Marine and Petroleum Geology 77 (2016) 865–881

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Shallow plumbing systems inferred from spatial analysis of pockmark arrays

Ana R. Maia [a,*], Joseph Cartwright [b], Espen Andersen [c]

[a] 3D Seismic Lab – School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3YE, United Kingdom
[b] Department of Earth Sciences, University of Oxford, United Kingdom
[c] Statoil ASA, Norway

ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form
29 June 2016
Accepted 29 July 2016
Available online 1 August 2016

Keywords:
Pockmark distributions
Spatial statistics
Shallow plumbing systems
Lower Congo Basin

ABSTRACT

This study describes and analyses an extraordinary array of pockmarks at the modern seabed of the Lower Congo Basin (offshore Angola), in order to understand the fluid migration routes and shallow plumbing system of the area. The 3D seismic visualization of feeding conduits (pipes) allowed the identification of the source interval for the fluids expelled during pockmark formation. Spatial statistics are used to show the relationship between the underlying (polarised) polygonal fault (PPFs) patterns and seabed pockmarks distributions. Our results show PPFs control the linear arrangement of pockmarks and feeder pipes along fault strike, but faults do not act as conduits. Spatial statistics also revealed pockmark occurrence is not considered to be random, especially at short distances to nearest neighbours (<200 m) where anti-clustering distributions suggest the presence of an exclusion zone around each pockmark in which no other pockmark will form. The results of this study are relevant for the understanding of shallow fluid plumbing systems in offshore settings, with implications on our current knowledge of overall fluid flow systems in hydrocarbon-rich continental margins.

1. Introduction

Pockmarks are evidence of highly focused fluid flow, and constitute one of the best-documented expressions of seabed fluid escape, occurring at a wide variety of marine environments (Judd and Hovland, 2007). They are shallow depressions on the seafloor, generally circular to elliptical in shape, with a diameter ranging from a few metres to hundreds of metres. Pockmarks are most commonly developed in soft, fine-grained sediments, which are remobilized or eroded by the expulsion of fluids of variable composition such as biogenic or thermogenic gas (methane), pore water, fresh water, and even oil (Berndt, 2005; Gay et al., 2006b; Judd and Hovland, 2007).

The latest advances in submarine imaging technology have led to the discovery of numerous pockmark arrays, particularly in the Holocene (Andresen and Huuse, 2011; Gay et al., 2006b, 2007; Hovland and Judd, 1988). The vast majority of pockmark studies describe a wide range of spatial distributions, from single isolated craters to large pockmark fields (Andresen and Huuse, 2011; Gay et al., 2006b; Judd and Hovland, 2007; Moss and Cartwright, 2010), reflecting the influence of underlying seal bypass systems. Pilcher and Argent (2007) and Gay et al. (2007) have presented descriptions of linear pockmark alignments related to structural features such as normal faults, suggesting that fluid migration through these discontinuities is favoured over a more pervasive flow through the sedimentary matrix. Gay et al. (2006a) and Davies (2003) interpret channel sand bodies as the shallow reservoirs supplying fluids to produce curvilinear pockmark trails. However, very few previous studies have explicitly identified the source layer(s) for the fluids involved during pockmark formation.

An extraordinary array of pockmarks is described here, formed at the modern seabed, offshore Angola, and based on a high-resolution 3D seismic survey. Two distinctive pockmark populations are compared and contrasted: one which is characterised by a semi-regular distribution, and one which shows pronounced alignments of pockmarks. By comparing these two sets and the feeder pipes that underlie some of the individual pockmarks, it is possible to describe in detail the shallow plumbing system of the studied area. We show that the linear alignments are entirely due to shallow normal faults. However, in contrast with previous

* Corresponding author.
E-mail addresses: MaiaAR@cardiff.ac.uk (A. R. Maia), joec@earth.ox.ac.uk (J. Cartwright).

http://dx.doi.org/10.1016/j.marpetgeo.2016.07.029
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studies, we further demonstrate that preferential alignment of pockmarks along fault strike is not due to flow focusing on the fault surface or the action of fault planes as conduits, but it is due to fault control of the position of feeder pipes that act as conduits for focused fluid escape during pockmark formation.

The main aim of this study is to explore the insights that pockmark distributions can bring on the question of source, timing, triggers, origin of fluids, and fluid migration routes, in order to improve our understanding of shallow plumbing systems in sedimentary basins.

2. Data and methods

The dataset for this study comprises a 3D seismic reflection survey from offshore Angola, covering an area of approximately 1600 km^2 in water depths ranging from 1425 m (1900 ms TWT) to 2440 m (3250 m TWT). Bin spacing is 12.5 m in both inline and crossline directions. The near stack volume used to study the subsurface displays an increase in acoustic impedance (hard reflection; black) as negative amplitude, whereas positive amplitudes characterise a decrease in acoustic impedance (soft reflections; grey). Seafloor depth conversions are computed using a seismic velocity of 1500 m/s for seawater. For the Pliocene-Holocene succession, a dominant frequency of 40–50 Hz yields a vertical resolution (λ/4) of 8.5–10.5 m, assuming an average seismic velocity of 1680 m/s for the shallow sediments (Bolli et al., 1978). The horizontal resolution is 25 m (2× bin spacing). Well data were not available from the study area. The lithologic and chronostratigraphic framework of the region was based on information provided by ODP Leg 175 sites 1075–1077 (Pufahl et al., 1998), and by published works on the stratigraphy of the Lower Congo Basin (Andresen and Huuse, 2011; Anka et al., 2013; Gay et al., 2007; Hempton et al., 1990).

To simplify the workflow, the study area was sub-divided into mini-basins 1 and 2 (MB1 and MB2), delimited by salt-related structures. The results and interpretations presented here are based on structure maps and seismic attribute maps (coherency, dip and amplitude) produced for key horizons, complemented with vertical seismic sections along areas of interest. Each horizon attribute map was examined in detail to detect pockmarks and potential fluid flow anomalies, and investigate their relationship to surrounding structures. ArcGIS 10.1 software was used to acquire locations and morphological measurements of pipes and pockmarks, map faults, and to compute spatial statistical analysis of pipe and pockmark distributions. The spatial statistical significance of these distributions was analysed using the following univariate spatial autocorrelation statistical methods: 1) Average Nearest Neighbour (Rn), 2) Anselin Local Moran's I cluster and outlier analysis (I_i), 3) Ripley's K Multi-distance Spatial Cluster Analysis (Ld), and 4) Density.

The **Average Nearest Neighbour (*Rn*)** measures the ratio of the observed average distance between each feature centroid and its nearest neighbour's centroid location ($\overline{D}_{Obs}$) to the expected average distance based on a hypothetical random distribution with the same number of features covering the same total area. The Average Nearest Neighbour ratio (Rn) is given as:

$$Rn = \frac{\overline{D}_{Obs}}{0.5\sqrt{\frac{a}{n}}}$$

where $\overline{D}_{Obs}$ is the mean observed nearest neighbour distance, n is the number of pipes or pockmarks, and a is the areal extent of pipe or pockmark coverage in the study area.

If the average nearest neighbour ratio is less than 1, the distribution exhibits clustering (the nearer to 0, the more clustered the distribution). If the ratio is greater than 1, the pattern trends towards dispersion. A random distribution yields a ratio of 1. To reject the null hypothesis that there is no pattern of pipe or pockmark distribution, the Z score is calculated. The Z score is a test of statistical significance that evaluates the standard deviation away from the mean for a normal distribution of the nearest neighbour distances (Rn):

$$Z = \frac{\overline{D}_{Obs} - 0.5\sqrt{\frac{a}{n}}}{SE}$$

$$SE = \frac{0.26136}{\sqrt{n^2/A}}$$

SE is the standard error, and A is the areal extent of pipe or pockmark coverage in the study area. Very high or very low Z scores are found in the tails of the normal distribution, which indicates it is very unlikely that the observed spatial pattern is there by chance.

The **Anselin Local Moran's I cluster and outlier analysis (*I_i*)** uses a set of weighted data points to identify spatial clusters of points with attribute values similar in magnitude, and to detect spatial outliers. It is used in this work to measure the spatial autocorrelation of pipe source intervals, i.e. whether pipes of a particular source are preferentially surrounded by pipes sourced either from the same or from a different interval. The Local Moran's I (Ii) statistic of spatial association is given as:

$$Ii = \frac{n\sum_i\sum_j w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_i\sum_j w_{ij}\sum_i(x_i - \overline{x})^2}$$

where n is the number of pipes indexed by i and j, x is the variable of interest or pipe source, $\overline{x}$ is the mean of x, and w_{ij} is a matrix of spatial weights. Pipes that are considered statistically significant outliers (pipes that have a statistically significant different source value from their neighbours) and clusters (pipes surrounded by others with a statistically similar source) have a local Moran's I (Ii) Z scores <-2 or >2, respectively. Pipes that are not statistically significant (i.e., that there is no spatial clustering of pipe source at the 95% confidence level) hold Ii Z scores between −1 and 1.

The **Multi-Distance Spatial Cluster Analysis** based on **Ripley's K-function** is a second order statistic that evaluates the spatial dependence (clustering or dispersion) of point data over a range of distances. The K function includes all neighbour points occurring within a given distance, rather than the distance to each point's single nearest neighbour. The analysis presented here implemented a transformation of the K-function referred to as $L(d)$:

$$L(d) = \sqrt{\frac{A\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n}k_{i,j}}{\pi n(n-1)}}$$

where d is the distance, n is equal to the number of features, A represents the total area of the features and $k_{i,j}$ is a weight (either 1 if the neighbouring point is within the distance of the target point, or 0 if it is not). The $L(d)$ method states that, given a random distribution of points, the expected value for any distance is the distance (d) itself (Mitchell, 2005). At any given distance, if the observed $L(d)$ values are above the expected values, the distribution is more clustered than expected for a random distribution. Lower and upper confidence envelopes for a random distribution are generated to indicate a statistically significant clustered pattern at any given distance.

PAST 3.06 software (Hammer et al., 2001) was used to detect pockmark alignments, and to perform directional statistics for one