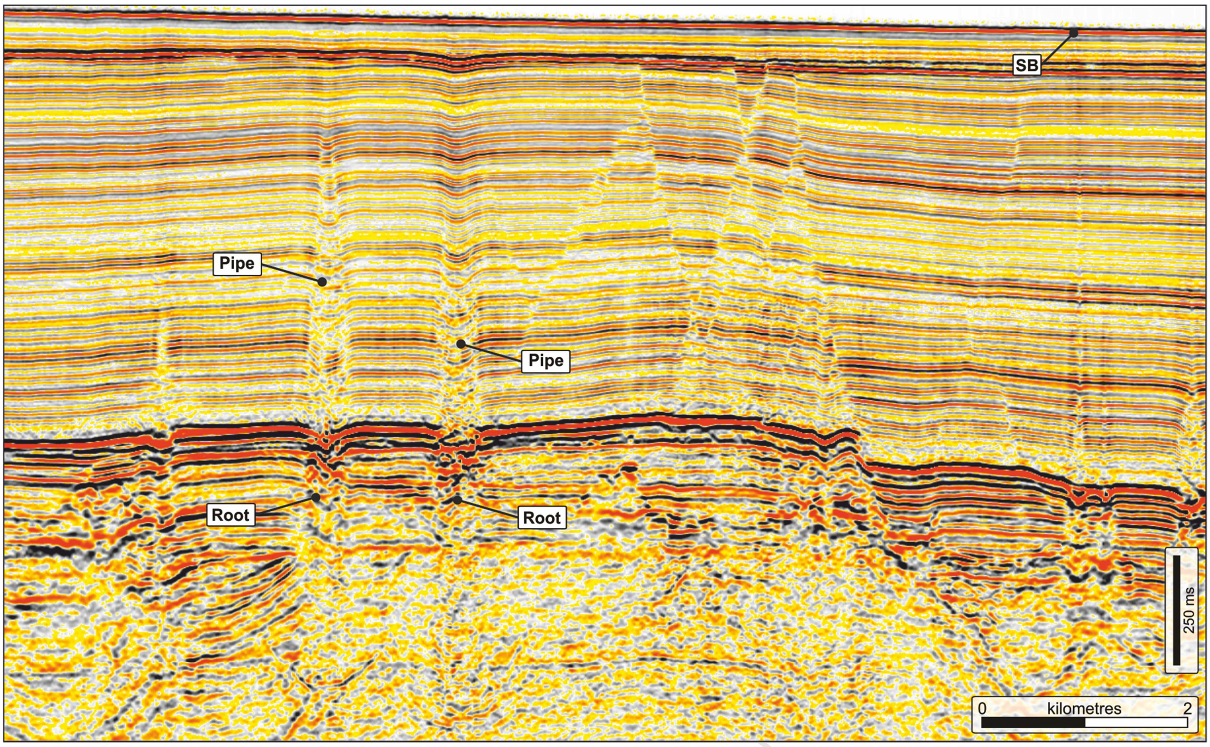

A
seabed
t_0
source
B
seabed
t_1
t_0
C
seabed
t_2
t_0
D
seabed
t_3
t_2
t_0


A
P
PR
Z
F
ZC
H
L
B
C
D


A
ejection of material from pipe
seabed
fluidized flow within pipe
upwards widening
B
overpressure cell
B
seal
C
reservoir
C


seafloor
0
0.2
0.4
0.6
0.8
1
z/h
A
B
C
D
h
d


Low K_h
High K_h
gas
reservoir


SB
Pipe
Pipe
Root
Root
250 ms
0
kilometres
2

Highlights for JMPG-D-14-00298

Cartwright and Santamarina

- Fluid escape pipes are formed by focused fluid expulsion, found in many petroliferous basins
- Characterized on seismic data by columnar zones of reduced reflection continuity
- Pipes are tens to thousands of metres tall, and tens to hundreds of metres wide
- Pipes are frequently associated with signs of free gas migration such as amplitude anomalies or cemented zones
- Genetic mechanisms include hydraulic fracturing, erosional fluidisation, capillary invasion, and volume collapse