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New statistical methods for investigating submarine pockmarks

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ABSTRACT

We investigate the applicability of some novel spatial analysis techniques, developed for studies of astrophysical datasets, to the analysis of spatial point data in sedimentary basins. The techniques are evaluated and compared with standard methods using two test areas that contain large numbers of submarine pockmarks developed in distributed arrays. The familiar Ripley *K* and Voronoi tesselation techniques are used, and the results are then compared with those obtained using more novel techniques, the correlation length and minimal spanning tree. The correlation length technique is found to identify the precise distances at which clustering occurs more accurately, making a physical interpretation more clear than is possible using the Ripley *K*. The minimal spanning tree is found to be powerful at identifying the space-filling nature of the pockmark distribution, and has the advantage of being immune to edge effects. The use of these two novel techniques permits more information to be extracted from the datasets, and demonstrates clear statistically significant differences between them, which are not detectable using standard techniques.

1. Introduction

Numerous geological features in sedimentary basins can be represented using spatial point data (Diggle, 2003). Examples include volcanoes, mud volcanoes, breccia pipes, blowout pipes or acoustic chimneys, kimberlite pipes, and pockmarks. Many of these features are the result of highly focused fluid flow, where the fluids involved are either magmatic, hydrothermal, or other types of mineralizing fluids containing hydrocarbons or metals. The spatial analysis of these point sources or conduits of fluids is thus of importance to those concerned with predicting resources in sedimentary basins, and also the retention of toxic fluids such as CO_2 (Cartwright et al., 2007).

The analysis of spatial point data is important in many other disciplines (Diggle, 2003), and recent advances in statistical techniques in astrophysics have the potential for wider application. The aim of this paper is to evaluate the applicability of these novel techniques for use in basin analysis. We focus on one specific type of spatial point data for this evaluation, submarine pockmarks, and examine whether using the novel techniques can elicit additional insights into genetic processes over and above those gained from using standard statistical methods.

Submarine pockmarks are widely distributed in sedimentary basins (Judd and Hovland, 2007) and have been reported by many workers. Increasing interest is being shown in pockmarks because they represent direct evidence of highly focused venting of high-pressure pore fluids (Cartwright et al., 2007; Hovland et al., 2010). They occur widely in areas of methane hydrate accumulation (Bunz et al., 2003; Gay et al., 2006; Van Rensbergen et al., 2002; Chand et al., 2008), and have been implicated in the bypassing of methane through the gas hydrate stability zone into the water column (Haacke et al., 2009; Hustoft et al., 2009; Netzeband et al., 2010; Paull et al., 2008).

Studies of pockmarks or closely allied fluid venting features have been largely descriptive (Garcia-Gil et al., 2002; Paull et al., 2002; Andresen et al., 2008; Gay et al., 2007; Van Rensbergen et al., 2007; Naudts et al., 2006). More recently, greater attention has been paid to factors influencing the spatial distribution of pockmarks and feeder conduits. For example, Pilcher and Argent (2007) noted the presence of alignments in their data, but attached no statistical significance to this observation. De Boever et al. (2009) performed a Variogram analysis on several elongated sets of tubular concretions, testing whether the perimeters of pockmark marks varied in a systematic way with the position within the elongated distribution. Rose plots were also used to demonstrate the directions of alignments of the concretions. Moss and Cartwright (2010) used a nearest neighbor analysis to demonstrate whether successive generations of pockmarks were clustered or dispersed and Moran's *I* to determine whether coeval pockmarks were grouped together in clusters.

Olu-Le Roy et al. (2007) used principal component analysis to identify correlations between species type and environmental

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factors. Galéron et al. (2009) and Li et al. (2007) performed similar analyzes. Other workers also calculated density and attempted to correlate it with gas fields and thickness of strata (Kelley et al., 1994; Rise et al., 1999; Rogers et al., 2006).

Here we investigate two study areas that contain large numbers of submarine pockmarks at or close to a discrete stratigraphic horizon. Large numbers of pockmarks occurring at a given horizon are usually referred to as pockmark fields (Judd and Hovland, 2007). The advantage of using a pockmark field to test spatial analytical techniques derives from the large numbers of spatial points and also from the fact that the pockmarks are developed within a short time period (Moss, 2010). This means that any statistical relationships that are derived from the analysis can be more simply related to the hydrodynamic regime operating at the time. If the pockmark field was emplaced in a longer time period, then spatial relationships would be much harder to link back to the hydrodynamics, because the pockmark distributions would reflect cumulative effects over a long period of time, rather than a snapshot of a specific hydrodynamic event of much shorter duration.

We apply several statistical techniques, with the aim of establishing effective methods for extracting physically relevant statistics simply from the positions of the pockmarks. In particular, we apply the familiar Ripley K-factor and Voronoi tesselation. We also introduce the correlation length and minimal spanning tree methods, which have become widely used by astrophysicists for the statistical analysis and characterization of star clusters (Cartwright and Whitworth, 2004). In Section 2 we describe the source of the raw data, and in Section 3 the construction of artificial comparison datasets. In Section 4 we describe the results obtained using the Ripley K and Voronoi tesselation techniques on these datasets. In Section 5 we introduce the correlation length and minimal spanning tree methods and compare their results with those obtained in the previous section. In Section 6 we discuss the results, and our conclusions and recommendations are in Section 7.

2. Observed data sources

2.1. Big Sur pockmark field

The Big Sur pockmark field in Monterey Bay lies <50 km from the California coastline on the lower continental slope of water depths of 700–1200 m (Fig. 1, left). The pockmark field contains 1000 large, circular seabed depressions or pockmarks. Big Sur pockmarks are conical depressions characterized by four-way dip slopes of c. 6°. Pockmark diameters range between 70 and 390 m (average 207 m), have an average ellipticity ratio of 1:1.17 (ratio between long and short axis length), and are between 8 and 12 m deep. The pockmark field covers an area of $<250\ \text{km}^2$ but is believed to extend beyond the limit of our dataset (cf. Paull et al., 2002). Pockmark density is spatially variable but can range up to 10 pockmarks/km. A missing strip of data toward the bottom of the field is due to the nadir footprint of the survey vessel (Paull et al., 2002).

2.2. Rosetta pockmark field

The Rosetta pockmark field lies in the Western province of the Nile Deep Sea Fan (NDSF), Mediterranean Sea (Fig. 1, right). The pockmark field is located <40 km from the Egyptian coast on the continental slope of water depths of 550–700 m. The pockmark field contains over 13,800 small unit pockmarks (cf. Hovland and Judd, 1988) and is believed to extend eastward beyond our dataset. For simplicity in handling the large dataset, a 2-km^2 study area was selected from within the pockmark field. The study area contains 1477 small circular unit pockmarks. The unit pockmarks are 5–41 m in diameter (average 17 m) and have an average ellipticity ratio of 1:1.1, with an average depth of 0.4–0.8 m. Pockmarks exhibit classic conical four-way dip structures with c. 6° slopes. Densities within the pockmark field are highly spatially variable and can range from <50 pockmarks/km^2 of the field edge to >650 pockmarks/km^2 in the center. Average study area pockmark densities range between 250 and 600 pockmarks/km^2.

2.3. Methodology

Both the Big Sur and Rosetta pockmark fields were recorded by multibeam echo sounder (MBES) bathymetric surveys (1998 and 2005, respectively). The surveys captured the echo sounder data at different resolutions (Big Sur at 30 kHz and Rosetta at 200 kHz) resulting in appreciably different bathymetric model cell sizes. The Big Sur data have a resolution of 25 m and the Rosetta data of 3 m. Consequently we are able to identify significantly smaller pockmarks in the Rosetta region, which would not have been resolvable in the Big Sur data. Both datasets were imported into a GIS (geographic information system) and interpolated into depth, slope angle, and slope aspect models. Pockmark coordinates were taken from the center of each pockmark as identified by the variation in slope aspect at the bottom of each depression. The pockmark rims were digitized by hand using depth, dip, slope angle, and azimuth maps of the seabed. The long and short axis of

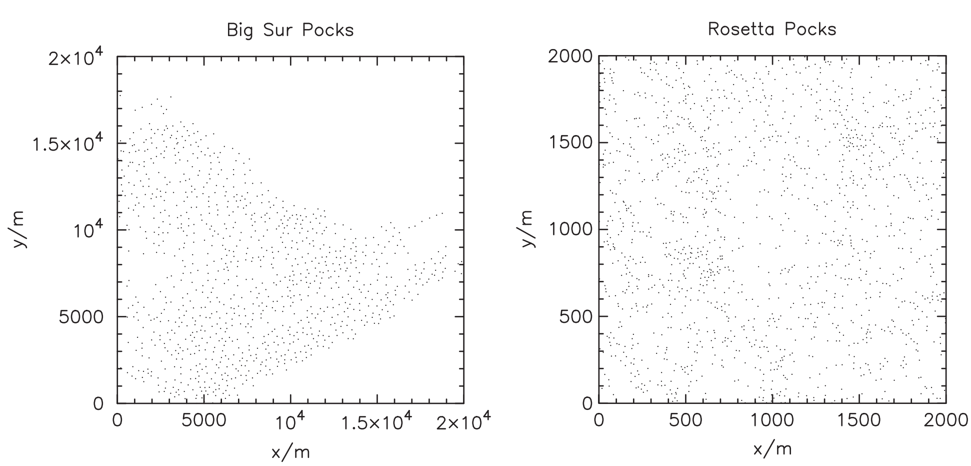

Fig. 1. Raw data positions. (Left) Big Sur; (right) Rosetta.