Marine and Petroleum Geology 65 (2015) 126–140

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

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

Joe Cartwright [a, *], Carlos Santamarina [b]

[a] Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, UK
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, Mason Building, 790 Atlantic Drive, Atlanta, GA 30332-0355, USA

ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form
16 March 2015
Accepted 27 March 2015
Available online 6 April 2015

Keywords:
Fluid escape
Overpressure
Pipe
Fluid flow
Basins

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).

---

* Corresponding author.
E-mail address: joec@earth.ox.ac.uk (J. Cartwright).

http://dx.doi.org/10.1016/j.marpetgeo.2015.03.023
0264-8172/

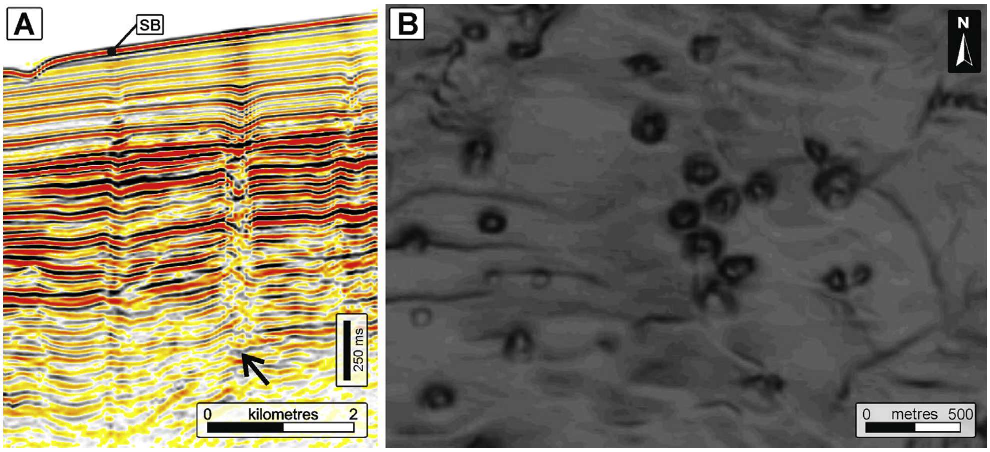

Figure 1. Seismic expression of fluid escape pipes. A: Vertical seismic profile through a series of fluid escape pipes from offshore Namibia (from Moss and Cartwright, 2010a). Arrow depicts the base of the pipe, SB- seabed. B: Coherence attribute time slice through a group of pipes showing the typical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

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 metres, fluid escape pipes may be important pathways for vertical fluid flow and secondary hydrocarbon migration in sedimentary basins (Berndt, 2005; Cartwright et al., 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., 2010; 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

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

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	<200 m?	N	Y	AAs		Davies and Clarke, 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. 2010	
Offshore Vancouver Is. Canada	100–200	<100	Y	N	AAs, blanking		Zuhlsdorff and 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	