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Journal of Structural Geology 27 (2005) 1778–1787

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Characterizing stress fields in the upper crust using joint orientation distributions

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Received 27 July 2004; received in revised form 15 April 2005; accepted 16 May 2005
Available online 9 August 2005

Abstract

Linear elastic fracture mechanics predicts that joint orientation is controlled by the stress field in which the joints propagate. Thus joint sets are effective proxies for stress trajectories during joint growth. Complexity in joint orientation indicates stress trajectory variability, a phenomenon quantified using an eigenvalue method that measures dispersion of joint normal vectors (i.e. poles) around the mean vector. Ratios between the eigenvalues of a joint orientation tensor give the clustering strength (ζ) and the shape factors (γ) of the distribution.

A joint set that forms in a relatively isotropic rock subject to a rectilinear stress field should exhibit strong clustering and small random orientation variation that can be described by the Fisher statistical model. However, most joint orientation distributions in bedded rocks have non-random variation, greater in strike than in dip. This relative stability of the vertical stress orientation is strongest when joints are bounded by bedding interfaces, reflecting the tendency for deflection in the local stress field arising from the growth of side cracks, joint segments and adjacent joints in joint zones. Even when joint growth across bedding interfaces indicates negligible strength anisotropy, joint orientation distributions reflect less joint–joint interaction during vertical growth than during horizontal growth. As strike variation grows due to the presence of a non-rectilinear stress field, the orientation data better fit a Kent statistical model. Joint sets formed during fold development or in rocks with irregular bedding boundaries are more weakly clustered with Fisher-like orientation distributions. Orientation distributions for joint sets formed throughout a stress rotation have Kent-like shapes that indicate the magnitude of stress trajectory variation and clustering strength that depends on the joint density at each increment of the stress rotation.

Keywords: Joint set; Rectilinear stress field; Joint orientation distribution; Overburden stress; Tectonic stress; Fisher statistical model; Kent statistical model

1. Introduction

Joints provide records of stress orientation at the time of propagation (Pollard and Segall, 1987). Provided the stress difference during joint propagation was sufficient to allow two relatively closely spaced joints to pass each other without deflection (i.e. Olson and Pollard, 1989), joint orientation data indicate the extent to which the principal stress trajectories remained parallel across a sample volume (Engelder and Geiser, 1980). If a rectilinear stress field governed propagation throughout the affected rock volume, poles to individual joints cluster strongly about the mean pole of the joint set. Alternatively, joint poles cluster weakly around the mean pole of the joint set if the principal stress trajectories were non-parallel spatially and/or changed orientation over time.

Joint patterns in the foreland portions of some mountain belts have well-defined orientation modes suggesting that portions of the upper crust are subject to rectilinear stress fields (e.g. Melton, 1929; Babcock, 1973; Hancock et al., 1984; Dunne and North, 1990) (Fig. 1A). Furthermore, the contemporary tectonic stress fields in the upper crust of eastern North America and northwestern Europe appear rectilinear to a first approximation (Zoback, 1992). However, joint patterns in orogenic forelands more often have weak or multiple orientation modes suggesting that rectilinear stress fields in the upper crust are the exception rather than the rule (Fig. 1B and C). In these latter cases, confusion arises when defining a joint set based on strike alone, because weak orientation modes can arise from a non-rectilinear stress field (e.g. Parker, 1942; Verbeek and

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doi:10.1016/j.jsg.2005.05.016

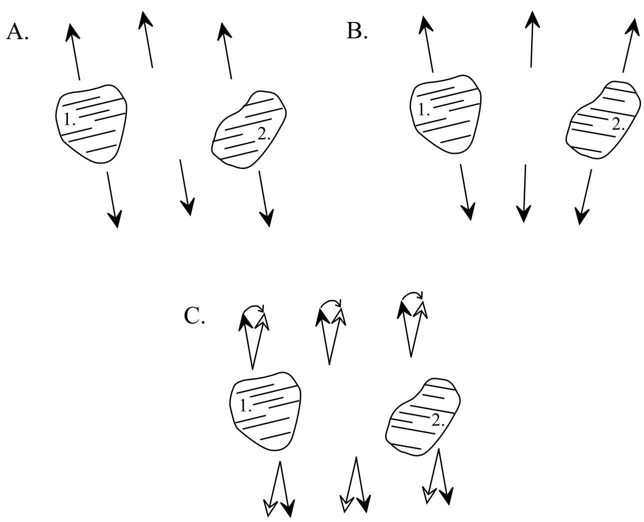

Fig. 1. Diagrams of joint patterns at outcrops separated by covered intervals. (A) A hypothetical regional joint set has the same orientation from outcrops 1 to 2. (B) A hypothetical regional joint set changes in orientation from outcrops 1 to 2 due to a radial stress field. (C) Two hypothetical joint sets develop in the region due to temporal variation in the stress field.

Grout, 1983; Laubach and Lorenz, 1992; Arlegui and Simon, 2001) (Fig. 1B) or through time during the regional rotation of a rectilinear stress field (e.g. Engelder, 2004) (Fig. 1C).

An analysis of a regional stress field using dikes around Spanish Peaks shows that stress trajectories were not parallel at the scale of the dike set (Odé, 1957). Rock discontinuities like bedding, faults, joints and inclusions like concretions also perturb regional stress fields (e.g. Olson and Pollard, 1989; Rawnsley et al., 1992; McConaughy and Engelder, 1999). In this context, the question that we raise and address is whether stress fields in the upper crust are *ever* rectilinear even at the scale of a sample volume the size of an outcrop. If not, we must conclude that as in the rock adjacent to the Spanish Peaks stocks (Odé, 1957), localized stress heterogeneities always add complexity to the stress field, and hence fracture pattern. Taken at face value, orientation data from the World Stress Map suggest that stress trajectories at scales larger than the outcrop are not strictly parallel even in places like the upper crust of eastern North America (Zoback, 1992).

Our approach to answering the question about the scale of rectilinear stress fields in the upper crust is to use the dispersion of orientation for a joint set as a proxy for the degree of variability of stress trajectories in a rock volume as a function of some combination of space and time. All joints in a set formed in a rectilinear stress field and hosted by an isotropic material should be parallel, and, if measured perfectly, their normal vectors (i.e. the projections of the poles in the lower hemisphere) should plot at a single point on a spherical projection. For any real joint set, however, the poles to joints plot in a region on the sphere, with their point concentration decreasing away from a mean vector (Fig. 2).

As long as joints propagate without being deflected by the presence of neighbors, we presume that joint sets formed in a rock displaying material isotropy and subject to a rectilinear stress field will have the strongest clustering about the mean orientation. In this case, joint set data would be subject only to random variation in orientation arising from the propagation of side cracks (e.g. Lacazette and Engelder, 1992) causing the overlap of joint segments (e.g. Hodgson, 1961) and the growth of joint zones (e.g. Engelder, 1987). These factors plus measurement error should yield a data set with dip dispersions equal to strike dispersions. Poles to such joints sets would fit the Fisher statistical model, where dispersion about the mean vector is assumed to be circular, i.e. unvarying with direction (Fisher, 1953).

When three-dimensional fracture variation is quantified in the literature, the Fisher model is most often applied under the assumption that joint dispersion is primarily governed by random variation (e.g. Priest, 1993; Song et al., 2001; Kemeny and Post, 2003; Engelder and Delteil, 2004). However, inspection of joint distributions on stereographic projections reveals that joint dispersion is not always random and that, specifically, strike dispersion generally exceeds dip dispersion (Fig. 2; Table 1). When joint dispersion is not random, the tightness, shape and orientation of the vector concentration reflect stress field complexity at the time of jointing and overlap of joint segments, as well as the compass's precision and the skill of the operator. By comparing joint distributions from various tectonic settings and noting the differences between strike and dip dispersions, we can assess the extent to which horizontal tectonic and vertical gravitational stresses remain rectilinear during jointing.

We apply the eigenvalue ratio method of Woodcock (1977) to quantify the distribution of joint poles in a set (Fig. 3). To assess the effect of increasing stress complexity on joint set dispersion, we analyze joint orientation data from horizontal sedimentary rocks, horizontal sedimentary rocks subject to a stress field rotation, folded rocks, and folded rocks subject to stress field rotation (Table 1). To demonstrate the effect of rock properties on joint set dispersion, we compare joint orientation data from black shale whose minor anisotropy arises from a pervasive compaction under overburden stress with data from bedded sediments whose major anisotropy arises from a change in lithology. In the former case, vertical joint propagation encounters little change in fracture strength whereas in the latter case there is a large contrast in fracture strength from bed to bed. From these results, we conclude that eigenvalue ratios of joint normal vectors are convenient for assessing stress complexity during fracturing, determining whether a joint sample represents one (unimodal) or more (multimodal) sets, and deciding which probability density model for the orientation data (e.g. Fisher, 1953 or Kent, 1982) applies to the joint set.