Journal of Structural Geology 31 (2009) 628–636

Contents lists available at ScienceDirect

Journal of Structural Geology

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

The spatial heterogeneity of structures in high porosity sandstones: Variations and granularity effects in orientation data

Jiulin Guo [a,*], Kenneth McCaffrey [a], Richard Jones [b], Robert Holdsworth [a]

[a] Reactivation Research Group, Department of Earth Sciences, Durham University, Durham DH1 3LE, UK
[b] Geospatial Research Ltd, Earth Sciences, Durham University, UK

ARTICLE INFO

Article history:
Received 25 April 2008
Received in revised form
17 December 2008
Accepted 21 December 2008
Available online 18 January 2009

Keywords:
Geospatial analysis
Spatial variation
Fracture heterogeneity
Spatial aliasing
Deformation bands

ABSTRACT

Despite many studies on the scaling and geometrical properties of fracture systems, much less attention has been paid to analysing their spatial characteristics. At a well exposed section at George Gill, Appleby, we investigated the spatial heterogeneity in deformation band orientations in a high porosity sandstone using bootstrap, variogram and hierarchical analysis methods. At metre-scales the structures displayed multimodal orientation patterns with orthorhombic symmetry whereas at 20 m scales they appeared bimodal. Our analysis shows that this situation arises due to a combination of small-scale noise superimposed on a regional trend related to the presence of a nearby major fault structure. We suggest that this type of geospatial analysis can be used as a general tool to investigate spatial heterogeneity in structural systems. We also suggest that these types of granularity and aliasing effect impact the prediction and modelling of rock properties and they therefore warrant further investigation.

1. Introduction

Our knowledge of the three dimensional (3D) characteristics of fracture networks is limited due to their inherent complexity, which results from their initiation and mutual interaction, and from constraints imposed by the incomplete sampling of rock volumes. The prediction of rock properties such as permeability, strength, seismic velocity and anisotropy in the Earth's subsurface, however, requires a complete understanding of the geometry and spatial attributes of fracture networks (e.g. Crampin et al., 1980; Barton and Zoback, 1992; Laubach et al., 2004; Philip et al., 2005; Ortega et al., 2006). Currently the model inputs for fractured hydrocarbon reservoirs and aquifers necessitate the characterization of fracture geometries, sizes and spatial properties at a range of scales (Fig. 1). These data are generated from well logs and core (one dimensional (1D), centimetre resolution), seismic attribute mapping (two dimensional (2D), tens-of-metres), and analogue outcrops (2D data at centimetre scales) (e.g. Gillespie et al., 1993). In this paper, we present a methodology that can be used to investigate the spatial heterogeneity of structures in a deformed host rock. Where we use the term 'fracture', we are referring in a general sense to any planar discontinuous surfaces or zones (such as joints, faults and deformation bands) generated by brittle deformation processes. The example given in this paper is a dataset collected from a high porosity sandstone outcrop and here we use the term 'deformation band' in a specific sense to refer to structures in the case study.

The attributes of fracture systems visible at different resolutions typically form a 'hierarchy' (Fig. 2). '*Granularity*' in a general sense refers to the relative size, scale, level of detail or depth of penetration that characterizes an object or activity (Zadeh, 1979). In this study, we illustrate the importance of granularity effects in analysing a fracture dataset collected from a natural system. This effect is not the same as scaling which is the extent to which structures are similar at different scales of observation and has been widely investigated for various dimensional and spatial properties for fractures (c.f. Bonnet et al., 2001).

The problem we initially encountered was that when viewed at the first-order hierarchical level (the complete deformation band dataset in this example), the orientation patterns seemed relatively simple, i.e. two clusters that are NE- and SW-dipping respectively. However, in most parts of the outcrop at metre-scale (a lower hierarchical level), we observed more complexity, with three or more orientation clusters developed.

In this paper, using a variety of statistical analyses, we demonstrate that substantial local scale variation in orientation is superimposed on overall trends at the scale of the outcrop as a whole. Our results show that spatial heterogeneity in fracture orientations

* Corresponding author.
E-mail addresses: jiulin.guo@yahoo.co.uk (J. Guo), k.j.w.mccaffrey@durham.ac.uk (K. McCaffrey).

0191-8141/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2008.12.002

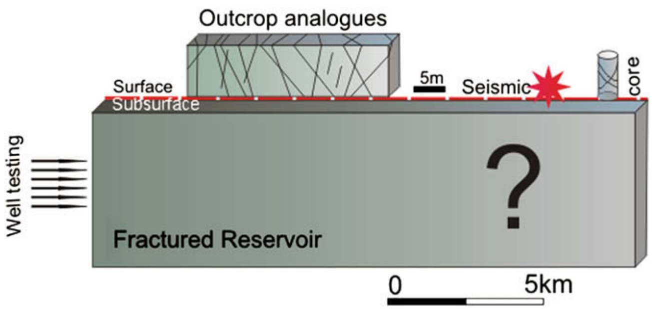

Fig. 1. Schematic diagram illustrating the techniques used to study fracture networks at different scales. All this information is required to predict the complete fracture network in three dimensions in the subsurface.

can be delineated by analysing the fractures at different resolutions, provided the locations of individual structures are also recorded. In our example, if the data are averaged at a coarse scale then important characteristics of the fracture system remain hidden. This granularity effect causes a type of spatial aliasing that is known in other systems (e.g. seismic processing, time series analysis) and requires explicit understanding if more realistic prediction of natural fracture network geometries is to be successfully made in the subsurface.

2. Geological background

We studied an outcrop of fractured aeolian red sandstone that occurs in the Permo-Trias Vale of Eden half graben at George Gill, Appleby, located east of the English Lake District and 20 km SE of Penrith (Fig. 3, NY716190), (Versey, 1938). Cataclastic deformation bands and deformation band clusters are well developed along both sides of a stream valley. Anastomosing deformation bands are ubiquitous and are best displayed on a 40-m long, south-facing cliff on the northern side of the valley (Figs. 3 and 4a). The host sandstone preserves widespread cross-bedding, is highly porous and poorly cemented, whereas the deformation bands (and deformation band clusters) are much finer grained, better cemented, and have lower porosity. As these low-porosity deformation bands can act as preferential groundwater flow paths, the orientation, continuity and physical connectivity of the bands determines their effectiveness as sealing or flow-reducing structures (Sigda et al., 1999; Fossen et al., 2007).

Deformation band density changes abruptly approximately 20-m from the eastern end of the cliff (Fig. 4a). A single deformation band is a narrow zone of grain fragments (ca. 1 mm), representing a single slip event with a small displacement; a deformation band cluster is formed by coalescence of single deformation bands (Aydin and Johnson, 1978). Both single deformation bands and deformation band clusters display a diffuse bimodal distribution pattern on stereonets (Fig. 4a and b). In the zone of low fracture density toward the east, three (multimodal) sets of mutually cross-cutting fractures in the form of single deformation bands can be recognized in the field (Fig. 4b and c). They are similar to the arrays of deformation bands in the Entrada and Navajo sandstones in southeastern Utah, where the faults form a network that usually has a rhombohedral pattern (e.g. Aydin and Reches, 1982; Shipton and Cowie, 2001; Johansen and Fossen, 2008). In the high density zone, the deformation band clusters almost obliterate the host rock entirely (Fig. 4d). Viewed as a whole, the deformation band clusters appear to be distributed into two broad groups (bimodal) striking generally NW–SE and dipping moderately to steeply either SW or NE (Fig. 4a). Sub-horizontal beds are offset across deformation bands in the low density zone typically by 1–2 cm at most, and by around 5 cm in the high density zone. Rare slickenlines found on a fracture plane beneath the cave are dip-slip, plunging SW (Fig. 4a and e). At other localities along Hilton Beck near Red Brow (NY708201), 1 km NW from George Gill, slickenlines are more commonly developed on the polished fault surfaces, and also show a dip-slip normal sense (Fig. 3). Faults that exhibit slickenlines around Hilton Beck and George Gill generally trend NW–SE, suggesting a regional NE–SW extension.

At the microscale, the host rock consists of ca. 80% quartz and ca. 10% feldspar grains, most of which are rounded and loosely packed (Fig. 5a). Cementation in the host rock is mainly due to pressure solution that occurred along the contacts between adjacent grains. In the inner zones of single (ca. 1 mm wide) deformation bands, grains are rotated, ruptured and more tightly packed than in the host rock (Fig. 5b). The offset for a given single deformation band is generally not obvious as simple discontinuities with offset grain fragments are absent. Slip surfaces can, however, occur within bands or, more commonly, along or within zones of multiple deformation bands, representing a more mature development stage for the deformation bands (Fossen et al., 2007). In deformation band clusters (ca. 5 cm width), the original grains are intensively brecciated to form very highly compacted cataclasites. Shear

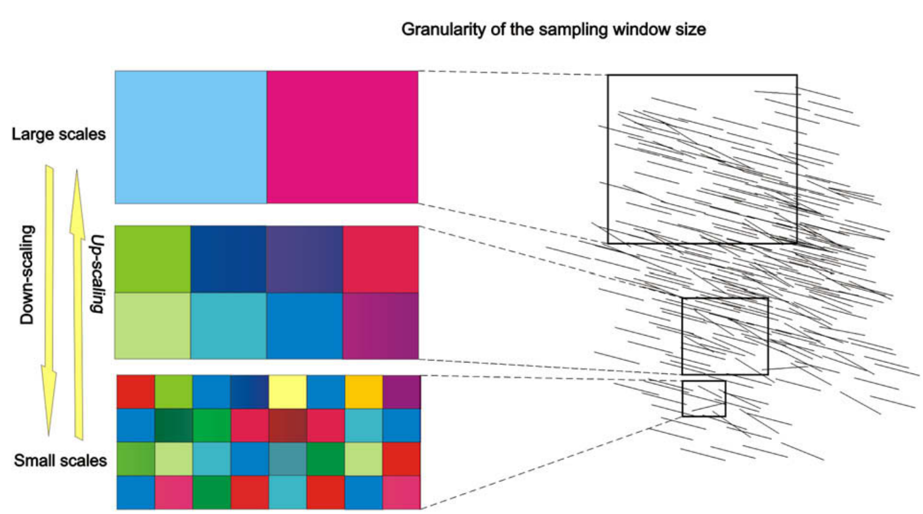

Fig. 2. Schematic diagram illustrating the granularity of a sampling window system. The colour maps show a hierarchical relationship between measurements from different sampling window sizes: the greater variety of colour at smaller scales compared with that at larger scales illustrates greater variation. Lines on the right are a schematic fracture network that is sampled at different window sizes shown as black boxes.