Computers & Geosciences 88 (2016) 97–114

Contents lists available at ScienceDirect

Computers & Geosciences

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

Case study

A descriptive study of fracture networks in rocks using complex network metrics

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ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form
24 December 2015
Accepted 29 December 2015
Available online 31 December 2015

Keywords:
Fracture networks
Complex networks
Centrality measures
Communicability
Topology of networks

ABSTRACT

In this paper we describe the static topological fracture structure of five rock samples from three regions in Eastern Mexico by the application of centrality and communicability measures used in the area of complex networks. The information obtained from fracture images is used to characterize the fracture networks. The analysis is divided into two groups of characteristics. The first provides a general summary of the fracture network through the description of the number of nodes, edges, diameter, radius, lengths and clustering coefficients. A second group of features centers on the description of communicability in the network by means of three indexes recently proposed. In addition, we apply centrality measures (betweenness, closeness, eigenvector and eccentricity) for quantifying the importance of nodes in the entire network. Finally, we identify a topology for fracture networks using a classification based on the degree of communicability. The most important results obtained in this work are focused in the topological characteristic patterns found in fracture networks applying the approach of complex networks that in general provide local and global parameters of connectivity and communicability.

1. Introduction

Fracture systems have a large impact on fluid flow and, therefore, a crucial influence on the productivity of geological formations especially in those of low permeability. Rock fracture systems have attracted much attention for a long time in fields such as hydrocarbon geology and hydrogeology (Cacas et al., 1990; Caine et al., 1996; Escuder-Viruete et al., 2003; Hitchmough et al., 2007; Narr et al., 2006; Sarda et al., 2002; Sarkar et al., 2004). Analysis for rock fracture systems is necessary in the evaluation of potential oil production in reservoirs (Bogatkov and Babadagli, 2007; Han et al., 2013; Hansford and Fisher, 2009; Witte et al., 2012). It is traditionally centered in the determination of fracture lengths, orientations, apertures, intensity and permeability; see for example (Dershowitz and Herda, 1992; Hakami and Larsson, 1996; Lee et al., 2011; Rouleau and Gale, 1985; Smith and Schwartz, 1984; Voeckler and Allen, 2012; Koike et al., 2015). In nature fracture networks are in 3D, and it is hard to study them from fracture networks in 2D only. In addition, fracture flow capability not only depends on the geometry and topology of the channel systems but also on other parameters such as viscosity, pressure gradient, rugosity of the surface (Berkowitz, 2002; Ghaffar et al., 2012). Nevertheless, in geological scenarios the analysis in 2D images can be useful in order to identify geometric and topological parameters that can support the characterization of the rock samples (Jafari and Babadagli, 2012; Santiago et al., 2012; Sarkar et al., 2004). In this work, we characterize the static properties in 2D fracture networks though which a fluid may flow in order to identify topological properties that may become important in conductive fractures.

Recent contributions in the study of fracture characterization are, for example, Lyman (2003), Santiago et al. (2014), Seetal and Natarajan (2010) and Wang et al. (2011). In particular, works focused in the topological analysis of 2D fracture systems that apply classical graph theory are reported (Andresen et al., 2013; Bour and Davy, 1998; Hardebol and Bertotti, 2013; Sanderson and Nixon, 2015; Santiago et al., 2014; Yang et al., 1995). These authors focus on computer image processing tools, techniques for extracting the rock fracture system from images, fracture tracing, extraction of features of fractures such as length, width, spacing, density, roughness, aperture and determination of orientations, detection and quantification of cross and ending points of the fractures, and in general computation of distributions of all of these attributes. In previous works (Santiago et al., 2012, 2014) a methodology is proposed for the identification of regions of

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http://dx.doi.org/10.1016/j.cageo.2015.12.021
0098-3004/

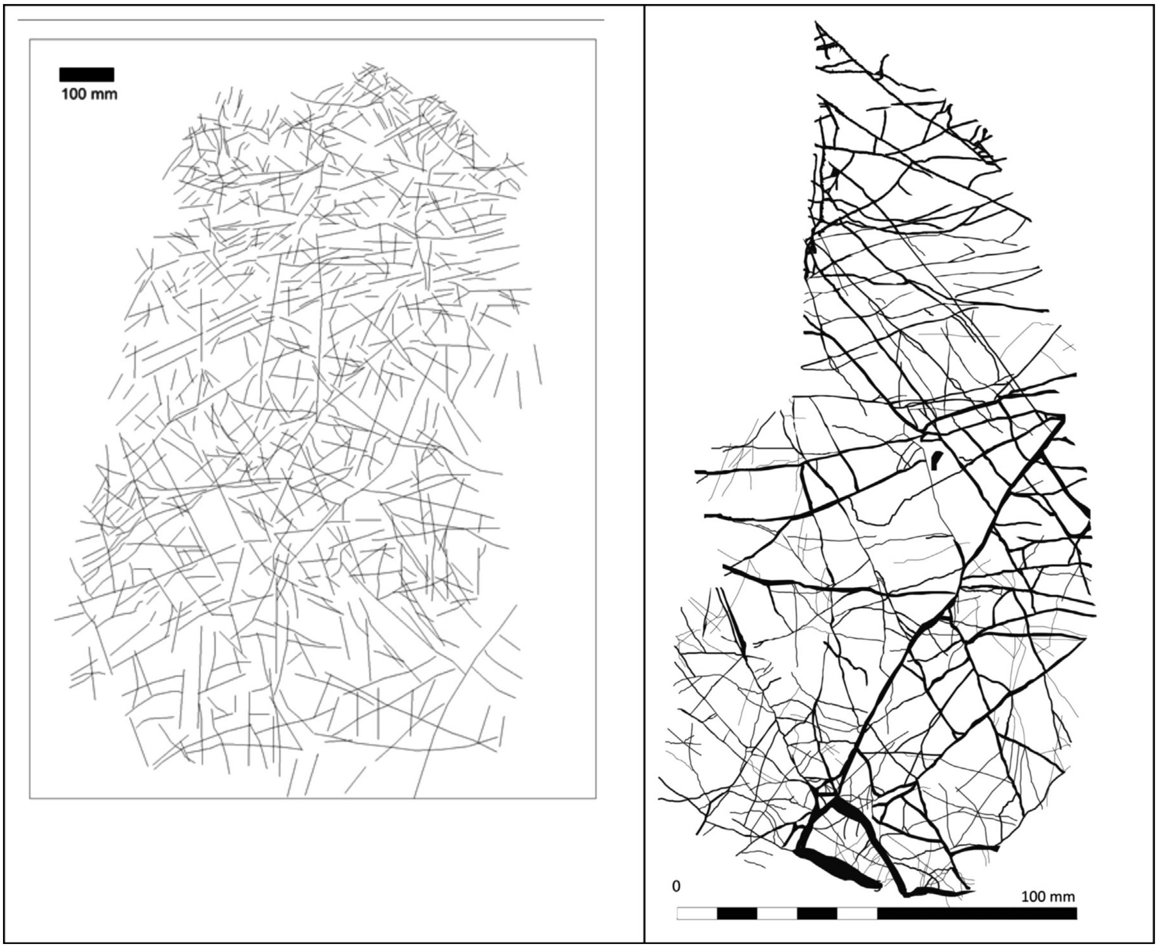

Fig. 1. Samples of original fracture networks. (Left) Sample of fractures JT-6 with number of nodes and links of 663 and 728, respectively. (Right) Sample of fractures MM with number of nodes and links of 1567 and 1996, respectively. A scale bar (mm) is included on each figure.

interest through a preprocessing of fracture images in rocks. Noise removal and filtering are applied to enhance the image quality and to facilitate further processing, where the rock fracture system is obtained after transforming it into a binary image.

In this work, for the analysis of the fractures in rocks, we use information from two-dimensional binary images where connected multiple fractures form a network. The five samples of rocks we analyze come from three different locations of South-Eastern Mexico, one of them (MM) comes from an outcrop (Jurassic–Early Cretaceous) located in Xochitlán, Chiapas; the sample labeled with CH-2 comes from the Northern Golf of Mexico (Paleocene-Eocene), and samples JT-3, JT-6 and JT-8 (Tithonian) are belonging to the Campeche region. These samples are studied due to the interest of characterizing naturally fracture reservoirs; and all these samples come from naturally fractured rocks except CH-2 that corresponds to a clayey-sandstone reservoir. Depending on the nature of the rock fracture system (cores, outcrops, hand-samples), the revealed structures have significant heterogeneity (Baker and Kuppe, 2000). Knowledge of the topological structural properties of such fracture systems may provide useful information for understanding their organization, function and dynamics. For establishing the relation between insights gained from this study and the fracture features that modelers need (Dershowitz and Herda, 1992; Lee et al., 2011), we characterize topological properties of the fracture networks by using quantitative measures used in complex network (Estrada, 2010a; Newman, 2003, 2010) in order to find distinctive patterns that modelers could use in practice. Furthermore, a topological approach that classifies networks in four classes is applied to fracture networks that is essentially based on local and global communicability. One of the most common indicators for identifying the most important nodes within the network is the centrality of a graph or network, and in this work, a set of centrality measures is applied and all of them are correlated themselves. Three of such measures stand out as important: closeness, betweenness, and eigenvector centrality (Bonacich, 1987; Freeman, 1977; Sabidussi, 1966).

The organization of the document is presented as follows. In Section 2, a fracture network is defined as a complex network describing its main elements. In Section 3, the images of fracture networks used are presented, first showing the original sources of fracture images, and then displaying them as graphs; also in this section, the methods and formulations of metrics applied are described. In Section 4, the results of the application of centrality and communicability measures and the relations among them are presented. The method for identify the topological class for fracture networks is also described in this section; and finally, in Section 5, we comment our conclusions and relevant points.

2. Fracture networks as complex networks

In general, a network is defined as a tuple $G=(V,E)$, where V is a finite set of nodes, and E is a relation between nodes. In an undirected graph, the relation is symmetric, that is, the links are bidirectional, and it is named unweighted graph when the value of connection is one if there is a relation between two nodes and